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Workability and strength attributes of RCC: Effects of different chemical admixtures and resulting paste

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Workability and strength attributes of RCC: Effects of different chemical admixtures and resulting paste

by

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Program of study committee:
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DEDICATION

This work is humbly and gratefully dedicated to
"The Teacher"
for His loving and ever-resilient effort

सुप्रणीतो जलौघो हि कुरुते कार्यमुत्तमम् ।
श्रन्धं जड़ं बलं प्राहुः प्रणेतव्यं विचक्षणैः ।।

महाभारत

Only a well-designed channel performs its functions best.
A Blind inert force necessitates intelligent control.

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ACKNOWLEDGEMENTS

At the conclusion of this research, more than as a matter of duty or gratefulness, in my recollection, retrospection and prospect, I am obliged to express my acknowledgements to the latent efforts of many including different institutions. I realize that I could only attempt to briefly thank them and with meagerly human words.

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Personnel of several DOT's, who responded to my communications and in quite unexpected ways need a word of appreciation. The list is long and a collective acknowledgement is not comprehensive. Amongst others, the IADOT staff was very supportive whenever I needed to use their test facilities. The National ready-mix concrete association's staff was also responsive to my queries. A nice thing to communicate with them was all of them tried to answer my questions giving me quite a range of perspectives. Tim Dolen (United States Bureau of reclamation) was supportive in the initial phases of this work and also supported my attempts of communicating with the hydraulic side of roller compacted concrete community.

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Steffes is a person who would give you the shirt off his back if he thought it would help you". I also enjoyed the support I received from Bryan and Jeremy. I am especially thankful to Jeremy for the lighter and distracting moments in the lab and for making me laugh when I was mostly focusing on work.

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Having had opportunities to meet and discuss my research with Dr. David Pittman was an honor. His insight on my research topic helped me appreciate this material at greater depths. During my discussions with him, I had opportunities to see a very well educated and detailed teacher in him. Some of the ways in which he explained me the concepts were very insightful. Apart from enjoying learning under his tutelage, I was also inspired to keep asking one question "so what?".

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If it would not be for all those who professed concrete technology over past couple of centuries, and more this research would not have taken shape. And those who helped advance relevant areas of material sciences and civil engineering. Their distinct contributions to the scientific, engineering and in-practice development has brought us to the level of understanding that is mostly taken for granted. The writings of Adam Neville, Sandor Popovics, T.C. Powers, P.K. Mehta have had a profound impact on my cultivation of interest in concrete technology. They very much inspired me by their unconventional and in-depth thinking. There are many others who have toiled to build the lineage and the body of knowledge and my appreciation goes to them as well.

It was very courteous of my first advisor, Dr. Halil Ceylan to have arranged for all the financial support during the period of my graduate studies. He did so in most troubled times, for which I will be ever-grateful to him. During my studies, the most wonderful and satisfying feeling of working with him was the judicious free hand that he most gracefully offered me. This in fact allowed me to follow some scientific paths rather than remaining purely engineering. As I stand near completion of this work, I am understanding how important it is sometimes to discriminate oneself from the limiting nature of engineering research. Dr. Ceylan's tenacity, inspiring resilience and an always willful attitude to help is very much appreciated.

My association with my second advisor, Dr. Peter Taylor, who is a highly learned student, has made long-lasting professional impressions on my mind. Amongst many other things, that he, by his mere presence diffused in me, his ability to always remain humble, grounded and practical was most stimulating. His encouragements were very subtle and timely. Of the earnings, I have made by spending several hours with him, often ending up arguing, my most treasured earning can most succinctly be summarized as - having a grave presence of mind and understanding of "the human" nature. He represents a beautiful fabric of scientific learning crossed over a clear understanding of human relations.

I feel it to be my fortune to have had extended opportunities of talking on different aspects of pavement technology with my third advisor, Dr. Kasthurirangan Gopalakrishnan. His ability to tolerate, while being patient at the same time, always kept

me inspired. Of the greatest and most invaluable gifts, that I have most graciously received from him is his ability to focus. His presence made me follow the same. My nomadic tendencies were most gently curbed by his grave, timely and carefully selected word of caution. I have learnt a great deal from him and not just modern science.

At the conclusion, I would like to thank my friends who have helped me during my attempts for educating myself. At the completion of this education, I feel a deeper level of ignorance and am facing the paradox of "*more you study, more you become aware of how little you know*". Although the world might see me as an expert, while the fact is not so and hence this is an acknowledgement to its humility.

ABSTRACT

Roller compacted concrete (RCC) is a drier consistency concrete proportioned with dense graded aggregates and has lesser paste content. Primarily owing to its drier consistency, the fresh and mechanical performances of RCC are distinctly different from conventional concretes. The objectives of this work were three fold. The first objective was to explain the anomalous behavior of fresh RCC in terms of different components of workability. The second objective was to explain the mechanisms of strength development in terms of paste quality and quantity. The final objective was to explain the roles of different chemical admixtures (water reducers, retarders, rheology modifiers, air entraining agents, dry cast products, etc.) in influencing the workability and strength performances of RCC.

It is observed that the relative volume and quality of the paste, in addition to combined aggregate grading, affect the overall workability of mixtures. The workability of concrete is characterized in terms of cohesion, angle of internal friction, air content, compactibility, and consistency retention over time. Air content plays a decisive role in influencing the performances of concrete. The resulting mobility of the paste influences the compactibility, which in-turn decides the strength as well. RCC shows anomalous behavior in terms of mechanical strength as shown by deviations in the Abrams' law. It is argued that water-binder ratio is not a comprehensive parameter to explain the overall concrete behavior and trends.

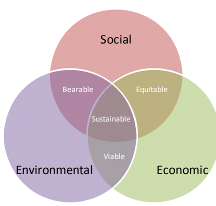
A significant body of knowledge is added in terms of the use of chemical admixtures in RCC. Atypical behaviors in influencing the fresh and hardened properties are explained by offering plausible mechanisms in terms of binder-admixture interactions. Irrespective of the admixture type, higher than normal dosages are required for RCC.

Keywords: roller compacted concrete, aggregates, paste quality, paste quantity, water/binder, aggregate/binder, air, workability, cohesion, friction angle, compactibility, gyratory compaction, consistency, strength, plasticizer, superplasticizer, air entrainer, rheology modifier, dry cast, robustness, method of mixtures, sustainability

CHAPTER 1 SUBJECT OF THE RESEARCH

SYNOPSIS

This introductory chapter lays the foundation stone for this dissertation. At the inception, the chapter discusses about the general subject matter, its scope and need for research. Once a clear identification of the subject matter is established, the chapter then discusses the possible applications of roller compacted concrete (RCC) as a pavement material and presents a synoptic comparison with other cement based pavement materials. The topic of the research is then tied in with the concepts of sustainability and green infrastructure.



Key words: context, roller compacted concrete, applications, sustainability, pavements

CONTENTS

1.1 Context of the subject

The reported work is situated in multiple fields of studies. However, the focus is located in the portland cement concrete area of civil engineering materials. And within portland cement concrete, this work is specifically dealing with the studies on the fundamental material behavior of a special type of concrete, which is known by the names such as roller compacted concrete (RCC), zero-slump concrete and dry concrete. RCC is used for construction of hydraulic structures and has an historical record of over half a century. For more than last quarter of the past century, this material has been sporadically applied for pavement construction. Figure 1-1 shows the construction of an RCC pavement.

RCC is a special mixture of controlled, dense-graded aggregates, portland cement and possibly pozzolans (fly ash), mixed with just enough quantity of water so that it could self-stand when paved using either a slip-form paver (without needle vibrators) or asphalt paver and is compacted using a vibratory roller. Once compacted well, the concrete is cured using conventional methods.

The body of knowledge for RCC as a material for hydraulic structures is rather comprehensive and detailed; however, a similar depth of knowledge is missing for RCC as a pavement material. When this work was undertaken, the industry was facing typical problem of infancy, whereby the knowledge about RCC as a concrete material for pavements was just growing. The fundamental information on the effects of several materials-related variables influencing the performance of fresh and hardened properties was not available. This raised many concerns pertaining to successful use of RCC for various pavement applications. The issues were not pertaining to the structural safety and adequacy, which happens to be comparable to conventional pavement concrete. However, these were more directed towards the practical problems of procedures for material selection, their mixing, placing and compactibility. In addition to this, the primary issues were tied up with the surface smoothness, riding quality and cold-region specific durability problems. There is no doubt that the industry has been viewing this with its conventional eye set for routine pavement concrete. Hence, substantial amounts of educational efforts have been and are being invested by organizations like the Portland Cement Association, Southeast cement association to name a few. This also offers avenues for further research and development on several matters including the materials related issues.

Figure 1-1 Construction of RCC pavement [1]

RCC has very bright potential for its application as a pavement material. Moreover, it has long-lasting, inherent benefits that render it as an environment friendly, sustainable, easily constructible and a cost effective material. The real issue is that of apprehension arising out of the lack of know-how and the muscular mechanism to spin the right momentum for getting to the root of the problem. There have been few studies on RCC and some of the latest developments include that in the mixture proportioning procedures and are reported in reference [2].

As stated earlier and in addition to the core area of work, the subject areas that this work has touched include mechanics of soil, rheology, calorimetry, chemistry of binder-chemical interactions and compactibility of different civil engineering materials including concrete. These are secondary or sub-areas of work; individual references to these are made and concepts are applied as and when required.

1.2 Versatility of forms and applications of roller compacted concrete

As stated above, RCC enjoys its multi-faceted nature and adaptability over a wide range of pavement applications. Figure 1-2 shows a comparison of cement based pavement materials. Of the available materials, RCC distinctly differentiates itself by offering much wider range of applications, lower unit cost/unit cement quantity and can function as a secondary or a primary pavement layer including wearing course.

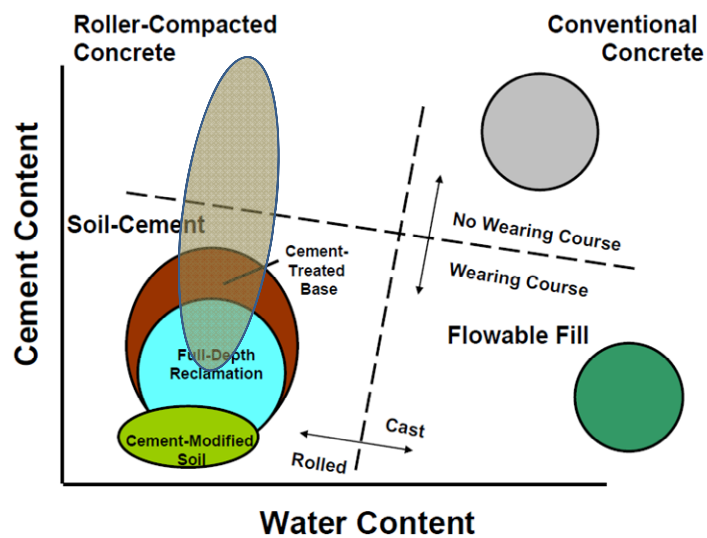


Figure 1-2 A comparison of cement-based pavement materials

RCC can be widely used for varied purposes and the following is a sampling:

- pavement bases;
- low-maintenance roads and parking;
- industrial access roads surfaced with or without concrete overlay;

- inlay rehabilitation;
- fast track intersections;
- shoulder constructions;
- city streets;
- industrial roads:
- heavy-duty pavements for ports and
- Airport pavements (e.g. taxiway).

1.3 Driving mechanisms: industry and sustainability

Noted professor of energy and resources from the University of California, Berkeley, Prof. Richard B. Norgaard offered the following comment in his famous book entitled *Development Betrayed: The End of Progress and a Coevolutionary Revisioning of the Future*, which was conceived as harsh, but is an inconvenient truth and unflinching reality:

“Modernism, and its more recent manifestation as development, have betrayed progress…while a few have attained material abundance, resource depletion and environmental degradation now endanger many and threaten the hopes of all to come… Modernism betrayed progress by leading us into, preventing us from seeing, and keeping us from addressing interwoven environmental, organizational, and cultural problems.” [3]

The concept of sustainability addresses these issues from a balanced perspective. The primary harmony is required between the social, environmental and economic developments in a manner such that we achieve a balance between our needs and the needs of the future generations. Figure 1-3 shows the interplay of these three aspects. Abundant literature is available on this subject matter, but a further discussion is considered to be beyond the scope of this work.

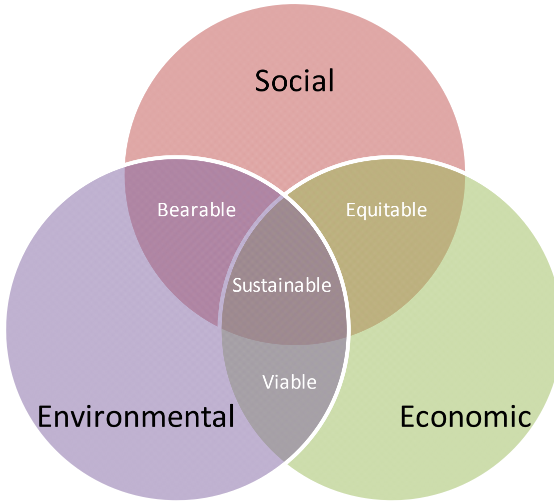
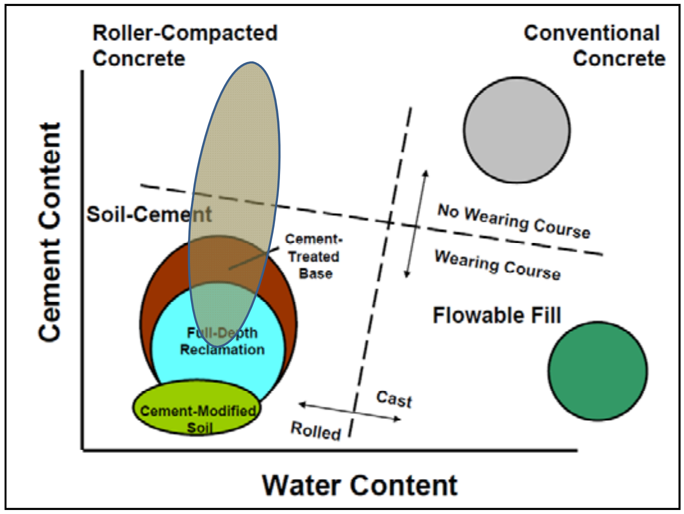


Figure 1-3 Sustainable development [4]

Civil engineering constructions are no exception to following of the principles of sustainability. In fact being one of the closest and owning the highest share of responsibility from a social vis-à-vis professional perspective, it becomes a primary duty of every civil engineer to think about sustainability. Driven by sustainability, the civil engineering community is driving itself towards sustainable development and this process addresses the construction materials related issues as well.

SUMMARY

This chapter explained the scope of the subject within the boundaries of which this research was conducted. An introduction to the concept of roller compacted concrete (RCC) was offered along with versatile nature of its application. It was commented that this material has a wider range of applicability in various pavement applications. Besides, it has a potential to compete and surpass the properties of other cement based pavement materials.



RCC has evolved over the past 25-30 years and is a well-used, adequately understood material for hydraulic construction. The body of knowledge of RCC for pavement applications is in its infancy, thus stipulating research with an objective of having better fundamental understandings. This will also open doors for furthering the advancements in improved applications.

With the emergence and overall growth of human race, sustainability has become a cause of greater than ever concern; inviting attention from different perspectives in the society. Having a high carbon footprint, portland cement concrete could be considered as a "culprit construction material", if not proven otherwise. It therefore becomes the elemental responsibility of concrete technologists to make it more sustainable, and environment friendly. There is going to be no 'one' solution to this grave problem and attempts at the levels of science, technology, and management shall be required to address it.

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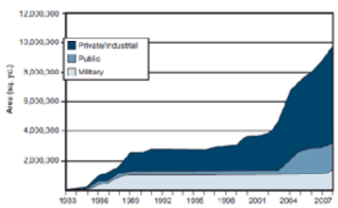
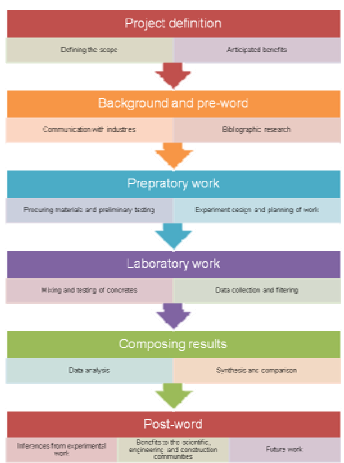
3. Norgaard, R.B., Development betrayed : the end of progress and a coevolutionary revisioning of the future. 1994, London: New York. xiii, 280 p.

4. Wikipedia. Ecoloigcal economics. 2010 [cited 2010 13 April]; Available from: http://en.wikipedia.org/wiki/Ecological_economics.

CHAPTER 2 PROLOGUE AND SCHEMA





SYNOPSIS

This chapter establishes the stage for the presented work. Initially it addresses several issues from industrial, scientific and engineering perspectives. Later on, these issues are tied with sustainability. The chapter then moves on with defining the problem statement and describes the three-fold objectives. A synoptic overview of the sub-objectives follows. Subsequently the chapter offers a detailed description of the approach taken, scheme of work and an overview of the architecture of this dissertation.

Keywords: sustainability, construction industry, problem statement, scope of work

CONTENTS

2.1 Research motivations

For over a quarter of a century, roller compacted concrete (RCC) has been applied for constructing pavements. The applications have been sporadic until recently. The increasing awareness of the engineering advantages of this type of paving material in conjunction with its multi-faceted nature in terms of its applications is gathering interest in engineering community and the much-needed momentum for its wide scale applications.

Unlike conventional concrete materials, including asphalt and portland cement concrete, this material is not widely studied; neither in the labs nor in field. There is thus a lack of comprehensive body of knowledge covering varied aspects RCC as a material. Being in its infancy both in terms of our knowledge about its theory and construction practice, there are many unanswered questions, which are eventually culminating in apprehension for applying this material for pavements. There are much awaited, variously positioned scientific, engineering and construction enquiries that are yet to be addressed to mobilize the muscular strength of the industry to accept this as a material of primary-choice. The following section identifies some of these issues and offers brief discussions about each.

2.1.1 Industrial context

The world cement production has increased over the years with a dramatic transition over this decade. The world production of cement was 1.6, 2.31 and 2.8 (estimated) billion metric tonnes in 2000, 2005 and 2008 respectively [1]. Figure 2-1 represents a comparative plot of cement production. Such gigantic leaps in the cement production also raise a red flag on the construction industry. The construction industry that is now learning and imbibing sustainability aspects into practice is alarmed by the environmental distortions such quantities could cause. Hence, it is becoming increasingly and exceedingly important priority to learn the methods of judiciously using cements and find ways and means to save this material for the future generations. This will also include an in-depth look at the conventional ways in which we have been producing and utilizing cements. Perhaps regulate the production and extend the serviceable shelf-life of cement could be an alternative.

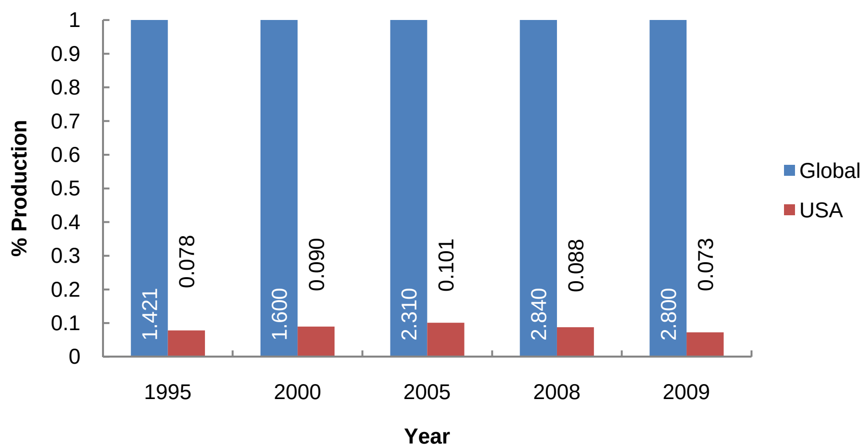


Figure 2-1 Trends in cement production. Numbers represent quantities in billion metric tonnes.

The concrete consumption is increasing globally and with the Nations attempting to build sustainable infrastructures, the need for pavement concrete is increasing as well. It is estimated that that the global production of concrete as of 2006 was approximately 7.5 billion m^3. In United States more than 89, 000 km of highways are paved with concrete [2]. The annual production of ready mix concrete has undergone dramatic change. The annual production of concrete was 359.9 million m^3 in 2008 in the countries in European Union [3]. Figure 2-2 shows the trends of ready-mix concrete production in United

States; the production was approximately 329 million m^3 in 2007. It is important to note that the demography of global production of cement and concrete is also changing.

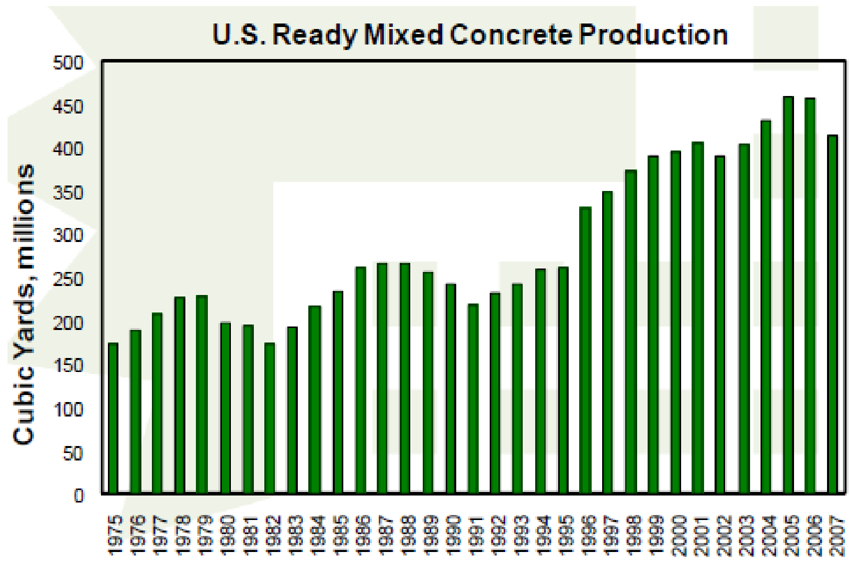


Figure 2-2 Concrete production in United States of America [4]

Another interesting fact to note is the average cement consumption of concrete mixtures. It is reported that the average cement consumption in 2008 were 291, 350 and 270 kg/m^3 in countries in the European Union, Russia and United States [3]. The author has himself worked with construction specifications where the minimum cement requirement was 350 kg/m^3 for highway pavements. In United States the typical pavement mixtures are 6 bags mixes meaning around 335 kg/m^3. In addition, it is quite surprising that there is a great imbalance between the cement strength, targeted concrete strength and the minimum cement content requirement vis-à-vis the water/cement ratio. For example, there are typically three grades of cements produced in India with specified minimum characteristic strengths of 33, 43 and 53 MPa. The trend is so poised that last and highest-grade cement is produced in much higher quantities than the other two and with average characteristic strengths surpassing 70 MPa. Still the minimum cement quantity is maintained at the same level and driven by the desire to complete the constructing the National infrastructure at faster pace, these mutually contradicting facts are either ignored or unseen. Actually, this represents a case of great National wastage. Juxtaposing this fact with our efforts for sustainable infrastructure makes these naked truths look more alarming than ever. Furthermore, it is surprising that with the modern generation chemical admixtures at disposal, we are not blending the facts that by using chemical admixtures in concretes, the strengths and other desired properties could potentially be achieved with enhanced cement consumption reduction.

Our convenience now is going to cause greater inconvenience to the future generations not only from the cement perspective, but also from the much depleting natural resources used in making concrete. This includes the mineral aggregates and water at first cut. In addition to this, the other byproducts from other industries are coming under stricter environmental regulations, which could one day cause an alarming trend. The chemical industry is no exception to this and the chemical admixture production is already coming under the scanner of the environmental protection agencies. The admixtures are mostly organic chemicals and therefore have high-embedded carbon (ECO2). It is estimated that the typically retarders, plasticizers and superplasticizers have ECO2 values of 80, 220 and 760 kg/tonne respectively [5].

The ageing infrastructure always poses challenging problems. The industry is invariably and steadily looking for better products. A tested technology usually takes somewhere between 10-15 years to be assimilated by the industry. Depending on the benefits a typical product can offer, urged by sustainability initiatives, and forced by the environmental protection agencies, the construction industry is increasingly growing in its speed and acceptability to newer technologies and materials.

RCC is one such technology, the merits of which are yet to be clearly and lucratively established by lab exploration and field trials. The lab investigations have responsibility of conducting exhaustive studies and report the results with an objective of establishing the advantages and disadvantages of this material. The industry is increasingly accepting RCC technology, but at the same time it needs the much-needed establishment of the body of knowledge to place their trust into. Chemical admixtures are the ingredients of choice of modern concrete production. Establishing their roles, benefits and understanding the limitations of use in RCC is becoming increasingly crucial. Since these products can offer superseding advantages, they need a detailed address in various lab and field studies.

Table 2-1 An example of mixture comparison between conventional pavement concrete and RCC [6]

Kind of concrete	Flexural strength after 28 days kgf/cm^2	Maximum size coarse aggre-gate (mm)	Fine aggre-gate ratio s/a (%)	Water/ cement ratio W/C (%)	Unit Coarse aggre-gate volume	Unit weight(kg/m^3)					Weight ratio of cement (%)	Water content (%)
						Water	Cement C	Fine aggre-gate S	Coarse aggre-gate G	Additive agent		
RCCP	60	20	44.0	40.6	0.80	104	256	936	1,241	0.640	10.6	5.4
Conventional	53	40	33.0	42.5	0.81	138	325	599	1,341	0.812	14.5	7.8

The use of RCC is growing in its applications. (Refer to Figure 2-3). Moreover, this concrete type offers a better potential for cement savings and is more robust in accommodating various aggregates from virgin mineral aggregates to marginal, recycled and contaminated as well [7-10]. Table 2-1 presents a comparison with conventional concrete mixture. With its inherited potential for cement saving, enhancing it further not only in terms of cement savings, but also in its aesthetic appearance appears to be very much desirable.

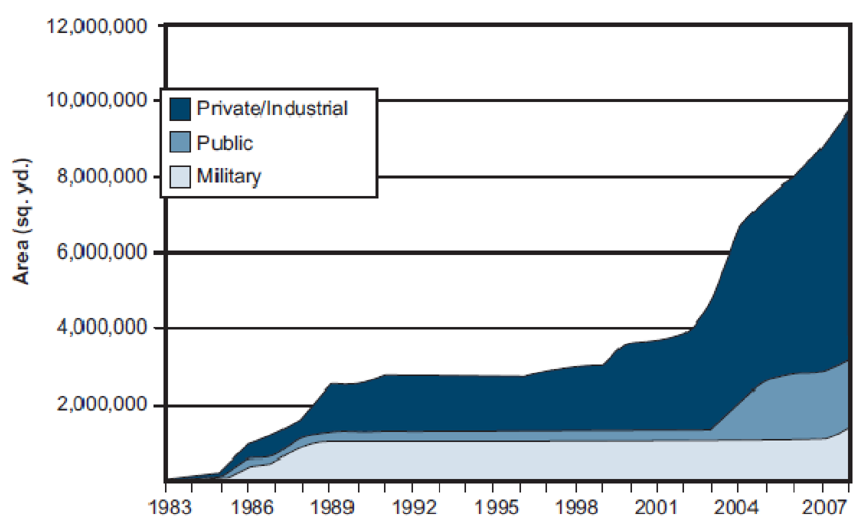


Figure 2-3 Growth in RCC applications in United States of America [11]

2.1.2 Scientific requirement

In retrospect, construction industry worldwide has been gradually yet selectively embracing the use of chemical admixtures. There are inherent complexities involved in understanding binder reactions, physio-chemical interactions between binders and chemical admixtures. The conventional education that civil engineering community undertakes is not geared towards studies of this nature. In addition, most construction material laboratory's analytical capabilities are not sufficient to study the associated chemistry. Consequently, the research on chemical admixtures was more or less restricted to a few, affiliated primarily with chemical formulations.

The chemical admixtures sales are increasing along with the preferences of their uses. For example, plasticizers remain a favorite, but the superplasticizer sales and consumption is increasing. Figure 2-3 shows a comparative breakdown of the admixture sales in Europe. It is said that over 75% of the ready-mixed and precast concrete plants use admixtures in Europe [12].

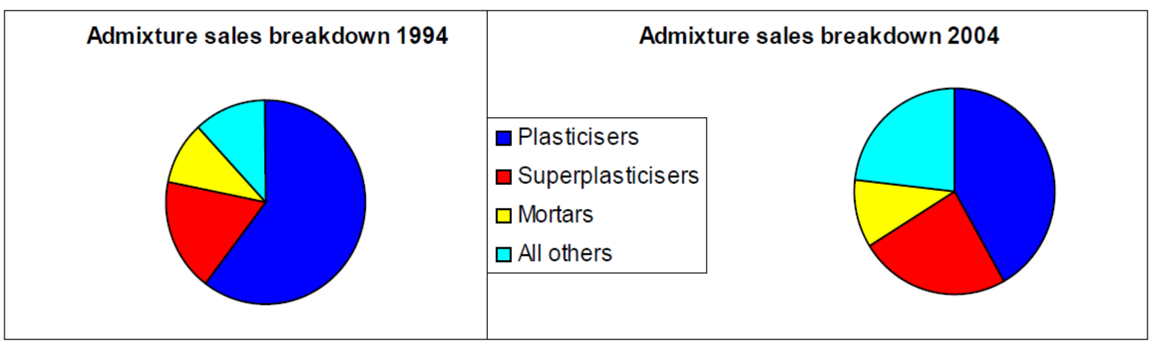


Figure 2-4 Admixture sales breakdown for 1994 and 2004 in Europe

Sustainability considerations are attracting the focal point of construction materials. Chemical admixtures are no exception to this. Admixtures, if aptly used, can potentially render economic benefits derived through mixture optimization, savings in mixing, placing and compacting/consolidating costs, reduction in curing costs, extended lifespan of a structure and enhanced durability. Each of these benefits can be derived with proper evaluation, selection and application of either a single or multiple admixtures. This however is concrete type and mixture proportion specific.

The role that an admixture could play in a family of concrete may be different in another. This requires a fundamental understanding of not only the chemical formulation of admixtures, but also the interactions that they could have due to alterations in the mixture compositions and the nature of resulting concrete. The intended benefits that can be achieved for a particular family of concrete could be greatly enhanced with an in-depth understanding of the nature and optimization of admixture type and quantity.

2.1.3 Engineering enquiry

RCC tenders the benefits of having higher flexural strength, high shear strength, high density, low absorption, enhanced aggregate interlock, no dowels required, no requirement of forms, no requirement of frequent joint sawing and a very durable concrete material. All these factors make it a very promising material from its speedy construction, long life cycle, higher durability, and lower construction and maintenance cost.

Of the primary drawbacks that restrict wide scale acceptance of RCC are its poor aesthetic appearance and lack of clarity about its freeze-thaw performance. This also includes a clear guideline on mixture selection and procedures for further optimizing the mixture composition. The author is of the opinion that the primary reason for this is our lack of understanding about the material's beauty from various perspectives. This therefore paves a way for having a better appreciation for the material properties and how they individually and collectively offer graded benefits and how each of these can be used up to their optimal potential.

One of the key issues of field compaction is the differential it creates in the density with depth. The primary reason for this could be the vibration response of the paste for a given compaction effort could differ at different levels [13-14]. Figure 2-4 shows the variations in permeable voids (and hence densities) for the different slices of RCC mixtures containing various cement contents. Moreover, the vibrations themselves may not be commensurate to compact the concrete uniformly to similar degree of compaction at all depths within a layer. The roles of optimizing a mixture proportion to render sufficiently fluid paste to respond uniformly to the vibrations in a given aggregate system are crucial and need a fundamental understanding of paste vis-à-vis aggregate behavior in response to vibrations. The above mentioned commentary is a result of author's discussion with Dr. David Pittman [15].

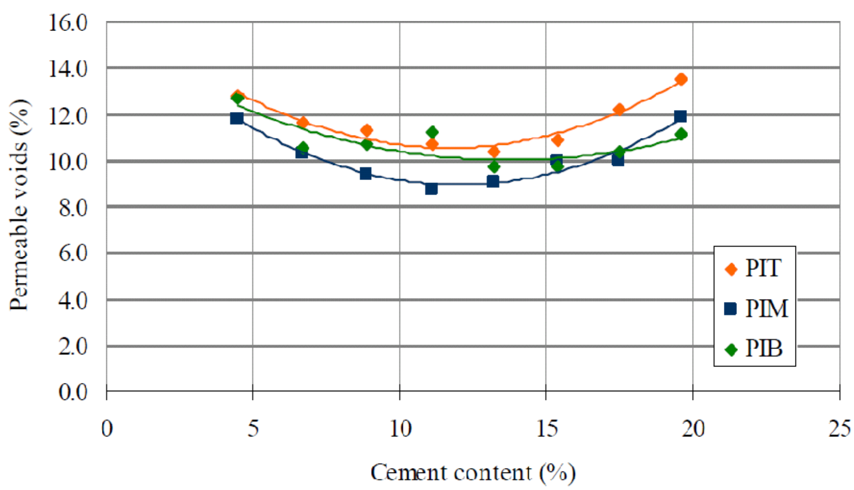


Figure 2-5 Variation of permeable voids at various depths. PIT: top 50 mm, PIM: middle 100 mm and PIB: bottom 50 mm in a 200 mm x 100 mm cylinder. All mixtures compacted at their optimum moisture contents

The aforementioned discussion is useful in finding a way in which a mixture can be proportioned. It will be of interest to find ways and means of characterizing various components of RCC so that the overall system can be optimized for better compactibility, while retaining or enhancing its self-standing ability. This further necessitates formulating a method/protocol for mixture proportioning, appropriate and discriminating test methods for characterizing different mixtures and components of workability (cohesion, angle of internal friction, compactibility, consistency, etc.) separately.

RCC is a multi-faceted pavement construction material that has the ability to be applied in various pavement layers. This invites an investigation with various mixture compositions each of which could be employed for different layers or functionality. For example if RCC is used as a pavement base, the binder content can be relatively much lower than when it is used for an application like pavement shoulder or ship container facility. Moreover, with admixture kicking in, the roles of each of these mixtures can be radically improvised.

2.1.4 The rise of a comprehensive statement: sustainability

Challenged by the quests for higher strengths, greater durability, efficient usage of binders, reduction of water, changeability of newer binders and other ingredients of concrete, changing construction technologies and associated factors, concrete technologists are compelled to be spontaneously responsive. Juxtaposed with this is the inconvenient truth of climatic change and incongruous consequences that are threatening to undermine the human existence itself. Material scientists, chemists and concrete technologists are investing their energies in trying to study and address this grave situation from multiple perspectives.

With sustainability becoming the 'buzzword' of the day, chemical admixtures cannot certainly escape the evaluation that the construction industry needs to offer in introspect, and, in their accounts to the society. The organic nature of most chemical admixtures makes them highly rich in carbon content, inevitably placing these under sustainability scanner, apparently and quite controversially challenging the very premise of their usage in concrete. The Cement admixture association however argues [5] that the quantity of chemical admixture added to concrete is small, rarely more than 0.3% on concrete weight and more typically less than half this quantity. At this dosage rate, the contribution to embedded carbon (ECO2) from admixtures at less than 1% is too small to be significant and can be ignored when calculating the ECO2 of the concrete. Against this, the environmental benefits from admixture use can be significant as they allow other carbon components of concrete to be reduced without affecting the concrete properties. Based on this argument, it is proposed that the current admixture usage already saves about 600, 000 tonnes of ECO2 per annum and this could be significantly increased by further mix optimization.

2.2 Defining the scope of work

An appreciation of the above stated issues at various levels leads to evolution of the problem statement for the work. The main objectives of this work are threefold:

I. Developing prescriptions for different test methods for characterizing the fresh properties of roller compacted concretes;

II. To evaluate different chemical admixture chemistries and their interplay with different mixture compositions. The following is a list of the primary actions of different admixtures used in this work:

   i. Water reduction;
   ii. Hydration retardation
   iii. Cement dispersion;
   iv. Air entrainment;
   v. Rheology modification;
   vi. Products used in dry cast industry and
   vii. Combinations of these admixtures to extract mutual benefits.

III. To evaluate the variations in the measured fresh and hardened properties of concrete with the variations in the binder content.

It was anticipated at this stage that this information could be translated into something useful to the engineering and construction communities. The intent of defining the goals in the above way was to render some methods for characterizing fresh RCC mixtures, generate a primary database of material characteristics at various levels for the engineering and research communities. On the other hand, it was also hoped that by the end of this work, the information would be smoothly translated into something that the industry could easily assimilate and accept in practice.

Comprehending such a scale of work certainly necessitated a refinement and further division of work. The following a synoptic list of sub-objectives:

- Identifying and/or evolving and evaluating methods for identifying the best aggregate combinations;

- Identifying and evaluating methods a method for quick screening of different chemical admixtures;
- Identifying and evaluating methods for characterizing different aspects of concrete workability of fresh RCC;
- Establishing statistical evidence for different test methods;
- Testing various admixtures over the defined binder content range;
- Testing the performance of different admixtures on a single binder content;
- Establishing a set of admixture selection criteria and
- Identifying a set of criteria for selecting the paste quality and quantity for practical mixture proportioning.

Each of these sub-objectives was further divided and is described in a later section.

2.3 Mythological approach

2.3.1 Scheme of work

The overall work was divided in several phases and each of these phases was identified with specific tasks. Figure 2-5 summarizes these phases

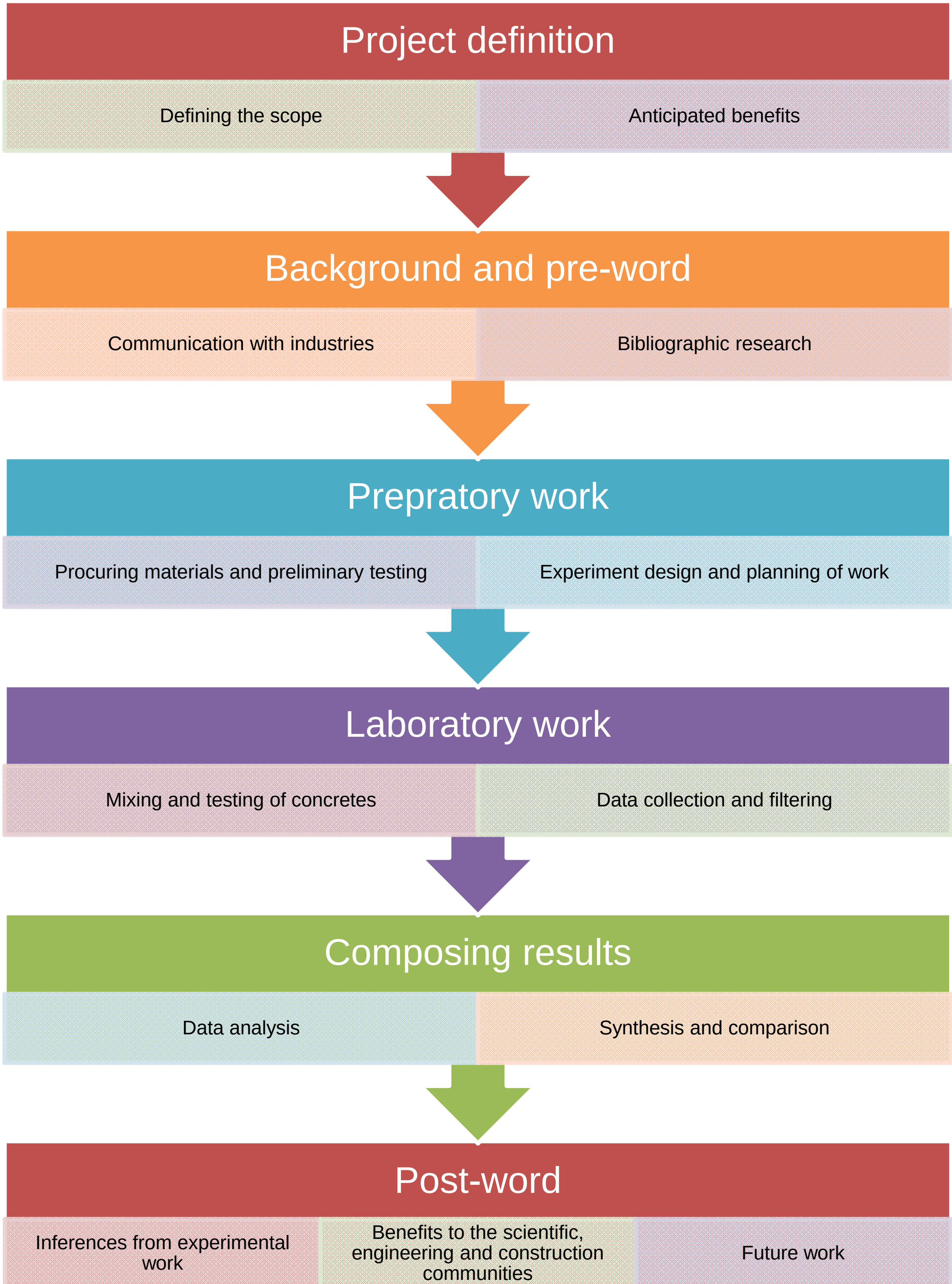


Figure 2-6 Division of work

2.3.2 Construction of dissertation

EVOLUTION OF BASIC FRAMEWORK: OBJECTIVES

The aforementioned description and nature of the subject and definition of the scope of work positioned this work at the intersection of multiple disciplines. Identifying each and deriving adequate momentum to address them while covering sufficient width and depth was one of the challenging tasks. This also made the study more than tricky, since applying methods and techniques from each of these fields were incomprehensive and were not rendering the desired degree of characterization. Figure 2-6 shows a summary of these fields.

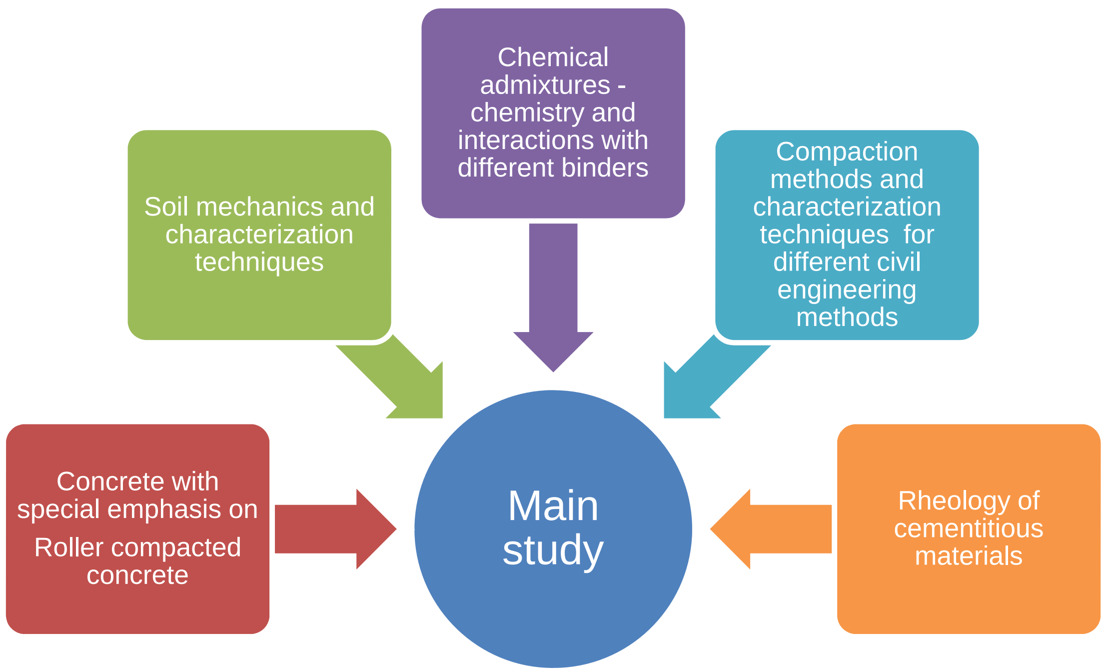


Figure 2-7 Main fields of application studied for this research

To deal with this problem with the core objective of gathering convincing evidence for the decided objectives, the following sub-tasks were clearly identified:

- Identifying and/or evolving and evaluating methods for identifying the best aggregate combinations:

- ✓ Method for characterizing the compactibility;
- ✓ Method for characterizing the least friction resistance so that best compactibility can be achieved while being cognizant of the needs from the concrete mix proportioning perspective;
- ✓ Method for evolving the best possible aggregate grading, considering the possible field tolerances;

- Identifying and evaluating methods for quick screening of different chemical admixtures;
- Identifying and evaluating methods for characterizing different aspects of concrete workability
  - ✓ Method for characterizing consistency of RCC mixtures;
  - ✓ Selecting the most appropriate lab compaction method for casting samples;
  - ✓ Method for characterizing the compactibility;
  - ✓ Method for characterizing the frictional resistance and cohesion;
  - ✓ Methods for characterizing the heat generation for comparison between mixes with different chemical admixtures;
- Establishing statistical evidence for different test methods:
  - ✓ Repetition of test methods over a single system to establish the variability, standard deviation and coefficient of variation;
  - ✓ Compactibility, consistency, cohesion, angle of internal friction, heat measurement;
- Testing various admixtures over the defined binder content range:
  - ✓ Select, evaluate and pre-screen the selected admixture functionalities on admixtures obtained from major suppliers;
  - ✓ Select varied chemical compositions for each of the admixture and run trials over each of these with a pre-selected dosage range;
- Testing the performance of different admixtures on a single binder content:
  - ✓ Select appropriate combinations of admixture to be blends to achieve the required mixture properties;
- Establishing a set of admixture selection criteria:
  - ✓ Selecting the right chemical admixture for a given set of conditions;
  - ✓ Selecting the optimal dosage vis-à-vis the binder content;

- Identifying a set of criteria for selecting the paste quality and quantity for practical mixture proportioning:
  - ✓ Identifying good indicators of paste quality vis-à-vis aggregate quantity;
  - ✓ Identifying good indicators of paste quantity vis-à-vis aggregate quantity

The ultimate goal can be summarized as shown in Figure 2-7. The eventual goal was to attempt at choosing the mixture ingredients in such a way that they could result in the desired properties of concrete.

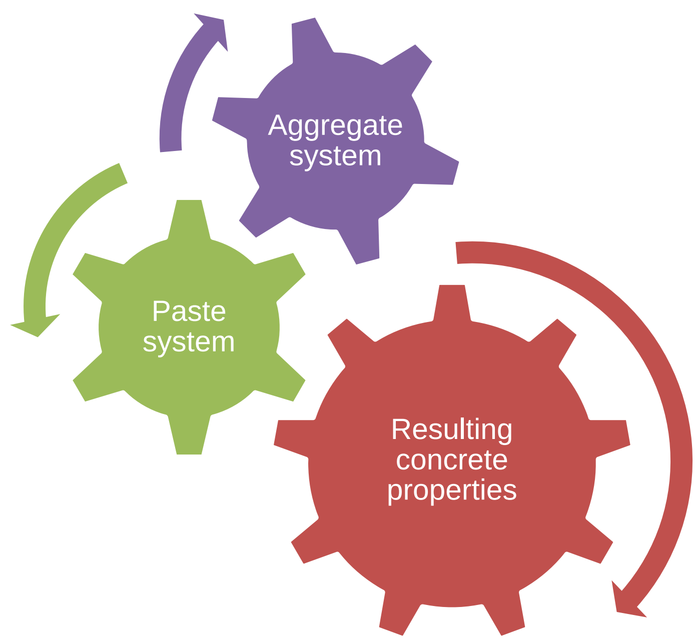


Figure 2-8 Conceived mechanism of selecting a RCC mixture composition

OUTLINE OF THE PRESENT WORK

The above description of the objectives and work outline lead to evolution of the framework for this document. Refer to Figure 2-8. To comprehend the identified goals in a plausible time-frame, the work was divided into five phases, written as five different sections in the dissertation as follows:

I. **General introduction** includes the identification of the subject matter under scope, and defining the objectives and methodology. It provides a comprehensive view of what can be anticipated from this dissertation.

II. **Bibliographic review** includes a critical review of the literature and reports comprehensive appraisal on the fundamental of concrete technology, roller compacted concrete, fundamentals of chemical admixtures, rheological characterization, gyratory compaction, compactibility of different civil engineering materials and state of the art on instrumentation used for characterizing different materials. Each of the chapter is constructed with an objective focused on the eventual goal. Finally, this section concludes with a capping chapter that critiques on the studied bibliography and clearly brings out the scope of the future work, while laying the foundation for this dissertation.

III. **Design and conduct of the experiments** deals with scoping the work and presents a list of limitations of the work and things that are not covered in this document. It also describes the materials used for this work and summarizes various characterization methods used in this work.

IV. **Analysis, presentation of results and discussions**' section presents a critical evaluation of the results on different aspects of fresh, transitioning and hardened properties of different concrete mixtures. These include separate chapters on the preliminary studies, different aspects of workability of fresh concrete, the transitioning phase evaluated by the temperature method and the strength aspects of the hardened concretes.

V. **Summary of the study and conversion to practical information** includes a comprehensive summary from each of aforementioned sections. It further specifically identifies the contribution that this work is making to the literature along with a distinct chapter on the derived industrial benefits. Finally, this section concluded with an essay that addresses some of the lacunae in this work and the future research need.

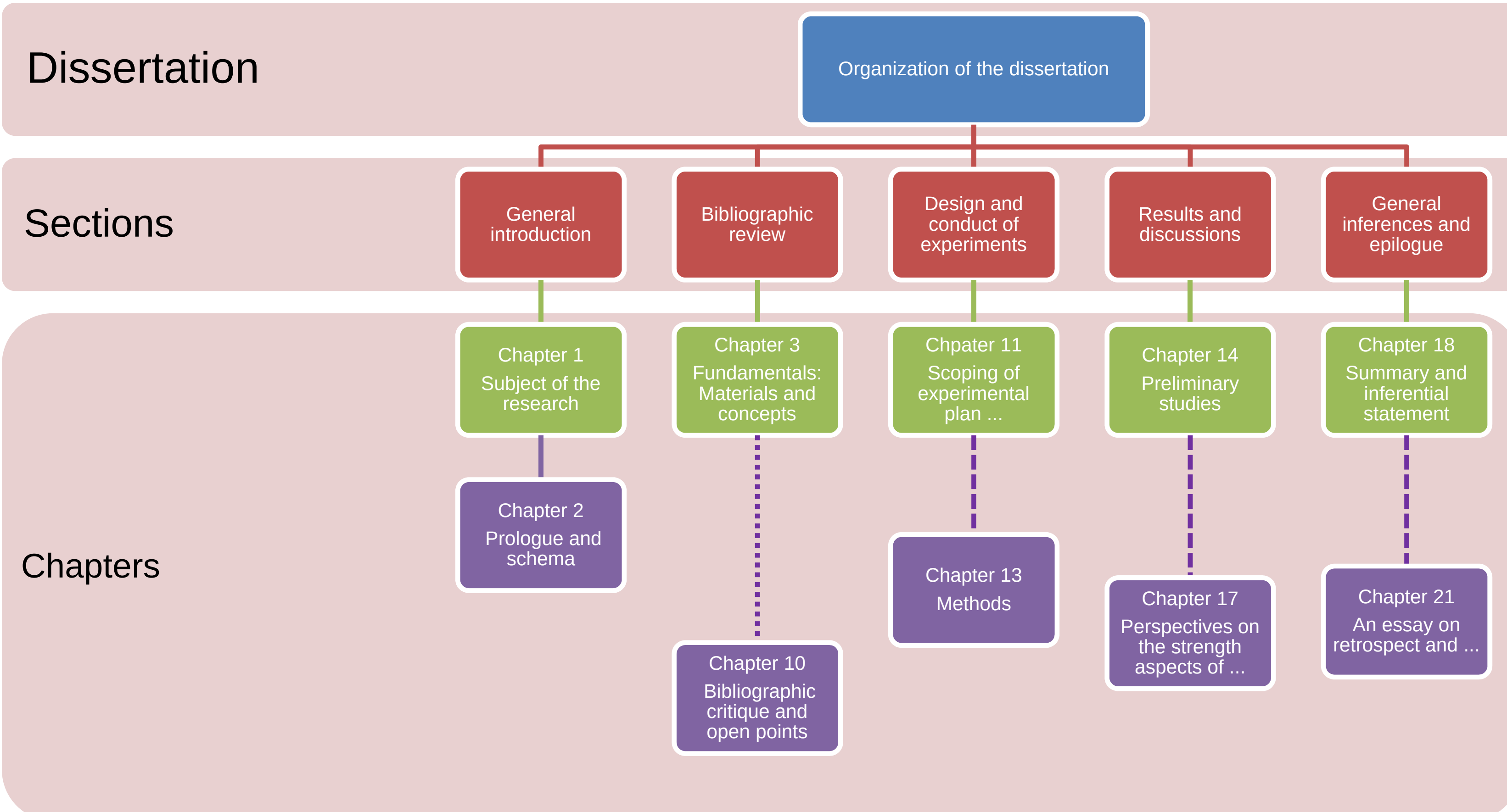
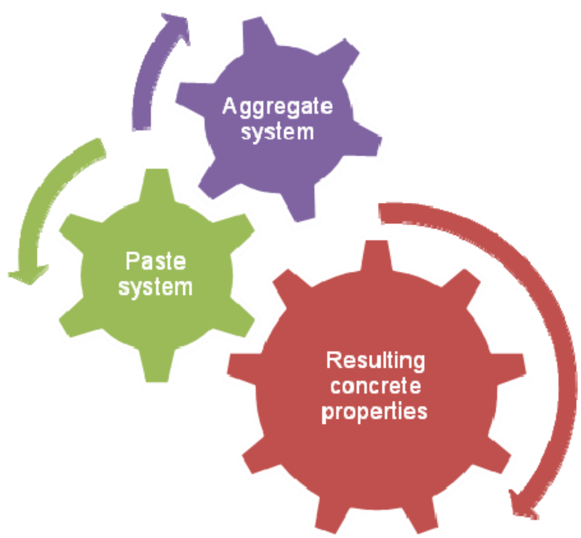


Figure 2-9 Dissertation outline

Each chapter begins with a synopsis that presents a comprehensive overview of the chapter. This is followed by a detailed list of items covered in the chapter. Subsequently each of the sub-topics is discussed in detail. A specific attempt is made to communicate the information in explanatory figures, diagrams, schematic sketches, tables so that the main ideas are communicated in most comprehensive ways. Finally, the chapter ends in a summary of the main points covered in the chapter along with how each of those can be or are utilized in realizing the ultimate goal of this study.

SUMMARY

This chapter explained the scope of the subject within the boundaries of which this research was conducted. An introduction to the concept of roller compacted concrete (RCC) was offered along with versatile nature of the application. It was commented that this material has a wider range of applicability in various pavement applications. Moreover, it also has a potential to compete and surpass the properties of other cement based pavement materials.



RCC has evolved over the past 25-30 years and is a well-used, adequately understood material for hydraulic construction. The body of knowledge of RCC for pavement applications is in its in-fancy, thus stipulating research with an objective of having better fundamental understandings.

With the emergence and overall growth of human race, sustainability has become a cause of greater than ever concern; inviting attention from different perspectives in the society. Having a high carbon footprint, portland cement concrete could be considered as a "culprit construction material", if not proven otherwise. It therefore becomes the elemental responsibility of concrete technologists to make it more sustainable, and environment friendly. There is going to be no 'one' solution to this grave problem and attempts at the levels of science, technology, and management shall be required to address it.

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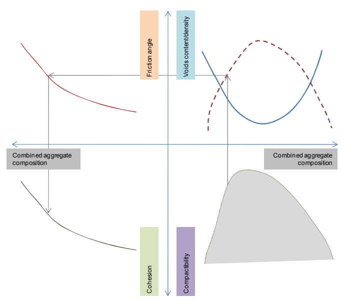
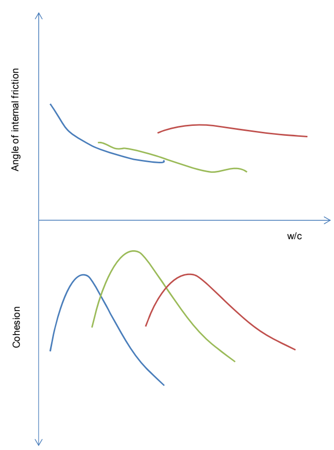
CHAPTER 3 BIBLIOGRAPHIC CRITIQUE AND OPEN POINTS





SYNOPSIS

The objective of this chapter is to offer a prelude to the anticipated research. This chapter is divided into six sections , based on the reviewed literature. The first section offers a discussion about some research conceptualization on aggregate characterization; while the second section discusses the rheological behaviors of mortars and concretes and how these could be derived from some fundamental testing. The third section primarily offers thoughts about stitching together the individual behaviors of cement paste and aggregate and the proposed methodology for evolving mechanistic-empirical correlations. The final three sections ponder about roller-compacted concrete (RCC), its fundamental behavior, compactibility and use of chemical admixtures.

Keywords: aggregate, friction, cohesion, Coulomb, mortar, cement paste, concrete, roller-compacted concrete (RCC), compactibility, chemical admixtures

CONTENTS

A caveat to this part of the thesis is that it is written based on the reviewed literature. It should also be noted that the views expressed in this chapter are solely of the author and have no bearing on others involved with this research. A detailed literature review if provided in the appendices as separate sections. The following is a list of the same:

- Fundamental aspects of cement, aggregates and associated relationships;
- Roller compacted concrete from the perspective of characterization of fresh properties, paste considerations and strength;
- A review of chemical admixtures, their compositions, functions and factors affecting their performance.
- Rheological definitions; rheology of cement based materials and factors influencing typical rheological parameters.
- The use, applications and limitations of gyratory compactor including the evolution of methodology.
- Factors affecting compaction and compactibility of different civil engineering materials typically used for pavement construction.
- A state-of-the-art review of instrumentation including a critique.

3.1 Aggregate characterization: a composite picture

Wide ranges of geologically natural and artificial aggregates are used in different types of concretes, pavement bases, sub-grades. These include virgin and recycled aggregates, and those obtained from industrial byproducts. To cope with the increasing complexity of their usage and driven by our desire to mathematically model their physical behavior, the characterization methods and our modeling capabilities have advanced tremendously. Characterization methods try to quantify one property or the other, often leaving the investigator to depend on several properties to comprehend a composite picture. Computational capabilities and modeling often take advantage of assumptions that may sometimes oversimplify the fundamental physical behavior. Their resemblance to lab-measured or in-situ characterized behavior strongly depends on the experience of the modeler and his ability to comprehend and then mathematically assimilate the physical behavior into tangible models.

More specifically, aggregates have been variously characterized for different purposes due to the multiplicity of their structural applications. Isolated research has been dedicated to characterizing aggregate shape, size grading, packing, strength/mechanics aspects, and durability. More often than not, these characterizations are application specific and consider the behavior of aggregates and sometimes their geology.

Concrete aggregates are conventionally characterized during

- Source approval stage using petrography to characterize mechanical strengths and potential durability against relevant deterioration mechanisms,
- Mixture proportioning and
- Construction for quality control using grading, shape, voids, and bulk properties.

The following is a sampling of the author's observations and concept for amalgamating different characteristics:

- Voids content: The actual voids content for the binary combinations of aggregates consisting of fine and coarse aggregate fractions is not routinely determined. The voids content will be decided by the relative specific gravities of different fractions, particle grading, shape and mode of compaction. The mixture proportioning strategies rely on already established charts and methods for deciding the optimum combinations. It can be seen that individually, different aggregates would pack in different ways and would render different bulk densities and voids contents. Although studies and protocols exist for characterizing the voids content, a routine method for characterizing the curve of voids content (or density) as a function of composition of aggregates is not institutionalized.

- Internal angle of friction: The internal angle of friction is determined by aggregate geology, shape, grading, moisture state and density. The way aggregates would behave in drier concrete like RCC, shotcrete, and precast/dry cast works would be totally different than that in high-consistency concretes like pumping concrete or self-consolidating concrete. In drier concretes, the angle of friction of the aggregate system would play a decisive role in deciding the workability of concrete.
- Compactibility: For a given pair of aggregates, there will be a combination (possibly a range) at which minimal voids is obtained. Compactibility in this document is defined as the rate at which the aggregates reach their least potential voids content. Depending on the composition of the aggregates, the compactibility of the mixture will differ and in turn will play an important role in defining the compactibility of concrete or its ability to reach the maximum possible density. It is also interesting to note that there is no notion of compactibility of aggregates.
- Cohesion: The fine aggregate grading and composition has some influence on the cohesiveness of the concrete. Although this is qualitatively accepted, the exact quantification of the influence of various factors is neither available yet fully understood.
- Missing composite picture: All the above stated factors have an important influence in deciding the overall concrete behavior, and it is anticipated that a composite picture consisting of these factors would improve the process for selecting the best aggregate combinations. Figure 3-1 shows the anticipated composite diagram.

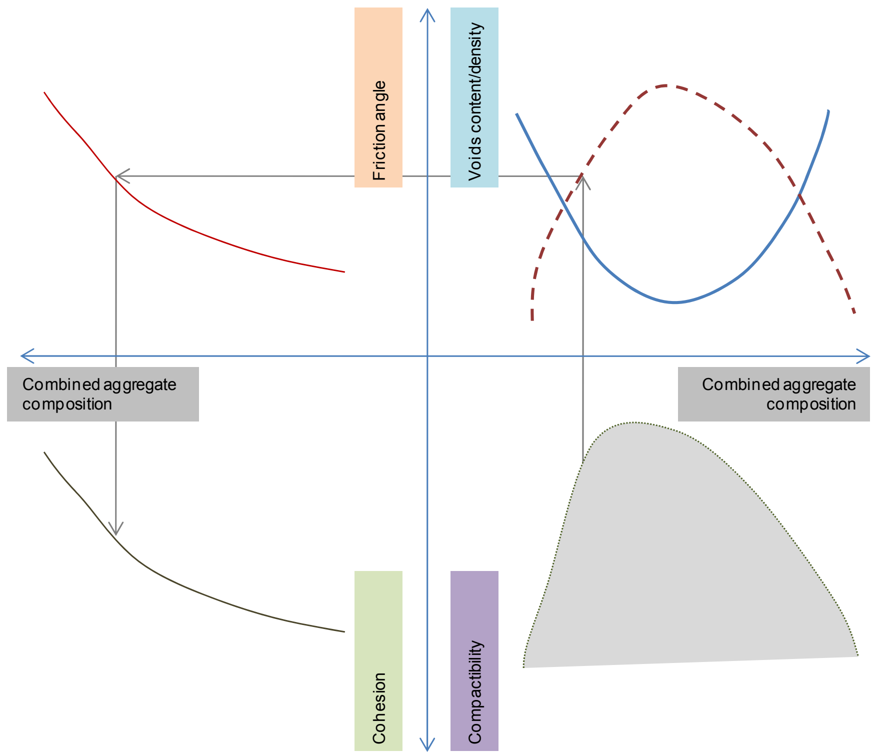


Figure 3-1 Conceptualization of the composite picture of aggregate properties

3.2 Rheology of dry mortars and concrete

Worldwide usage of Portland cement concrete-based pavements is increasing. Paving concrete is a topic of great interest to engineers, designers, specifying agencies and contractors. The concrete consistency range for paving is very narrow. In the author's experience, it is the feel of concrete that plays a more important role than any quantification of workability. Paving engineers and site supervisors are so well trained in estimating the ability of concrete to be paved that sometimes the characterization of consistency is overlooked.

Another interesting observation regarding paving concrete is the momentary liquefaction of dry concretes under vibration. Depending on the consistency of the concrete, the vibration responses would change. Furthermore, for a given consistency, there would be an optimum frequency and amplitude at which compaction characteristics would be obtained most efficiently. The rheology of concrete under vibration differs distinctly from the same concrete in a static condition.

The application of concepts from rheology and associated models has been more or less restricted to concretes with higher consistencies resembling semi-solids or fluids. However, similar models may not be applicable for drier concretes typically used for pavements. Moreover, the methods of characterization would not apply as well.

Interestingly, pavement concretes closely resemble higher moisture content soil-like behavior. Soils typically follow Mohr-coulomb failure behavior. This behavior can be effectively applied in describing the shear responses of pavement concretes. This is pictorially shown in Figure 3-2. These parameters, once established for concretes, can be further correlated to the paving ability of concrete and used for drawing the envelopes or boundaries for paving concrete in a quantifiable manner.

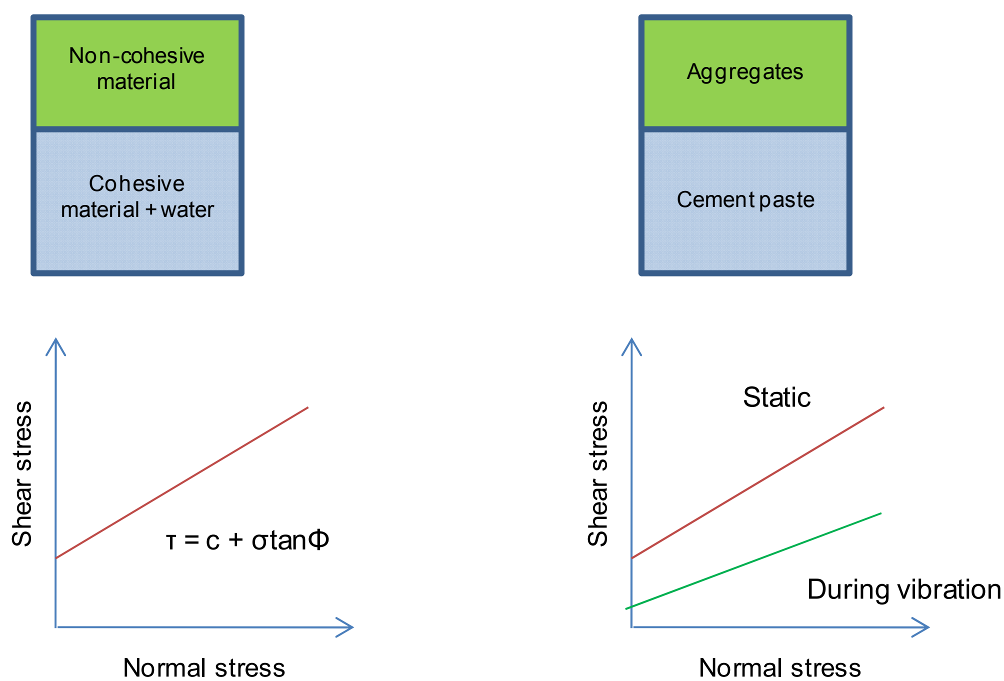


Figure 3-2 Soil-Paving concrete analogy

There has been some limited work done on paving concrete vis-à-vis shearing behavior using soil-analogy. The topic however is awaiting further investigation, especially with respect to horizontal slip-form paving. It can be anticipated that the resulting stress strain graphs can be correlated well with the conventionally used consistency tests (slump, compaction factor, Vebe) and would offer some more information about the relative stiffness and compactibility of paving concretes. Such data in terms of yield stress or cohesion and the angle of internal friction would also help distinguish a range of water/cement ratios and combinations of materials. A similar process would also help identify the most workable mortars that would eventually go into concrete. In addition, this can be concrete specific. For example, a mortar can be optimized for cohesion or friction angle depending on the need. This is shown pictorially in Figure 3-3.

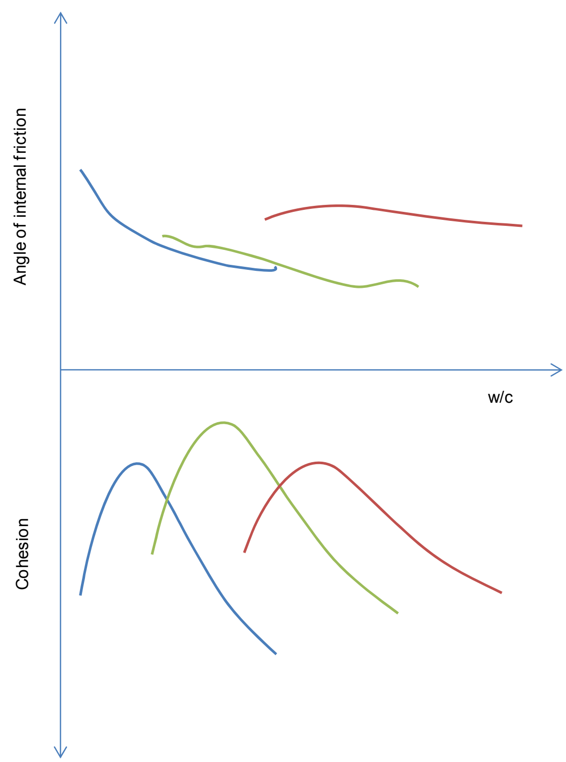


Figure 3-3 Conceptualization of optimization of cohesion and angle of internal friction for mortars with different aggregates or aggregate/cement ratio

Continuing from the work on aggregates, it would be interesting to plot the friction-cohesion values of different combinations of aggregates and see the impact they produce on the friction-cohesion of concrete. The cement paste cohesion, w/c ratio, qualitative composition and quantity of paste would decide the cohesion part of concrete, while the aggregate composition would primarily decide the friction component. This again will be contingent to the overall volumetric composition of concrete. The evolution of such an optimization process based on cohesion-friction is missing in the literature.

3.3 Integrating the behavior of paste-mortar-concrete

Isolated work has been conducted in characterizing the rheological behavior of cement paste, mortar and concretes. Few studies have been undertaken in appreciating the correlations and links between the rheological parameters of the individual phases and tying them in a simple yet comprehensive model. The primary difficulties for this arise from the following factors:

- Inherently distinct natures and behaviors of cement pastes and aggregates (granular);
- Complicated, time-dependent, progressive and dynamic behavior of cement paste which is not yet fully understood;
- Clear relations between ever evolving cement paste microstructure and rheology are not fully understood;
- Complications involved with the introduction of chemical admixtures;
- The scales of the forces acting within each particle system are so qualitatively and quantitatively diverse in nature that tying them up together is a challenge requiring an understanding of chemistry, kinetics and thermodynamics;
- Measuring concrete rheology requires large scale instruments and most of these are tailor made for specific concrete types;

Attempts have been made to correlate paste behavior to mortar and concrete properties through the medium of analogous empirical, semi-empirical and mechanistic-empirical tests. However, there exist two clear schools of thought, one in favor and the other against using such correlations.

Of relevance is the behavior of roller-compacted concrete. It can be anticipated that simple relationships like that shown in Figure 3-4 can be established by combining empirical and mechanistic tests. The Y-axes can be replaced with parameters like peak shear stress, cohesion, friction angle, or a combination of mini-slump test and cohesion-friction data. It is also interesting to know that the there are no widely published values describing cohesion-friction for dry cement powder and cement paste.

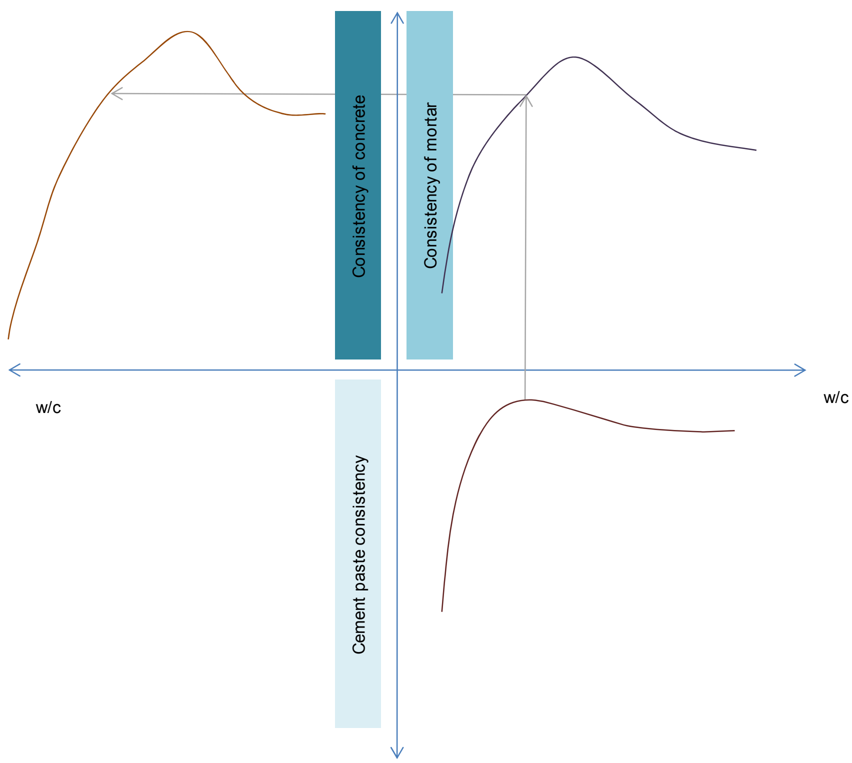


Figure 3-4 Conceptualization of a model integrating the behavior of cement paste, mortar and concrete

3.4 RCC behavior

With growing applications of RCC, interest in understanding the fundamental behavior is also increasing. The following points are of critical importance in advancing our understanding about the behavioral traits of RCC as a material.

- Basic mechanisms: RCC resembles soil-like material. Initially as the moisture content of the mixture is increased, there is a transition in the behavior of the constituent materials. Fine aggregate and cement are known to show bulking behavior. When these materials are introduced with coarse aggregates, there is a transitioning behavior in response to the changes in the moisture contents. The exact mechanisms of these transitions vis-à-vis the volumetric composition of the mixture are not fully understood.
- w/b-aggregate/binder ratio: RCC can be widely applied for different pavement applications. As such, the cement contents can vary over a wide range (less than 100 to 500 kg/m^3). This also implies that the aggregate/binder ratio would vary over a wide range (~22 to 3). Although this can be done in theory, there would be practical limitations in achieving workable mixtures with different aggregate/binder ratios. There are no such clear boundaries limiting these ratios in published literature. Moreover, with the changing aggregate/binder ratio, the water demand of the mixture would change. Furthermore, depending on these two ratios, the air content and hence compactibility of the mixture would change. There is no such data in published literature. **Error! Reference source not found.** shows a conceptual model for air content in a ternary diagram.

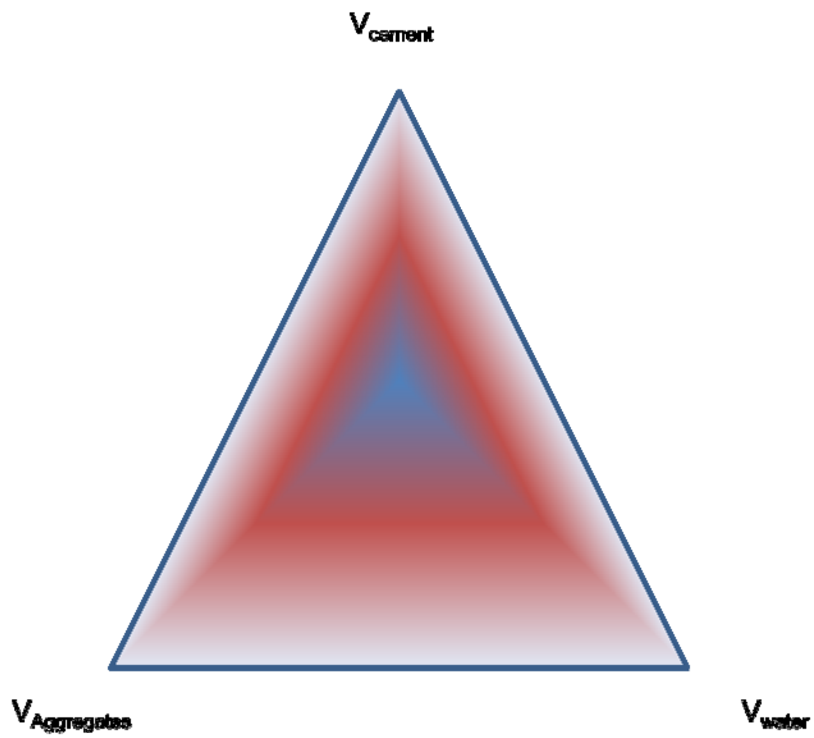


Figure 3-5 Entrapped air as a function of the volumetric composition of RCC mixtures shown as a ternary diagram

- Effect of cement paste quality: Similar to the above argument, the cement paste quality and composition would decide the workability and strength characteristics of RCC. Studies providing explanations on this basis have not been conducted.
- Failure of Abrams law: RCC is a drier concrete, mostly, out of the workable range of conventional concretes. The Abrams law for strength is not followed as a function of the w/c ratio. The exact mechanism for? this is not fully understood. Depending on the cement and aggregate type and content, and the amount of water in the mixture, the law can be anticipated to deviate at different w/c ratios (refer to Figure 3-6). There should be valid explanation for this.

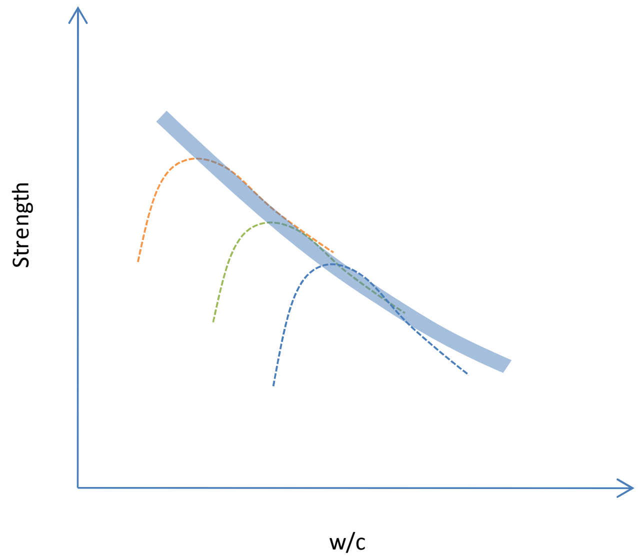


Figure 3-6 Anticipated working curve for RCC

3.5 What is a compactable mixture?

Compactibility as defined in an earlier section can help choose the optimum mixture. For a given aggregate grading, cement content, there will be an optimum water content at which the mixture will be most compactable. Few studies on compactibility of RCC have been conducted. Most of these were based on using the gyratory compactor as used for asphalt specimen preparation. Optimized compaction parameters for RCC are not established yet. Developing the compactibility curves would help in better understanding the compactibility of different mixtures. In turn, this would also enhance consistency design of constituent mortar and cement paste. Diagrams similar Figure 10-5 can be plotted for compactibility indices.

3.6 Admixtures in RCC

Use of chemical admixtures is not much accepted in practice in RCC. The strength of RCC is primarily derived from the dense aggregate skeleton. As such, improving the paste has never been thought about seriously. Consequently, no comprehensive study has been undertaken to understand the role of chemical admixtures in RCC. The primary difficulty in using admixtures in RCC originates from the fact that it has less water and as such mobilizing the action of chemical admixtures is a challenge in itself.

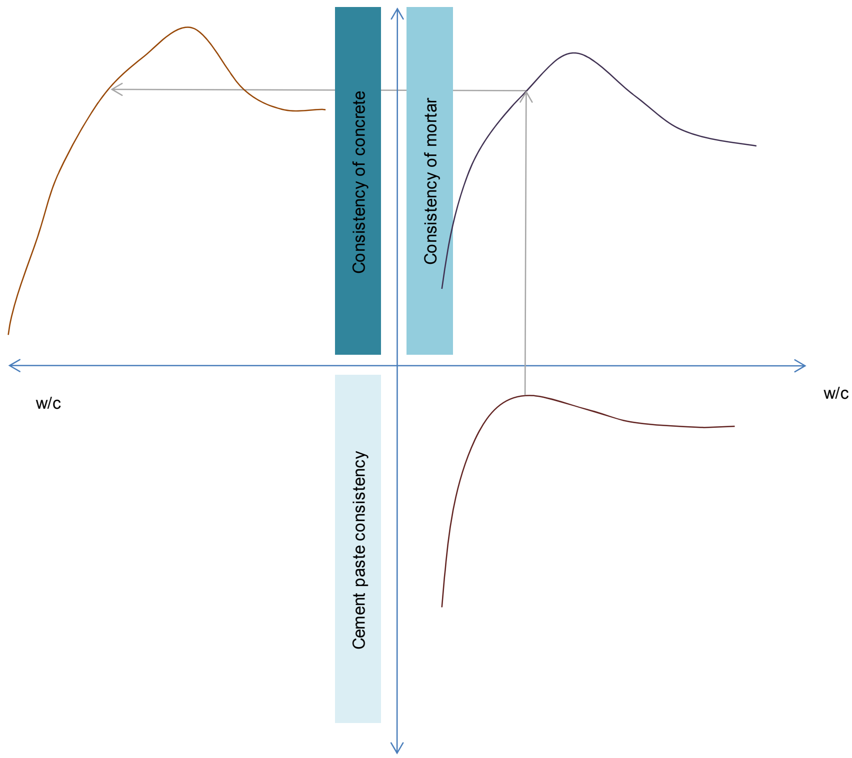
There could be few possible solutions to this problem. The first one is with regularly available chemical compositions; the admixture dosage could be increased to assess the effects on water reduction, consistency, compactibility and strength. The second solution could be to alter the chemistry of existing admixtures or possibly change the dosage of the active ingredient present in the admixture. The primary candidate list of chemical admixtures includes water reducers, retarders, air-entraining admixtures, and rheology modifiers.

Due to the very nature of this concrete, using a single admixture may not produce desirable results. As such, it seems to be quite relevant to try combinations or cocktails of admixtures. These may include combinations that would act complementarily or synergistically. For analyzing such results, use of appropriate statistical techniques would be effective.

SUMMARY

Proper aggregate characterization is essential in any mixture proportioning philosophy. There are various method available for characterizing the aggregate grading, but it is important to recognize a suite of most influential and essential properties that are closely related to the most important property of resulting concrete. In case of RCC, the compactibility of aggregate grading is important and is discussed in this chapter. Closely related to it is the relative friction angles between various components of an aggregate system.

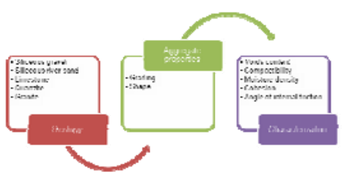
Estimating the rheology of concrete is a cumbersome task, often requiring larger volumes of concretes to be tested with sensitive rheological instruments. Cement paste and mortar testing are relative easier to perform, but have their own complications. What has further skewed the feel for the rheological parameters is that they have been measured with several types of rheometers, each having its own merits and drawbacks. Furthermore estimating the rheology of concrete from its constituent mortar or paste is having difficulties because of the differences in the nature and range of forces involved in each composition.

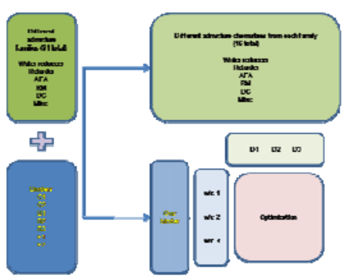


The behavior of RCC in response to its material composition is not fully understood. Moreover the factors that influence compactibility of different mixtures are not appreciated well. This may involve the effects of aggregate grading, relative volumes of water and binder, relative volume of paste, voids in aggregates, effects produced by the air entraining admixtures among others.

Another important thing related to RCC is the relationship of strength with water/binder ratio. It has been observed that due to incomplete compaction the inverse relationship is only followed upto a certain limit, going below which results in decreasing of the strength. Hence, better understanding related to this is required in order to explain the deviant behavior.

CHAPTER 4 SCOPING OF EXPERIMENTAL PLAN AND LIMITATIONS





FA (%)	100	90	70	50	30	10	0
CA (%)	0	10	30	50	70	90	100
Moisture-density	x	x	x	x	x	x	x
Cohesion	x	x	x	x	x	x	x
Friction	x	x	x	x	x	x	x
Compactibility	x	x	x	x	x	x	x
Voids content	x	x	x	x	x	x	x
Voids ratio	x	x	x	x	x	x	x

SYNOPSIS

This chapter presents an overview of the broad objectives of undertaking this experimental program. At the onset, the chapter describes the specific applications of RCC and prioritizes these for research. It is also important to define the scale of work so that over-simplification or unnecessary details are discreetly avoided. This is the theme of the following section. Subsequent to this, the two-fold objectives of the test program are described. Later on, a detailed look at these objectives and framing of sub-objectives along with typical test matrices are discussed.

Keywords: RCC applications, scale of work, workability, mixture proportioning, chemical admixtures, aggregates, concrete, instrumentation, experiment matrix

CONTENTS

4.1 Specificity of applications

RCC is applied primarily in two types of civil engineering constructions viz. hydraulic and pavements structures. The considerations for mixture proportioning depend on the structural requirements, economical availability of appropriate materials and durability. Conserving this discussion for RCC for pavement applications, Figure 4-1 shows typical ranges of binder contents as applied for potential RCC applications.

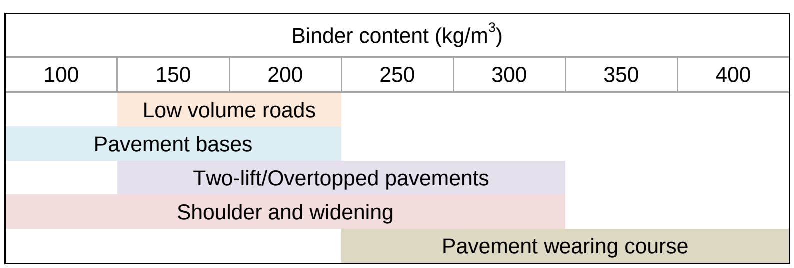


Figure 4-1 Typical binder content ranges for RCC applications

Due to the diversity of applications even within a pavements structure, considerations for mixture proportioning vary. For example, in two-lift pavements the abrasion resistance of

concrete is not that critical as it is in the wearing course. In pavement bases, higher levels of cement replacement with SCM's can be than the other types of applications.
The following aspects were considered while structuring the width of the experimental program:

- anticipated growth in applications of RCC for different pavement applications
- widely available and applied material combinations
- possible alterations in various RCC characteristics vis-à-vis usage of different chemical admixtures
- how could the basic material behavior be understood
- ways for appreciating the workability of drier concretes like RCC

The aggregate/binder ratio would approximately range between 4 and 20, while covering the complete range of applications with local materials. The scope of this work was however restricted primarily based on the priority of tentative applications, available time and resources and possibility of safe extrapolation based on the defined scope. The aggregate/binder ratio range fixed between 4 and 11.

4.2 Scale of work

An important aspect of studies of such extent is defining the scale of work. The following section describes the same.

- Dimensional scale: all the studies conducted were restricted at the macroscopic level.
  - Essentially, this means that the studies were restricted at the smallest visible particle level viz. cement;
  - Although studies were done at cement paste, aggregate, mortar and concrete levels and included chemical admixtures, no microscopic studies were proposed and conducted;
  - With respecte to the forces studied, macroscopic forces resulting at cement paste, aggregate, concrete levels were studied with the available instrumentation;

  - o The chemical interactions of cement-fly ash-water systems and chemical admixtures were planned to be inferred based on existing body of knowledge and discussions with the industry.
  - o No studies pertaining to chemical interactions, their kinetics, thermodynamics and relevance to paste behavior were planned.

- Materials related:
  - o The maximum size of the aggregates was restricted to 19 mm.
  - o Only two types of fly ashes viz. type C and F were considered. No other SCM was taken into account.
  - o The chemical admixture selection would be governed by the most widely available and accepted materials rather than an exhaustive, material wide exploration

- Modeling:
  - o It was pre-decided that no effort to model the overall material behavior would be made.
  - o Although simple regression models generalizing the overall behavior at the macroscopic level would be attempted, no detailed statistical analysis was planned.

4.3 Framing the broad objectives

Based on the review of existing body of knowledge, the need for understanding the fundamental material behavior, possible scientific and engineering advancements, the scope of this work was broadly divided into two main objectives and are described in the following sections. A schematic diagram of the work proposal and its distribution is shown in Figure 4-2. It should be noted that only relevant results shall be presented in this thesis.

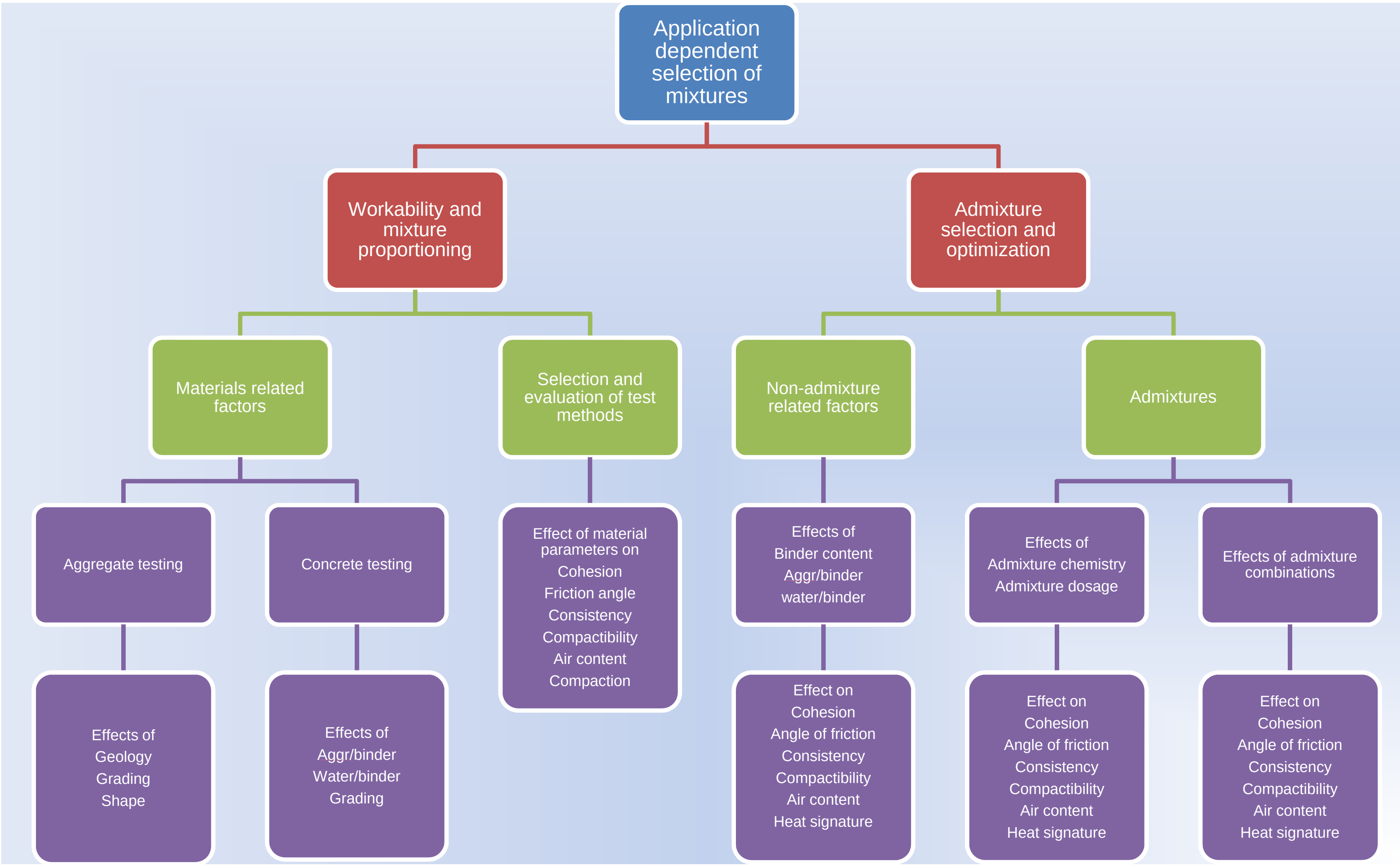


Figure 4-2 Schematic diagram for the work proposal

4.3.1 Studies on the workability and mixture proportioning

There are many methods for characterizing the consistency, compactibility, rheology, cohesion angle of internal friction of fresh concretes. As seen before, these are the building blocks of the overall workability of concrete. Different tests are able to characterize these and other workability related attributes of concrete. A comprehensive study characterizing the cohesion, friction angle, consistency, compactibility, air content has not been taken up. This forms the basis of the first objective of this thesis.

In this phase of the study, the effects of aggregate particle shape, grading, geology on the moisture-density profiles, compactibility, voids content, cohesion and friction angle of the aggregate systems were studied. The objective here was to select the most suitable aggregate grading based on the measured properties. Following were the premises:

- The moisture-density profiles would offer an idea about the effect of moisture on the compactibility and compacted density of aggregate system;
- It was anticipated that the aggregate system with least angle of friction would offer least resistance to compactibility;
- Working closely around this optimized grading would evolve an aggregate system with highest compactness achieved with minimal effort and hence a most compactable system. Compactibility here means the rate at which the aggregate system would achieve the maximum potential degree of compactness (or minimum voids content)

Further to this, the effects of material parameters (aggregate geology, shape, particle grading, aggregate/binder and water/binder ratios) on cohesion, angle of internal friction, consistency and compactibility were studied. Following were the premises:

- It was anticipated that the compactibility of a concrete mixture would be a function of cement paste consistency and the compactibility of the aggregate system used in that mixture;
- There would be an interplay of aggregate shape, grading (fine, medium and coarse) and the water/cement ratio;

- Additionally, the binder (and hence w/b) and aggregate (and hence aggregate/binder) contents would have an influential role on the measured properties of concrete.

A composite picture resulting out from the above studies would help in evolving a method of mixture proportioning for roller compacted concrete based on the measured properties. Additionally, a fundamental appreciation of the material behavior of dry concretes and the transitions that these mixtures undergo as a function of their compositions would be obtained. The quantification of cohesion and friction angle would help build a preliminary database that can be extended to other concretes and distinguish between the governing components in concrete workability. This would also advance the mechanistic-empirical procedures for concrete workability design and mixture proportioning.

4.3.2 Studies on chemical admixture selection and optimization

There has been no extensive study on use of chemical admixtures in RCC. The scarcity of water, reduced paste content, higher aggregate content makes RCC quite a different concrete material. It can be anticipated that the chemical admixture behavior would be quite different in RCC than in the conventional and modern concrete types. Moreover, some of the admixture formulations may not render similar trends in affecting the concrete properties as they would in conventional concretes. This forms the basis of the second objective of the thesis.

In this phase of the study, at first, an admixture-cement screening was done. Five different cements (two type I and three blended) were tested over 31 different chemical admixtures (water reducers, retarders, air entraining agents, hydration stabilizers, dry cast products, etc) with different chemical compositions. This part of the study was undertaken to appreciate the effects of different combinations of binders and chemical admixtures on compatibility and empirical consistency tests. It was anticipated that this phase would provide first-cut information on the following

- suitable combinations of binders with different chemical admixtures

- compatibility issues
- influence of chemical admixtures on the empirically measured consistency
- a comparative set of information with different binders and chemical admixtures

Subsequent to the first-cut of the study, 16 chemical admixtures were finalized for further experiments with one of the type I cements and class F fly ash. The screened chemical admixtures were selected based on the following:

- superior consistency performance for a given or similar chemical composition
- compatibility with the selected binder combination
- consistency retention in case of water reducer cum retarder and hydration stabilizers

Along with the above binder-admixture screening studies, preliminary mixture development schedule was run. In this part of the study three aggregate/binder ratios viz., 4, 7 and 10 were selected. Mixtures with different water contents and hence water/binder ratios were proportioned and moisture-density profiles were developed to obtain the highest dry density and the optimum moisture content. For these mixtures, consistency, cohesion, friction angle, compactibility and heat signatures were recorded. These sets of mixtures formed the control group of mixtures for the concrete mixtures with chemical admixtures.

Chemical admixtures, binder composition and the optimal concrete mixtures finalized from the above studies were used in the experiments on concrete mixtures containing chemical admixtures. For this phase, the aggregate/binder ratio was varied between 4 and 10; alterations on the water requirement for achieving similar initial consistency were observed along with the cohesion, friction angle, compactibility, consistency retention, heat signatures and the temporal evolution of compressive strength. Due to the distinct chemical origins of the admixtures and hence different functions performed in concretes, setting a single evaluation criterion was difficult. Hence, all the admixed concretes were measured for the above-mentioned properties. The eventual objective was to perform a comparative evaluation of different chemical admixtures and to obtain optimal dosages required for arriving at the optimal properties individually. The following objectives can be summarized:

- Evolution of the process/protocol for selecting the right chemical admixtures for achieving the desired performance of RCC mixtures based on the characterization used in this work.
- To evaluate the roles played by the conventionally and contemporarily available chemical admixtures in RCC.
- To check if the chemical admixtures play similar roles in RCC as they do for conventional concretes.
- To observe and evaluate the variances in the roles played by different chemical admixtures as a function of aggregate/binder ratio and their impacts on the measured properties including air content, cohesion, friction angle, compactibility up to 120 min, heat signature and the temporal evolution of compressive strength up to 28 days, when the initial consistency of concretes were kept constant.

4.3.3 Selection and evaluation of test methods

For characterizing the decided properties of concretes for different phases of work, different test methods including those that are not used for concrete testing were studied and evaluated. As such, a pre-screening of the test methods and their appropriateness for the tested materials was necessary. Additionally, establishing precision statements and performing repeatability studies was also felt necessary since some of the test methods were offering material specific repeatability and some of them had no such statements (about repeatability and precision) in the published standards. The following criterions were used for preliminary evaluation and selection of the test methods:

- Relevance to measured properties and applicability to drier concretes like RCC;
- Depth or level of information offered and the effort required for obtaining such data;
- Time required for obtaining and extracting easily readable data;
- Manufacturing ease, cost, maintenance and serviceability;
- Operational ease and safety during operation;

- Repeatability and precision;
- Ruggedness ;
- Material quantity required for testing and
- In-house availability and associated modification costs

The test methods that were considered for this process of screening included a combination of empirical and mechanistic tests. The list includes is shown in Table 4-1

Table 4-1 Characteristics studied for different materials

Material	Type	Characteristic
Cement paste	Empirical	Consistency, estimation of rheology, consistency retention
Aggregates	Empirical	Compaction, compactibility
	Mechanistic	Cohesion, friction angle
Mortar	Empirical	Compactibility, consistency
	Mechanistic	Cohesion, friction angle
Concrete	Empirical	Consistency
	Mechanistic	Cohesion, friction, setting time estimation

4.4 Descriptions of variables

4.4.1 The first objective: Workability and mixture proportioning

AGGREGATE OPTIMIZATION

As described above, aggregate optimization studies were precursors to concrete studies. Figure 4-3 shows the material and test variables used in aggregate characterization. The aggregate geologies were selected based on the highest National consumptions and availability of these rocks and their usage in concretes.

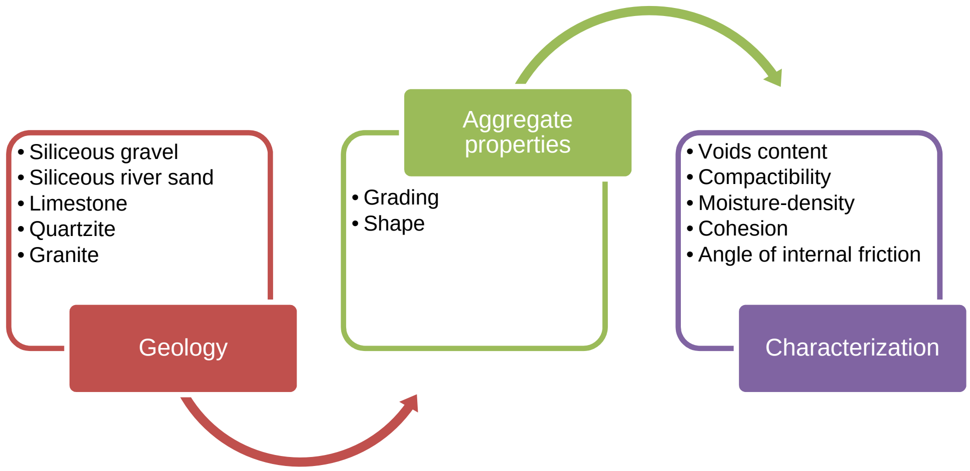


Figure 4-3 Aggregate testing scheme

Once the aggregate geologies were selected, coarse and fine aggregates were combined based on the routinely used combinations. For example, river sand was combined with gravel as coarse aggregate and with limestone as coarse aggregate. Subsequently, Limestone coarse aggregate was used with crushed limestone fine aggregate. For each pair, properties were quantified on combinations starting with 0% fine aggregate and running through 100% at frequent intervals. Table 4-2 shows a typical matrix.

Table 4-2 Typical aggregate test matrix

FA (%)	100	90	70	50	30	10	0
CA (%)	0	10	30	50	70	90	100
Moisture-density	x	x	x	x	x	x	x
Cohesion	x	x	x	x	x	x	x
Friction	x	x	x	x	x	x	x
Compactibility	x	x	x	x	x	x	x
Voids content	x	x	x	x	x	x	x
Voids ratio	x	x	x	x	x	x	x

CONCRETE OPTIMIZATION

Concrete optimization studies were taken up after aggregate grading was optimized for different properties with the objective of obtaining the most compactable material. The objective of this phase was to evolve the optimal mixture composition from compacted density perspective. Three different binder contents resulting in three distinct aggregate/binder ratios were chosen. Figure 4-4 shows the material and test variables used in this study.

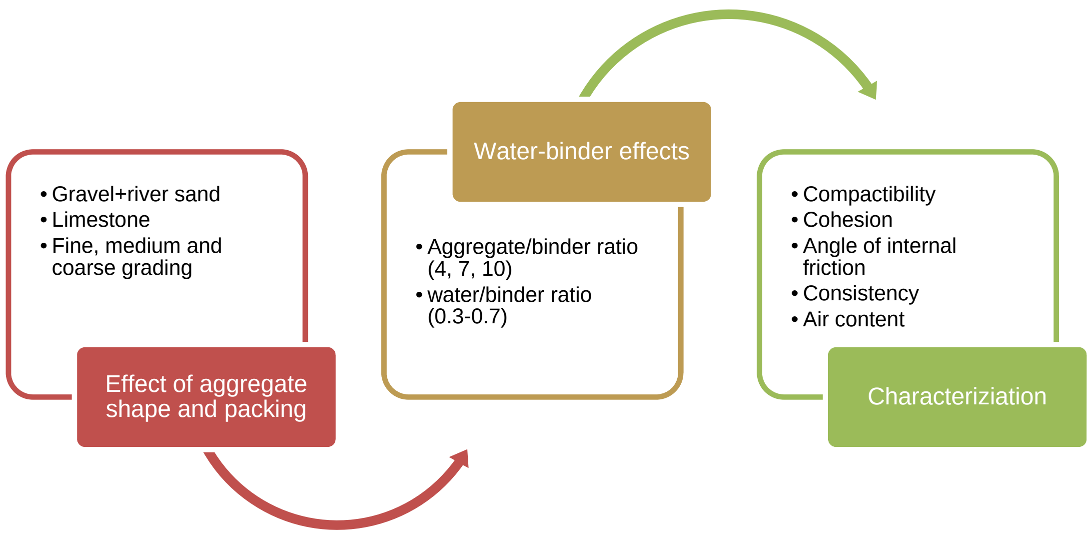


Figure 4-4 Evolution of control mixtures

Aggregate/binder ratio ranging between 4 and 10 and water/binder ratio ranging between 0.3 and 0.7 were used for a given blend of fine and coarse aggregates. Three different aggregate grading viz. fine, medium and coarse were studied to obtain an appreciation of fresh properties of concretes that contributing towards workability. The water/binder ratios used for different aggregate/binder ratios were not exactly the same, but were altered slightly depending primarily on the anticipated water demand and the resulting fresh properties. For example, finer aggregate grading mixtures especially with higher binder content tended to have higher water demands and hence slight higher water/binder ratios were used. Table 4-3 shows a typical matrix.

Table 4-3 Typical matrix for workability studies on concrete mixtures

Aggregate/binder		4			7			10	
water/binder	0.3	0.5	0.7	0.3	0.5	0.7	0.3	0.5	0.7
Cohesion	x	x	x	x	x	x	x	x	x
Friction angle	x	x	x	x	x	x	x	x	x
Compactibility	x	x	x	x	x	x	x	x	x
Moisture density	x	x	x	x	x	x	x	x	x

4.4.2 Selection and evaluation of test methods

A scheme for studies on selection and evaluation of test methods is shown in Figure 4-5.

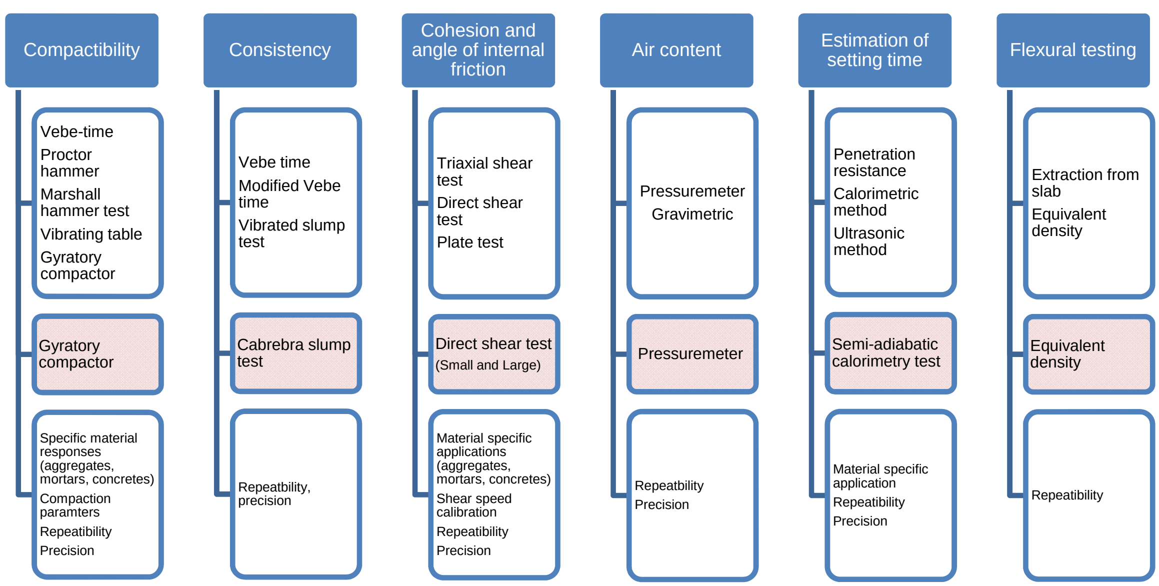


Figure 4-5 Scheme for test method selection and evaluation

The candidate test methods were screened against the pre-decided evaluation matrix. Once a test method was finalized, further studies pertaining to repeatability and establishment of precision statements were undertaken depending on the individual test requirements. Table 4-4 shows a typical screening matrix.

Table 4-4 Typical test method screening matrix

Criteria	Candidate tests			Selection	Evaluation	
	M1	M2	M3		Repeatability	Precision
Relevance and applicability						
Level of information and the effort required						
Time and ease of data extraction						
Manufacturing ease, cost and maintenance						
Operational ease and safety during operation						
Repeatability and precision						
Ruggedness						
Material quantity required for testing						
In-house availability and associated modification costs						

Note: M_i: method, i = 1, 2, 3

4.4.3 The second objective: Admixture selection and optimization

NON-ADMIXTURE RELATED FACTORS

Subsequent to studies on the aggregate grading optimization and concrete optimization, one set of fine and coarse aggregate combinations were finalized and used for rest of the test program. With this aggregate combination, three aggregate/binder ratios viz. 4, 7 and 10 were chosen and further optimization studies were done specifically focusing on the effects of moisture contents (as % of total dry solids) on the cohesion, friction angle, consistency, compactibility, heat signature and temporal evolution of strength. These mixtures constituted the control mixtures for further work. Table 4-5 shows the study matrix.

Table 4-5 Matrix for evolving control mixtures

Aggregate/binder	4				7				10			
Moisture content	1	2	3	4	1	2	3	4	1	2	3	4
Cohesion	x	x	x	x	x	x	x	x	x	x	x	x
Friction angle	x	x	x	x	x	x	x	x	x	x	x	x
Compactibility	x	x	x	x	x	x	x	x	x	x	x	x
Moisture density	x	x	x	x	x	x	x	x	x	x	x	x
Consistency	x	x	x	x	x	x	x	x	x	x	x	x
Heat signature	x	x	x	x	x	x	x	x	x	x	x	x
Strength evolution	x	x	x	x	x	x	x	x	x	x	x	x

Note: Moisture contents were chosen depending on the volumetric composition of mixtures and therefore are not mentioned here in quantified numbers

ADMIXTURES

The admixture studies were initially conducted on five different cements. The admixtures were selected on the basis of the market availability, contemporary applicability and relevancy. Initially 31 different admixtures were selected and tested on five different binders (two type I and three blended cements). Each of the types of admixtures had candidates with different chemical compositions and in some cases had two or three candidate admixtures that were chemically similar in composition but offered slight differences in their performances. A schematic is shown in Figure 4-6.

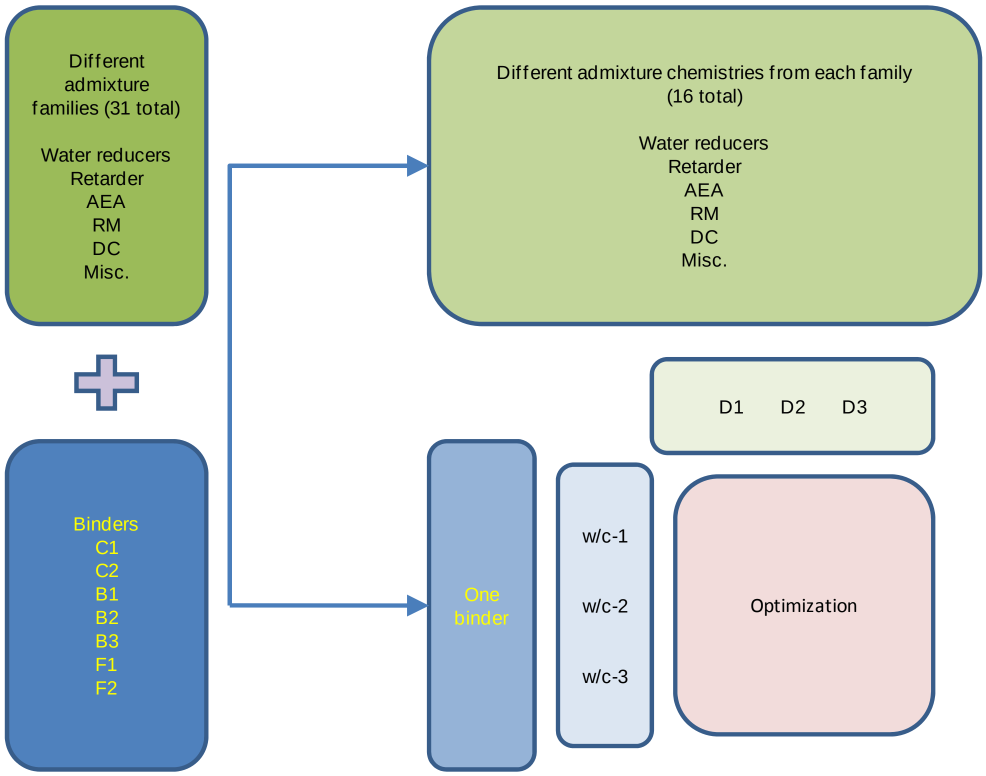


Figure 4-6 Binder-admixture screening and preliminary selection based on cement paste tests: Materials only

Based on the above tests, one binder composition and 16 different chemical admixtures were chosen for further work. With each of the selected admixtures, trials were run on paste at three different water/binder ratios and each ratio was run with three increasing dosages. The water/binder ratios were analogous to the anticipated water/binder ratio in the optimized concrete mixtures. Measured properties included consistency, retention up to 120 min, and in some cases Marsh cone flow times. Table 4-6 shows a typical matrix.

Table 4-6 Typical admixture-paste trials

	Admixture M-06		
w/c	D1	D2	D3
w/c-1	x	x	x
w/c-2	x	x	x
w/c-3	x	x	x

Subsequent to binder-admixture behavior studies, the focus was shifted on concretes. The materials' variable included the aggregate/binder ratio and water/binder ratio. Sixteen admixtures of different chemical families and variable dosages were tried on concretes with different aggregate/binder ratios. Initial consistencies of all the mixtures were kept similar. Measurements included water reduction, consistency, air content, cohesion, angle of internal friction, compactibility, heat signatures and temporal evolution of strength. Figure 4-7 shows the scheme of work.

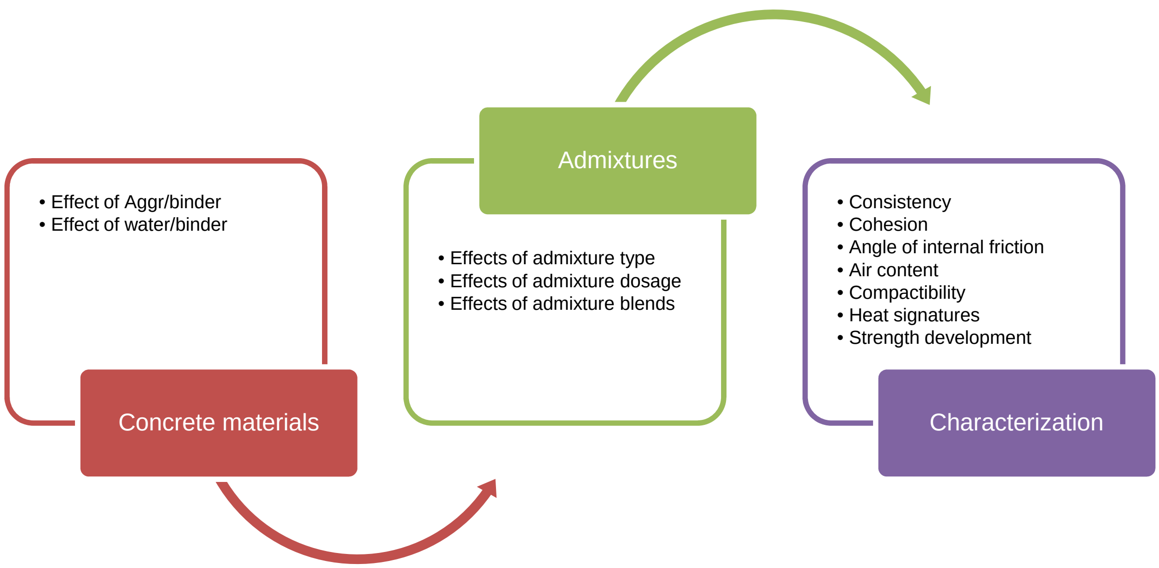


Figure 4-7 Concrete-admixture test scheme

Each of the aggregate/binder ratios were tried with several admixtures and the alterations in the measured properties recorded. Table 4-7 shows a typical matrix for one of the aggregate/binder ratios.

Table 4-7 Typical admixed concrete matrix with aggregate/binder = 7

Admixture type	Water reducer					Retarder		AEA			DC		RM			M
Characteristic	1	2	3	4	5	1	2	1	2	3	1	2	1	2	3	1
Water reduction	x	x	x	x	x	x	x	x	x	x	x	x	--	--	--	x
Consistency	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Retention	x	x	x	x	x	x	x	x	x	x	x	x	--	--	--	x
Cohesion	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Friction angle	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Air content	--	--	--	--	--	--	--	x	x	x	--	--	--	--	--	--
Compactibility	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Heat signature	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Strength development	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

Notes: AEA: air entraining agent; DC: dry cast; RM: rheology modifier; M: Misc.

Upon completion of single admixture trials, admixture cocktails were studied only on the most typical pavement mixture i.e. aggregate/binder = 7. The study matrix is shown in Table 4-8. For each of the combination two dosage levels were used and same set of properties as in the above phase were used for characterization purpose.

Table 4-8 Admixture combinations: duets

	AEA-1	Dry cast-1	RM-1	RM-2
Water-reducer-1	x		x	x
Water-reducer-2	x			
Retarder-1		x		

Similarly, three combinations of admixture triplets were used and same set of properties were measured. These are pictorially shown in Figure 4-8. The selection criteria for this will be discussed in one of the later sections.

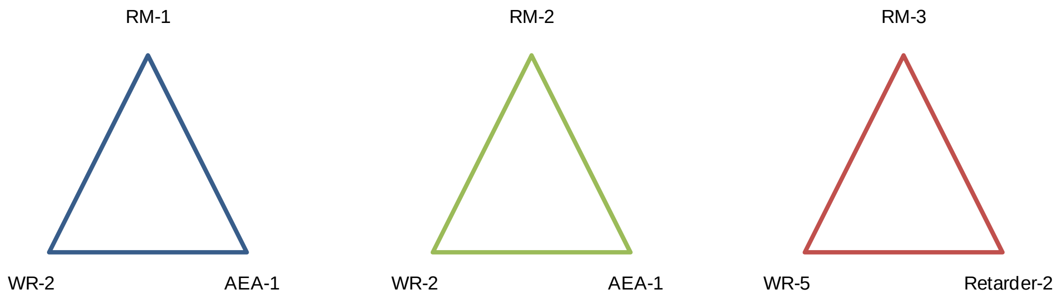


Figure 4-8 Admixture triplets used in the study

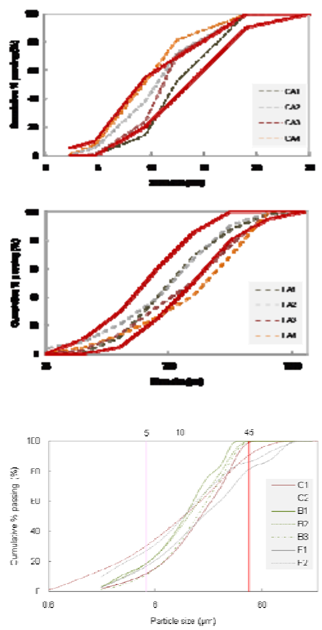
SUMMARY

Two primary objectives were identified and described. The first objective of this work was to identify and evaluate the components of workability of RCC. These included cohesion, angle of internal friction, compactibility, and consistency. In addition to these, the heat generation using semi-adiabatic calorimetry was planned. The workability studies on concrete were founded on the compactibility and gradation studies on aggregates. Gradually building on this foundation were the studies on the effects of aggregate grading curves on the compactibility of concretes.

The second objective of this work was to select and evaluate different admixtures in RCC. These included water reducers, retarders, air entraining admixtures, rheology modifiers and dry cast products. Each of these admixture types had specific chemistries selected after evaluating the available products in the market from five major admixture manufacturers. Multiple dosages were used in concretes with three different binder content levels, thus the spans were covered on both the binder and admixture volumes.

Once individual admixtures were evaluated, combinations of different admixtures complementing each other's functionalities were evaluated. These included binary and ternary combinations. The *method of mixtures* was applied for statistical evaluation of ternary admixtures.

CHAPTER 5 CONSTITUENT MATERIALS



SYNOPSIS

Material selection process is pivotal in any experiment design. The philosophy of material selection has been described in the chapter. The primary criteria considered were relevancy, market acceptance, performance capability and economics. This chapter briefly scans over and offers relevant information of different constituent materials and their relevant properties. The materials listed include the binders, aggregates, chemical admixtures and water.

Keywords: Cement, Fly ash, aggregate, geology, water reducer, retarder, air entraining agent, rheology modifier, dry cast, water

CONTENTS

5.1 Binders

A total of two Type I Portland cements, one Class C fly ash, one Class F fly ash and three blended cements were used in this study. These binders and supplementary cementitious materials were chosen while taking into account the probability of their usage in RCC for pavement applications. A comprehensive study was conducted on the cementitious materials to screen out binders and chemical admixtures that had physical incompatibility issues. Moreover, taking into account the nature and extent of the anticipated studies on mortar and concretes with and without admixtures, economics, construction ease and engineering factors, one system of binders was finalized. Table 5-1 presents a summary of mill certificates supplied by the manufacturer. In addition to the data revealed in this table, the particle size distribution all these binders was conducted in two different labs. This data is presented in Figure 5-1.

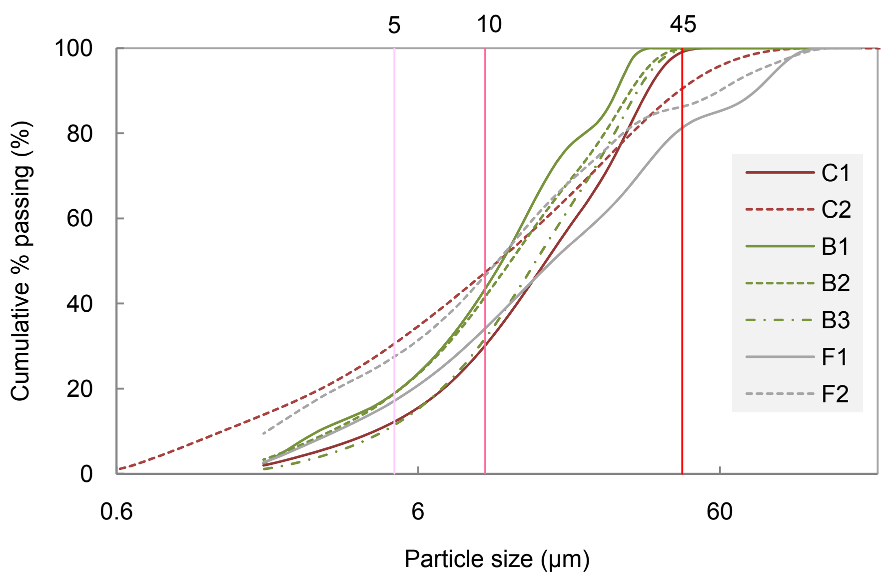


Figure 5-1 Particle size distribution of binders. Note: C2 was done on a different instrument.

Table 5-1 Physical properties and chemical constitution of binders [1-13]

Description	Units and ASTM test standard	C1	C2	B1	B2	B3	F1	F2
		Type I	Type I	IP (FA)	IP (IS)	IP (SF)	Class F	Class C
				Physical				
Fineness by Air Permeability	*(m^2/kg; C204-07)*	402	384.3	444	444	562	NA	NA
Fineness by 45 micron	*(% passing; C430-08)*	NA	91.8	98.7	91.7	96	80.55	84.93
Compressive Strength	*(C109/C109M-08)*							
1-day	(MPa)	NA	16.5	NA	NA	15.9	NA	NA
3-day	(MPa)	12	25.2	13	13	24.5	NA	NA
7-day	(MPa)	19	30.9	20	20	31.5	NA	NA
28-day	(MPa)	NA	40.9	25	25	50.4	NA	NA
Time of Set, Vicat	*(initial, min.; C191-08)*	93	79.7	157	115	96	NA	NA
Air Content of Mortar	*(%; C185-08)*	6.00	7.00	6.00	5.00	8.00	NA	NA
Autoclave Expansion	*(%; C151/C151M-09)*	0.00	0.03	-0.01	-0.01	-0.03	-0.01	0.07
Sulfate Expansion	*(%; C1038-04)*	NA	0.0	NA	NA	0.008	NA	NA
Specific Gravity	*(%; C188-95)*	3.14	3.150	NA	NA	3.05	2.36	2.75
Water required	*(% of control)*	NA	NA	NA	NA	NA	95.5	93.8
Strength activity index	(w/ OPC, *C311-00)*							
at 7d	*(% of control)*	NA	NA	NA	NA	NA	80.1	99.5
at 28d	*(% of control)*	NA	NA	NA	NA	NA	88.4	99
				Chemical				
Silicon Dioxide	(SiO_2; C114-09)	19.7	20.4	NA	NA	26.0	54.1	31.5
Aluminum Oxide	(Al_2O_3; C114-09)	5.1	4.3	13.0	13.0	4.6	23.7	18.2
Ferric Oxide	(Fe_2O_3; C114-09)	2.1	3.2	20.0	20.0	3.1	5.3	5.4
Calcium Oxide	(CaO; C114-09)	63.0	63.2	25.0	25.0	58.8	8.5	28.1
Magnesium Oxide	(MgO; C114-09)	2.1	3.0	1.8	5.6	1.4	2.4	7.3
Sulphur Trioxide	(SO_3; C114-09)	3.1	3.4	2.5	2.8	3.0	0.4	2.9
Loss on Ignition	(L.O.I.; C114-09)	1.9	1.1	0.9	1.1	1.7	0.6	0.4
Insoluble Residue	(C114-09)	0.6	0.2	NA	0.1	NA	NA	NA
Free Lime	(f-CaO)	NA	1.1	NA	NA	1.4	NA	NA
Tricalcium Silicate	(C_3S; C150-09)	57.0	58.3	NA	NA	NA	NA	NA
Tricalcium Aluminate	(C_3A; C150-09)	12.0	6.0	NA	NA	NA	NA	NA
Equivalent alkalies	(NaEq, %)	0.5	0.5	NA	NA	0.6	1.3	2.3
% pozzolan addition rate	(%)	NA	NA	25.0	NA	6.9	NA	NA

Note: Cements are classified according to ASTM C150-09 and C595-09; fly ash classification is in accordance with ASTM C618-08a

5.2 Mineral aggregates

Four aggregate geologies were selected in order to appreciate the effects of surface texture, shape and mineralogy on the categorically selected properties of mortar and concrete mixtures. The geologies are siliceous river gravel, Limestone, Quartzite and Granite. The NMSA for each coarse aggregate was 19 mm. Significant bulk aggregate properties are reported in Table 5-2.

Table 5-2 Geology and bulk properties of coarse (CA) and fine (FA) aggregates [14-15]

Property	Gravel	Limestone	Quartzite	Granite
	CA1	CA2	CA3	CA4
Bulk specific gravity (oven dry)	2.600	2.653	2.622	2.648
Bulk specific gravity (SSD)	2.654	2.676	2.630	2.664
Apparent specific gravity	2.747	2.716	2.643	2.693
24 hour water absorption	2.1	0.9	0.3	0.6
LA Abrasion (%)	22	26	20	21
	FA1	FA2	FA3	FA4
Bulk specific gravity (oven dry)	2.613	2.525	2.581	2.610
Bulk specific gravity (SSD)	2.633	2.604	2.600	2.631
Apparent specific gravity	2.665	2.743	2.633	2.665
24 hour water absorption	0.7	3.2	0.7	0.8

In addition to the bulk properties reported in the above table, additional properties are reported in the later chapters. Durability tests were conducted on the carbonate aggregates and they were found to be satisfactory. Figure 5-2 reports the particles size distributions of these aggregates.

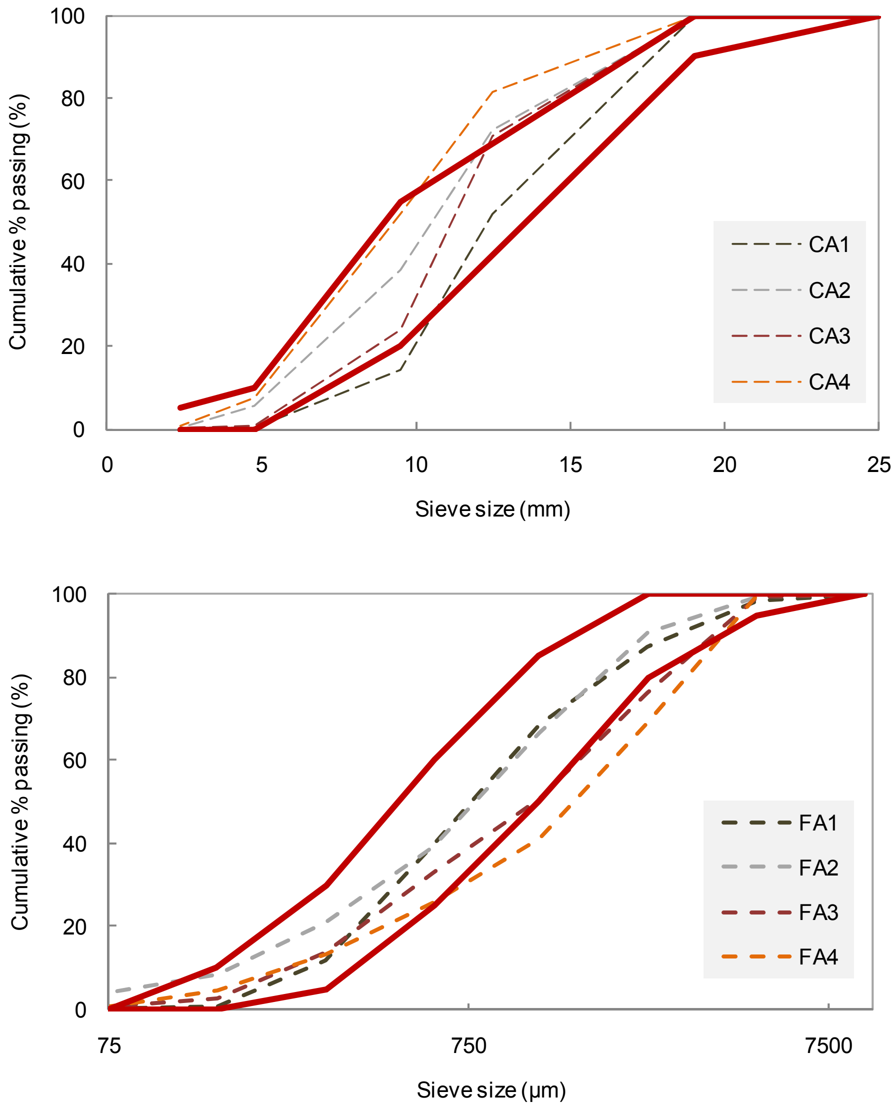


Figure 5-2 Particle size distribution of aggregates along with ASTM C33 [16] grading bands

5.3 Chemical admixtures

Chemical admixtures were procured from five different manufacturers after due consultation and thought. Table 5-3 and Table 5-4 present the primary composition, functional classification, basic properties and recommended dosages of these admixtures. For maintaining confidentiality of manufacturer and their products, the manufacturers and their products were coded and are represented in these tables. Further information pertaining to composition and other properties are intentionally avoided. Further details relevant to further screening shall be discussed later in the thesis.

Table 5-3 Primary chemical composition and functional classification of chemical admixtures [17-18]

Manufac. Code	Product Code	Primary chemical constitution	Functional classification								
			WR		Retarder						
			ASTM C494 Type					AEA	RM	DC	Misc
			A	F	B	D	G				
M-04	P-01		■	■							
M-03	P-02	Na Sulfonated/gluconate	■			■					
M-03	P-03	Poly-Melamine sulfonic acid	■	■							
M-03	P-04	Naphthalenesulfonic acid	■	■							
M-03	P-05	Polycarboxylate resin	■	■							
M-05	P-06	Triethanolamine	■								
M-05	P-07	Triethanolamine	■			■					
M-01	P-08	Ethylenediamine	■	■							
M-01	P-09	Ethylenediamine	■	■							
M-02	P-10	Ca-Lignosulfonate	■	■	■	■	■				
M-04	P-11		■		■	■					
M-04	P-12				■						
M-04	P-13				■	■					
M-03	P-14	Phosphonic acid/Na gluconate/NaOH				■					
M-03	P-15	Na-gluconate			■	■					
M-05	P-16	Na-gluconate/Sucrose			■	■					
M-01	P-17	Phosphonic acid			■						
M-04	P-18							■			
M-03	P-19	Sodium olefin sulfonate						■			
M-03	P-20	Na-tetradecenesulfonate						■			
M-03	P-21	Tall oil/Na salt						■			
M-05	P-22	Polyacrylate aq.						■			
M-01	P-23	Tall oil/Polyethylene glycol						■			
M-03	P-24	Polysaccharide							■		
M-03	P-25	Naphthalene sulfonate/ Welan gum							■		
M-01	P-26								■		
M-04	P-27								■		
M-04	P-28									■	
M-03	P-29	Polycarb. resin + Polethylene glycol								■	
M-05	P-30									■	
M-05	P-31										■

Notes: AEA: Air entraining admixture; RM: Rheology modifier; DC: Dry cast. Admixtures were collected from five admixture manufacturers. These manufacturers were given code numbers between 01 and 05, while the products were designated in order of their primary function in conventional and self-consolidating concretes. Filled area represents the classification type of the admixture.

Table 5-4 Sampling of properties and recommended dosages for normal/pavement/self-consolidating concretes

Manufac. Code	Product Code	Properties						Recommended dosage (ml/100kg binders)
		Form	Color	SG	pH	Water solubility	Solids content (%)	
M-04	P-01	Liquid	Blue	1.075-1.085	3-7	Soluble	31-41	130-780
M-03	P-02	Liquid	Brown	1.2065±0.0207	5.5-8.5	Soluble	30-60	125-375
M-03	P-03	Liquid	Clear	1.21 ± 0.01	7.5-9.5	Complete	30-40	500-1125
M-03	P-04	Liquid	Brown	1.18-1.22	6-8	Soluble	40-70	500-1125
M-03	P-05	Liquid	Amber	1.04 ± 0.01	5-7	Soluble	15-40	341-650
M-05	P-06	Liquid	NA	1.1	8.5-11.5	Unknown	NA	195-455
M-05	P-07	Liquid	Dark Brown	1.18-1.22	6-8	Unknown	NA	195-390
M-01	P-08	Liquid	Dark Brown	1.068	5-6	Complete	NA	195-780
M-01	P-09	Liquid	Violet/Brown	1.038	4.9	NA	NA	190-780
M-02	P-10	Solid	Dark Brown	NA	7.5 ± 0.8	~ 99.5	27	NA
M-04	P-11	Liquid	Dark Brown	1.14-1.31	> 8	Soluble	31-39	130-390
M-04	P-12	Liquid	Colorless	1.099-1.127	2.5-4.0	Soluble	20-26	130-3100
M-04	P-13	Liquid	Green/Brown	1.15-1.32	> 8	Soluble	30-35	130-260
M-03	P-14	Liquid	Brown	1.12 ± 0.01	5-7	Soluble	30-40	250-1000
M-03	P-15	Liquid	Brown	1.2 ± 0.02	5-8	Soluble	30-60	125-375
M-05	P-16	Liquid	Clear green	1.1-1.2	5-8	Complete	NA	180-8350
M-01	P-17	Liquid	Dark Brown	1.061-1.075	2.2-2.6	NA	NA	195-325
M-04	P-18	Liquid	Dark Brown	1.008 ± 0.005	11-13	Soluble	7-9	65-195
M-03	P-19	Liquid	Light Yellow	1.015 ± 0.01	8.5-11.5	Soluble	5-10	30-60
M-03	P-20	Liquid	Off white	1.07	?	Soluble	NA	15-500
M-03	P-21	Liquid	Brown	1.025 ± 0.015	9-12	Soluble	>60	30-60
M-05	P-22	Liquid	Brown	NA	5.1-6.5	Unknown	NA	32-195
M-01	P-23	Liquid	Brown	1.01	10.7-12.3	Complete	NA	8-98
M-03	P-24	Liquid	White/Tan	1.01-1.08	11.5	Soluble	15-40	500-2300
M-03	P-25	Liquid	Brown	1.207	7.5-10.5	Soluble	30-60	39-460
M-01	P-26	Liquid	Light Brown	1.002	8	NA	NA	130-910
M-04	P-27	Liquid	Green/ Blue	1.019-1.039	> 7	Soluble	5.5-7.5	65-455
M-04	P-28	Liquid	Clear	1.007 ± 0.005	> 7	Soluble	4.8 ± 1.5	130-390
M-03	P-29	Liquid	Amber	1.02	5-7	Soluble	< 40	130-391
M-05	P-30	Liquid	NA	NA	NA	NA	NA	130-325
M-05	P-31	Liquid	NA	NA	NA	NA	NA	325-975

The preceding selection procedure was based on the following initial criteria:

- Local availability and market acceptability;
- Chemical composition and tentative roles that individually each admixture could play;
- Enhancing the binder efficiency in improving the mechanical strength;

- Technical objectives included the following
    - Modifications in the workability
    - Retention of workability
    - Modifications in the setting time
    - Improved product finishibility
    - Improvement in mechanical strength
    - Tentative improvement in durability (indirect) and
- Overall economics

During initially communications with the admixture manufacturers, the following salient points were observed:

1. In general, there is a lack of complete appreciation of the nature of RCC and the tentative chemical families and dosage ranges that could be used in RCC for pavements;
2. Lignin-based and the new generation Polymer based chemical admixtures are the most manufactured chemical admixtures. Sulfonated Naphthalene and Melamine based admixtures are occupying much less share in North American markets when compared to yesteryears. There are manufacturers who only manufacture the earlier two families of products and their blends when it comes to water reducers and
3. As commented before, it was anticipated that the current ASTM C494 system of admixture classification might not be adequate for RCC applications.

5.4 Water

Potable tap water was used for this research.

SUMMARY

Materials used in this research are described along with their properties in this chapter. Two ASTM type I cements, three blended cements and two fly ashes were selected and screened for further use. No in-house testing of these cements was conducted. Their composition, physical properties and particle size distributions are reported.

Four different aggregate geologies were used to test various test variables. Their properties are reported. In addition to this, 31 different chemical admixtures were selected for screening; their available constitution and properties are reported.

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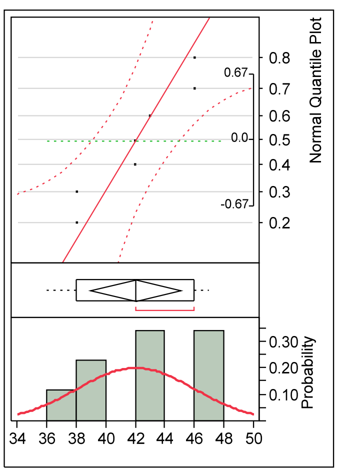
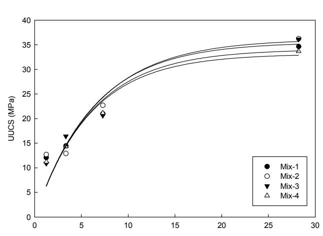
CHAPTER 6 CHARACTERIZATION METHODS





SYNOPSIS

The primary intent of this chapter is to have an appreciation for the causes and extent of variations in the measurements that could eventually result into the spread of data. In addition, studies of this kind also establish a valid range of results from those obtained by performing tests on fewer specimens. This chapter discusses the test methods used in this work for characterizing different materials. Setting the scene with definition of objectives for studying the variability in testing, the chapter describes the basis of statistical analysis. A special set of nine repeat mixtures on intermediate binder content mixtures were mixed and tested to appreciate the variation and to set out the status of control for the lab. The chapter then discusses the variations caused in various measured parameters like compacted density, Cabrera slump value (CSV) cohesion and angle of internal friction from the shear box, gyratory compaction and the strength measurements.

Key words: repeatability, compacting hammer, Cabrera slump value, shear box, AdiaCal, gyratory compactor, dry concrete

CONTENTS

6.1 Introduction

In any scientific testing, a spectrum of errors is invariably present due to one cause, the other, or a combination of multiple causes. An understanding of the sources of errors and their effects is essential in drawing comprehensive inferences based on any measurement study. Figure 6-1 shows the taxonomy of error types.

Most of the tests used in this work were either borrowed from other fields of applications or developed in-house. Some of these test methods had no standards wither National or International. Moreover, whatever standards are available are tailored towards specific materials, which are different in not only their compositions but also the behavior and responses to mechanical and thermal loadings relevant to this work. Even with the available standards and specifications, statistical data and uniformity standards pertaining to the precision and bias are not clearly cited.

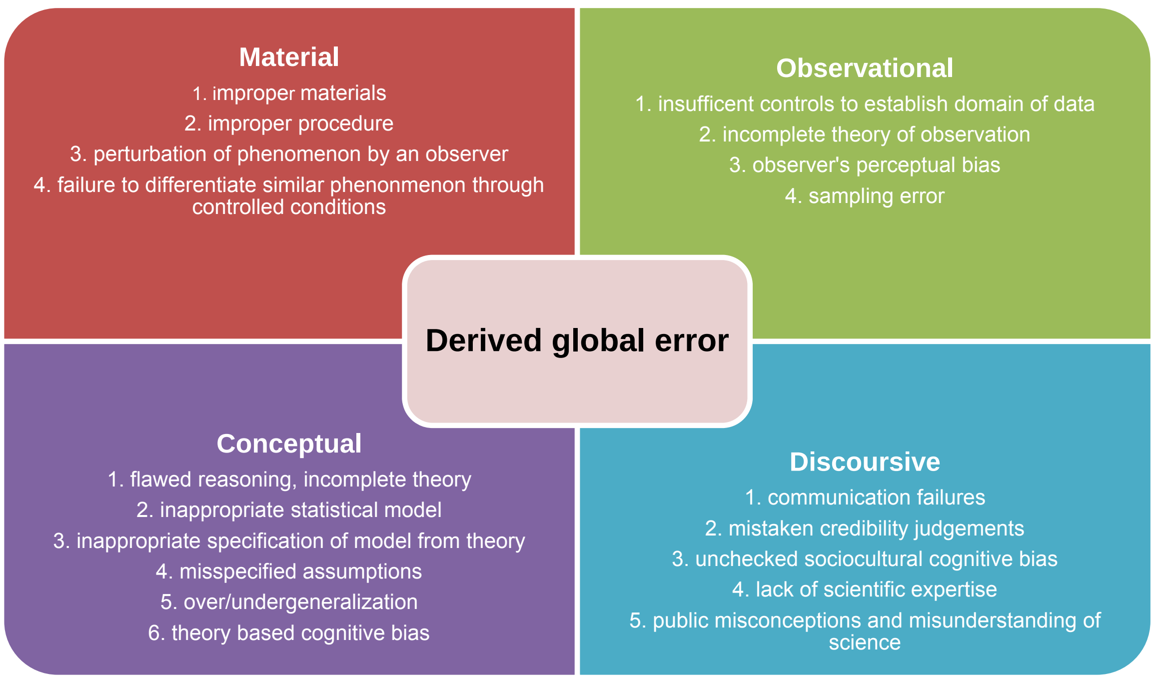


Figure 6-1 Taxonomy of errors [1]

6.1.1 The paradox of modern-day research

The author, while reviewing the literature, came across references that reported results based on a significantly large datasets. For example the paper on proportioning concrete mixtures by Abrams [2] states that the reported results were based on 100, 000 tests. In this regard, it is quite disproportionate to conclude on basis of few test results. It should also be noted that although inference and conclusions are many-a-times used interchangeably, the American heritage dictionary defines inference as “concluding from evidence", while conclusion as "to reach a decision or form an opinion about", the use of inference seems to be more appropriate from statistical standpoint. Statistical inference can point out interesting associations but offering statistical conclusions requires further studies. Hence, the word inference shall be used in this work.

Arguing further, one of the typical drawbacks of contemporary studies on cement-based materials is the lack of statistical backbone to establish a broader acceptability of the results. Most, if not all studies, report their conclusions based on very few samples, thus to a certain degree, undermining complete appreciation for the inherent variability and non-uniformity in construction materials. Figure 6-2 shows a summary of survey responses on the perceptions about the impact of variability of constituent materials on concrete performance

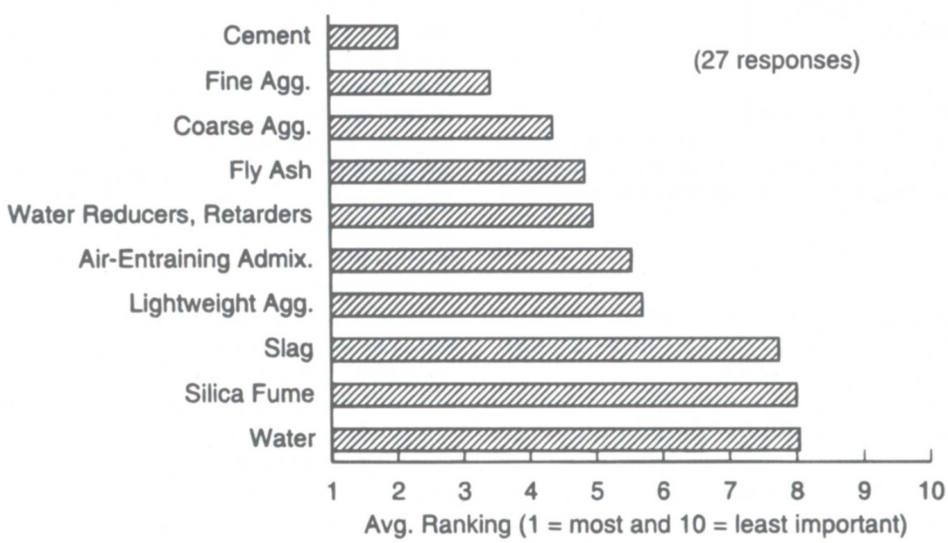


Figure 6-2 Perceptions about the impact of variability of constituent materials on concrete performance [3]

6.1.2 A primer on statistical parameters

The fundamental statistics derived from variables inspection that are most useful in making decisions concerning concrete and concrete-making materials are the arithmetic mean and standard deviation. Although mean is very important and offers a comprehensive idea about the central tendency of a sample data, it does not indicate the nature and extent of the spread of the data, which is conveyed by standard deviation. The standard deviation indicates, in one figure, how far above or below the mean other values will be and how many values will likely be found at any distance from the mean [4]. In addition to expressing variability, standard deviation is commonly used in constructing confidence interval [5]. The coefficient of variation is useful because the standard deviation of data must always be understood in the context of the mean of the data. The coefficient of variation is a dimensionless number. Therefore, when comparing between data sets with different units or widely different means, one should use the coefficient of variation for comparison instead of the standard deviation. However, when the mean value if near zero, the CoV is sensitive to small changes in the mean, thus limiting its usefulness. In addition, it cannot be used for constructing the confidence intervals for the mean [6]. The following are the three frequently used formulae used in this chapter:

$$Sample\ mean = \bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i$$

$$Standard\ deviation\ of\ a\ sample = s = \sqrt{\frac{1}{(n-1)}\sum_{i=1}^{n}(y_i - \bar{y})^2}$$

$$Coeffiecient\ of\ variation = CoV = \frac{s}{\bar{y}}$$

Other statistics described in this chapter is readily available in the standard texts and references and hence is not discussed further.

6.2 Quest for repeatability

6.2.1 Defining the objectives

Before the entire suite selected test methods were used, they had to undergo evaluation. This includes the mixing procedure as well. The objectives of conducting this evaluation were to establish a single operator precision and also appreciate the level of concrete in the lab used for this work. The framing of objectives included the following considerations:

- To capture the potential variations in the materials used for mixing concrete;
- To find the variability in the mixing of concrete itself;
- To verify the cylinder casting procedure;
- Evolving the precision statements for the following test methods:

    - Compacting hammer: uniformity is casting samples;
    - Sample casting procedures;
    - Air content measurements using pressure meter test;
    - Shear strength measurements (cohesion and friction angle);
    - Gyratory compaction;
    - Compressive strength measurement and
    - Flexural strength measurement

It needs to be agreed here that due to limited resources, an exhaustive statistical study was not possible. The presented data is based on what could be accomplished in a reasonable period, while being comprehensive.

6.2.2 Some notes on batching and mixing procedures

The weighing scales were selected such that the material weight to be measured did not exceed 50% of the maximum weighing capacity. All the cements and mineral admixture (fly ash, typically) were stored in 200 gallon barrels. Within the possible scope of the equipments, where this work was carried out, certain amount of tolerances were decided for batching the materials and are reported in Table 6-1. It is interesting to note that there are no tolerances specified on batching materials in laboratory, however the standard prescribes specifications for the weighing scales.

The batch volumes are of critical importance, since RCC being a very dry mixtures needs more energy for proper mixing and hence it is critical that both the mixing method, sequence of batching and the volume mixing are carefully evaluated and used. For this work, the following mixing procedure was used based primarily on the author's previous works [7-9]:

- Initially, the mixer was buttered with a mortar of a fixed composition;
- Then all of the coarse aggregate and ¾ of fine aggregate were added and allowed to dry mix for 1 minute;
- All the admixture was dosed with about 60% of the total water and dispensed to mix with the aggregates for about 3 minutes;
- Then the cement and fly ash was added and the mixture was allowed to mix for about 3 minutes. During this period, the required water to reach the pre-defined consistency was gradually added;
- The mixed batch was allowed to stand for about 3 minutes and
- Finally the mixture was mixed for about two minutes before starting the pouring the concrete in a wheelbarrow.

Table 6-1 Batching tolerances

Material	Allowed tolerance	ASTM C192* [10]	ATSM C94 [11]
Binder	± 5 g	Not specified	± 1 %
Aggregate	± 10 g	Not specified	± 2 %
Water	± 5 g	Not specified	± 1 %
Chemical admixture	± 0.05 g	Not specified	± 3 %
Concrete	± 10 g	Not specified	Not specified

*, this ASTM prescribes the use of scales that can determine the mass of batches of materials and concrete to be within 0.3% of the test load at any point within the range of use. The smallest mass determined on a scale should be greater than about 10% of the maximum capacity of the scale.

6.2.3 The preamble

For achieving the above-established objectives, the experiments shown in Table 6-2 were planned and conducted. Since the intermediate binder content of 282 kg/m^3 was the focus of the work, this was used in performing this statistical study.

Table 6-2 Scheme for establishing statistical information for the lab mixing and testing procedures

Details	Details (Number of repeats)	Remarks
Mixing of mixtures	9 x 1	
Compacting hammer	9 x 2	Measured by density of cylinders
Fresh density	9 x 1	
Air content	9 x 1	
Cabrera consistency test	9 x 1	
Cohesion	9 x 1	
Angle of internal friction	9 x 1	
Gyratory compaction	9 x 1	@ 15, 60 and 120 minutes
Compressive strength	9 x 2	@ 1, 3, 7 and 28 days
Flexural strength	3 x 2	@ 28 days

6.3 Compacting hammer

6.3.1 Moisture – density

The construction of moisture density plot requires four to five trial runs per set of materials. For a fixed aggregate/binder ratio, the moisture content is varied and fresh density is measured. No attempts were made to have repeats on these test procedures. It is however interesting to note that ASTM D698 on standard Proctor test method offers precision statements for triplicate lab tests as a function of the soil type. Table 6-3 reproduces these summaries for single-operator results.

Table 6-3 Summary of test results from triplicate test laboratories for single operator precision [12]

Soil type/ Number of triplicate test labs			Test value	Average value			Standard deviation			Acceptable range of two results		
CH	CL	ML		CH	CL	ML	CH	CL	ML	CH	CL	ML
11	12	11	$\gamma_{d,\ max}$ (pcf)	97.2	109.2	106.3	0.5	0.4	0.5	1.3	1.2	1.3
			w_{opt} (%)	22.8	16.6	17.1	0.2	0.3	0.3	0.7	0.9	0.9

Note: CH: Fat clay, 99% fines, Liquid limit = 60, Plasticity index = 39, Local name - Vicksburg Buckshot clay; CL: Lean clay, 89% fines, Liquid limit = 33, Plasticity index = 13, Local name - Annapolis clay; ML: Silt, 99% fines, Liquid limit = 27, Plasticity index = 4, Local name – Vicksburg silt.

6.3.2 Densities

Compacting hammer as shown in Figure 6-3 was used for making cylinders and beams and other tests as required. The uniformity tests on this were indirectly the tests for establishing the variability of the casting procedures. The variability was primarily measured based on the fresh density and the densities of the compacted cylinders to be tested at various ages.

Figure 6-3 Compacting hammer

Figure 13-4 shows the distribution, normal fit and normal quantile plot for the fresh densities measured on the compacted air pot. The compaction was achieved by the compacting hammer. The resulting distribution is normal, N (2525.78, 24.196). The resulting coefficient of variation was 0.3187 %, with the 95 % limits of 2547.37 and 2510 kg/m^3. ASTM C1170 reports that the precision for fresh density has not been determined and data is being collected for it.

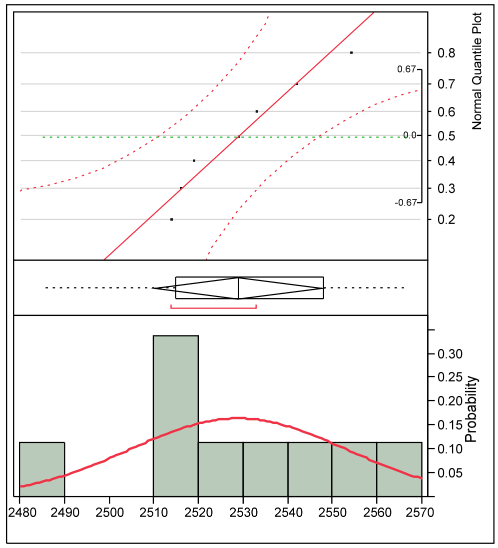


Figure 6-4 Distribution plot for fresh density

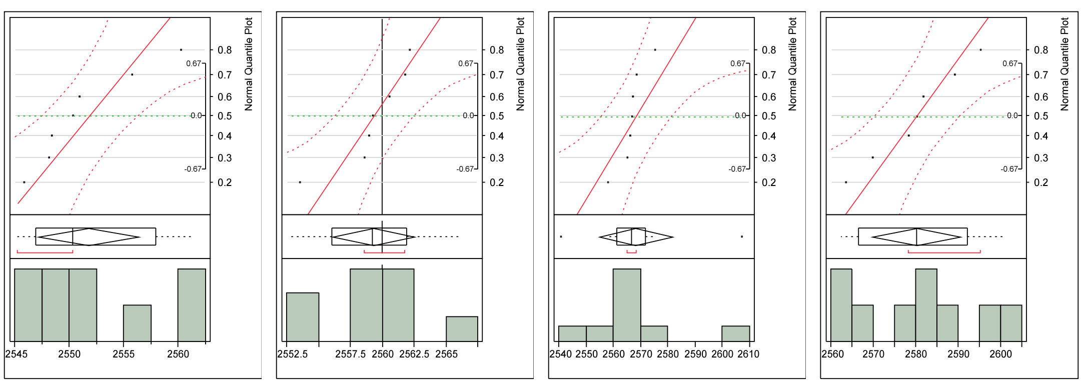


Figure 6-5 Density distributions at 1, 3, 7 and 28 days respectively (L to R)

An important note regarding this is that the observed compacted density is a function of the specimen size. The fresh densities obtained from the air pot measurements are representative densities and are in line with the theoretical calculations. The densities obtained in smaller specimen are higher due to wall- and specimen-size effects. The density of concrete specimens is known to increase with the curing age [13] and therefore the following analysis for the compacted cylinders is presented at different curing ages. It should be noted that the ASTM C873 [14] does not recommend or specify the weighing of the concrete samples before testing for the compressive strength. Figure 6-5 shows a summary of density distributions at 1, 3, 7 and 28 days.

Table 6-4 summarizes the information from these density plots.

Table 6-4 Descriptive statistics for densities at various ages

Age	1	3	7	28	Units
Mean	2551.77	2559.31	2568.22	2580.15	(kg/m^3)
SD	5.92	4.17	17.43	13.47	(kg/m^3)
CoV	0.23	0.16	0.68	0.52	(%)

Figure 6-6 plots the average density along with 95% confidence band and the variation with age. It is interesting to note that the temporal evolution follows a trend similar to that of compressive strength.

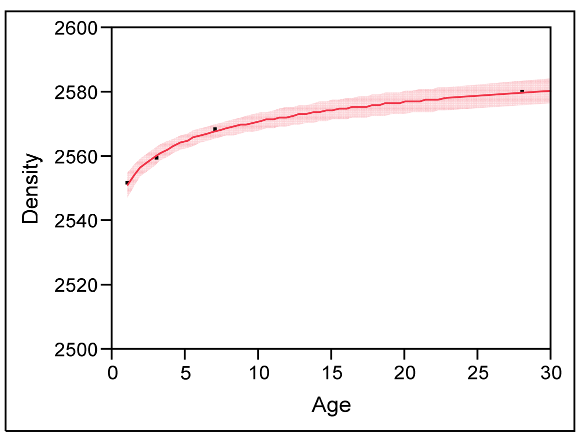


Figure 6-6 Variation of density with curing age

The distribution of the air content of the fresh concrete is shown in Figure 6-7. The normal distribution, N (1.8388, 0.1746) shows a good degree of control. The coefficient of variation obtained is 9.49%. ASTM C231 [15] does not specify the single operator precision, since there is no time for an operator to conduct more than one test on a sample. The standard however specifies a multi-operator precision in terms of standard deviation of 0.28%. This means that the test is time sensitive.

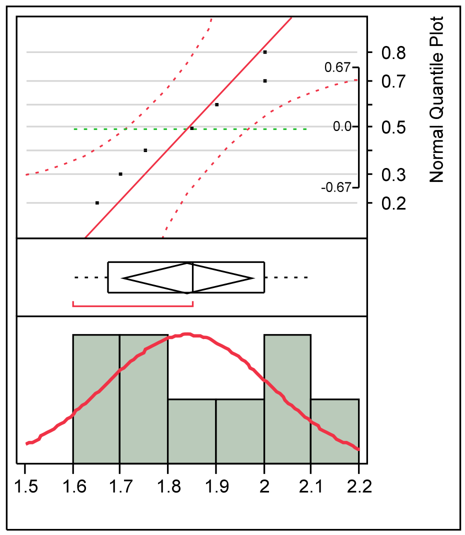


Figure 6-7 Distribution plot for air content

6.4 Cabrera slump value

Cabrera slump value (CSV) was measured on all the nine mixtures and the results are summarized in Figure 6-8. The analysis indicates that the mean is 42 mm, with a corresponding standard deviation of 3.96 mm and a CoV of 9.45%. The observations ranged between 36 and 47 mm indicating that the values are estimated within ± 6 mm of the average value. The standard deviation is approximately 1/10th of the measured value.

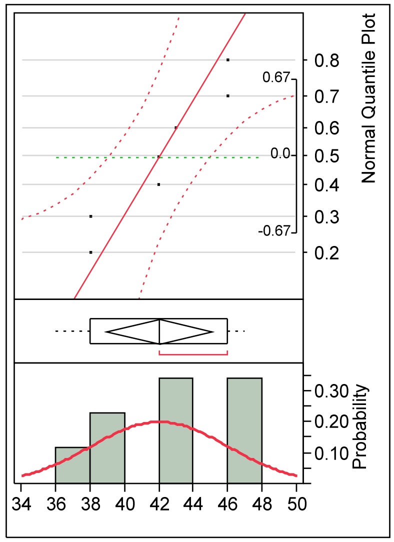


Figure 6-8 Distribution of Cabrera slump value (CSV)

6.5 Shear box

6.5.1 Design and fabrication

The direct shear box used for testing the shear strength of soil and as specified by ASTM D3080 [16] was used for testing the shearing strengths of various fresh concretes. The scaling up of the instrument was required. The following specifications (for specimen sizes) from the above standard formed the basis of designing and constructing the shear box:

- The minimum width of the specimen shall be 50 mm or not less than 10 times the maximum particle size diameter, whichever is larger;
- The minimum thickness shall be 12 mm, but not less than six times the maximum particle size diameter;
- The minimum specimen diameter to thickness or width to thickness ratio shall be 2:1.

Considering the above guidelines, dimensions shown in Table 6-5 were used for designing and constructing the shear boxes.

Table 6-5 Dimensions for direct shear boxes for mortar and concrete testing

Ref.	Units	Minimum			Proposed and used		
		NMSA (d)	Width (w)	Thickness (t)	Width (w)	Thickness (t)	w/d
ASTM	(mm)	D	10D	6D	15.8	7.9	2.00
Concrete	(mm)	19	190	114	300.0	150.0	2.00
Mortar	(mm)	4.75	47.5	28.5	100.0	50.0	2.00

6.5.2 Calibration

The driving speed of the mortars in pulling the upper shear box was calibrated because a specially fabricated motor and load cell were used. Figure 6-9 shows the calibration chart with respect to the markings on the motor regulator. Since the intent of the test was to capture the average cohesion and angle of internal friction and since this requires three runs of the test on a given sample, a speed of 15 on shear machine corresponding to 6.55 mm/min was selected. This speed allowed timely completion of three runs of fresh concretes for a time-sensitive material, fresh concrete with adequate repeatability.

In addition to afore-mentioned fabrication and calibration, it was necessary to run blank runs of the machine, since with the available level of instrumentation, a friction-less interface between the two shearing boxes could not be achieved.

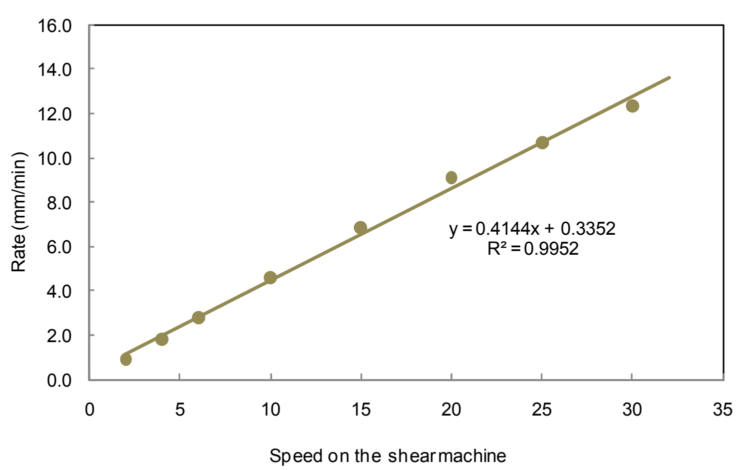


Figure 6-9 Displacement rate calibration

ASTM D3080 [16] does not prescribe any precision and bias data for the direct shear test.

6.6 Gyratory compactor

6.6.1 Selection of compaction parameters

The selection of compaction parameters for aggregates, mortars and concretes is a crucial step in gathering a consistent data for further analysis. In the initial stages of this study, multiple samples were run to establish the appropriate compaction parameters for aggregates, mortars and concretes. Some of the key considerations that lead to the use of the final parameters for mortars and concretes are as follows:

- Confining pressure (kPa)
  - ► should be as close as possible to actual compaction pressure that RCC has to bear under field conditions;
  - ► should not cause excessive aggregate background;
  - ► should render meaningful comparative values for mixtures with different volumetric compositions, without yielding distorted values;
  - ► should not lead to rapid and excessive squeezing out of the paste from the samples while the gyrations are being applied;
- Rate of gyrations (number/min)
  - ► was fixed for the machine used in this work and could not be changed;
- Angle of gyration
  - ► was not considered as a variable in these experiments;
- Internal diameter of the mold
  - ► The maximum size of the aggregate was 19 mm;
  - ► Avoid the wall effects as much as possible;
- Number of gyrations
  - ► The number of gyrations was primarily decided by the nature of the mixture.

Table 6-6 Compaction parameters for the gyratory compactor

Parameter	Available machine range	Final value used for current work
Consolidation pressure (kPa)	200-1000	200
Rate of gyrations (number/min)	30 ± 0.5	30
Angle of gyration (degree)	0.5 to 2.0 ± 0.02	1.25
Internal diameter of mold (mm)	100 or 150	150
Number of gyrations	1 to 999	< 150

Based on above considerations, Table 6-6 shows the final compaction parameters used in this study. A fixed weight of mortar or concrete were added to the mold and with the application of the pre-defined compaction parameters, the sample was allowed to compact. The termination point was the least number of gyrations

- no change in the height of the sample for 10 gyrations;
- beginning of squeezing out of the paste from the sample;
- 150 gyrations whichever was least.

6.6.2 Limitations of the GC used in this study

The gyratory compactor used for this work is actually a compactor for asphalt materials. Asphalt cement, depending on its grade typically has a viscosity in the range of 20 – 220 Pa.s (at 60 degree C) [17], while portland cement paste, depending on its solids concentration has a typical range of viscosity between 0.01 – 1.5 Pa.s [18-19]. These magnitudes of differences in the basic flow property makes the gyratory compactor with its current state of art, at large, a little less feasible for direct use on cement based materials. Apart from the chemical formulation, nature of the material and the interaction each of these undergo with aggregates during compaction are responsible for the manifestation of different nature of compaction processes.

One of the limitations with a minimum consolidation pressure of 200 kPa was compacting samples with relatively higher water/binder ratios. Higher water content accompanied by the limiting ability of the mixture to hold that water under sustained pressure lead to squeezing of paste from the bottom of the mold, which is open and offers a pathway for the water to escape. To avoid machine damage due to percolation of the paste into the mechanical parts, a set of plates were fabricated and put under the mold to arrest and hold the running paste. Figure 6-10 shows some pictures of this phenomenon. The running out of paste from the concrete mixture leads to termination of the tests very early in mixtures that showed higher tendencies to give out the paste.

Figure 6-10 Gyratory compactor: squeezing out of paste

ASTM D6925 [20] provides the precision estimates for single operator based on the nominal maximum size of the aggregate (NMSA). Table 6-7 is reproduced from this standard.

Table 6-7 Single operator precision statement for gyratory compaction [20]

NMSA	Relative density (%)	
	1s limit	2s limit
12.5 mm	0.3	0.9
19 mm	0.5	1.4

6.7 Uniaxial, unconfined compressive strength (UUCS)

The compressive strength was measured on Φ100 · 200 mm cylinders at 1, 3, 7 and 28 days. The average of two sample values is reported in this work. Figure 6-11 shows the distributions of strengths at different curing ages. Strength distributions at different ages showed normal distributions.

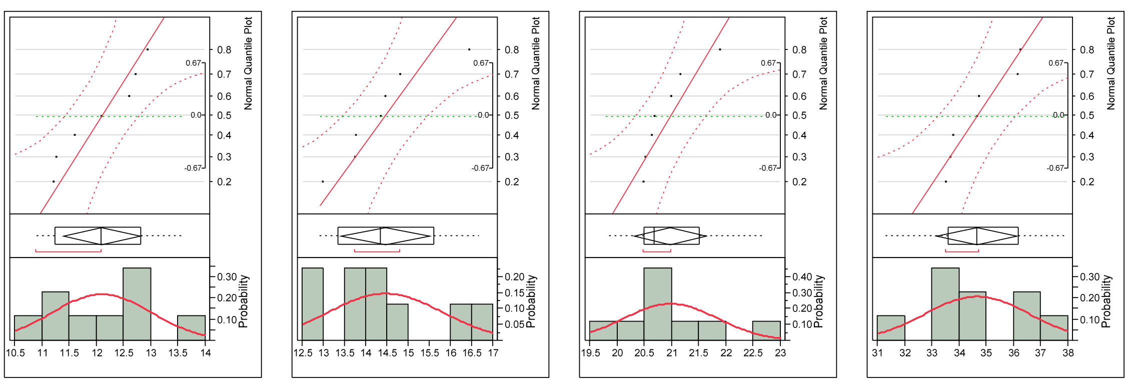


Figure 6-11 Strength distributions at different ages fitted to normal distribution

Table 6-8 shows a summary of the descriptive statistics for strengths at different ages. Overall, the highest coefficient of variation recorded was 9.31% for 3-day strength testing, while the highest standard deviation was 1.915 MPa.

Table 6-8 Summary statistics for UUCS measurement at different ages

Age (days)	Mean UUCS (MPa)	SD (MPa)	Std. error	CoV (%)	Lower 95% (MPa)	Upper 95% (MPa)
1	12.09	0.912	0.3041	7.54	11.39	12.79
3	14.45	1.346	0.4489	9.31	13.41	15.49
7	20.98	0.859	0.2865	4.09	20.31	21.64
28	34.65	1.915	0.6383	5.52	33.17	36.12

The temporal evolution of UUCS was modeled using a simple exponential relationship as follows:

$$S = a(1 - \exp(bt))$$

Where a and b are coefficients and t is time in days. The data obtained from the repeatability studies was modeled using this form of equation. Figure 6-12 shows a plot of four such curves.

Table 6-9 shows a summary of the descriptive statistics of the coefficients a and b.

Table 6-9 Summary statistics for coefficients of temporal evolution of UUCS

Coefficient	Mean UUCS	SD	Std. error	CoV	Lower 95%	Upper 95%
a	34.11	2.087	0.6957	6.12	32.51	35.72
b	-0.1663	0.0209	0.0069	12.56	-0.1824	-0.1503

In order to appreciate the possible variations in the coefficients a and b as obtained from these studies their distributions was plotted and is shown in Figure 6-13. Both the coefficients show a normal distribution.

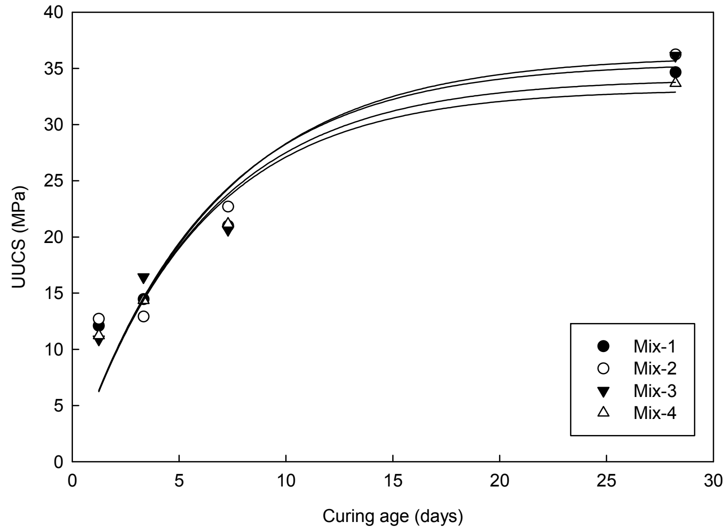


Figure 6-12 Modeling the temporal evolution of strength

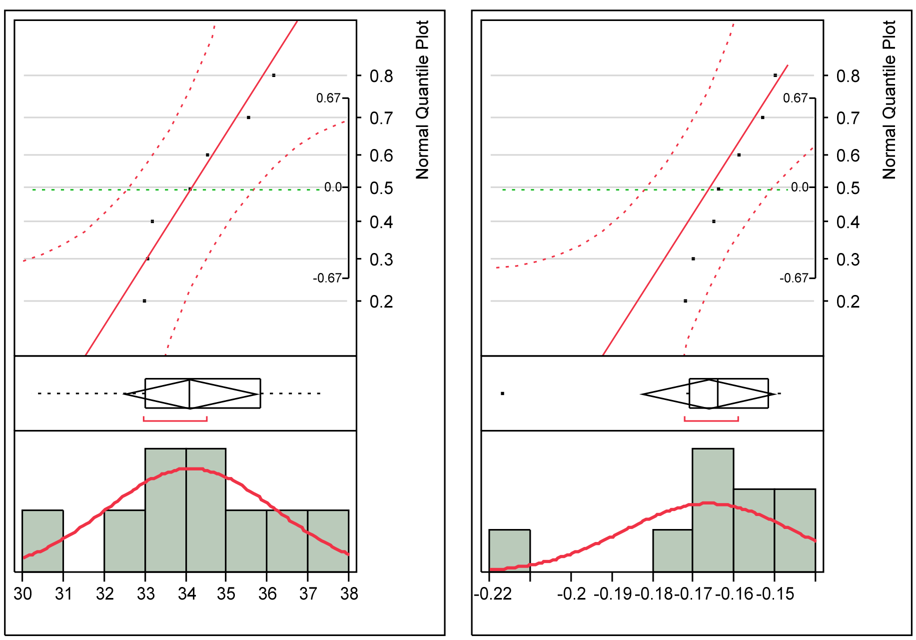


Figure 6-13 Distributions for the coefficients a (L) and b (R)

SUMMARY

This chapter briefly described various sources of errors in an experiment offering a taxonomy for better appreciation of the scope of extent to which these could affect the interpretation of results. Critically appreciating the fact that modern day experiments are conducted on very few test samples, the chapter expressed concern about the broader applicability of the results and inferences.

Multiple test methods, not routinely used for concrete testing, were used and required a statistical foundation or at least some comparison with the established data from other materials. This was the objective of having this part to the study. These included not only the instruments, but also the methodologies for evaluating the results. Limited results from the statistical analysis are presented in this chapter. These include the compaction hammer, density, consistency using the Cabrera slump value, the cohesion, angle of internal friction, gyratory compactor and strength measurements. These results will help evaluate the range of results and possible variability in them.

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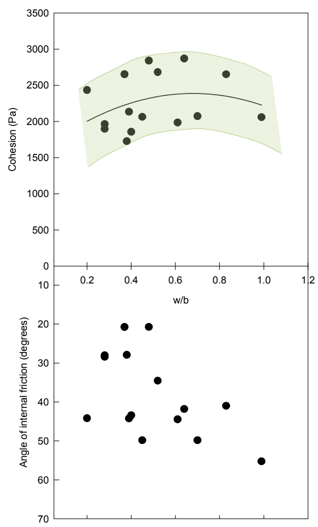
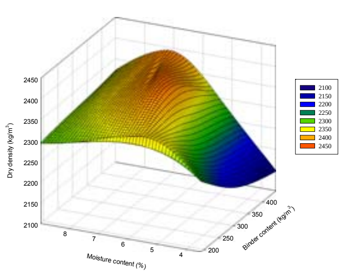
CHAPTER 7 COMPONENTS OF WORKABILITY AND ANOMALOUS STRENGTH BEHAVIOR: CONTROL MIXTURES





SYNOPSIS

This chapter presents a summary of the significant findings from the work done on aggregate blending, cement-admixture compatibility and fresh properties of control mixtures. Initially a summary of the aggregate tests is reported. This includes various approaches taken to derive relevant information and parameters required for assessing the most compactable and dense grading. A summary of the cement-admixture compatibility is presented.

This is followed by descriptions of the compactibility studies on concrete mixtures and the influences of aggregate grading, w/b and A/B ratios. Further to this, the moisture-density-air content interactions are defined and described. Plots related to cohesion and angle of internal friction for fresh concretes are developed and discussed. Finally, a discussion on the anomalous behavior of concrete mixtures vis-à-vis Abrams' law are described. Thus, this chapter isolates various components of concrete workability.

Keywords: workability, air content, Cabrera slump value, shearing stress, work done, cohesion, friction angle, roller compactibility

CONTENTS

7.1 Interaction diagrams for aggregates

The suite of critical properties of an aggregate system in a concrete depends on its application vis-à-vis the geology in a particular geography. For example, the aggregate abrasion resistance is an important index for pavement wearing course application, but it may not be that crucial for a bridge pier. Finishibility is another such criteria. Such identification of relevant aggregate properties is important for proper selection and evaluation of different aggregates.

The matter presented henceforth approaches aggregate grading selection from compactibility perspective. Factors like geology, particle shape, relative proportions of fine and coarse aggregates, and the combined aggregate gradings are taken into account while evaluating the gradings from different perspectives. Detailed discussion of these results can be found in Appendix AA.

7.1.1 Conventional approach

VOIDS CONTENT AND COMPACTIBILITY

Figure 7-1 shows a plot of volume of voids as a function of the blend of aggregate for different geologies. The following observations are important from these plots. The rounded particles from both coarse and fine fractions of aggregates (GRRS) produce mixtures with least volume of voids and this combination is the most robust. Paste requirement for QZRS combination of aggregates would be highest, while the GRRS blend would have the least paste demand. A combination much similar to the above one results from combining the limestone coarse and fine aggregates, as they also tend to offer higher volumes of voids. The particle shape of individual aggregate fractions and the interactions and interferences influenced by the relative friction between them result in different residual voids contents. This also means that the paste demand would also depend on these relative interactions.

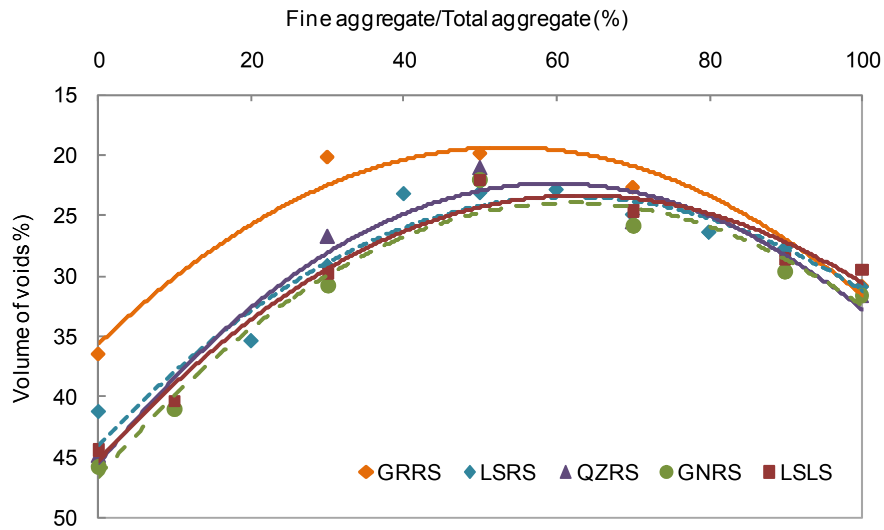


Figure 7-1 Effect of aggregate blends and geologies on the volume of voids

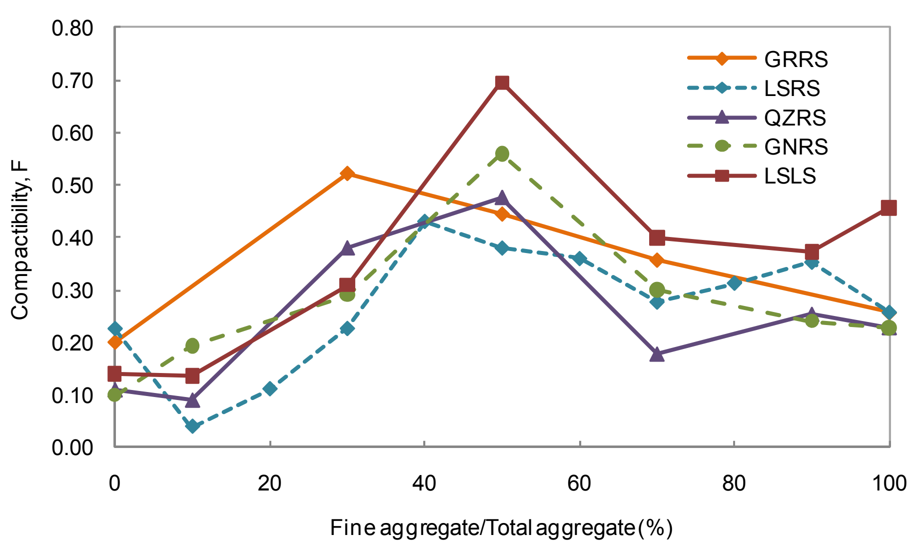


Figure 7-2 Aggregate blend versus compactibility (F)

Figure 7-2 shows comparative plots of compatibilities as a function of aggregate blends for different aggregate combinations. This plot helps understand two significant attributes of aggregate combinations. The first being the robustness of compactibility to different aggregate blends. In the present case, it can be seen that the blends from combination GRRS are rendering most robust compactibility. This implies that slight changes in the composition of aggregate would not significantly influence the compactibility. The other opposite of robust is a sensitive system of aggregates. In this case, the LSLS system is the most sensitive, implying slight changes in the composition of aggregates would lead to dramatic changes in the compactibility of that aggregate system. This could be due to higher volume of finer fraction coming from fine aggregate. Moreover, using such a system would require higher level of attention to be paid to the consistency of aggregate gradings.

The second facet of such a plot is that it renders a comparison between different aggregate systems when multiple options at relatively comparable prices are available. For example, a comparison between GRRS, LSRS and LSLS seems evident. The combination LSRS could offer an intermediate solution. It may neither be the most compactable grading nor the most robust combination, but it offers a balance between robustness and compactibility, in addition to other potential advantages.

THE INTERACTION PLOT

Figure 7-3 is constructed to illustrate the interaction of above two methods of representation. This interactive plot conveys two important things viz.

- a range of most compactable aggregate blends and
- a range of aggregate blends that will present least paste demand.

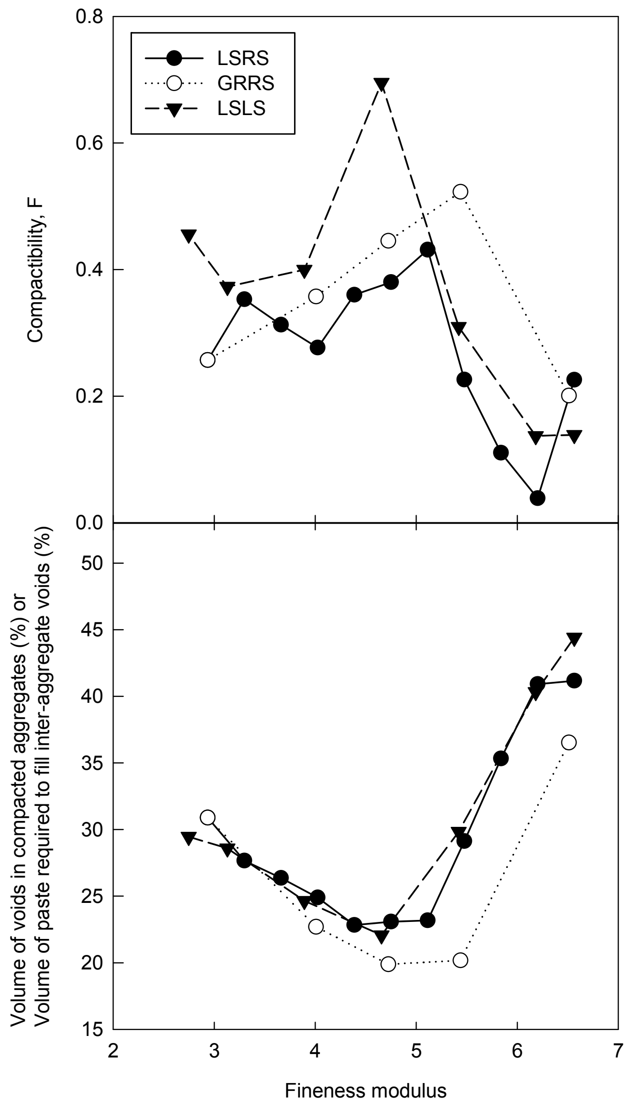


Figure 7-3 Interaction diagram: Fineness modulus-compactibility-paste requirement to fill the voids

One of the limitations of above analyses and attempts at correlating the empirical parameters like fineness moduli or surface areas is that both of these approaches fail to take into account two important facts. These are the shape of the particle and the fines content (typically below 150 μm). This is an known limitation of this index, which further explains why concretes made with various gradings of identical fineness modulus may have significantly different water permeability or bleeding under otherwise identical conditions [1]. Fineness modulus cannot be used as a single description of the grading of an aggregate, but is a valuable measure of variations in aggregates from same source, since it offers an indication of the probable behavior of concrete [2].

7.1.2 A geotechnical outlook

Taking into account the inherent variations of fineness modulus, an attempt to find indices to further differentiate between different aggregate gradings was made. One of the plausible set worth discussion is the coefficient of uniformity (C_U) and coefficient of curvature (C_C) as used in evaluating the particle grading in soils. The mathematical formulae are as follows:

$$C_U = \frac{D_{60}}{D_{10}}$$

and

$$C_U = \frac{(D_{30})^2}{(D_{10} \times D_{60})}$$

where,

D_{10}, D_{30} and D_{60} are the (effective) grain diameters corresponding to 10, 30 and 60% passing on a particle distribution plot. In geotechnical engineering, a soil having Cu less than 2 is considered uniform, whilst one with value greater than 10 is considered to be well graded. This also means that higher the C_U value, the broader is the range of particle size. A well-graded soil has a coefficient of curvature between 1 and 3 [3]. Compared to FM, these two indices take into account the particles finer than 150 μm.

Figure 7-4 is constructed based on the above discussion. It can be seen that C_U holds good relationship with the fineness modulus and the volume of voids in the compacted state, n_c. The effects of finer particles can be seen from the enhanced discriminating power this coefficient has over the fineness modulus. For a given aggregate system, the volume of voids initially decrease as the C_U increases reaching a peak at the minimum volume of voids and then due to increased fine aggregate content, the volume of voids remains more or less the same, but the C_U value drops down. The particle shape effects are more pronounced.

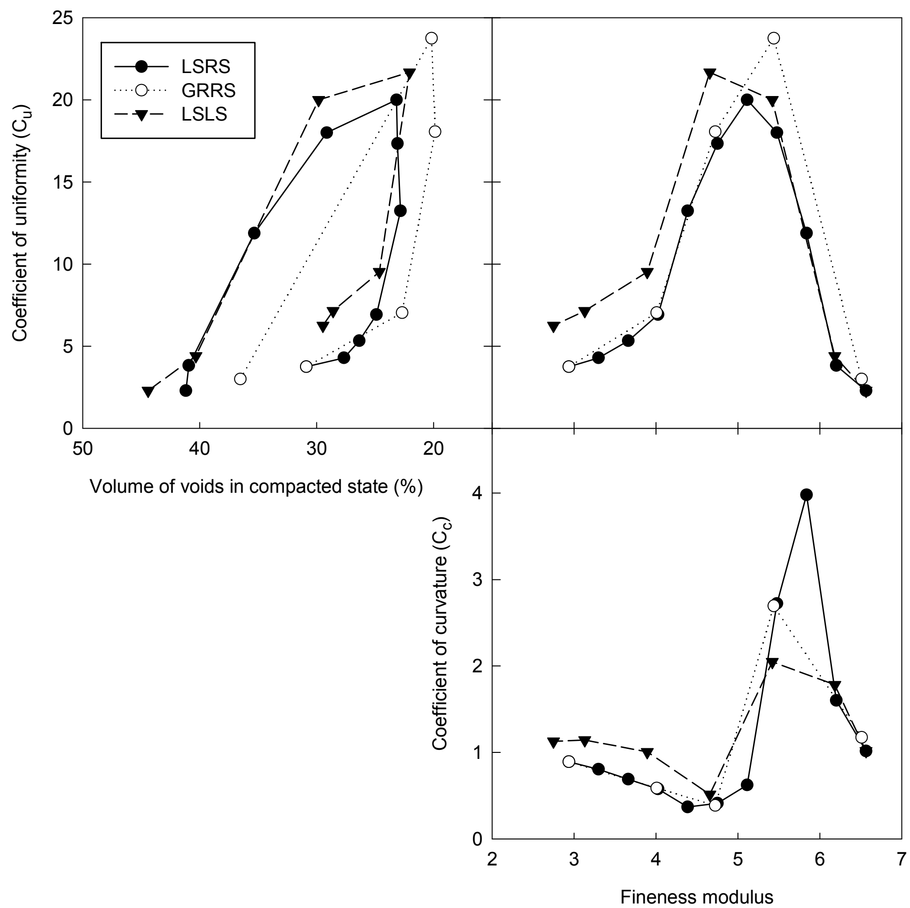


Figure 7-4 C_U-C_C-FM-n_c interaction diagram

To further substantiate the validity of this argument, another plot with FM as a common axis was constructed. A composite plot of this kind helps understand the robustness of a grading and the susceptibility of volume of voids to changes in the grading, which the FM cannot clearly bring out. Figure 7-5 shows one such composite chart.

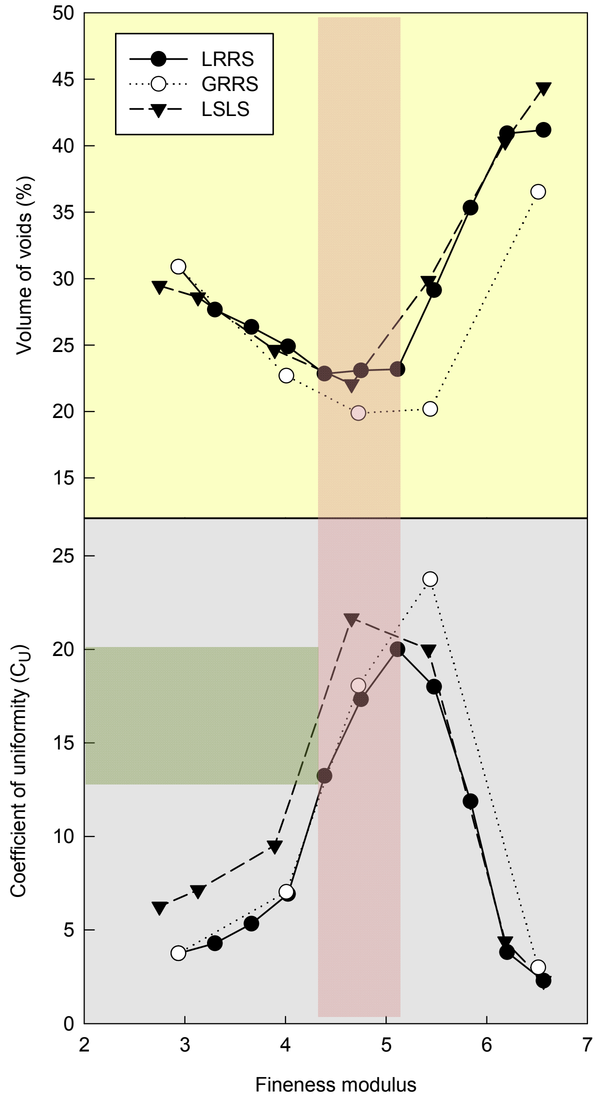


Figure 7-5 FM-C_U-n_c interaction diagram

7.2 Cement-admixture compatibility

Five different cements were tested on 31 different chemical admixtures. These included different types of admixtures (covering the width) and for each of these types of admixtures, there were multiple chemistries. Table 7-1 reports a list of most suitable admixture chemistries that was used for further testing and experiments.

Table 7-1 Final list of chemical admixtures

Manufac. Code	Product Code	Primary chemical constitution	Functional classification								
			WR		Retarder			AEA	RM	DC	Misc
			ASTM C494 Type								
			A	F	B	D	G				
M-05	P-06	Triethanolamine	■								
M-04	P-11		■		■	■					
M-04	P-13				■	■					
M-03	P-05	Polycarboxylate resin	■	■							
M-02	P-10	Ca-lignosulfonate	■	■	■	■	■				
M-01	P-09	Ethylenediamine	■	■							
M-03	P-19	Sodium olefin sulfonate						■			
M-03	P-20	Na-tetradecenesulfonate						■			
M-03	P-21	Tall oil/Na salt						■			
M-03	P-24	Polysaccharide							■		
M-03	P-25	Naphthalene sulfonate/ Welan gum							■		
M-01	P-26								■		
M-04	P-28	Surfactant								■	
M-03	P-29	PC resin + Polethylene glycol								■	
M-01	P-17	Phosphonic acid			■						
M-05	P-31	New formulation									

7.3 Compactibility of concrete

The objective of this part of the work was to understand compactibility as a function of concrete composition. The composition of mixtures was characterized by different aggregate grading, aggregate/binder and water/binder ratios. In the mixture proportioning of any concrete it is important to understand the limitations of a mixture in terms of different properties it could render. The objectives of this part were as follows:

- To understand and evaluate the effects of aggregate gradings on the compactibilities of concrete mixtures;
- To understand and comprehend the compactibility behavior as influenced by the aggregate/binder ratio and
- To understand and comprehend the compactibility behavior as influenced by the water/binder ratio.

7.3.1 Background

Considering the available materials and conceived objectives, three distinct aggregate gradings were evolved and are shown in Figure 7-6. These are the coarse grading (C) having a fineness modulus of 5.26, the medium grading (M) having a fineness modulus of 4.46 while the fine grading (F) having a FM of 3.94. These curves are plotted along with the ACI 211 [4] recommended grading band and the 0.45 Powers curve for 19 mm maximum size of aggregate.

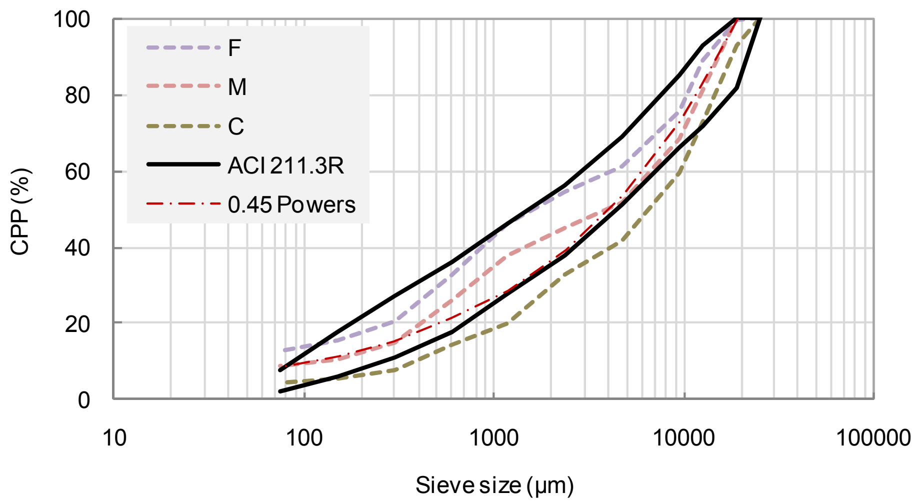


Figure 7-6 Combined aggregate grading for compactibility study

Each of these gradings was tried with three different binder contents and five different water/binder ratios. Table 7-2 shows a summary. A mixture's ability to accommodate and retain a volume of water is a function of the amount of reacting (cement) and non-reacting (aggregates) solids. Higher volume of finer solids will increase a mixture's ability to hold more water and vice versa. Moreover, higher fines content will also enhance a mixture's ability to resist loads. In addition to the requirement of finer fines, a concrete mixture should also have well-graded aggregate system to be able to offer volumetric stability under load and when it is fresh.

Table 7-2 Concrete compactibility study matrix

Aggregate grading	Aggregate/binder	water/binder	Remarks
F	4, 7, 10	0.30 – 0.50	The water/binder ratios were adjusted further considering the aggregate grading
M	4, 7, 10	0.35 – 0.55	
C	4, 7, 10	0.45 – 0.65	

7.3.2 Effects of aggregate grading, A/B ratio and w/b ratio

TYPICAL RESULTS AND COMMENTS

Density trends as a function the number of gyrations (hence compactive efforts) were evolved to appreciate the compactibility of different concrete mixtures. Figure 7-7 shows a typical density profiles as a function of the number of gyrations.

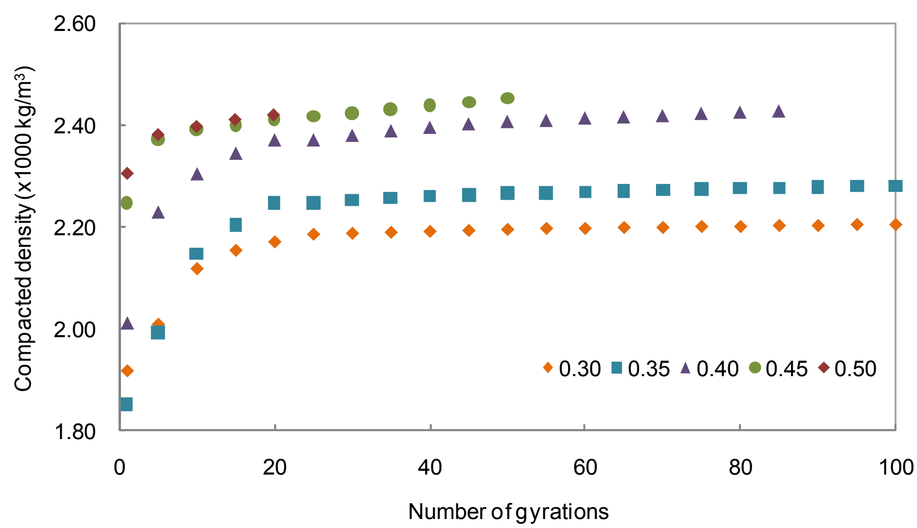


Figure 7-7 Density profiles for A/B = 7 and CAG-F

The following observations are relevant for further discussions:

- The selection of the water/binder ratio is limited by the aggregate/binder ratio. The lower this ratio, the higher is the ability of the mixture to accommodate more water and vice versa. In the present study for aggregate/binder ratio of four, the water/binder ratio could be varied between 0.3 and 0.5; going beyond 0.5 lead to excessive expulsion of water. On the other hand, the water binder ratio was varied between 0.45 and 0.65 for mixtures with aggregate/binder ratio of 10. Although the ratios appear to be higher in the latter case, the fact that these mixtures were binder deficient in comparison to the earlier mixtures should be taken into account.

- The second interesting thing is the spread of density responses at a fixed number of gyrations. For richer mixtures, the change in the density is more sensitive to the change in the water/binder ratio, while it is least sensitive in case of leaner mixtures. The intermediate mixtures fall in between. This can be observed while comparing the three plots together. Rich mixtures (low aggregate/binder ratio) show wider gaps in the densities obtained at the lowest and highest water/binder ratios. This gap narrows down, as the mixtures get leaner. This also means that rich mixtures are relatively more sensitive to the changes in the water content (less robust), while the leaner mixtures are less sensitive to the changes in the water content (more robust).
- The self-compacting ability of different mixtures is a function of their compositions. The self-compacting ability of a mixture is perceived as the ability of a mixture to reach a certain degree of compaction (characterized by density) when it is dropped in the compaction mold. In practice, this can be understood to be analogous to the compaction achieved by a pavement concrete mixture when it is dumped from the truck. From the plots under discussion, this sensitivity can be very easily seen for mixtures with aggregate/binder ratio of 4, while the clarity is reduces as the binder content of the mixtures is reduced. For a given aggregate/binder ratio, the start-up density is a function of the relative volume of water in a mixture. Physically this can be explained based on the relative volume of water to the binder present in a mixture. The riche mixtures being more sensitive to the change in the moisture content especially at lower water contents, the start-up density for these is very low as compared to mixtures with higher water/binder ratios. As discussed above, this sensitivity gradually reduces as the mixture become leaner.

METHOD OF ANALYSIS

For comparing compactibility of different concrete mixtures, a common basis for comparison is necessary. This basis has to also acknowledge the fact that not all the material compositions will be able to acquire or reach similar density in quantified terms. However the materials could be benchmarked with reference to the maximum potential density it could achieve with a given composition. The benchmarking has to exclude the variable factor (e.g. air content in a fresh concrete mixture) density, which leaves us with a theoretical basis of comparison. This work makes use of a term called as relative compaction and is formulated as follows:

$$(Relative\ compaction)_N = \frac{(Compacted\ density)_N}{Air-free\ theoretical\ maximum\ bulk\ density\ (TMBD)}$$

The relative compaction is measured at a fixed number of gyrations (N) and from the density compacted at that level of compactive effort. The computation of the air-free theoretical maximum density is based on the following formula analogous to that given by Atkins [5]:

$$TMBD = \frac{\sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} \frac{P_i}{G_i}}$$

where, P_i is the percentage by weight of the i^{th} material and G_i is the specific gravity or relative density of that material. Note that the air content is not considered in this formula. A similar approach was adopted by Nader et.al. [6].

7.3.3 Interaction diagrams for compactibility

SELF COMPACTING INDEX (SCI)

Figure 7-8 is developed or prepared to appreciate the aforementioned fact for the mixtures under consideration. This figure was developed with % moisture content to have a common basis of comparison. Two things can be clearly observed from this set of plots. The first being the definition of the self-compacting index (SCI). This is defined as the relative compaction at beginning of first gyration and reflects the each with which a mixture can be compacted without the application of compactive effort. It can be seen that different mixtures have different SCI indicating their ability to be get self-compacted as a function, primarily of relative moisture and binder contents. The second being the slope of the equations of the lines of fit indicates the responsiveness of an aggregate-binder system to changes in the moisture content. For the mixes shown in this figure, it can be seen that the slope of mixtures with aggregate/binder ratio of 4 is 0.0604, which is four and six times that for mixture with aggregate/binder ratios 7 and 10, thus indicating very high sensitivity of rich mixture.

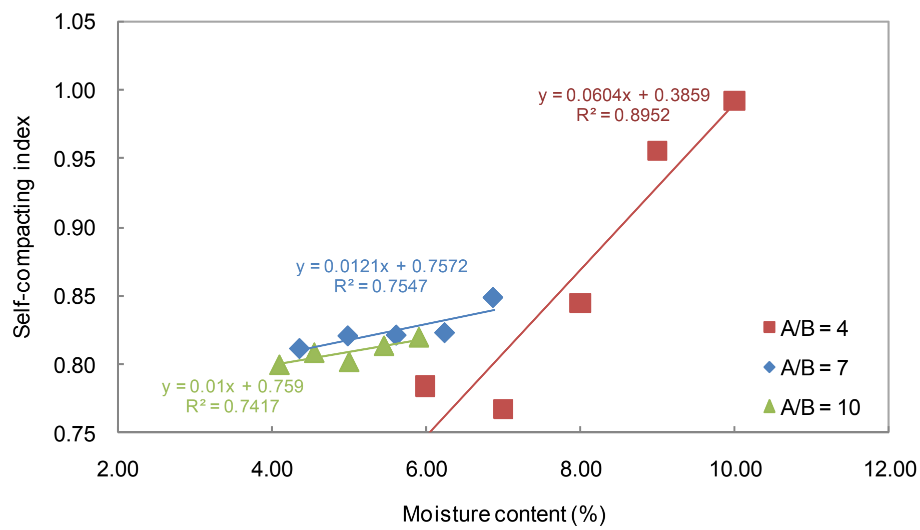


Figure 7-8 Responsiveness of mixtures (F grading) to moisture content

EFFECTS OF A/B AND W/B RATIOS

The self-compactibility of a mixture is a composite function of A/B and w/b ratio. The effects produced by w/b are more pronounced than the A/B ratio. A discussion is offered in the section on WEI, which is quite similar for SCI.

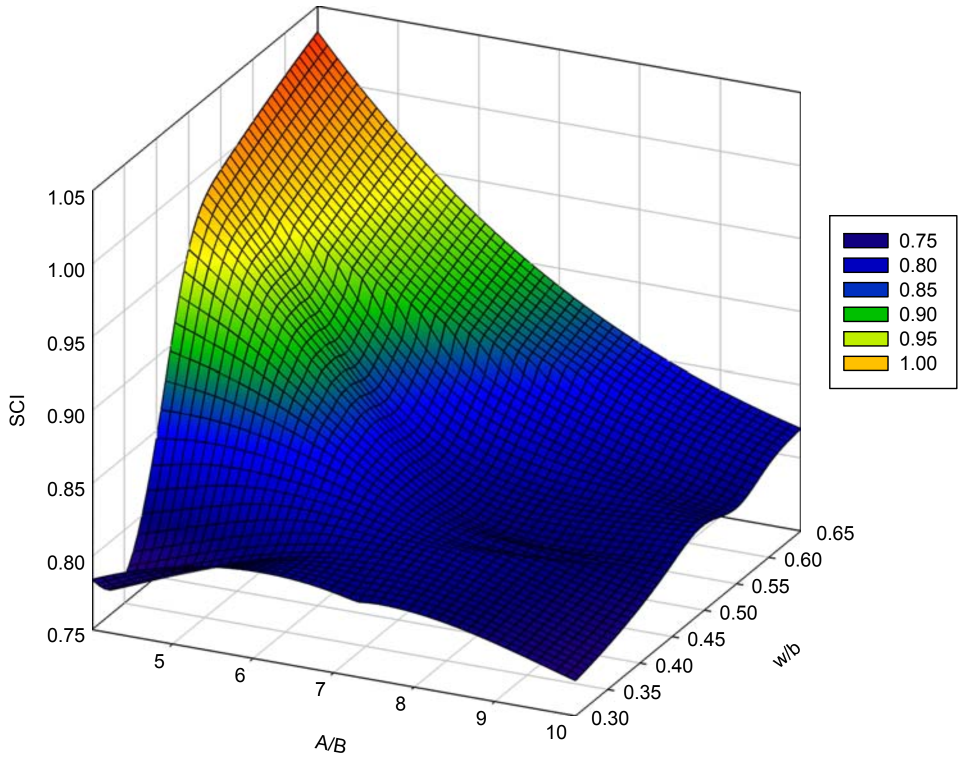


Figure 7-9 Interaction effects of A/B, w/b ratios on SCI for F-grading

OTHER INDICES

This data was analyzed in terms of the workability energy index (WEI) and compaction densification index (CDI) as defined in the literature review section. A simplification for obtaining the indices was as applied as follows. The WEI is defined as the area between the first and fifth gyratory compaction and is obtained by approximating the area under the relative compaction curve by the trapezoidal rule. The CDI on the other hand is shown considered to be the area above the relative compaction at N_5 and confined by N_5 and N_{20} and the relative compaction plot. These definitions are pictorially represented in Figure 7-10.

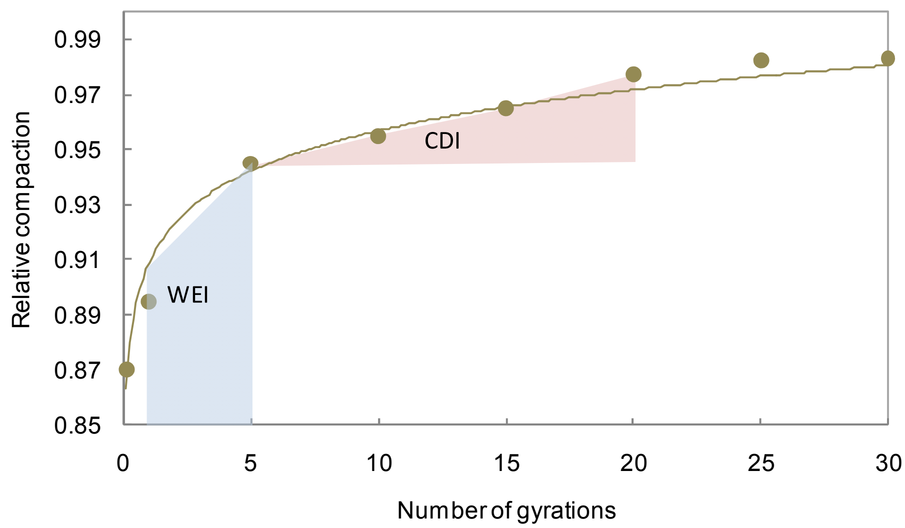


Figure 7-10 Definitions of WEI and CDI

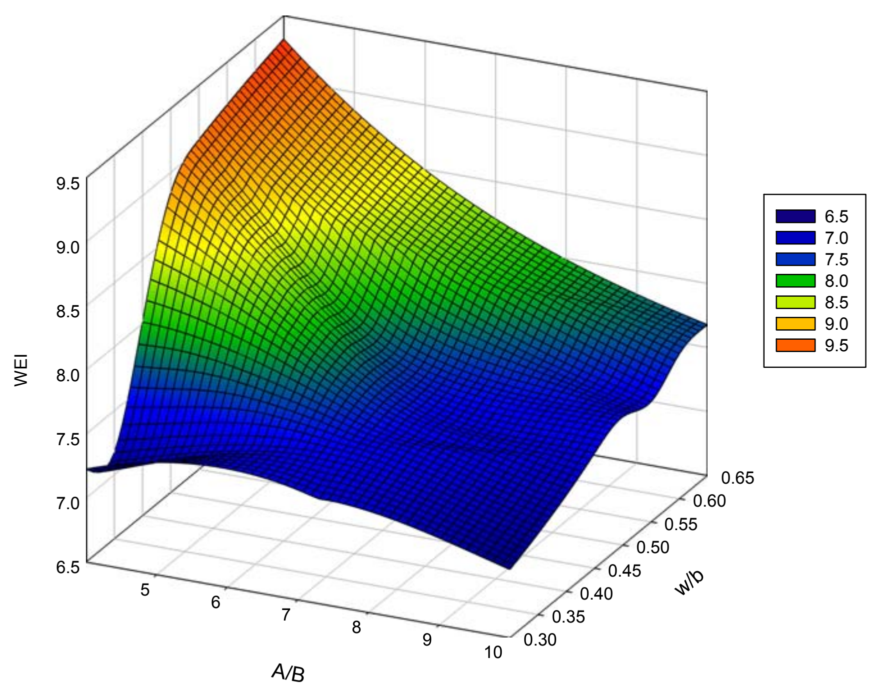


Figure 7-11 Interaction effects of A/B, w/b ratios on WEI for F-grading

Figure 7-11 shows the interaction effects of A/B and w/b ratios on the WEI. It can be seen that both of these ratios have a meaningful influence on how compactable a concrete could be.

The following observations are relevant:

- With the increase in the w/b ratio, a mixture becomes more compactable; however, the relative proportions of aggregate and binders influence the rate of change of compactibility. This means that for a given A/B ratio, as the w/b ratio increases the trends take different profiles. At lower A/B ratio, the compactibility is highly sensitive to the changes in the moisture content, while the sensitivity reduces as the A/B ratio is increased.
- With the increase in the A/B ratio, the mixture looses its compactibility, while being a function of the relative proportions of water and binder. It is interesting to note that there are three different trends followed as a function of w/b ratio. At lower w/b ratio, parabolic trends are followed, implying with the increase in the A/B ratio the compactibility increases initially, reaches a peak and then starts dropping down. At intermediate w/b ratios, initially with an increase in the A/B ratio, there is a sharper drop in the compactibility followed by a flattening effect with further increase. At higher w/b ratios there is however a continuous decrease in the compactibility with increasing A/B ratio.
- It can be said that w/b and A/B ratios play a very influential role in shaping the nature of workability. A mixture at a fixed A/B ratio and with a specifically narrow range of w/b ratio will only produce potentially highest compactibility.
- It should also be noted that aggregate shapes would also influence the compactibility; the results of those studies are not produced here.

The CDI however follows a complicated trend as shown in Figure 7-12. Based on the available data, it is difficult to offer any comprehensive inference and hence this plot is not discussed in detail.

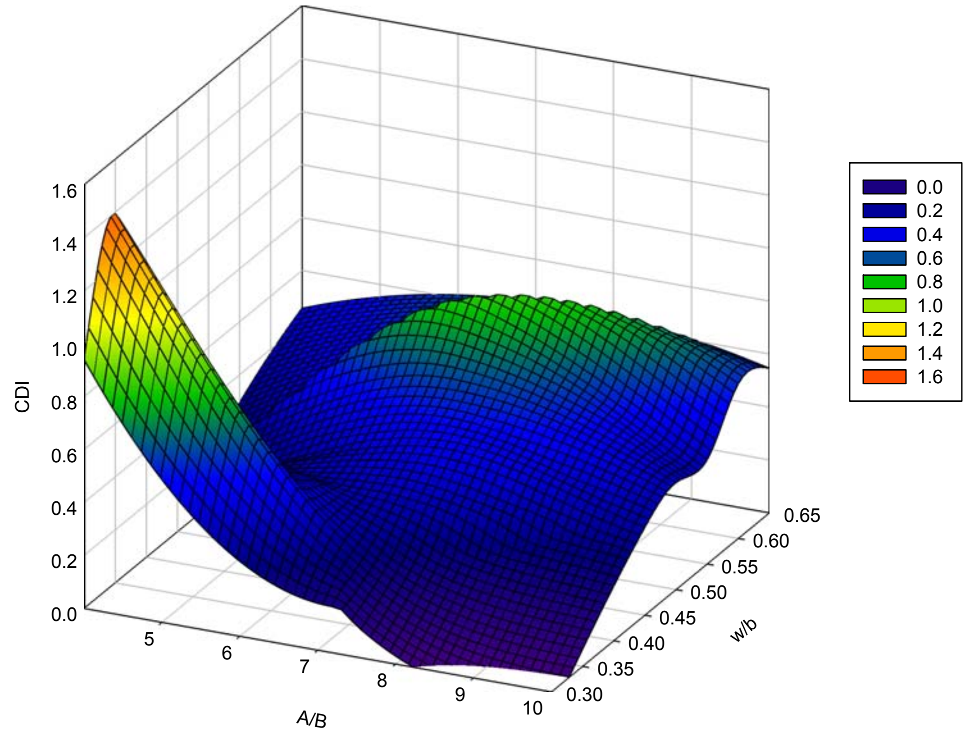


Figure 7-12 Interaction effects of A/B, w/b ratios on CDI for F-grading

7.4 Control mixtures

Table 7-3 shows the mixture proportions used in evolving the moisture-density plots. While keeping the Aggregate/Binder (A/B) ratio constant, the moisture content was varied and the changes in compacted density and other properties of fresh concretes were observed and are reported in this chapter.

Table 7-3 Mixture proportions for non-admixed concretes: Moisture density plots

A/B	Materials, kg/m³				w/b
	Cement	F Fly ash	Aggregates	Water	
4	322	106	1731	72	0.1681
4	334	110	1795	108	0.2432
4	334	110	1796	153	0.3434
4	320	106	1721	178	0.4185
4	336	111	1803	149	0.3341
7	210	69	1974	63	0.2242
7	218	72	2047	100	0.3444
7	215	71	2021	121	0.4245
7	203	67	1906	158	0.5848
7	212	70	1998	131	0.4653
10	144	48	1938	59	0.3052
10	149	49	2005	104	0.5257
10	151	50	2024	149	0.7461
10	143	47	1925	174	0.9115
10	154	51	2068	128	0.6244

7.5 Density, air and consistency

7.5.1 Effects of A/B, w/b ratios

Figure 7-13 is constructed to present the variation of density in a conventional X-axis of w/b ratio format. It can be seen that as the binder content of the mixtures increases, the water sensitivity of the mixture increases, i.e. even a small change in the w/b ratio would make a significant difference in the dry density of concrete. On the other hand, lean mixtures are least sensitive to changes in the w/b ratio. Richer mixtures are quite significantly affected by lower w/b ratio (or water content), while the leaner mixtures are less affected.

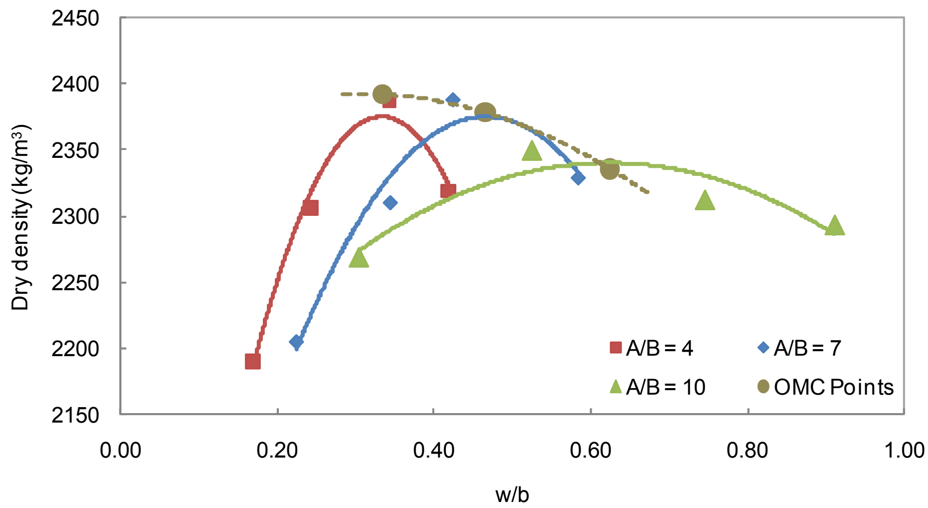


Figure 7-13 w/b ratio versus dry density: effect of binder content

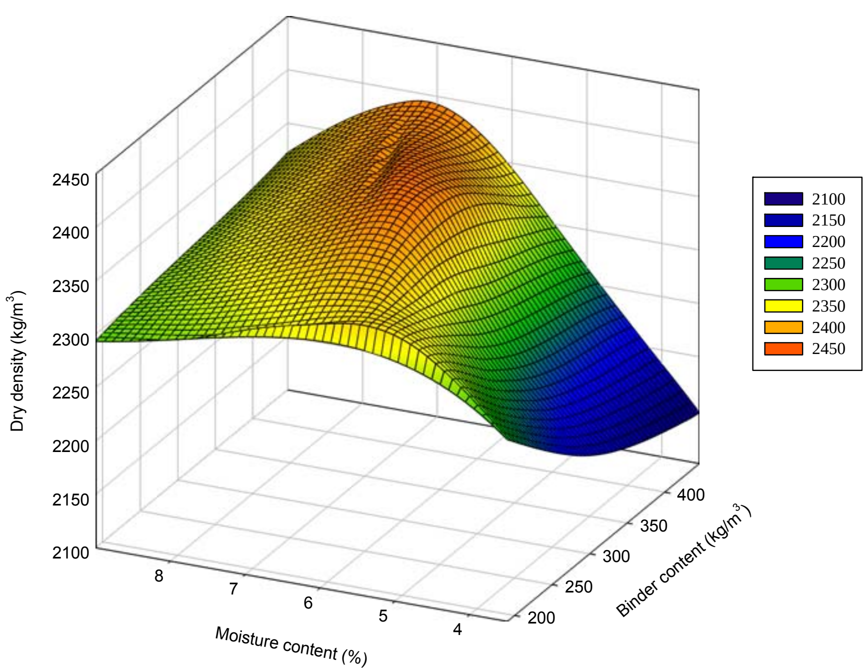


Figure 7-14 Interaction effects of binder and moisture contents on the dry density

The plot of maximum dry density at the respective optimum moisture contents indicates that the dry density decreases as the mixtures become leaner. Although the quantity of water required to reach the maximum possible density reduces as the mixture becomes leaner, the w/b ratio increases due to a simultaneous reduction in the binder content.

Figure 7-14 shows the variation of dry density as a composite function of binder and moisture contents. Here the interaction effects produced by these two components of the mixtures are evident more clearly. This graph has a very high utility in mixture proportioning. Knowing the aggregate composition, and start-up binder content, this plot can let one estimate the water content of the mixture and also the dry density of concrete.

7.5.2 Cabrera slump value (CSV) and compactibility

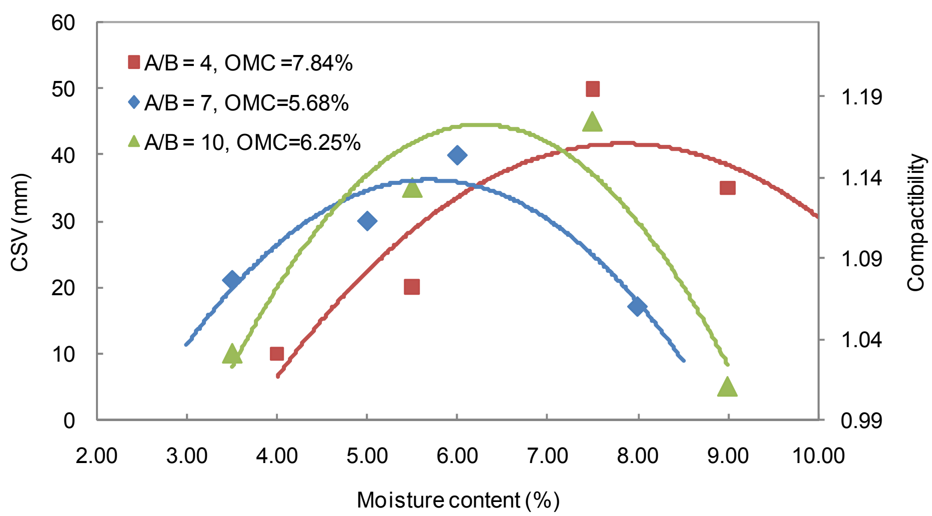


Figure 7-15 Moisture content versus CSV

Figure 7-15 shows the variation of the Cabrera slump value (CSV) [7-8] as function of moisture content for various A/B ratios. Using these plots the optimum moisture content offering most compactable mixture can be obtained for a fixed A/B ratio. The values obtained for each A/B ratio are given in the Figure 7-15. These values are comparable to the values obtained by the actual moisture-density plots. It should however be noted that the responses of the mixtures to compaction by vibrating table and compacting hammer is slightly different. In case of vibrating table, the vibrations are applied from bottom in upward direction and without any surcharge weight. While in case of compacting hammer, the vibrations are applied for a relatively longer time, in vertically downward direction and with a specific surcharge weight. The differences in the optimum moisture contents could partially be accounted to be due to these reasons.

7.5.3 Air content

The variations of air content as measured by pressure-meter for different mixtures are shown in Figure 7-16. In general, the air content reduces as the moisture content is increased, reaches minima and then shows a slightly increasing trend. This behavior is quite typical and is discussed previously. Figure 7-16 shows the variations of air contents as a function of w/b ratio for various binder contents

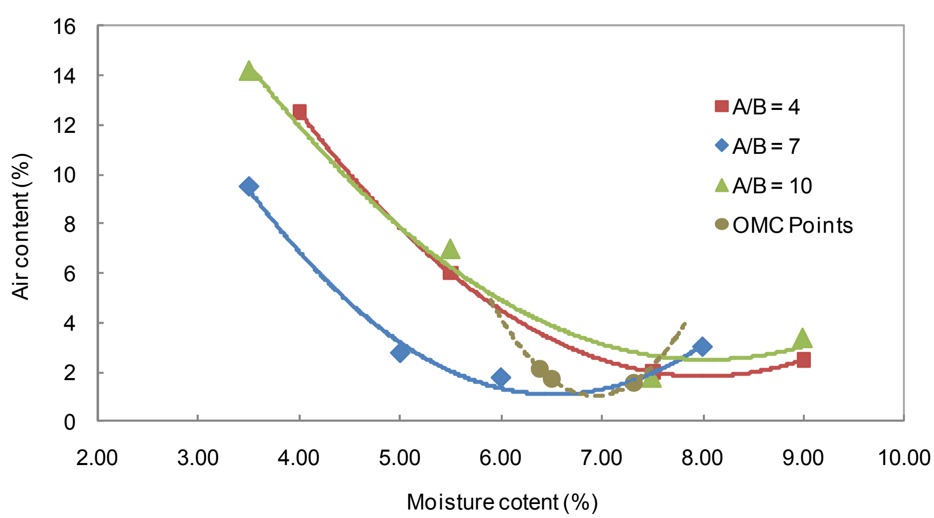


Figure 7-16 Variation of air content: effects of binder moisture contents

Figure 7-17 shows a ternary plot of the variations of air content as a function of the composite volumes of binder, aggregate and water. The pink area is an artifact resulting from the software and may not offer physically compatible information. A caution should be exercised in interpreting this ternary plot. A construction of this kind would need more data points for improved robustness.

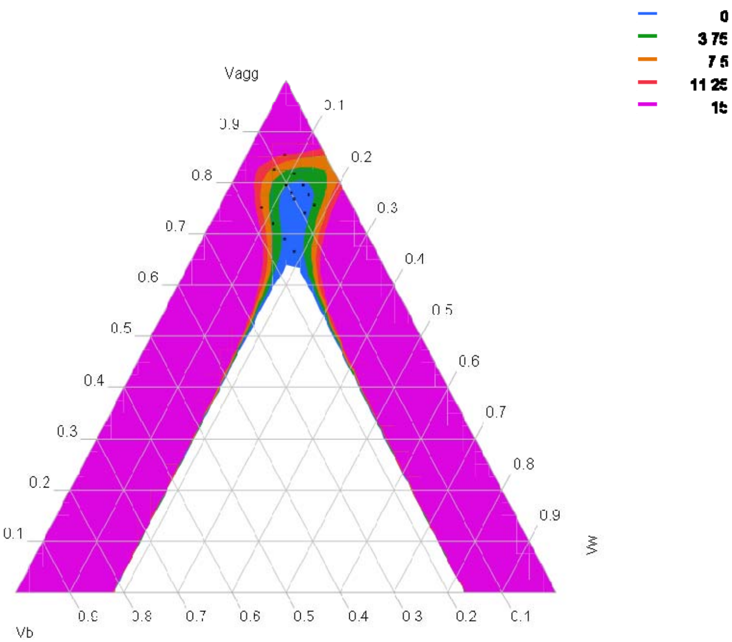


Figure 7-17 Ternary diagram showing variation of air content as a function of volumetric composition of mixture.

7.5.4 Interaction diagram: density and compactibility indices

After doing this analysis, it is necessary to connect it with what will be roller compactable. For this, an intermediate aggregate grading was selected, moisture density plots were constructed, and an interaction plot was constructed to link roller compactibility to the indices obtained from gyratory compaction. It should be noted that this type of interaction diagram will differ under field conditions, but is a good starting point. Figure XX shows an example proof of this concept. The step-wise procedure is as follows:

- First a moisture density plot for different A/B ratio is constructed;

- Gyratory compaction plots and the corresponding indices are obtained for these mixtures;
- A connection between these plots is made for similar w/b ratios;
- The w/b ratio in proximity of the w/b ratio would render roller compactable points and hence WEI indices.

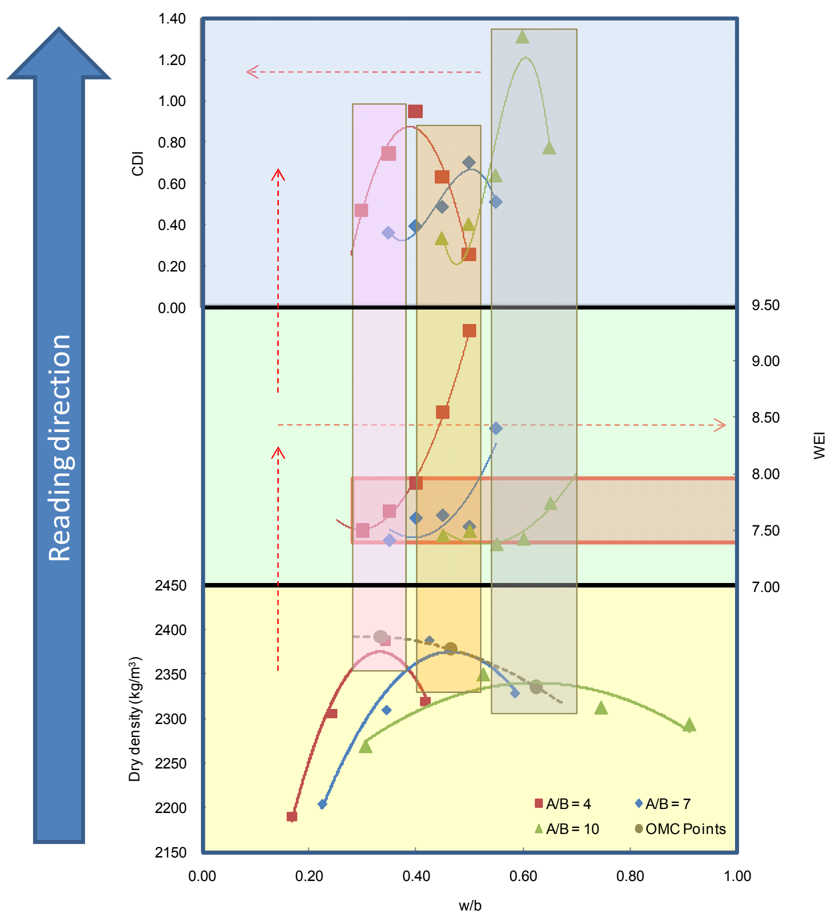


Figure 7-18 Deriving indices for roller compactable mixtures

7.6 Yield stress and angle of internal friction

As discussed previously, the shear resistances of different concrete mixtures were characterized by the direct shear test conventionally used in geotechnical engineering. The scaled up test box was used at a nominal shear displacement (s) time rate of 6.55

mm/min. It should be noted that the shear stresses and displacements developed in the direct shear box are non-uniformly distributed within the specimen. Consequently, an appropriate height cannot be defined for calculating the shear strains. Therefore, true stress-strain plots and associated shear modulus cannot be obtained based on the results from this test [9]. Considering this, the strains and stresses developed in the samples shall be considered as nominal.

7.6.1 Data manipulation and work index

For each sample, three tests at increasing normal loads were run. The method of analysis used in this work is a bit different from that conventionally used. These are not discussed in detail here. The data obtained from the tests was plotted in three different ways as follows:

- Nominal shear displacement versus nominal shear load;
- Nominal Shear displacement versus friction ratio and
- Normal stress versus nominal shear stress

While appreciating the results, the inherent heterogeneous nature of concrete as a material should always be borne in mind. It also implies that there could be more than conventionally observed variations. Another phenomenon of interest is the slip between the concrete and the shear boxes. Different concrete mixtures at differing water contents were tested; potentially some of the drier mixtures could not have been in complete contact with the walls of shear boxes during shearing.

The work done is considered to be equal to the area under the curve. The following is the general formula:

$$W = \int_{0}^{12.5} S ds$$

Typical plots are shown in Figure 7-19. The displacement versus load plots was used for computing the work done.

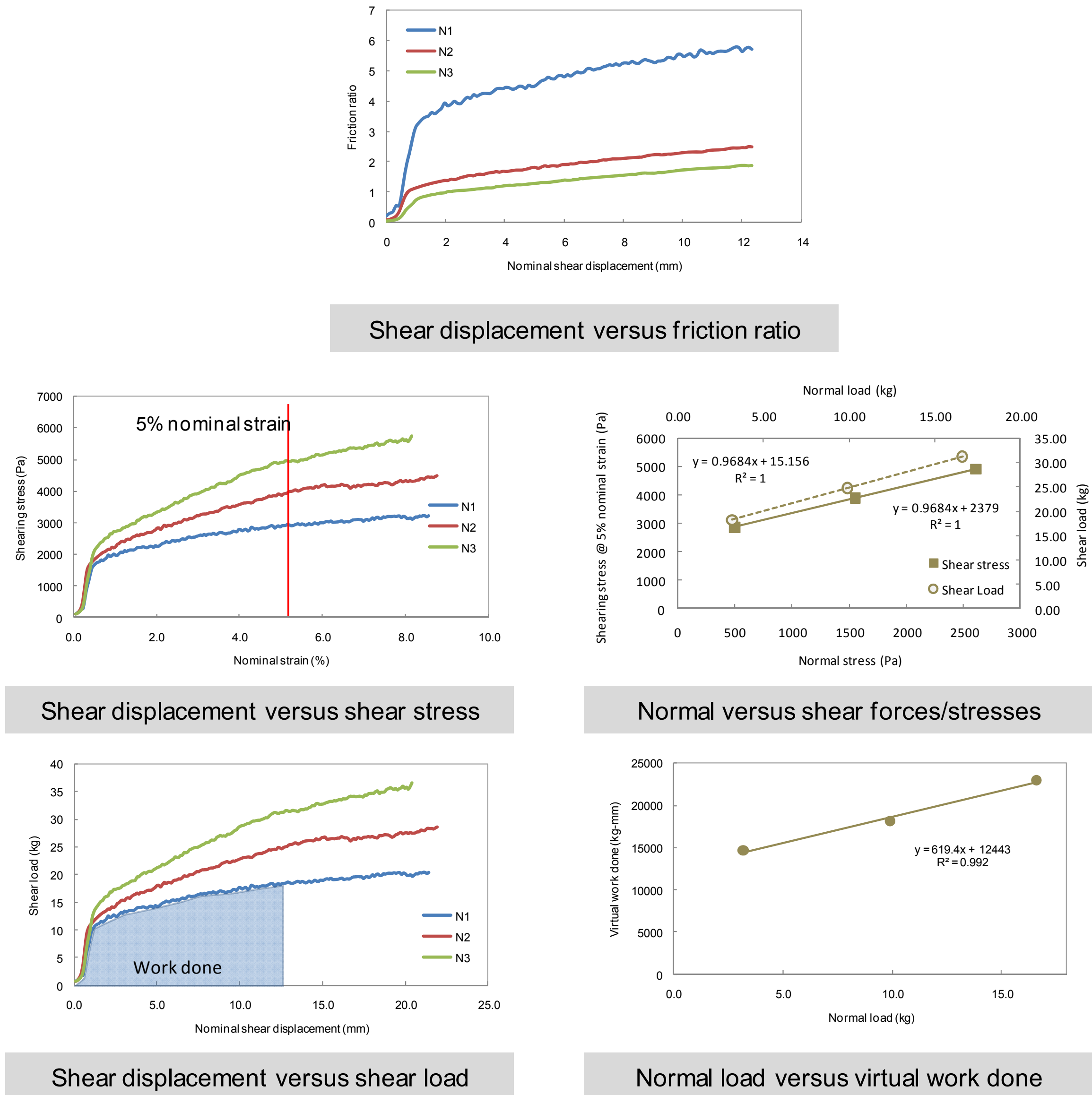


Figure 7-19 Typical plots from direct shear test. Note: $N_1 < N_2 < N_3$

The area was computed using the trapezoidal rule. The area so computed from each of these plots was used in developing the normal load versus work done plot. This plot offers a relative idea about the roller compactibility of a concrete mixture with different static weight rollers. This in simulation is shown in Figure 7-20. The slope of the line indicates the relative easy with which deformation can be achieved with increasing roller weights. A flatter line will indicate that there is not much advantage in increasing the static weight of a roller, while a steeper line will indicate that the concrete is relatively less workable with lesser roller weights and need to be improved in composition to achieve better compactibility and economically. This plot also gives an idea about the roller weight selection. While comparing two mixtures, a mixture that has a lower intercept on work-axis would mean the mix is readily compactable, while a higher intercept will mean that the mixture has lower compactibility and would require longer compaction times.

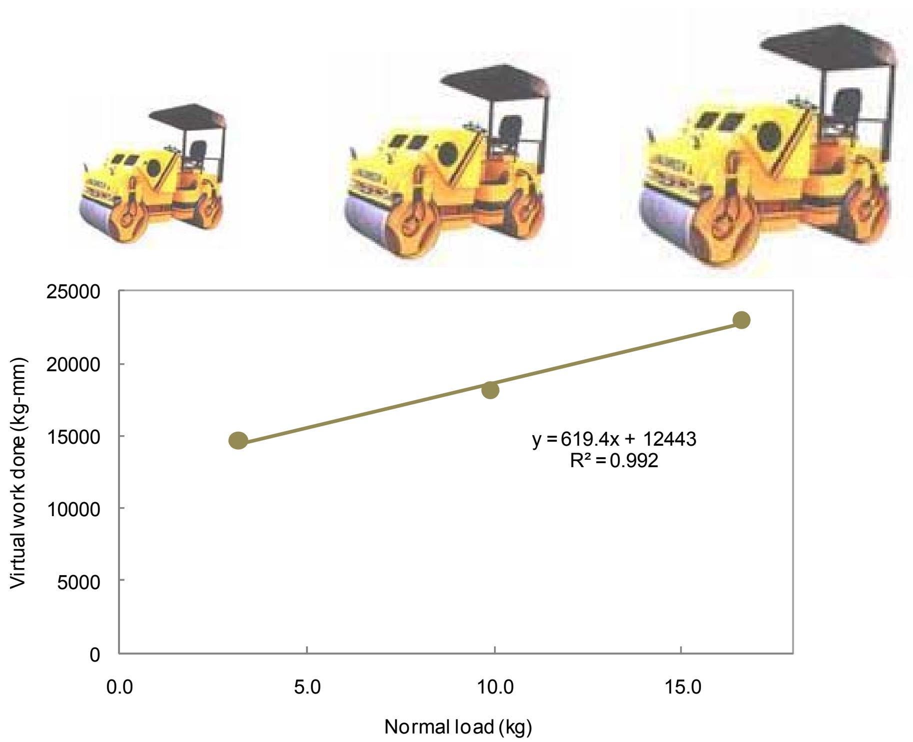


Figure 7-20 Analogy with roller weight selection

The nominal shearing strain versus stress plots were constructed to obtain the cohesion and angle of internal friction. Considering the strain hardening nature of the curves, selecting a distinct and consistent point of failure was difficult, hence a nominal strain of 5% was used to determine the stress. This stress at this point was used in composing the normal stress versus nominal shear strain plot. The intercept of this plot gave cohesion (C′), while the slope of the line represented the angle of internal friction (Φ′).

7.6.2 Cohesion and angle of internal friction

This section offers trends observed in the control mixtures. Instead of presenting separate pictures for different aggregate/binder ratios, a composite picture as a function of water/binder ratio is presented here.

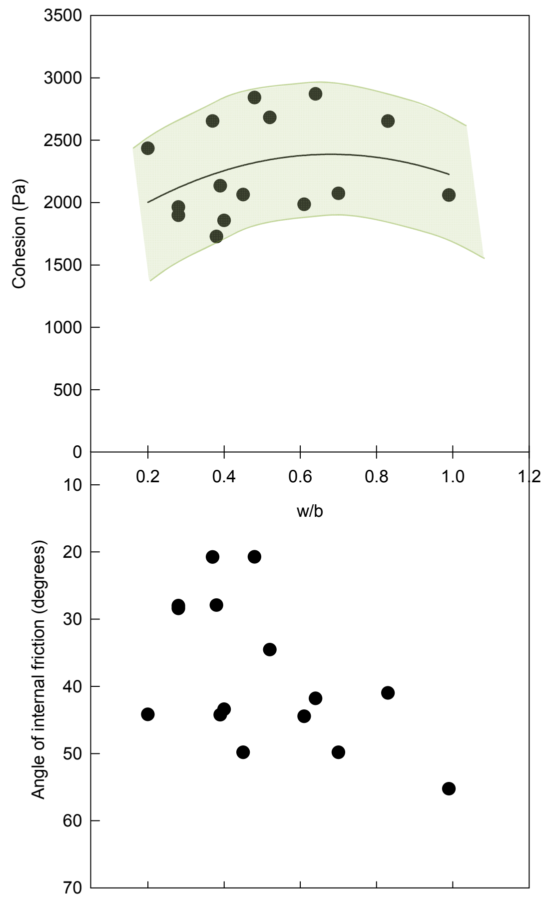


Figure 7-21 Cohesion and friction angle for control mixtures

Figure 7-21 shows the trends in the cohesion and angle of internal friction. The data is scattered over a wider range and this could be possibly due to the noise in the measurements. This being the first study of its kind, further fine tuning would be required. The cohesion shows a trend with water/binder ratio, but the angle of internal friction is scattered over a wider range. To infer with greater confidence repeat trial runs will be required. Less cohesion is mobilized at lower water/binder ratio, with an increase in the water/binder ratio, the cohesion increases reaches a peak and then with further increase in the water content, the cohesion drops down. The angle of friction is however showing a higher variability with the vales spanning between 20 and 55˚.

7.6.3 A composite picture

Figure 7-22 shows a composite figure that helps select multiple parameters at the same time, all a function of water/binder ratio. The following are salient inferences:

- The CSV shows a parabolic variation, lower w/b ratio representing less compactibility because of presence of higher air volumes and higher w/b ratio representing lower compactibility because of presence of higher water or voids flooded with water;
- Each of this cohesion value will correspond to a pair of ratio of volume of paste/volume of voids in aggregates. Not all pairs can be used for making roller compactable concrete. for example in the case highlighted in the figure, at the lower end of this ratio, due to higher air content, the concrete will not be economically roller compactable, while at the higher end there is a possibility of making good concrete. Care should be exercised in selecting this ratio properly, since the economics of material selection shall be influenced by proper paste selection.

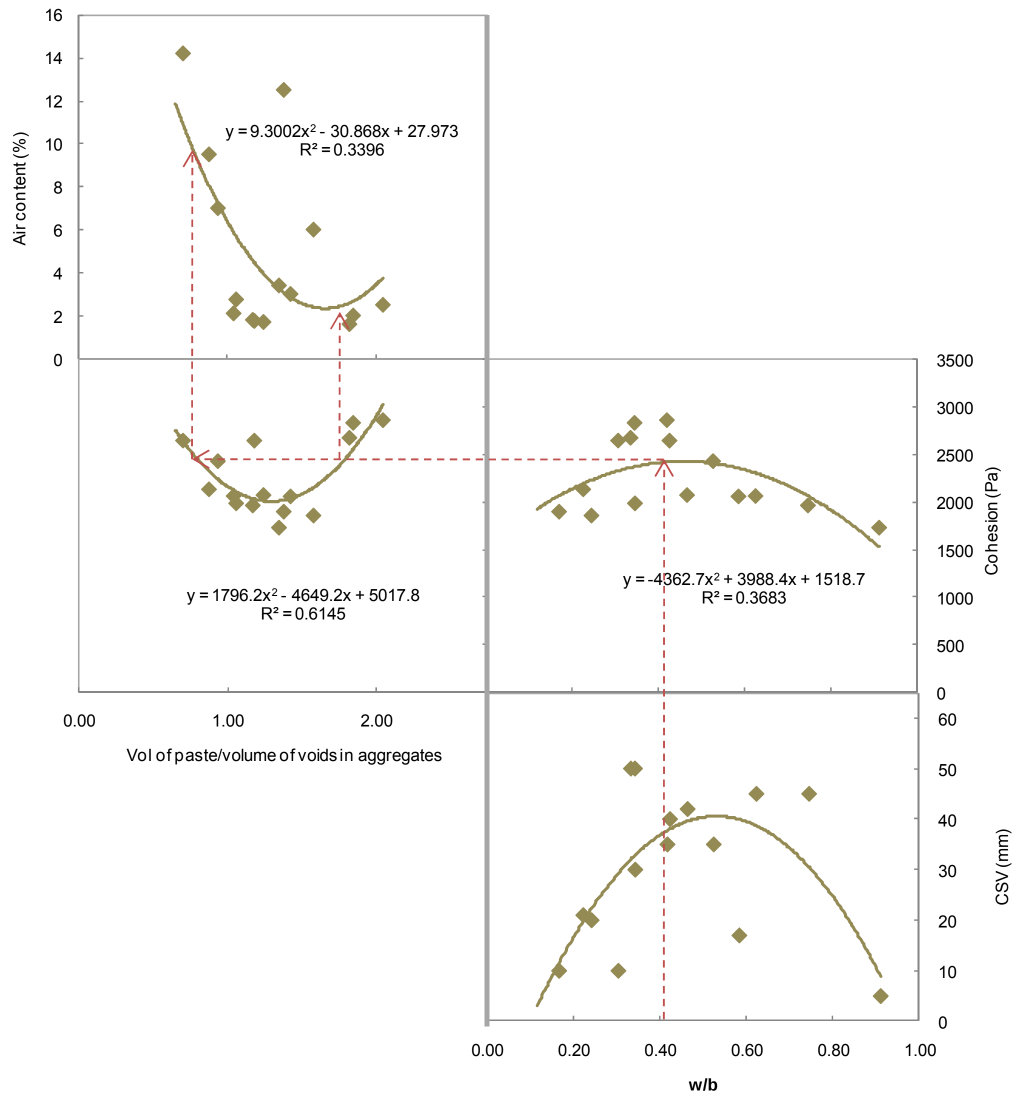


Figure 7-22 w/b ratio-CSV-Cohesion-relative volume of paste in aggregate voids -Air content

7.7 Strength aspects

7.7.1 Background

In this section, the mixture compositions for non-admixed concretes is reproduced and discussed. All the mixtures used for developing the moisture-density profiles are considered control/neat or virgin mixtures. Table 7-4 offers a summary of mixture proportions along with the uniaxial-unconfined compressive strength (UUCS) at various ages. These will be used for further discussion.

Table 7-4 Mixture proportions and strength development for non-admixed concretes

A/B	Materials, kg/m^3				w/b	UUCS, MPa			
	Cement	F Fly ash	Aggregates	Water		1-day	3-day	7-day	28-day
4	322	106	1731	72	0.1681	1.66	3.03	4.74	5.07
4	334	110	1795	108	0.2432	16.55	23.72	28.11	32.39
4	334	110	1796	153	0.3434	13.44	28.49	34.71	47.26
4	320	106	1721	178	0.4185	8.23	21.50	30.95	38.72
4	336	111	1803	149	0.3341	19.07	31.28	41.87	54.00
7	210	69	1974	63	0.2242	4.24	6.52	6.89	10.82
7	218	72	2047	100	0.3444	8.12	15.01	17.76	21.22
7	215	71	2021	121	0.4245	11.14	20.41	30.11	32.49
7	203	67	1906	158	0.5848	4.89	10.70	17.00	23.52
7	212	70	1998	131	0.4653	12.09	14.45	20.98	34.65
10	144	48	1938	59	0.3052	3.43	5.44	9.67	12.79
10	149	49	2005	104	0.5257	5.13	12.84	15.44	21.61
10	151	50	2024	149	0.7461	3.29	4.98	7.69	10.98
10	143	47	1925	174	0.9115	2.20	3.31	3.99	6.07
10	154	51	2068	128	0.6244	4.99	9.12	12.19	18.57

Notes: The material weights are rounded off. Green shaded rows indicate optimum moisture content mixtures. UUCS: uniaxial, unconfined compressive strength

7.7.2 Strength evolution and binding efficiency

The temporal evolution of UUCS was modeled using a simple exponential model of the form

$$S = a(1 - \exp(-bt))$$

This relation was observed to follow the hydration process trend and captures the development in two parameters. The term b should be carefully interpreted, since it carries a negative sign meaning the higher this number is, the slower is the rate of strength development at greater ages. Figure 7-23 represents the typical strength development trends for A/B = 7.

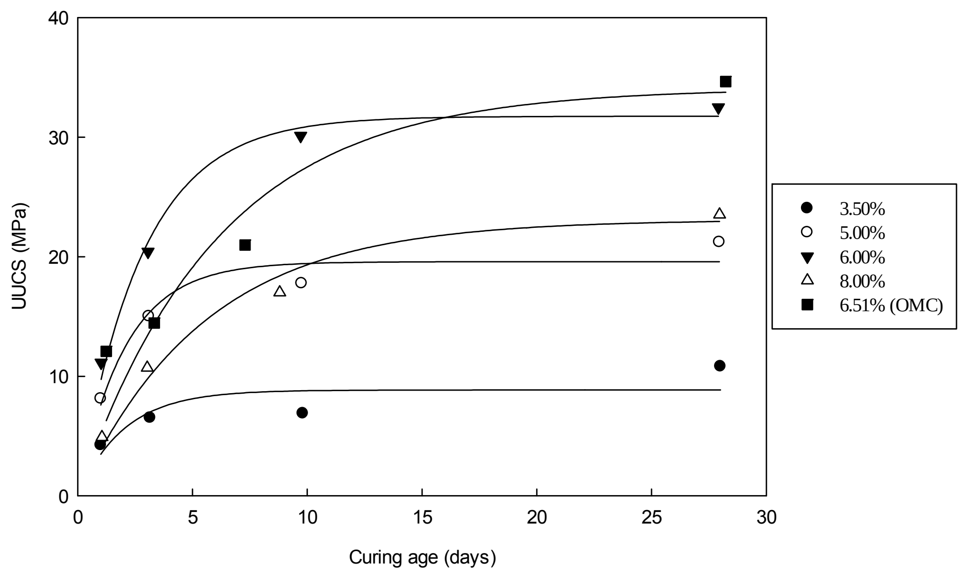


Figure 7-23 Modeling temporal evolution of strength development for various moisture contents and A/B = 7

Taking a time derivative of the above equation offers estimates of the rate of strength development. Here the life of concrete is considered to sufficiently long for a day to be small. The following equation results:

$$\frac{dS}{dt} = abexp(-bt)$$

This rate of strength development can be obtained for various ages. Figure 7-24 shows typical curves for A/B =7. It can be seen that the initially the rate curve is asymptotic to rate-axis while it later becomes asymptotic to the time-axis. This means that the rate of strength development approximates zero at longer ages. Based on this dataset, it is rather restricting to draw inferences about the relations between the rate of strength development and the w/b ratio or moisture content. A further analysis is offered in a later section.

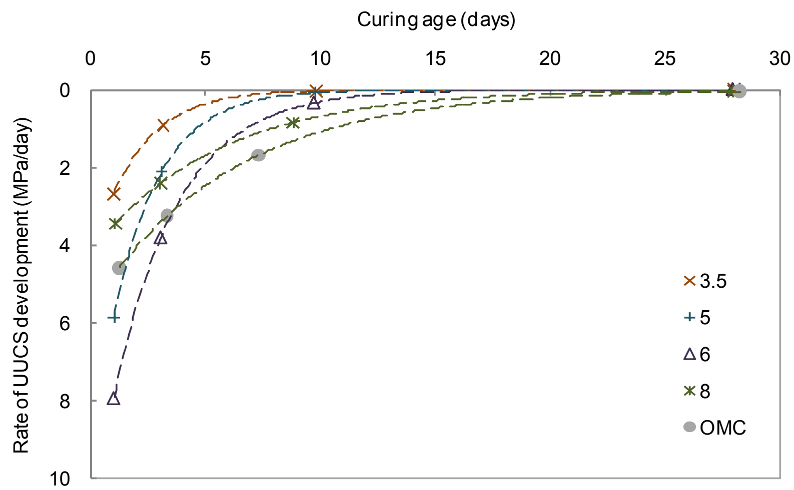


Figure 7-24 Time rate of strength development for different moisture contents

These curves are significant from a practical perspective. Knowing the rate of strength development would assist in estimating strength at first day. At later ages, if the area between these curves and the axes is integrated it would provide an estimate of the strength of concrete at any age starting at one day along with an idea of *how fast* would the remaining (*how much*) strength would be achieved.

Cementing efficiency factors are often used in RCC dam construction to characterize the efficacy of cement or binder in providing strength. In this thesis, a similar term called binder efficiency [10] is used. At a given age, the following formula is used for computing the binder efficiency:

$$Binder\ efficiency\ (\eta) = \frac{UUCS\ (MPa)}{Binder\ content\ (\frac{kg}{m^3})}$$

Figure 7-25 represents the binder efficiency at different ages as a function of moisture content at a fixed A/B ratio. It can be seen that the binder efficiency increases with age, however its time rate with curing age decreases. This follows the trend shown by the hydration reactions, quite fast initially gradually transitioning to minimal at later ages. This will be discussed in detail in a later section, when analysis for all the control mixtures will be presented.

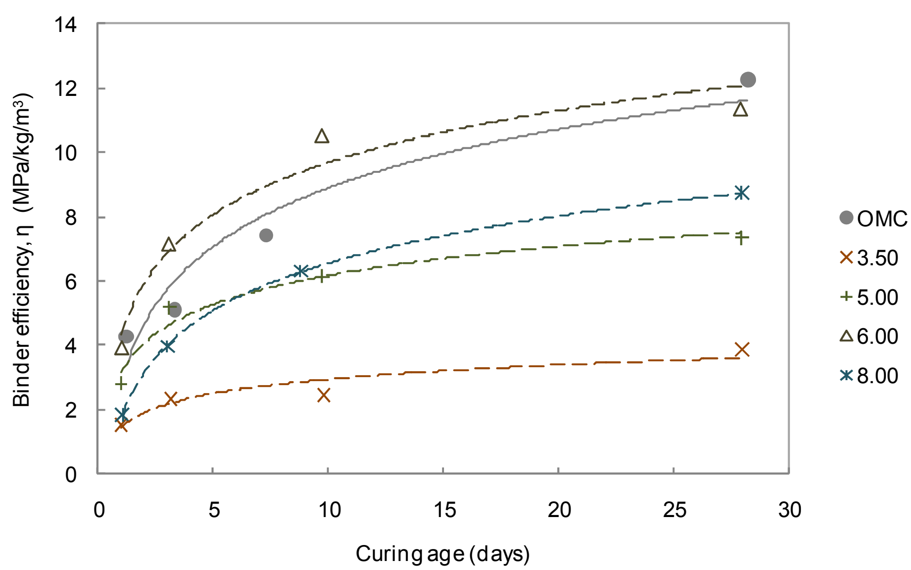


Figure 7-25 Effect of moisture content and curing age on binder efficiency

7.7.3 Abrams' law: Anomalous behavior

Figure 7-26 shows the strength trends as function of w/b. This data is for 28d UUCS. The following observations are relevant:

- In general, there are deviations from the conventionally accepted Abrams law for each A/B ratio. The deviations originate at different w/b ratios, however it is interesting to see that the water content of these mixtures are quite comparable at optimum moisture contents.

- The optimum moisture content and w/b ratios beyond it follow the Abrams' law, however the points on the drier side of optimum show significant deviations.

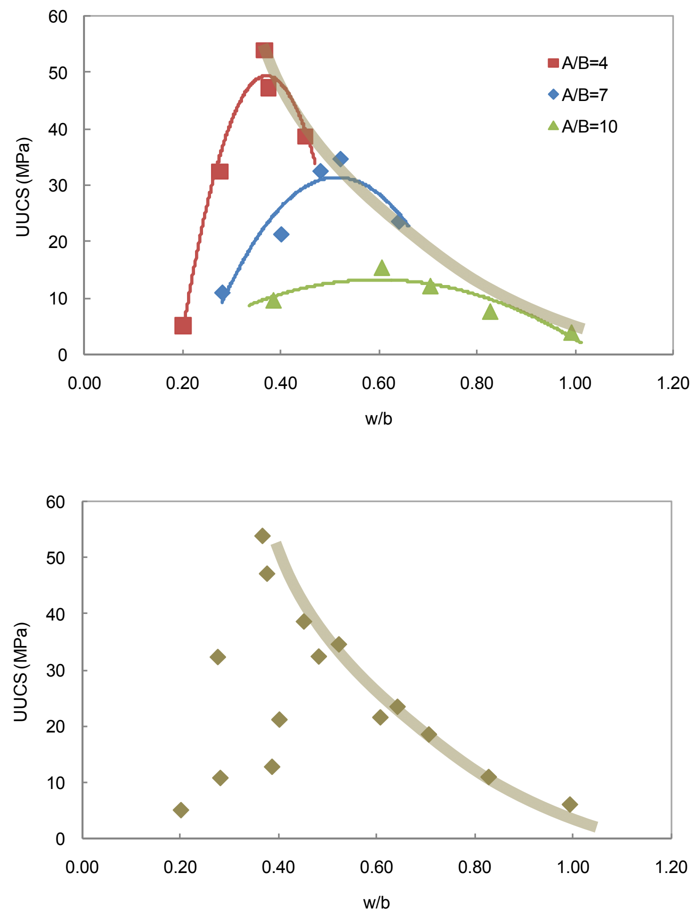


Figure 7-26 Deviations from conventionally accepted Abrams law: Individual A/B and composite curves

- The drop in the strength depends on the binder and aggregate content of the mixtures. Richer mixtures (A/B = 4) show a dramatic drop with reduction in water content and this is characterized by a steep slope. While intermediate binder content mixture follows a transitory behavior, it is quite interesting to note that leaner mixtures are far less sensitive to the alterations in the moisture content. This is shown by a flat curve and very gentle slope. A possible explanation is presented. Higher cement contents would need a higher volume of water to achieve a similar amount of hydration. Moisture additions to these mixtures were done based on percentage moisture content on the dry solids basis. As the mixtures become leaner, the volume of cement and hence the water requirement for hydration reduces. Moreover, the aggregates make higher contribution to strength than in the richer mixtures.

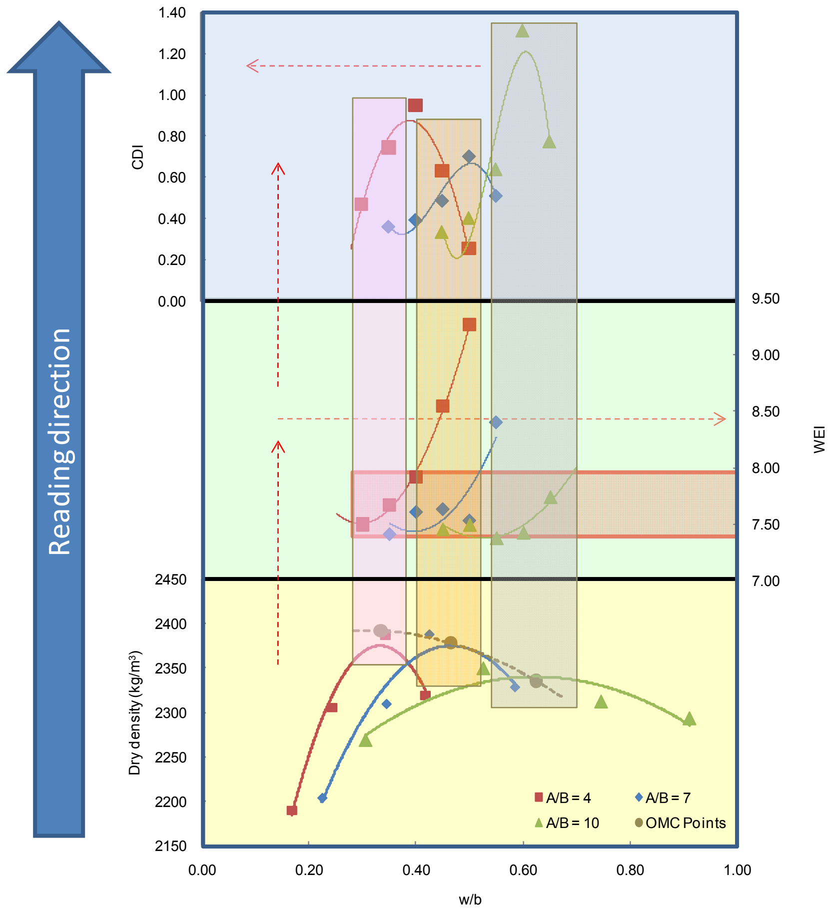
- The composite picture shows that the deviation from Abrams law is observed in general. Here, the effects produced by aggregate quantity are not accounted for and the strength is considered only a function of the w/b ratio. Only mixtures that can be compacted to potentially maximum density followed Abrams' law.

SUMMARY

This chapter summarized four key investigations reported in this work. The first investigation is about the utility of different aggregate parameters in assessing the most compactable grading. It was observed that the coefficients used for characterizing soil grading can be used in concrete for correlating with the compactibility. Parameters were related to conventional fineness modulus index and interaction charts were evolved.

This was followed by compactibility studies of concrete mixtures, whereby the influences of several parameters including the aggregate/binder and water/binder ratios were reported. It was observed that the sensitivity of mixtures to compaction depends on their composition. Higher binder content mixtures are more sensitive than the lower binder content mixtures.

Different aspects of workability of fresh concretes including the moisture-density-air, the CSV, cohesion and angle of internal friction. Combined plots from all the mixtures were developed for cohesion and angle of internal friction. The cohesion values showed a clear trend when plotted against water/binder ratio, while the angle of friction showed a wider spread. Few indices like the self compacting index, workability energy index, work index were evolved to better appreciate the variations of different attributes of workability. Interaction plots exploring the inter-relations amongst these parameters (water/binder ratio, air content, cohesion, compactibility indices) were developed with an intention of making easier transitions from one attribute to another and evolve a method for mixture proportioning.



Finally, a discussion on the strength aspects of the control mixtures was offered. It was argued that the Abrams' law is not followed if adequate compaction is not achieved. The reduction in strength, despite reduction in water was explained primarily on the basis of inadequate compaction for various combinations of aggregate-binders.

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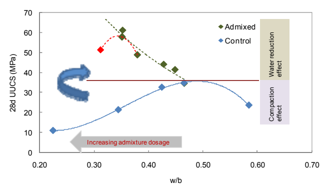
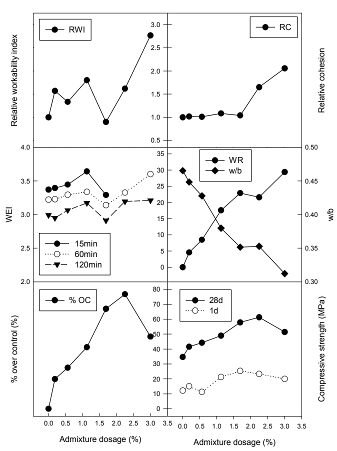
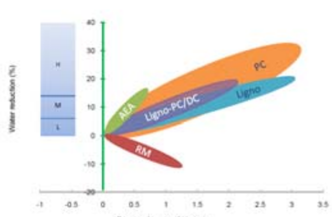
CHAPTER 8 SUMMARY OF EFFECTS OF DIFFERENT ADMIXTURES







SYNOPSIS

This chapter presents a summary of the significant findings from the work done on admixed concretes. The reported admixtures include different chemical compositions of admixtures performing functions like water reduction, retardation, air entrainment, rheology modification, etc. Integrated composite diagrams are constructed to offer a holistic perspective of the changes in the properties of concretes with the use of different chemical admixtures at tested dosage ranges. Along with the presentation of typical results obtained from testing intermediate binder content mixtures, the effects of these admixture dosages at higher and lower binder contents are summarized. After describing the performances of single admixtures, sample results obtained from combinations of duets and triplicates are reported. This includes the statistical analyses of typical results. Finally, the composite results are reported in terms of typical properties. An appreciation of such plots is important in selecting the right admixtures and comparing their performances.

Keywords: water reducer, retarder, air entraining admixture, rheology modifier, dry cast admixture, binary, ternary, method of mixtures, water reduction, cohesion, workability, strength

CONTENTS

Like the previous chapter, this chapter summarizes and reports key results obtained for admixed concrete mixtures. Therefore examples are chosen and cited in the respective sections. For detailed discussions and individual representation of results, please refer to the respective appendices.

8.1 Typical behaviors

The control mixtures showed some anomalous behaviors. This section discusses some important aspects of admixed concretes viz. partial reinstatement of Abrams' law, an analysis of the air entrained concrete mixtures, binder-admixture interaction effects.

8.1.1 Examples on reinstatement of Abrams' law

As discussed previously presence of less than optimal moisture content leads to reduction in the density, entrapment of excessive air and reduction in the strength of concrete. Consequently, for a given composition, the strength of concrete shows a deviation from the Abrams' law. Use of some water reducing admixtures leads to partial reinstatement of this law.

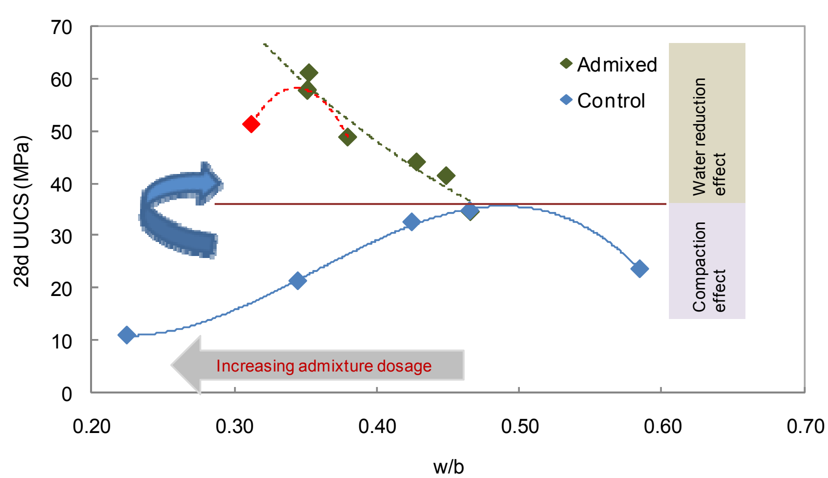


Figure 8-1 Partial reinstatement of Abrams' law

Figure 8-1 offers an explanation of the reinstatement of Abrams' law with one of the water reducing admixtures. The strength could to be analyzed and understood from two distinct perspectives. The first is the *compaction response* while the second is *water reduction response.* These two composite actions decide the total increase in the compressive strength observed for a given w/b and curing age. As is shown in the above Figure, the drier mixtures are initially plasticized so that they could come to a level of maximum possible compacted density. Some of the admixture power or efficiency is consumed in mobilizing this plasticity required for compacting a mixture to its potentially maximum density. Up to the point of optimum moisture content (OMC), the mixture has the potential and composition (in terms of binder content at a fixed Aggregate/Binder ratio) to produce maximum strength comparable to that obtained by the mixture at OMC and compacted to its maximum density. It is just due to the lack water resulting into reduced or no plasticity and mobility of binder paste that the mixture cannot be compacted fully in its non-admixed form. Adding a plasticizing effect through the via-medium of a water reducer assists in overcoming this barrier. Consequently, a mixture's strength is initially raised to that achieved by the mixture at OMC. The drier the mixture, the higher is the expenditure of a water-reducer's power to plasticize and vice versa. If all these mixtures were to be admixed at OMC, the strength increase that would be produced will show quite a different trend.

Along with the plasticizing role, the water reducer also produces water reduction effects. The exact demarcation may not be possible based on available data. After the plasticizing role is completed, the water reducer is starts to initiate its actual strength-increasing role. Again the higher the w/b ratio, the higher is the % power used in producing the water reduction effect. Thus differentiating the two roles can help assess the actual water reduction produced by a water reducer. For example, if we consider w/b = 0.35, the overall strength increase was about 40 MPa, of which approximately 14.65 MPa (Strength at OMC minus that at w/b = 0.35) comes from plasticizing effect, while the rest comes from water reduction effect. It should be noted that this analysis was based on the available strength data. Further studies pin pointing the exact origins and mechanisms of the composite action were beyond the scope of this work. Figure 8-2 shows a composite plot of w/b versus UUCS. It can be seen that the Abrams law is reinstated with the use of this water reducing admixtures.

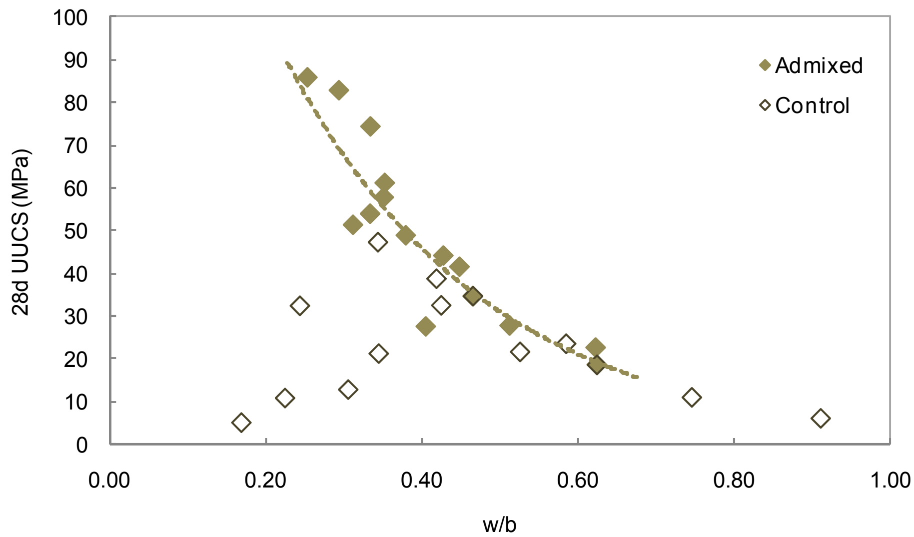


Figure 8-2 Composite picture of the partial reinstatement of Abrams' law

8.1.2 Effects of entrained air

A ratio proposed by Feret and later used by Talbot and Richart [1-2], cement paste ratio (or cement space ratio), r_F can be used in estimating the strength of air-entrained concrete. It should however be noted that the Faret's concept tends to over-estimate concrete strength at higher cement contents and under-estimates them at lower cement contents. Following formula is relevant to this discussion,

$$f = K r_F^2$$

where,

f is the concrete strength

K is an empirical constant

$r_F = C/(C+W+V_a)$, C and W are weights or absolute volumes of cement and water and V_a is the volume of air in compacted concrete

Compressive strength of comparable concretes are reduced by approximately five percent of air-free strength for every one percent of air in the fresh concrete [3] and is given by the following formula

$$f = f_0(1 - 0.05V_a)$$

It is essential to recognize that the composite action of w/b ratio and the volume of air voids influence the strength of concrete. A unit volume of capillary pores, in general, does not have a similar effect as the same volume of initial air voids (reference). Moreover, the capillary porosity is age-dependent and reduces with continuing hydration. On the other hand, air voids once created, either due to entrainment or lack of compaction are stable over time [2].

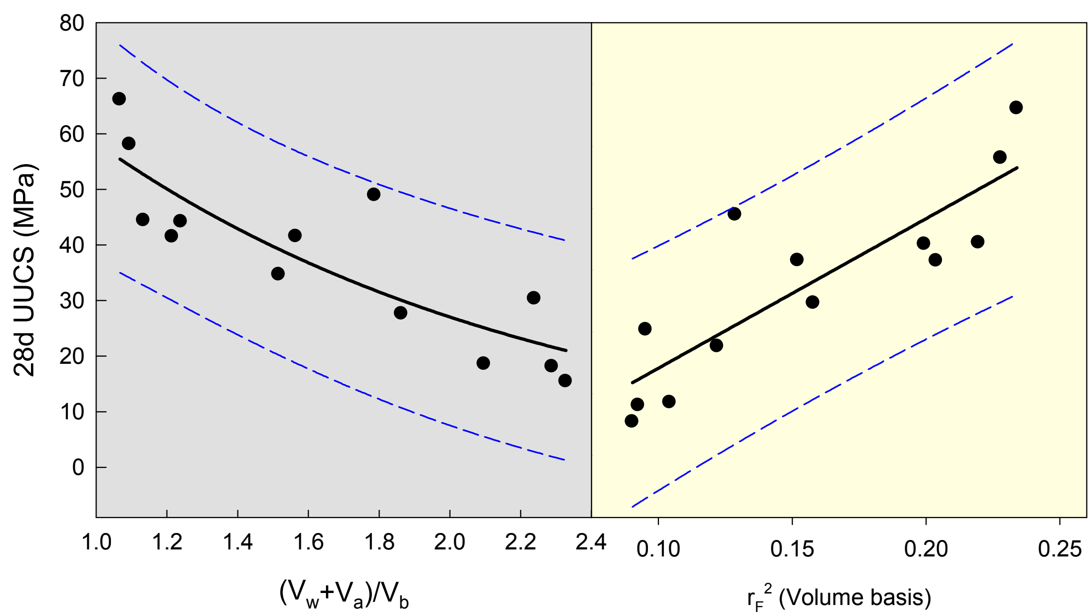


Figure 8-3 Strength-w/b-air content interaction effect and strength cement-space ratio effect

Figure 8-3 shows two plots with their respective trends and 95% confidence limit bands. The plot on the left hand shows the relationship of strength to the volumetric ratio of (water+air)/binder. This relationship is analogous to Abrams' law and takes into account the combined effects produced by the volume of air and w/b ratio on the strength of concrete. Similar relations were developed by Feret and are reported by Popovics [2]. Similarly as discussed above, the relationship between strength and the square of cement-space ratio (r_F) is given by a straight line. For the test data, there is a negligible intercept and the value of k is -241.95.

8.1.3 Binder-admixture interaction effects

There are definite interactions effects produced between the binder and admixture contents. This is illustrated by the following two examples.

EXAMPLE 1

Figure 8-4 shows the binder efficiencies of various A/B ratios at different dosages. It can be observed that the dosage of 1.5% offers the highest binder efficiency. Moreover, for this admixture the A/B ratio of 7 achieves the highest efficiency. There is definitely an interaction going on between the binder content and the admixture dosage. The binder efficiency increases with age and with the admixture dosage. These series of graphs indicate that the binder efficiency initially increases with the dosage, reaches a peak and then decreases. This can be partially explained on the basis of increased w/b ratio due to the water coming from the liquid admixture, which is not taken into account for this study. In addition to this, the air content could potentially increase at higher dosages.

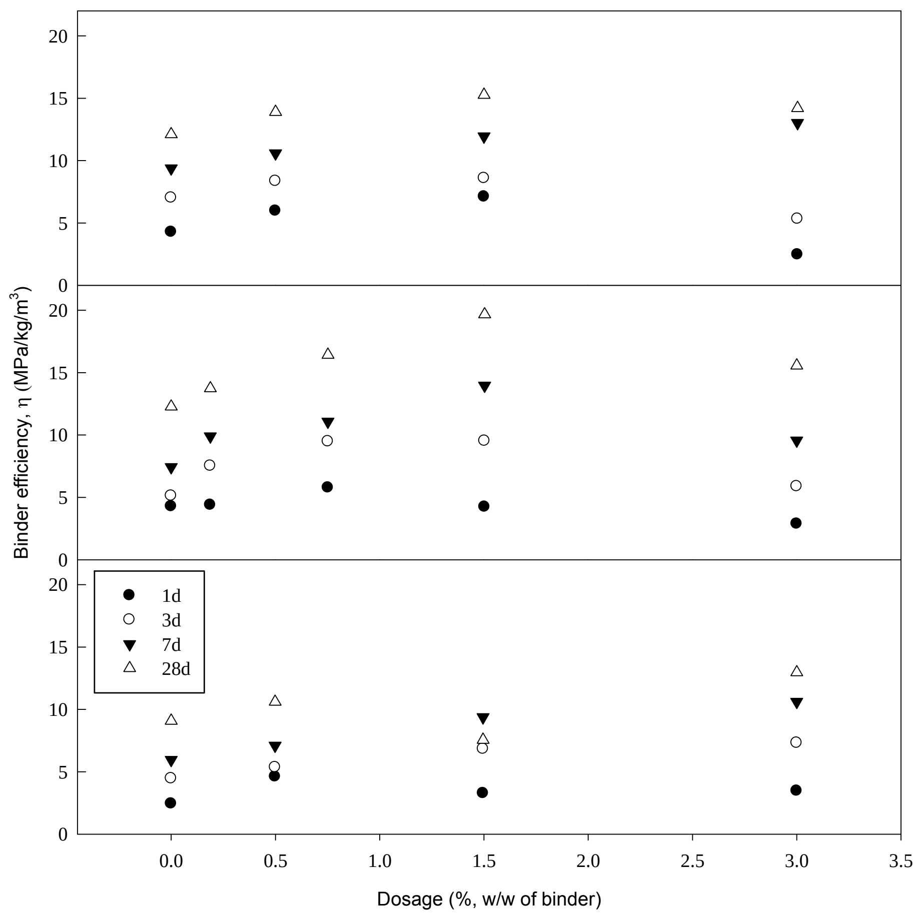


Figure 8-4 Effect of admixture dosage and A/B ratio on the binder efficiency. A/B ratios for Top: 4, Middle: 7 and Bottom: 10

A 3D plot is constructed to illustrate the interaction of the binder content and the dosage of admixture on the binder efficiency. Figure 8-5 offers such a representation. It is evident from this figure that the intermediate binder content and a dosage close to 1.5% offers the highest binder efficiency.

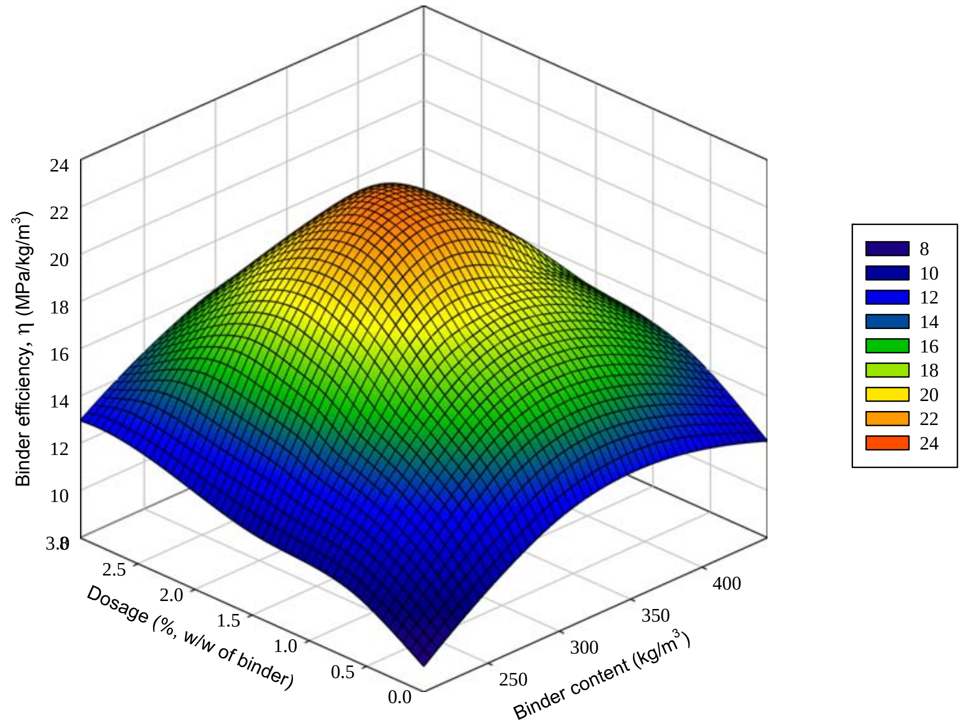


Figure 8-5 Interaction of the binder content and the admixture dosage for Type A (P-06)

EXAMPLE 2

A typical data was analyzed for interaction effects using the least squares model to understand interaction effects of binder and admixture dosages. This analysis was performed with JMP [4] program. Three binder contents (205, 282, 446 kg/m^3) and four admixture dosages (0, 0.5, 1.5, 3.0 %) were used in this analysis. A model consisting of binder content, admixture dosage and the interaction term of binder content *admixture dosage was used in constructing the model. The resulting model showed a very good fit (R^2 = 0.99) is plotted against actual values and is shown in Figure 8-6. A residual plot showing good distribution is also obtained and shown along with the model plot. With the available data the objective was to

- Effects of binder content (CC)
- Effects of admixture content (Adm)
- Obtain optimal mixture parameters
- Trace the interaction effects and

- Rank the mixtures

The effects of binder contents and admixture dosages are individually shown in Figure XX. This figure also shows the desirability profiles for the highest UUCS. The binder content of 446 kg/m^3 and admixture dosage of 1.5% produce the maximum UUCS.

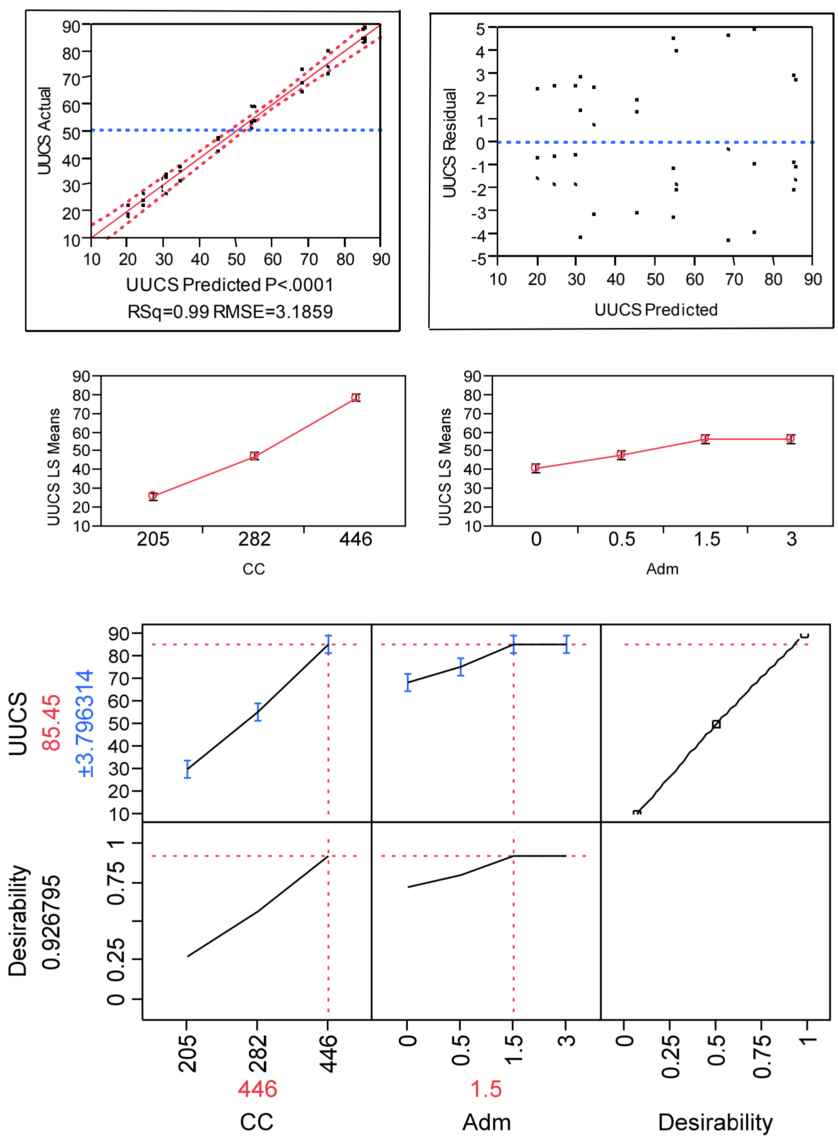


Figure 8-6 Prediction models attributing individual and interaction effects. Desirability trends obtained for maximum strength

Analysis of variance (ANOVA) and F-tests were used to check for differences and to assess whether they were statistically significant or not. Refer to Table 8-1. Different letters here mean that the effects produced by the binder contents on the strength are different and are statistically significant.

Table 8-1 Establishing statistical difference in binder contents

Binder content (kg/m^3)	Designation	Least squares mean
446	A	78.58
282	B	47.35
205	C	26.15

Similarly, admixtures were individually checked for differences. The results of the analysis are shown in Table 8-2. In this case, however, the admixture dosages of 1.5 and 3.0 % were not found to produce statistically significant differences. The values of least square means were quite close to one another.

Table 8-2 Establishing statistical differences in admixture dosages

Admixture dosage (%)	Designation	Least squares mean
3.0	A	56.84
1.5	A	56.83
0.5	B	48.24
0.0	C	40.86

Further to this, statistical analysis of different dosages and binder contents together was conducted in order to trace the interaction effects produced on the strength. Table 8-3 offers the summary.

Table 8-3 Establishing statistical difference due to interaction effects

Binder content (kg/m^3)	Admixture dosage (%)	Classification A	B	C	D	E	F	G	Least Squares Mean
446	1.5	■							85.45
446	3.0	■							85.23
446	0.5		■						75.14
446	0.0			■					68.53
282	1.5				■				55.37
282	3.0				■				54.44
282	0.5					■			45.36
282	0.0						■		34.24
205	3.0						■		30.86
205	1.5						■		29.69
205	0.5							■	24.24
205	0.0							■	19.83

Figure 8-7 shows the least squares mean plot for the interaction effects. The following is a summary:

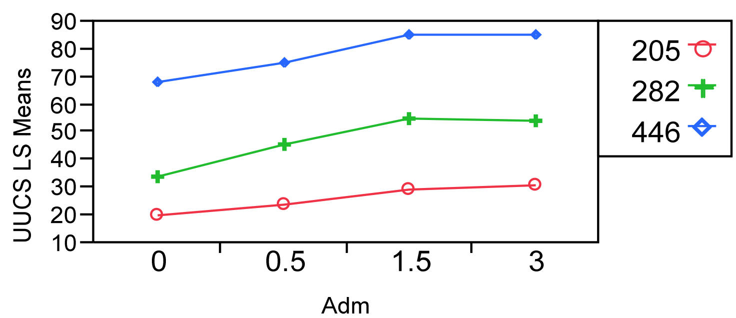


Figure 8-7 Least squares mean plots for the interaction effects produced by binder content and admixture dosages

- Irrespective of the binder content, there is no statistically significant difference between 1.5 and 3.0% admixture dosages
- In mixtures with higher A/B ratio, there is no significant effect produced by adding 0.5% admixture dosage. Statistically the strength produced by the control mixture and the mixture with 0.5% water reducer produces similar compressive strengths

- The strengths produced by the control mixture with A/B = 7 are similar to the strengths produced by mixtures with A/B = 10 and admixture dosages above 1.5%

8.1.4 A list of relevant observations

Detailed discussions about the results from different tests have been discussed in the respective appendices on fresh properties and strength. In this chapter, only the summary figures are provided. These composite figures are constructed for the intermediate binder content mixtures from six key perspectives as follows

- ► Water and water/binder reduction
- ► Relative cohesion with respect to the control mixture
- ► Relative workability index
- ► Workability energy index (15, 60 and 120 min)
- ► Compressive strength at 1 and 28 day
- ► % strength over control
- ► Air content, in case of air entraining admixtures only.

Each of these figures is followed by comments on the relative behavior of mixtures with lower and higher binder content. Detailed discussions of these binder contents are presented in the appendices.

8.2 Composite effects of unary admixtures

8.2.1 The study matrix

The test matrix for each of the admixtures consisted of testing several dosages over a broad range on all the three binder contents. This resulted in a proper appreciation of the following effects:

- ► Effect of admixture dosage
- ► Effect of binder content

► Interaction effects caused due to the binder and admixture dosages

An understanding of the interaction effects is important as it provides a perspective on proper and optimal selection of binder and admixture contents. For example increasing the dosage of a particular admixture might perhaps lead to substantial cement or binder savings. It is important to appreciate the fact the concrete performance can be optimized by optimizing the constituent materials and not just a component of it.

8.2.2 Primarily water reducing admixtures

This section reports results for water reducing and retarding admixtures. Results of five different admixtures tested over three binder contents and with varying dosages are reported here. These are typical results from the most widely used admixtures belonging to this family. The preliminary recommendations for these were made by the manufacturers and subsequent screening and testing were used for finalizing the products.

POLYCARBOXYLATE BASED WATER REDUCER [PRODUCT P-05]

Study matrix

This product was tested on all the three binder contents with different dosages. The manufacturer recommended dosage is in the range of 0.341 to 0.650 l/100kg of cement for normal concretes. Table 8-4 presents the experimental plan. The dosages ranged between 0.19 (0.19 l/100 kg of cement) and 3.00% (3 l/100 kg) w/w of binder for all the binder contents, with detailed investigations performed on the intermediate binder content.

Table 8-4 Experimental plan for PC-based water reducer

Binder content (kg/m^3)	A/B	Dosages (%, w/w of binder)							Remarks
		1	2	3	4	5	6	7	
205	4	0.00	0.25	1.50	3.00	--	--	--	
282	7	0.00	0.19	0.56	1.13	1.69	2.25	3.00	Detailed investigation
446	10	0.00	0.25	1.50	3.00	--	--	--	

Composite plots

Figure 8-8 shows the relative properties for this admixture at various dosages. It can be seen that the strength increases as the dosage increases, reaches a peak and then decreases. The decrease is due to the water contributed by the admixture. The water reduction ranged between 0-30% and the corresponding w/b ratios are shown in the plot. The relative cohesion remains constant, but it actually increases, since the w/b ratio is decreasing with increasing dosage. After a certain dosage (2.25%), the cohesion increases dramatically making concrete extremely cohesive, this could be difficult to work with. Similar trend is observed for work index. The compactibility indices therefore could not be obtained for these dosages at 15 min. This admixture shows good retention of compactibility as can be seen from the relative trends at 60 and 120 min.

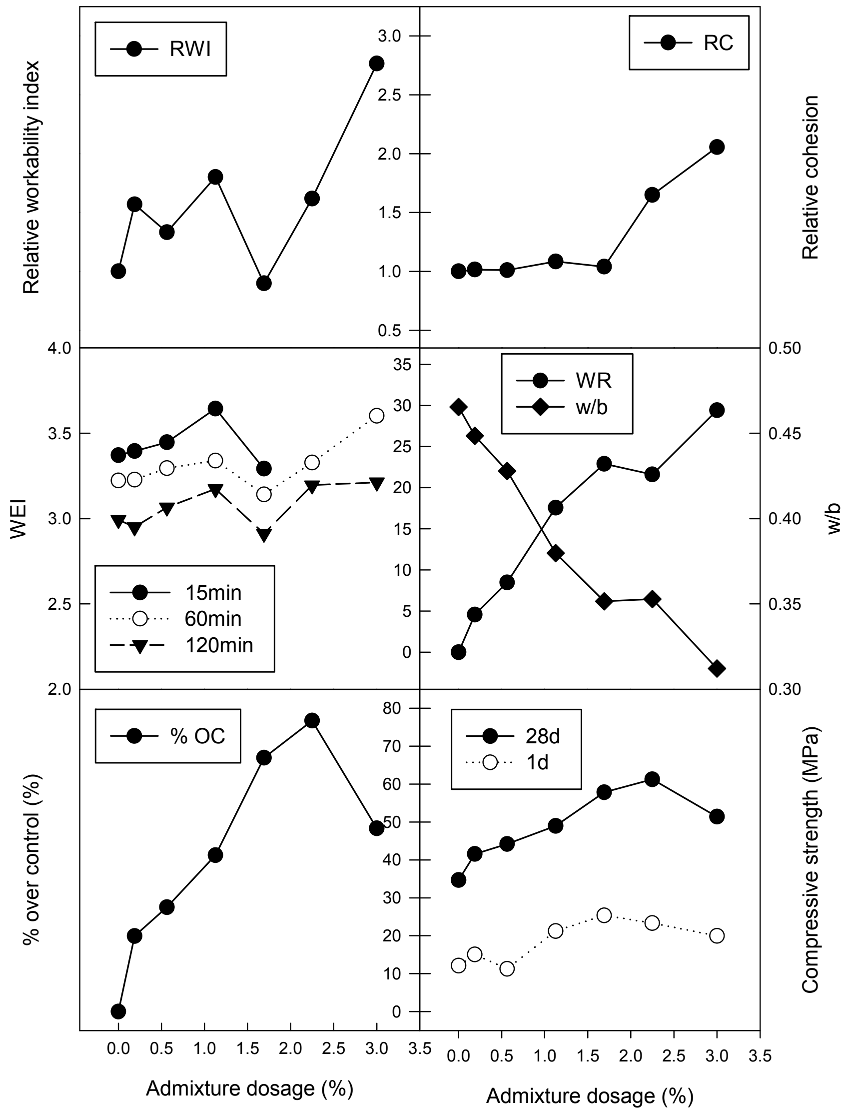


Figure 8-8 Relative properties for P-05 admixed concrete mixtures. RWI: Relative workability index; RC: Relative cohesion; %OC: % over control

Sample interaction effects

Refer to Figure 8-9. It can be seen that the water reduction is binder content specific. Irrespective of the binder content the water reduction increases as the admixture dosage is increased. For the intermediate binder content, the admixture shows higher responsiveness. This could possibly be due to the optimal effectiveness of this admixture for this binder content range. A premise that could be offered to this behavior is as follows.

The composition of a binder has a specific surface area and the admixture has a specific effectiveness over that surface area.

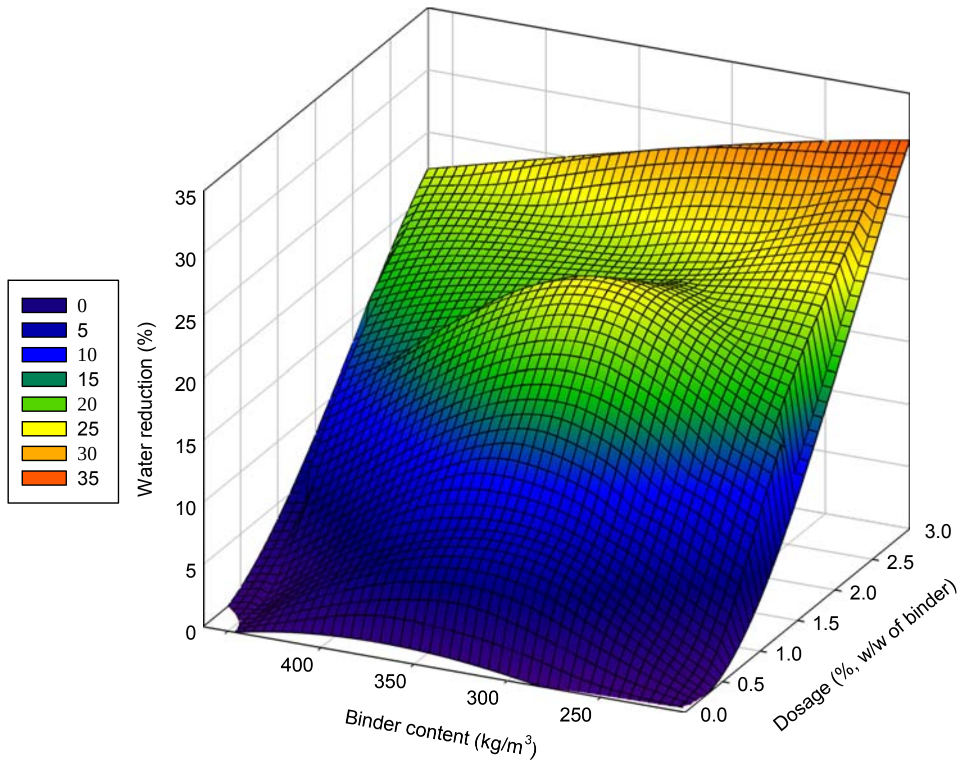


Figure 8-9 Interaction effects of binder content and admixture dosage on water reduction: P-05

A similar plot for the interaction effects on strength is plotted and shown in Figure 8-10.

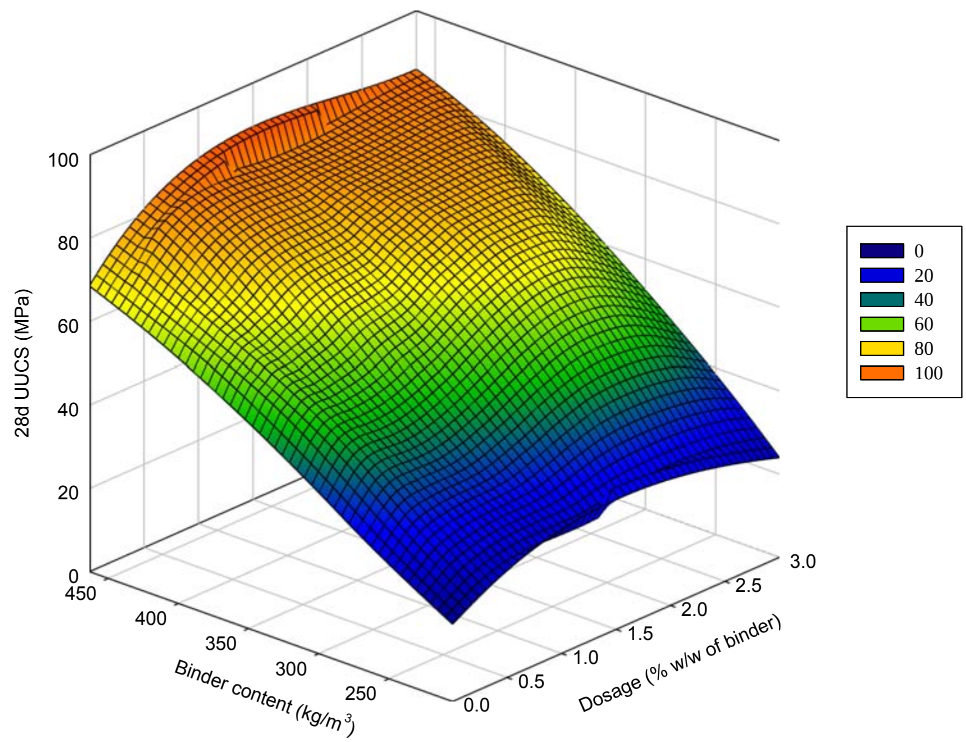


Figure 8-10 Interaction effects of binder content and admixture dosage on the 28d UUCS (MPa): P-05

Relevant observations

The following observations are relevant while considering the interaction effects:

- This admixture is less effective and might prove uneconomical for lower binder content mixtures.
- For higher binder content mixtures, this admixture is effective however, it adds to the stickiness of the mixture even at lower dosages. This stickiness is quite distinct, less useful from the usual cohesiveness observed in routine concretes.
- Similarly, the WEI is affected for higher binder content and the mixture might tend to get negatively affected with increasing dosage.
- The binding efficiency is observed to increase up to a certain dosage and then starts showing a decreasing trend. This probably happens due to the contribution of water from the admixture, which is not accounted for these computations. As the dosage increases, so does the water contributed from the admixture.

- As far as retention of compactibility is concerned, this admixture offers decent performance. However the effectiveness in retaining compactibility decreases with increasing admixture dosage. The performance of this admixture is relatively poorer when compared to pure lignosulphonate.
- This admixture is effective in improving the finishibility of RCC mixtures for the tested binder content range. At higher dosages, the mixture tends to develop cracks, possibly due to excessive stickiness.
- It is also important to remember that PC based admixtures tend to entrain air at higher dosages. This air entrainment is binder content specific.
- This admixture provides rapid early age strength gain and can be effectively used when early opening to the traffic is required.

In summary, care must be exercised in selecting the right chemical constitution of this admixture along with the optimal binder content range over which it offers appropriate and required performance properties.

ASTM classification

Based on the strength gain over the control, the admixtures at different dosages could be classified as either fulfilling the role of type A or type F water reducers. Figure 8-11 was constructed with this objective. It can be seen that this water reducer shows varying performance based on the dosage and binder contents. It is interesting that a clear distinction into types mentioned by ASTM C494 cannot be applied.

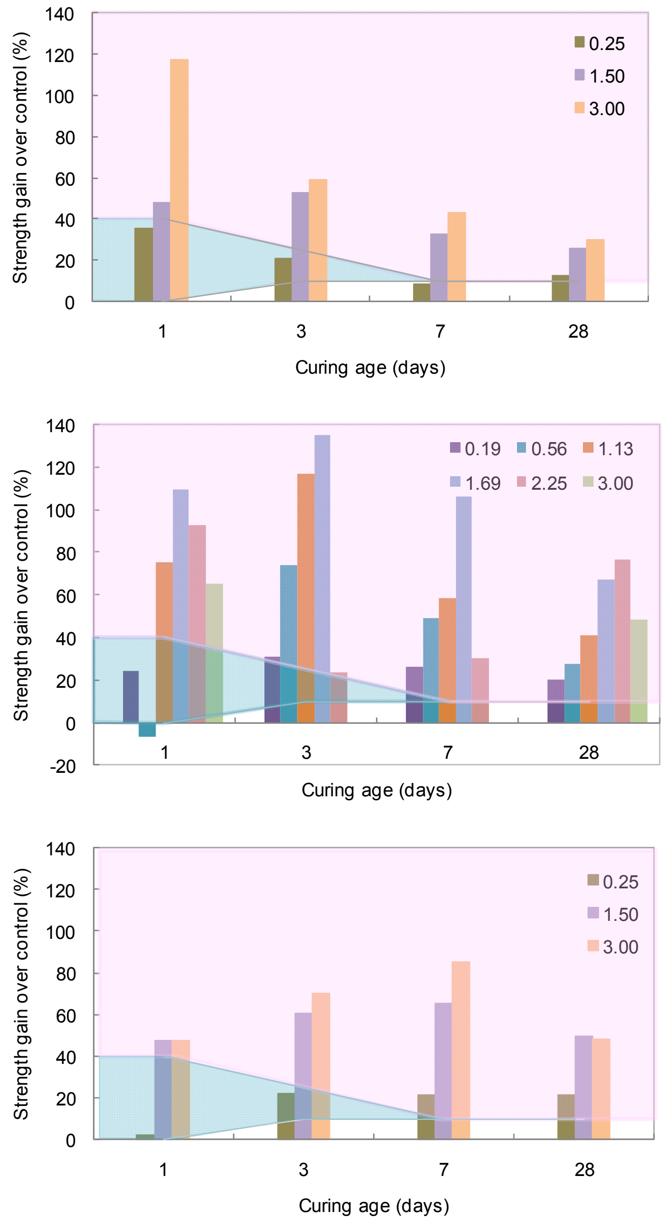


Figure 8-11 ASTM C494 classification based on UUCS. A/B for Top: 4, Middle: 7 and Bottom: 10. Blue region shows requirements for type A while Pink region shows requirements for type F water reducers. No strength requirement for one-day tests for type A water reducer.

LIGNO-PC BASED WATER REDUCER [PRODUCT P-06]

Study matrix

The manufacturer of this product claims more complete hydration of Portland cement with no effect on concrete air entrainment and a typical water reduction of 3-10%. The recommended dosage is in the range of 0.130 to 0.455 l/100kg of cement for normal concretes. Table 8-5 presents the experimental plan which tested the admixture between 0.19 (0.19 l/100 kg of cement) through 3.0 % (3 l/100 kg), w/w of binder.

Table 8-5 Experimental plan for a Type A water reducer

Binder content (kg/m^3)	A/B	Dosages (%, w/w of binder)					Remarks
		1	2	3	4	5	
205	4	0.00	0.50	1.50	3.00	--	Detailed investigation
282	7	0.00	0.19	0.75	1.50	3.00	
446	10	0.00	0.50	1.50	3.00	--	

Composite plots

Figure 8-12 shows the relative properties for this admixture at various dosages. The strength behavior is similar to the PC based product; however, the point of maximum increase in strength arrives relatively at an earlier dosage. This may be due to the presence of ligno-based component, which has a retarding tendency. The water reduction ranged between 0-24% with relative lesser water reduction than the PC-based product. The relative cohesion remains similar to control mixture with increasing water reduction; however, after an inflection point shows a reduction. Similar trend is observed for work index, which after showing initial increase attends a constant value. This admixture shows good retention of compactibility as can be seen from the relative trends in compactibilities at 60 and 120 min. The strength increase is relatively smaller than the corresponding dosages for the PC-based product.

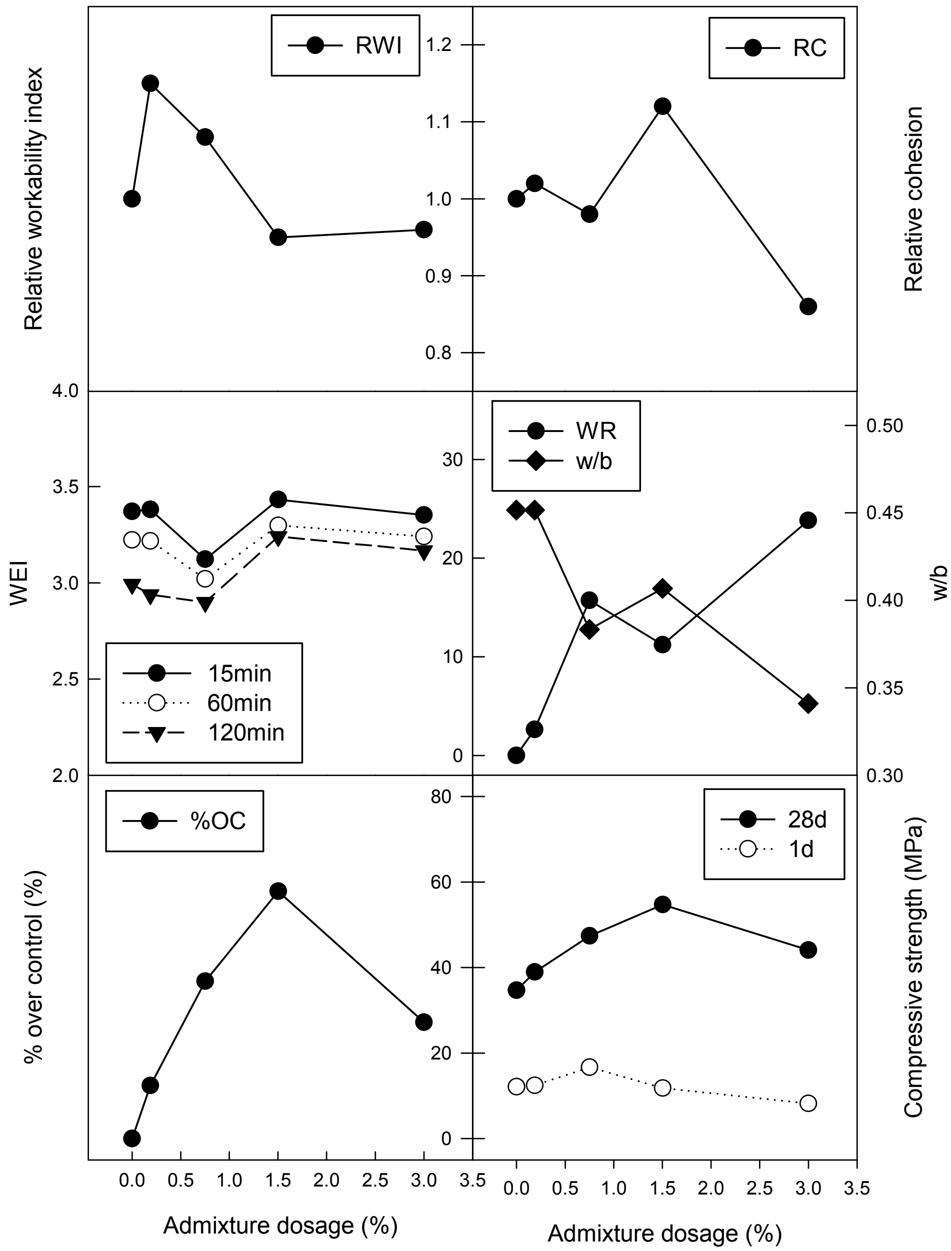


Figure 8-12 Relative properties of P-06 admixed concrete mixtures

Sample interaction plot

Figure 8-13 shows the interaction plot of the 28-day binder efficiency. It can be seen the optimization for binder efficiency is a two-way process. This admixture is optimized for better performance over the binder content ranging between 350 ± 25 kg/m^3. Similarly there is no incremental advantage in increasing the dosage beyond 2%, since it leads to no enhancement in the binder efficiency.

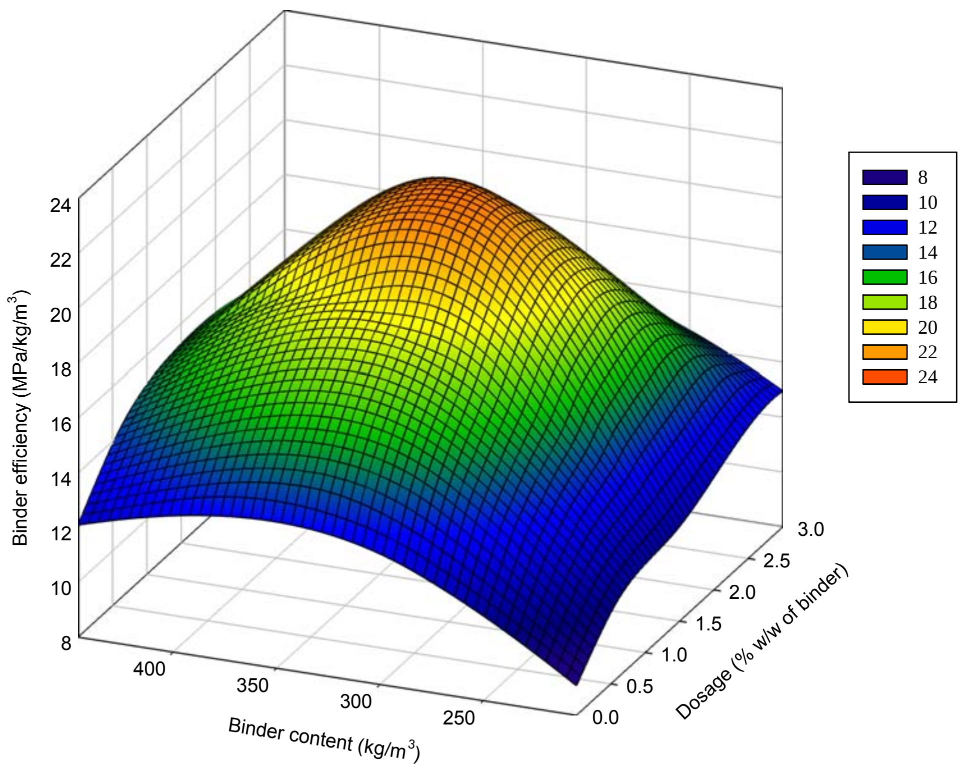


Figure 8-13 Interaction effects of binder content and admixture dosage on 28-day binder efficiency ($MPa/kg/m^3$): P-06

Relevant observations

The interaction effects of this admixture with the binder are qualitatively similar to product P-05. It derives the benefits of both of its components the lingo- and the PC and thus offers intermediate choice. The following is a sampling of the salient observations:

- This admixture is relatively more balanced in its effectiveness over the tested binder contents. It could potentially economical for lower and intermediate binder content mixtures.

- It has the ability to enhance the cohesiveness of the mixtures, however, if too much of water reducing capacity of this admixture is utilized, it tends to leave the fresh concrete with rock pockets. With increasing dosage and hence water reduction, the cohesiveness remains more or less the same and after a certain point it starts dropping down. This could potentially happen due to the presence of the lingo-based component.
- The workability also shows a drop after a certain dosage.
- The binding efficiency is observed to increase up to a certain dosage and then starts showing a decreasing trend. The reason for this is similar to that offered for P-05 product. However, the efficiency is relatively lesser than P-05.
- As far as retention of compactibility is concerned, this admixture offers better than P-05 performance.
- The finishibility is not very much improved, even at higher dosages.
- Due to the presence of lingo-based component in the admixture, the effect of air entrainment at higher dosages could not be neglected. However, this cannot be stated with confidence due to lack of supporting data.
- This admixture does not provide rapid early age strength gain however, the later age strengths are higher than the control mixture. The gain in strength is comparatively lower than the PC-based product.

LIGNO BASED WATER REDUCER [PRODUCT P-10]

Study matrix

A detailed investigation was undertaken to compare the tested PC-based with a purified ligno-based water reducer. The selected ligno-based water reducer was claimed by the manufacturer to behave as type A, B, D and F and for extended applications as type G admixture. Table 8-6 revisits the dosage comparison.

Table 8-6 PC-, Ligno-based admixture dosage comparison

Product chem.	A/B	Dosages in %, w/w of binder														
		4				7							10			
	Prod.	1	2	3	4	1	2	3	4	5	6	7	1	2	3	4
PC-	P-05	0.00	0.25	1.50	3.00	0.00	0.19	0.56	1.13	1.69	2.25	3.00	0.00	0.25	1.50	3.00
Ligno-	P-10	0.00	0.25	1.50	3.00	0.00	0.25	0.75	--	1.50	2.25	3.00	0.00	0.25	1.50	3.00
Remarks						Detailed investigations										

Composite plots

Figure 8-14 shows the relative properties for this admixture at various dosages. Although relatively lesser, the strength behavior is similar to the PC based product, with the point of maximum increase reached at 2.25% dosage. The water reduction ranged between 0-20% with relative lesser water reduction than the PC-based and Ligno-PC based products. Initially, the relative cohesion remains similar to control mixture but with increasing water reduction shows a gradual reduction. Similar trend is observed for work index, which shows a gently reducing trend. This admixture shows excellent retention of compactibility as can be seen from the relative trends in compactibilities at 60 and 120 min. The retention is comparable to Ligno-PC based product. The strength increase is relatively smaller than the corresponding dosages for the PC-based and Ligno-PC based products. A caution to be exercised with ligno-based product is to check the finishibility of concrete, which may be relatively poor.

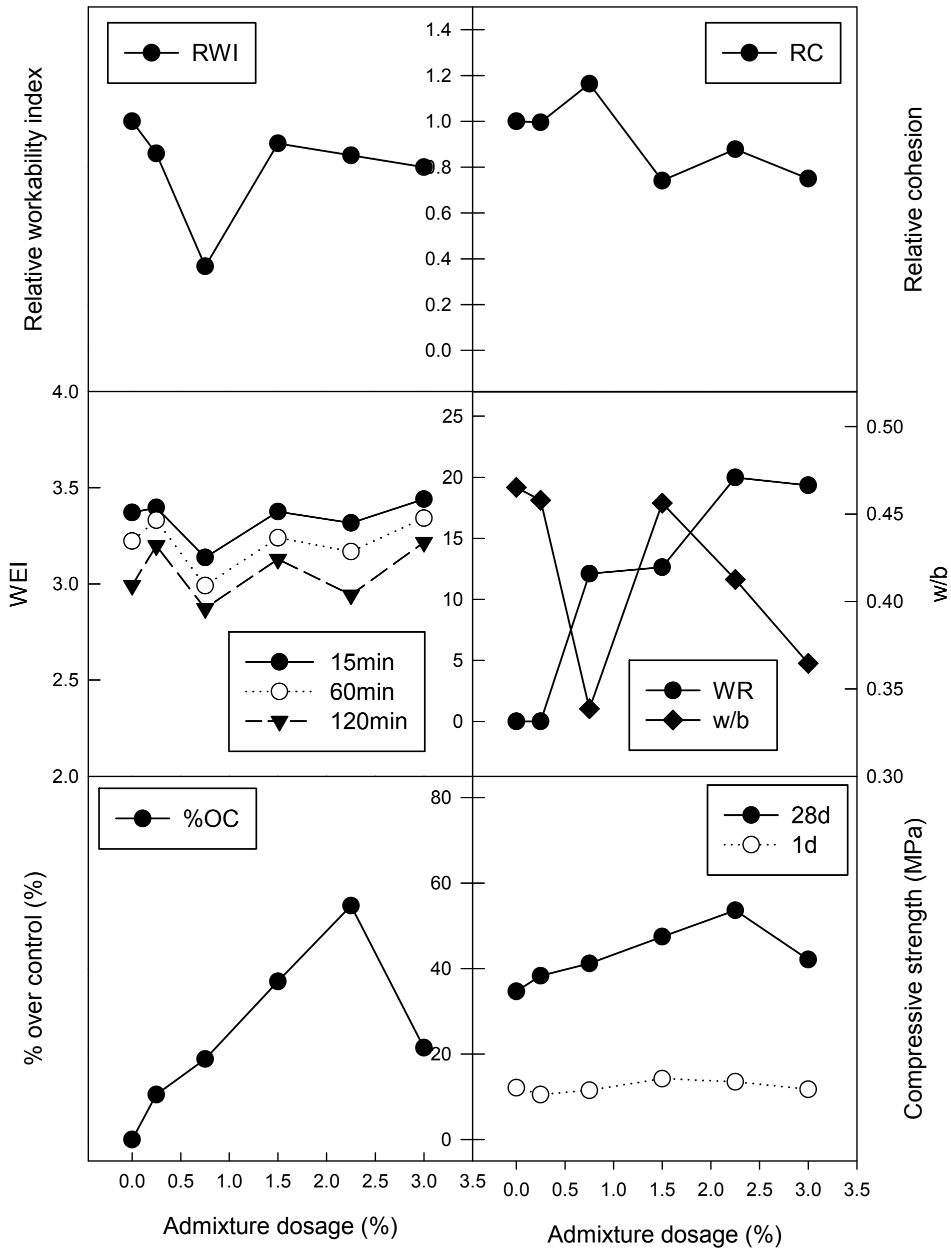


Figure 8-14 Relative properties of P-10 admixed concrete

Sample comparison

The time evolution as modeled using above mentioned equation is compared for the two admixtures in Figure 8-15. It can be seen that for similar w/b ratio, the PC based admixture is potent of producing higher ultimate strength as shown by the coefficient a. On the other hand, lower b values for ligno-based admixture; indicate that the rate of strength development for this admixture is comparatively lower than the corresponding PC-based admixture dosage.

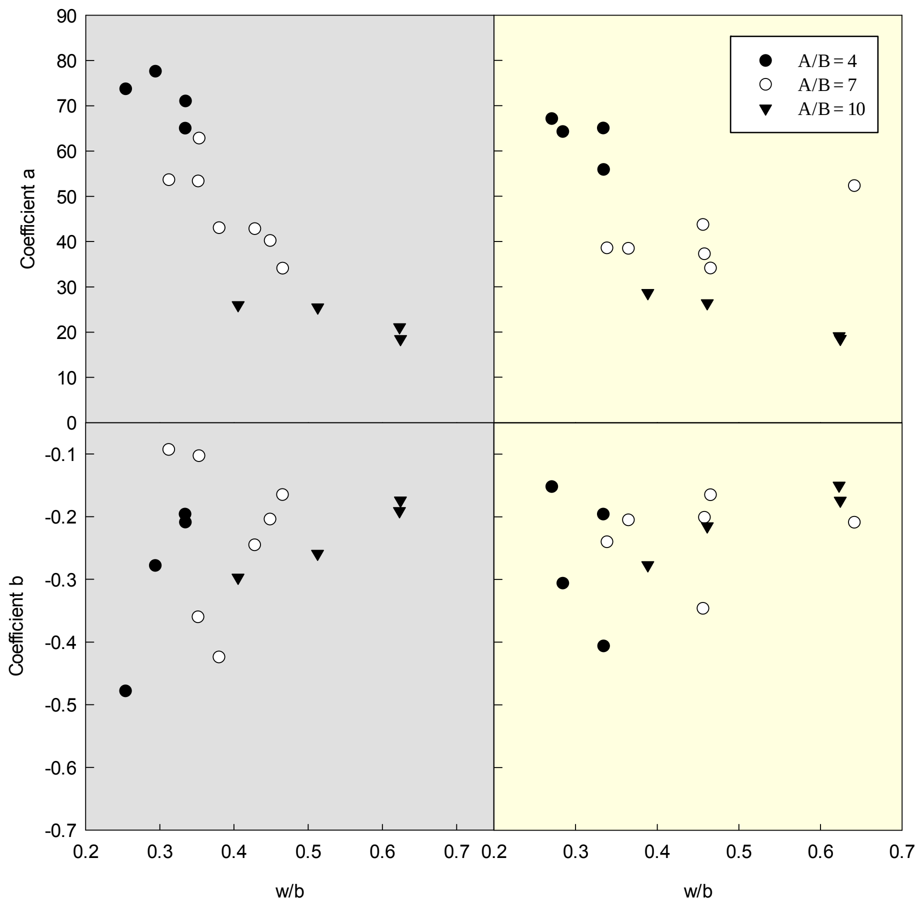


Figure 8-15 Strength development coefficients: Effects of different admixtures. Gray: PC, Yellow: Ligno

Relevant observations

The following is a sampling of the salient observations:

► This admixture relatively better effectiveness towards the lower binder contents. Higher binder contents are susceptible to delayed setting, which if balanced with sufficient water reduction and proper finishibility could potential lead to balancing of the effectiveness.

- This admixture enhances cohesiveness of lower binder content mixtures better than higher binder content mixtures. The cohesiveness however shows a dropping trend with increasing dosage (and hence water reduction).
- The workability also shows a drop after a certain dosage. However increased compaction load could potentially improve this behavior.
- The binding efficiency is observed to increase up to a certain dosage and then starts showing a decreasing trend.
- As far as retention of compactibility is concerned, this admixture offers excellent performance.
- The finishibility however reduces even at lower dosages. This could potentially lead to rock-pocketing and improperly finished surfaces.
- Due to the presence of lingo-based component in the admixture, the effect of air entrainment at higher dosages could not be neglected. However, this cannot be stated with confidence due to lack of supporting data. This effect could be much less than the routine lingo-based products because this is a purified ligno.
- This admixture delays early age strength gain however, the later age strengths are higher than the control mixture. On the basis of the reported results, it could be said that the water reduction is appropriately balanced with setting behavior. This is so because the one day strength is not reduced substantial with increasing dosage. The gain in strength is comparatively lower than the PC-based product.

RETARDING WATER REDUCER [PRODUCT P-11]

This is a type A, B, D admixture for normal concretes. The manufacturer recommended dosage is in the range of 0.130 to 0.399 lit/100kg of cement for normal concretes. Table 8-7 presents the experimental plan. The dosages were fixed at 0.25 (0.25 lit/100kg of cement), 1.00 and 2.00% (2.00 lit/100 kg) w/w of binder for all the binder contents. The corresponding water reduction, fresh properties and strength development were evaluated.

Table 8-7 Experimental plan for a water-reducing cum retarding admixture: Type A, B, D (P-11)

Binder content (kg/m^3)	A/B	Dosage (%, w/w of binder)		
		1	2	3
205	4	0.25	1.00	1.50
282	7	0.19	0.75	1.50
446	10	0.25	1.00	1.50

Composite plots

The dosage of this retarding admixture was restricted to 1.5% maximum. Trials at higher than this dosage lead to failures and hence these results are not reported. Figure 8-16shows the relative properties for this admixture at various dosages. At lower dosage, the strength showed a slight reduction, this might be due to the use of that dosage (@ 0.19%) without any water reduction. Strength increase is relatively poor at early ages and some of these mixtures showed lower than the control concrete strength. This may be due to the presence of ligno-based component, which has a retarding tendency. The water reduction ranged between 0-14%. The relative cohesion remains similar to control mixture with increasing water reduction. Relative work index however shows a decreasing trend initially and then shows an increase. This admixture shows better than P-05 and P-06 retention of compactibility as can be seen from the relative trends in compactibilities at 60 and 120 min.

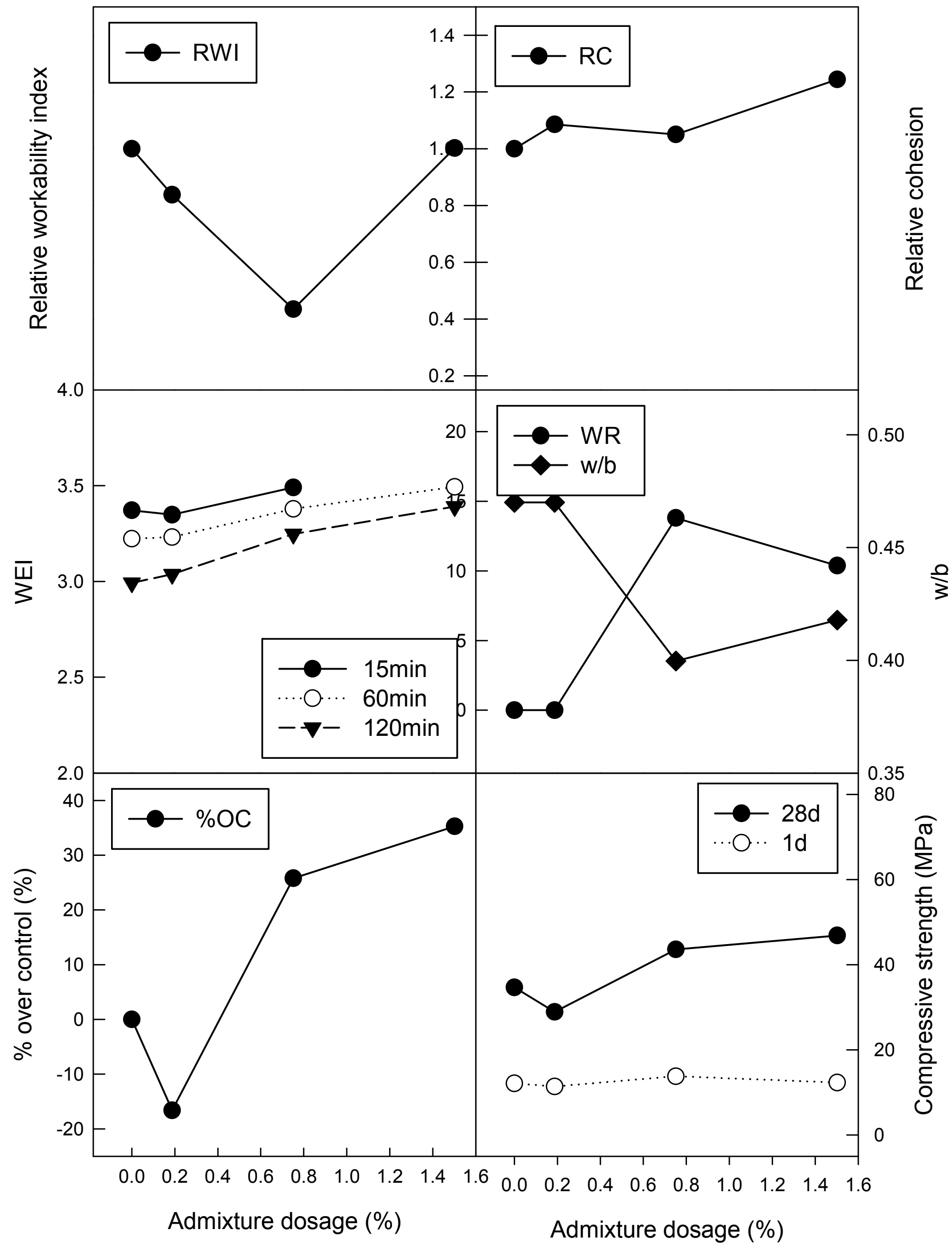


Figure 8-16 Relative properties of P-11 admixed concrete mixtures

Relevant observations

The following is a sampling of the salient observations:

- This admixture is relatively more balanced in its effectiveness over the tested binder contents, however, it could potentially retard the setting in higher binder content mixtures. Hence higher dosages should be categorically avoided.
- It has the ability to enhance the cohesiveness of the mixtures. This is demonstrated by the fact that even with increasing admixture dosages (and hence water reduction) the relative cohesion remains more or less constant.
- It is however interesting to see that the workability index however shows a reduction with increasing dosage. The reason for this is not clear.
- The binding efficiency is observed to increase up to a certain dosage and then starts showing a decreasing trend.
- As far as retention of compactibility is concerned, this admixture offers excellent performance.
- The finishibility is slightly improved for all dosages as compared to the control mixtures.
- No comments about the air entraining behavior can be offered.
- This admixture delays early age strength gain and offers a small strength gain at higher dosages vis-à-vis to the corresponding water reduction.

RETARDING ADMIXTURE [PRODUCT P-13]

Study matrix

Admixture meeting ASTM C494 requirements for Type B (retarding) admixture (P-13) was used in assessing its effectiveness in different RCC mixtures. The manufacturer recommended dosage is in the range of 0.130 to 0.266 l/100 kg of cement for normal and mass concretes. This admixture is a strong retarder and is expected to delay the setting times, reduce w/b ratio and improve the density of the mixtures. Table 8-8 presents the experimental plan. The dosages were fixed at 0.20 (0.2 l/100 kg), 0.60 and 1.20% (1.2 l/100 kg) w/w of binder for all the binder contents. The corresponding water reduction, fresh properties and strength development were evaluated.

Table 8-8 Experimental plan for a retarding admixture: Type B (P-13)

Binder content (kg/m^3)	A/B	Dosage (%, w/w of binder)		
		1	2	3
205	4	0.20	0.60	1.20
282	7	0.20	0.60	1.20
446	10	0.20	0.60	1.20

Composite plots

This is primarily a retarder and hence the dosage of admixture was restricted to 1.2% maximum. Figure 8-17 shows the relative properties for this admixture at various dosages. There is in fact no relative strength gain at early ages; however, the strength picks up at the latter ages. This may be due to the presence of strong retarding component present in the admixture. The water reduction ranged between 0-18%. The relative cohesion shows a slightly decreasing trend. Relative work index however shows a continuously decreasing trend. This admixture shows the best retardation, which can be observed from the compactibility trends.

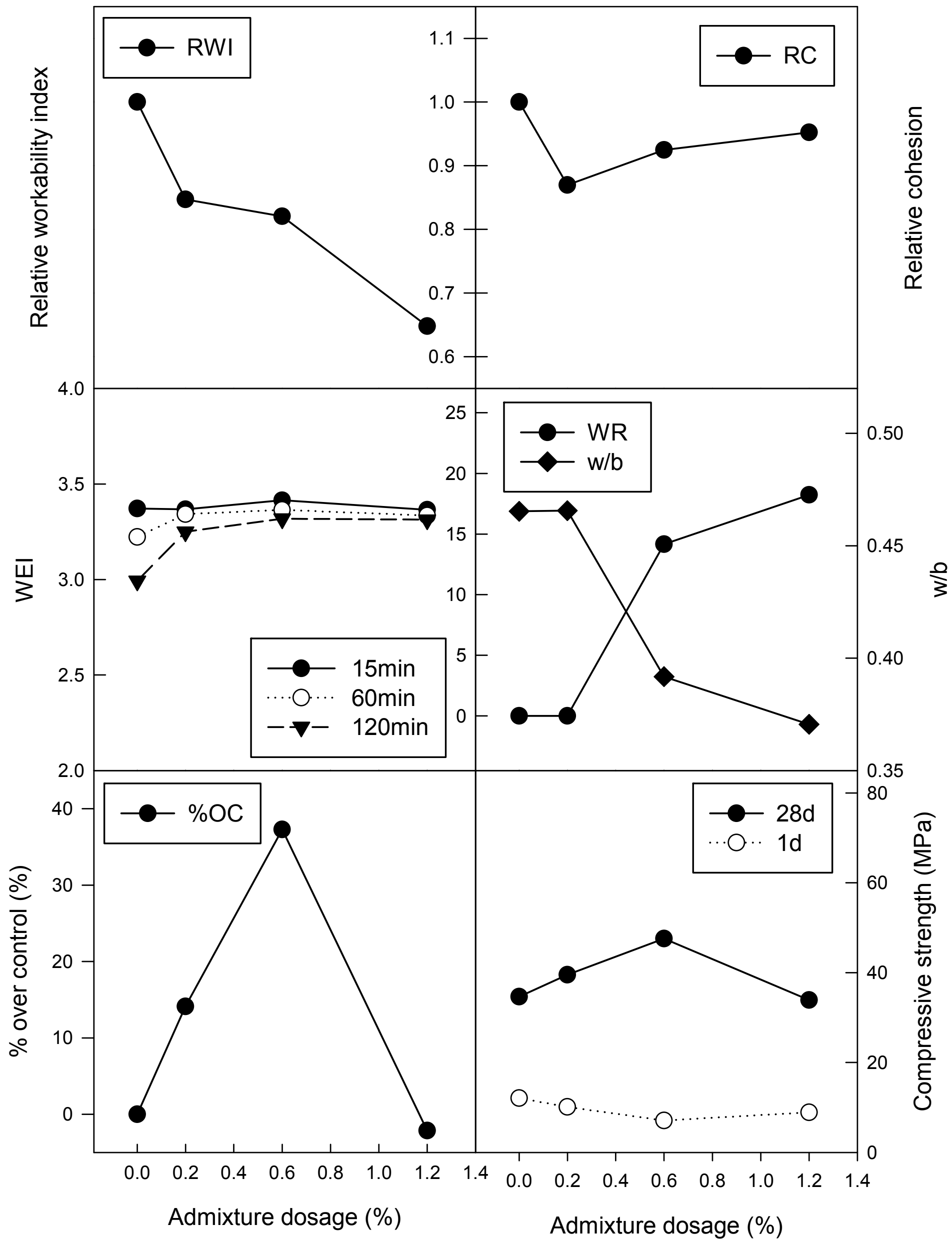


Figure 8-17 Relative properties of P-13 admixed concrete mixtures

Sample report

This admixture offers a strong retardation and reduction in the strength. It is relatively more sensitive to higher binder content mixtures and at higher dosages. It possibly leads to strength increase due to the combined effect of improved density and water reduction effects for the intermediate binder contents. Refer to Figure 8-18 for comparative details.

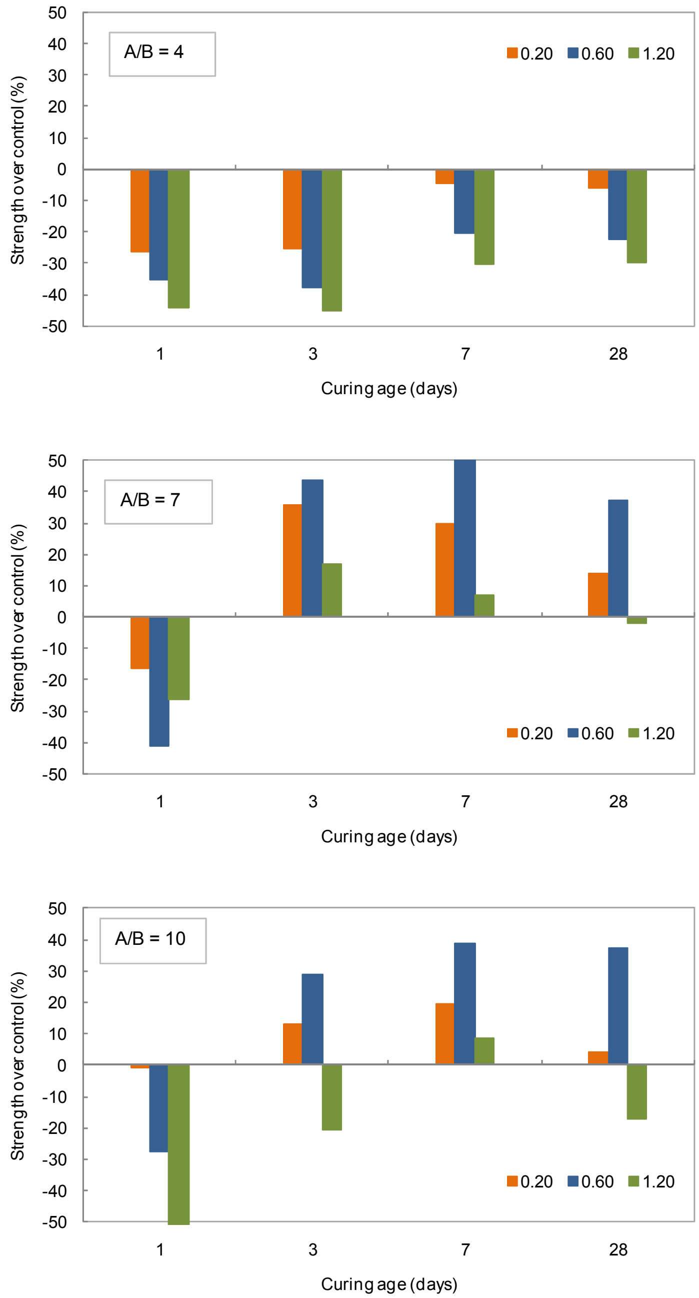


Figure 8-18 Relative strength with P-13 (Type B) admixture

Relevant observations

The following observations are relevant for this admixture:

- This admixture is sensitive to the binder content in a mixture. As the binder content increases, this admixture becomes highly sensitive to minor changes in the dosages. It is more robust at the leaner end of binder content.
- The improvement in cohesiveness is not distinct and in fact the cohesiveness goes down with increasing water reduction.
- Similarly, the workability index also goes down following steepest of the slopes amongst the water reducers and retarders. The exact cause of this could is unclear.
- The binding efficiency is observed to increase up to a certain dosage and then starts showing a dramatically decreasing trend.
- As far as retention of compactibility is concerned, this admixture offers excellent performance for the first two hours.
- The finishibility is slightly improved for all dosages as compared to the control mixtures.
- Being a retarder, this admixture delays early age strength gain and offers a small strength gain at higher dosages vis-à-vis to the corresponding water reduction.

8.2.3 Primarily air entraining admixtures

STUDY MATRIX

This section reports results for three types of air entraining admixture chemistries. Initially a range of admixture dosages was run over the intermediate binder content to screen the best admixture for a detailed investigation. The detailed investigation was carried out over all the binder contents to see the effects of binder contents and also the interaction effects. The objective of this part of the work was twofold (Table 8-9):

- To find the best admixture chemistry from strength perspective and
- On the selected chemistry, the effect of binder content was to be studied

Table 8-9 Experiments on AEA's. SD: synthetic detergent, WH: water soluble hydrocarbon, MR: modified resin

A/B	SD (P-19)				WH (P-20)			MR (P-21)		
	1	2	3	4	1	2	3	1	2	3
4	0.10	0.35	0.70	--	--	--	--	--	--	--
7	0.076	0.188	0.376	0.700	0.150	0.300	0.750	0.076	0.188	0.376
10	0.10	0.35	0.70	--	--	--	--	--	--	--

COMPARATIVE EFFECTS OF AEA CHEMISTRY

Figure 8-19 demonstrates three important properties in summary as a function of AEA dosage and chemistry. The following inferences are important:

- The maximum dosages used for SD, WH and MR were approximately 15, 8 and 3 times the average recommended dosages, respectively. In general, with the increase in the dosage of the admixture the strength increases, reaching a maximum and then starts to reduce. Since the initial consistency was kept constant, the explanation of this phenomenon is two-fold. It is known that in drier concretes, the compaction response of a mixture improves with the presence of entrained air [5]. Better compaction leads to reduction in the entrapped air voids with a corresponding improvement in the density and an increase in the mechanical strength. As the dosage is further increased, this effect is reduced while the presence of a network of entrained air bubbles resulting in the increase in the volume of air starts to be manifested. The effect thus produced supersedes the water reduction effect, resulting in a decrease in the strength.
- For a fixed dosage, SD based AEA seems to entrain the highest air followed by MR and WH. The flattening effect with increasing dosage could not be captured with the used dosage ranges.
- Quite interestingly, the effect of SD based AEA is to yield higher content and strength compared to other AEA's. The mixtures produced using this AEA are less robust when compared to the mixtures with WH or MR. It is also important to recognize that the initial consistencies of these mixtures were kept constant, while observing the water reduction. As such, the mutually competing effects of w/b ratio and air content as discussed above cannot be fully appreciated. Another caveat to this is the mixtures have different air contents, thus qualitatively

representing a different internal structure. The optimal dosage at which the highest strength is obtained is a function of admixture chemistry.

- ► The SD based AEA offers greater air entrainment and also dramatically improves the finishibility of concrete.

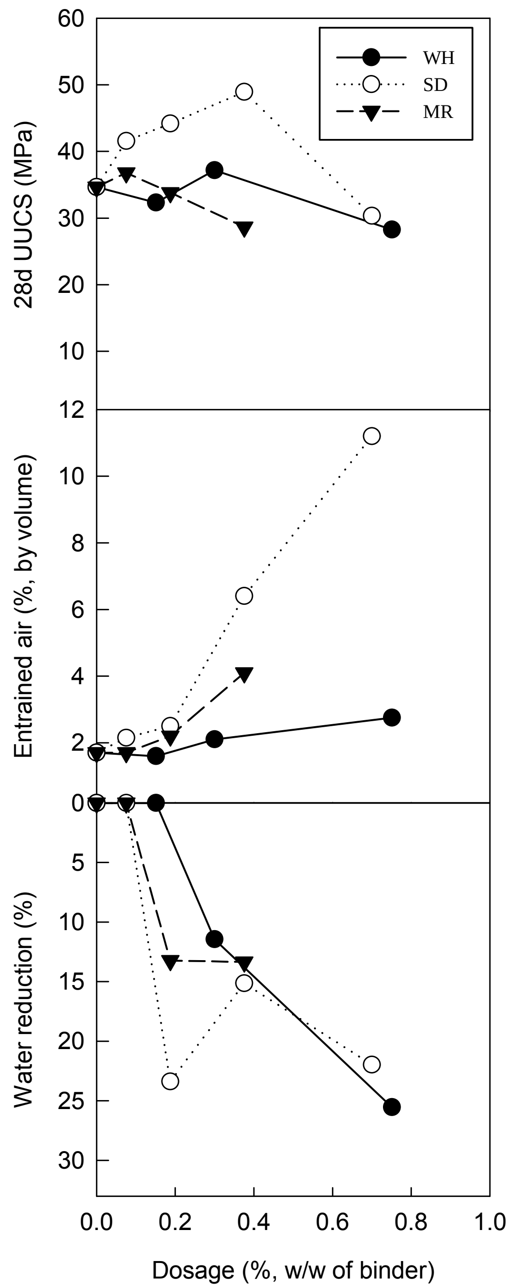


Figure 8-19 Effect of AEA chemistry

COMPOSITE PLOTS FOR SD BASED AEA [PRODUCT P-19]

Figure 8-20 shows the relative properties for this admixture at various dosages. The dosage ranged between 0 and 0.7%. The corresponding water reduction ranged between 0 and 23%. The relative cohesion shows an initial increase followed by a decreasing trend, while the work index shows a continually decreasing trend. It is possible to entrain substantial amount of air (up to 11%) using this type of AEA. As was expected, due to lack of a retarding component in this admixture, there was no retention of compactibility over the first two hours. It is interesting to note that it was difficult to determine the initial compactibility due to oozing out of water from the compacted sample under pressure. Initially the strength increases, reaches a peak and then decreases. The increase in strength is primarily due to water reduction.

Relevant observations

The following inferences are relevant vis-à-vis the binder and admixture contents and the interaction effects in relation to the measured properties:

- This admixture increases in its effectiveness as the paste content of the mixture increases. At lower binder content end, this admixture helps improve the strength of concrete while at the higher binder content end it makes the mixture highly sensitive to the dosage of admixture.
- In general the cohesiveness of the mixtures is much improved initially but is instantaneously lost as the admixture has no retention ability. The improvement in cohesiveness is much more at the lower binder content range. However, the mixture might tend to segregate at higher binder content due to rapid loss of cohesiveness.
- Similarly, the WEI is affected.
- The binding efficiency is observed to increase up to a certain dosage and then starts showing a decreasing trend.
- As far as retention of compactibility is concerned, this admixture does not at all offer retention over a period of time.
- This admixture is effective in improving the finishibility of RCC mixtures for the tested binder content range and especially at lower binder content. If aided with a

retarder, it could possible show an improved performance in terms of overall performance.

- The strength gain is a composite action of water reduction and air entrainment as explained before. This has been cover in the earlier section, where Faret's relationship was discussed and the data was presented in relevant manner.

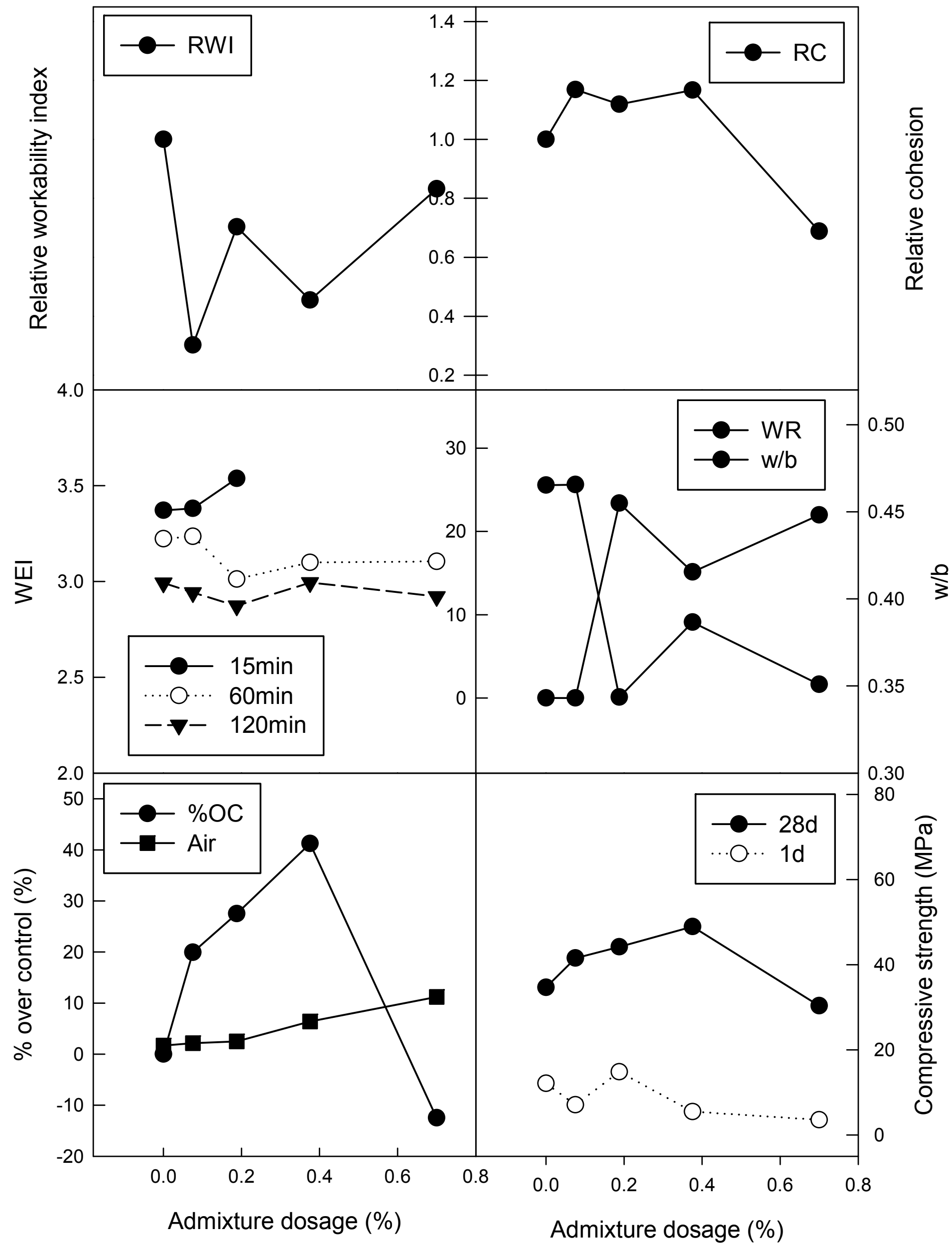


Figure 8-20 Relative properties of P-19 admixed concrete mixtures

COMPOSITE PLOTS FOR WH BASED AEA [PRODUCT P-20] AND MR BASED AEA [PRODUCT P-21]

Product P-20 is a water-soluble hydrocarbon based product while P-21 is a modified resin. The relative properties are shown in Figure 8-21 and Figure 8-22. The compactibility properties were not obtained because the AEA's do not have any retarding component at the dosage ranges tested. An important thing to note is that the synthetic detergent based AEA is most effective in entraining air in fresh RCC.

Relevant observations

- WH-based AEA has a better water reducing potential than the MR-based AEA.
- WH- and MR-based tend to reduce the cohesion of the mixtures vis-à-vis the water reduction.
- The workability index also appears to reduce with increasing water reduction (and hence dosage).
- These admixtures cannot be used for retention for workability. However, overdosing (> 0.2% solids content/weight of binder) of these admixtures could potentially lead to retardation of mixtures [6].
- Both these chemistries can potentially entrain air in RCC, however they are more robust as compared to the SD-based AEA.
- In terms of UUCS, the WH-based AEA is more robust, while the MR appears to affect the strength with higher sensitivity.

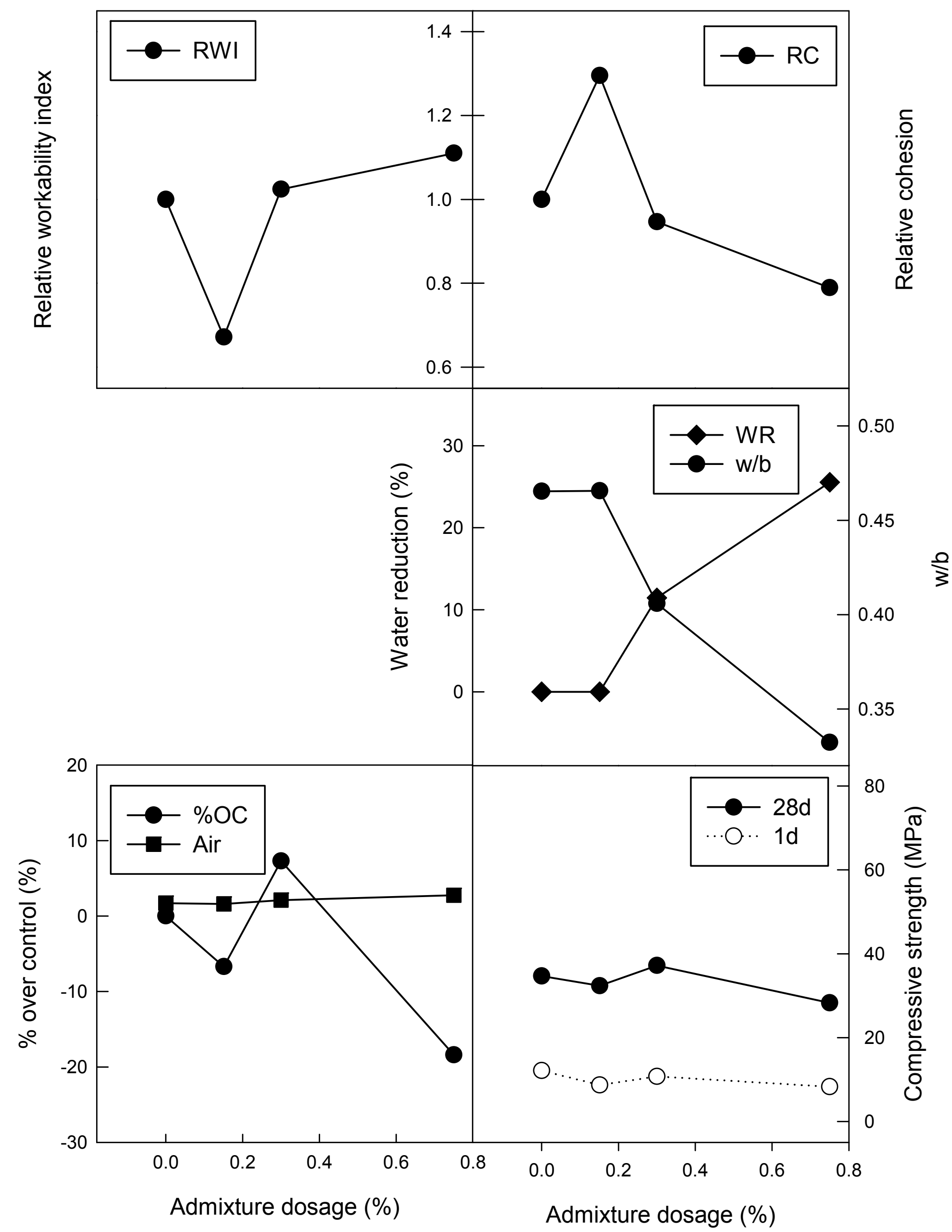


Figure 8-21 Relative properties of P-20 admixed concrete mixtures

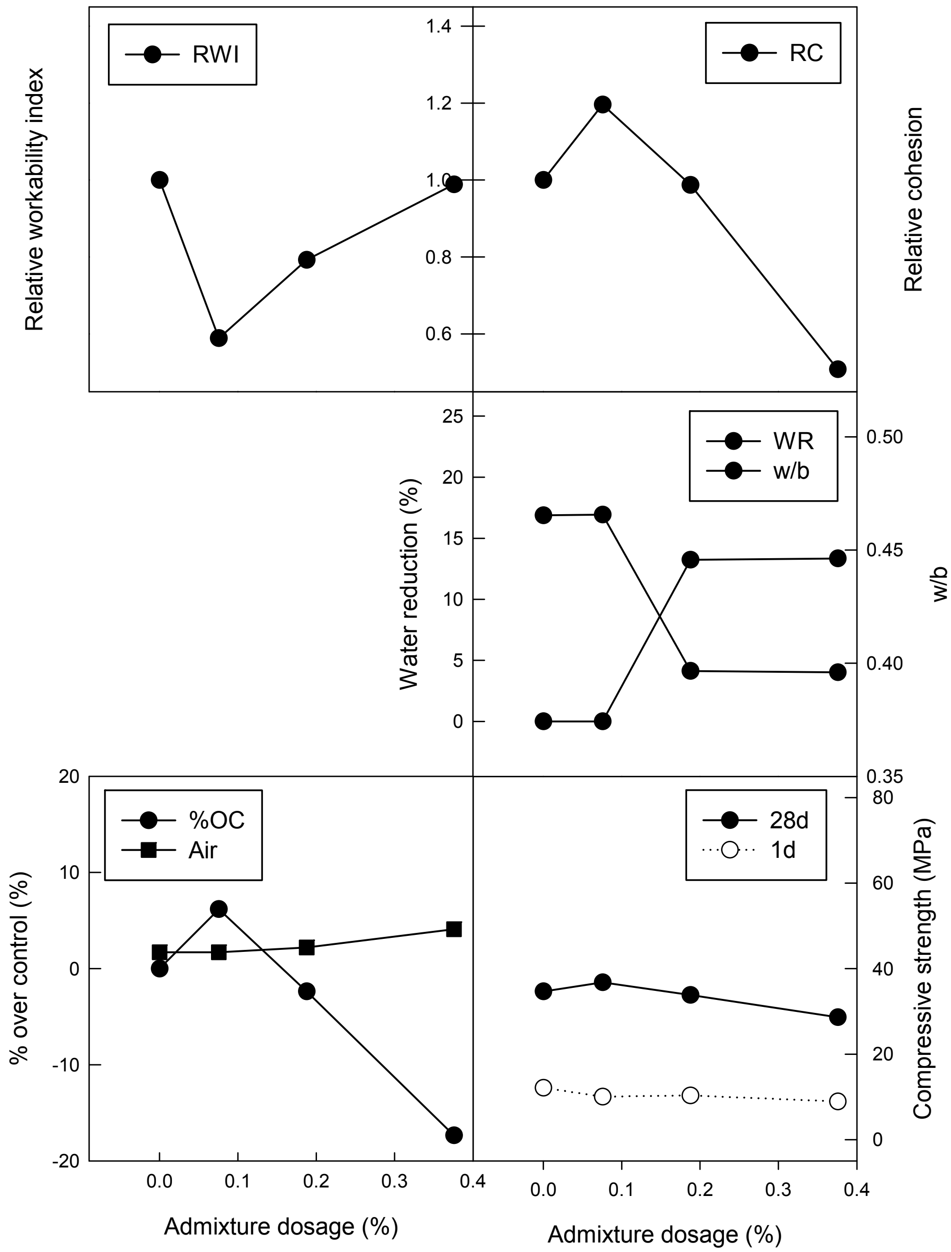


Figure 8-22 Relative properties of P-21 admixed concrete mixtures

8.2.4 Dry cast admixtures

The DC products were tested because they are used in drier concretes and it was anticipated that the properties of RCC could similarly be influenced. Results from two types of DC products viz. surfactant based (P-28) and a polycarboxylate based (P-29) are reported here. The surfactant based DC admixture is quite similar to the AEA. The PC based product is fine tuned for DC applications.

SURFACTANT BASED DC PRODUCT [PRODUCT P-28]

Study matrix

This being a surfactant based admixture, the dosage was restricted to 1.5% w/w of binder. The manufacturer recommended dosage is in the range of 0.19 – 0.391 l/100 kg of cement. The tested dosage ranged between 0.25 – 1.5% (or 0.25 – 1.5 l/100 kg). at the leaner and richer end of the binder contents, only two dosages each were tested, while three dosages were tested for the intermediate binder content. Table 8-10 shows the test matrix.

Table 8-10 Experimental plan for surfactant based DC admixture [P-28]

Binder content	A/B	Dosage (%, w/w of binder)		
(kg/m^3)		1	2	3
205	4	0.50	1.50	--
282	7	0.25	0.75	1.50
446	10	0.50	1.50	--

Composite plots

Refer to Figure 8-23 for trends. The corresponding water reductions ranged between 0-21%. Quite similar to SD-based AEA, the surface finish can significantly be improved with the use of this admixture. The relative cohesion improves slightly over control and remains more of less same, while the work index decreased slightly over the tested dosage range. The retention of workability was rather poor. The initial strength did not improve much, while the later strength showed small increase.

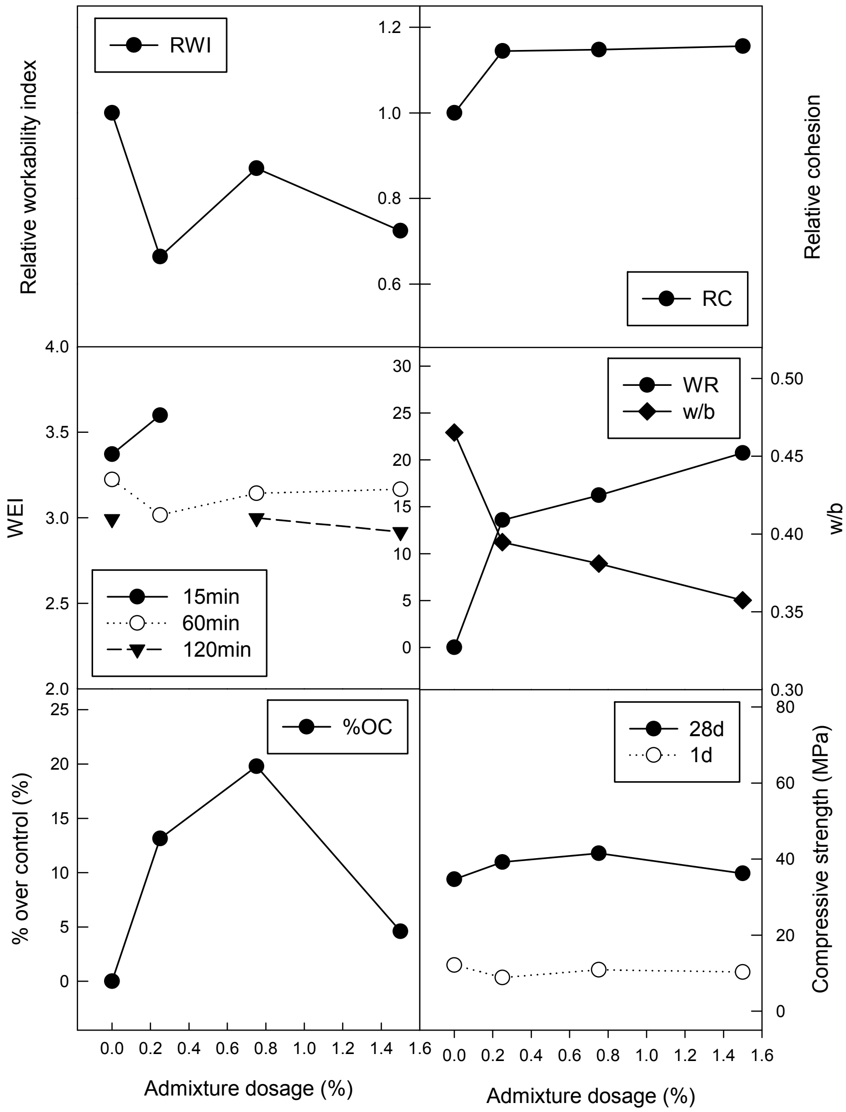


Figure 8-23 Relative properties of P-28 admixed concrete mixtures

Relevant observations

The following observations are relevant:

- ► This admixture showed similar water reduction over all the binder contents. Hence, it could be inferred on the basis of the test matrix that the optimization effects could not be captured.
- ► The cohesiveness of the mixture improves slightly and the improvement is a real improvement in cohesiveness without making the mixture sticky. The improve-

ment at the lower binder content end is much higher than the higher binder content end.

- The workability shows a continuous drop with increasing dosage of admixture
- This admixture cannot be employed for retention, since the alterations in the properties of fresh concretes are transitory.
- The finishibility could invariably be improved.
- The strength of admixed concretes becomes more sensitivity as the dosage and binder content increases. The gain in strength is not commensurate to the water reduction, hence the possibility of air entrainment cannot be denied. It is however not possible to comment further on this because the air content was not measured.

PRODUCT P-29: PC BASED DC PRODUCT

Study matrix

The manufacturer recommended dosage is in the range of 0.19 – 0.391 l/100 kg of cement. The tested dosage ranged between 0.25 – 1.5% (or 0.25 – 1.5 l/100 kg). at the leaner and richer end of the binder contents, only two dosages each were tested, while three dosages were tested for the intermediate binder content. Table 8-11 shows the test matrix.

Table 8-11 Experimental plan for surfactant based DC admixture [P-28]

Binder content (kg/m^3)	A/B	Dosage (%, w/w of binder)		
		1	2	3
205	4	0.50	1.50	--
282	7	0.25	0.75	1.50
446	10	0.50	1.50	--

Composite plots

Refer to Figure 8-24 for trends. This is a PC based DC product tested over a dosage range of 0-2%. The corresponding water reductions ranged between 0-34%. The relative cohesion improves slightly over control and shows a decreasing trend subsequently;

while the work index decreases with increasing dosage. The retention of workability was rather poor. The strength in general showed a decreasing trend in general.

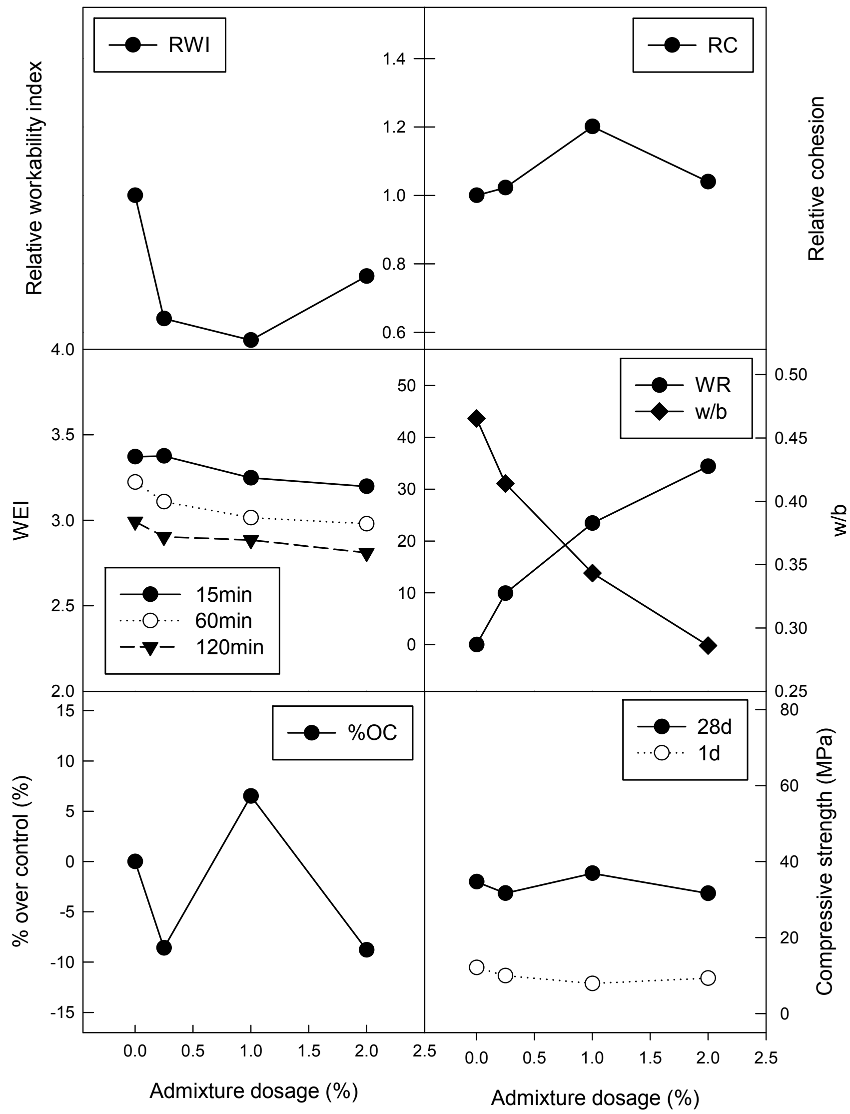


Figure 8-24 Relative properties of P-29 admixed concrete mixtures

8.2.5 Rheology modifiers

Two rheology modifiers were tested in detail for the modifications in the fresh properties of concrete. These were the starch based rheology modifier (P-24) that was claimed to primarily affect the yield value of concrete and the welan-gum based rheology modifier (P-25), which was claimed to primarily affect the viscosity of the concrete. The manufacturer recommended dosages for P-24 and P-25 are 0.5 to 2.3 lit/100kg and 0.039 to 0.46 lit/100kg of cement. Table 8-12 summarizes the test matrix.

Table 8-12 Test matrix for rheology modifiers

A/B	Starch based (P-24)			Welan gum based (P-25)		
	1	2	3	1	2	3
4	0.25	1.00	--	0.4	1.2	--
7	0.19	0.38	0.75	0.3	0.6	0.9
10	0.25	1.00	--	0.4	1.2	--

No water reduction was observed for the rheology modifiers. In fact, the water demand of the mixtures incorporating the rheology modifiers increased and was subjectively observed in the fresh concrete mixtures by their increasing tendency of segregating as the dosage increased. This tendency was higher in the starch based product than in the welan-gum based product. This may perhaps be due to better enhancement of viscosity of paste with one rheology modifier than the other.

Figure 8-25 shows the 28-day strengths of products P-24 and P-25 admixed concrete mixtures at different dosages and for different binder contents. The strength development starting from one-day strength was not affected by the presence of these admixtures in concrete mixtures. Although the effect of product P-25 on strength is relatively lesser, this may or may not be statistically significant.

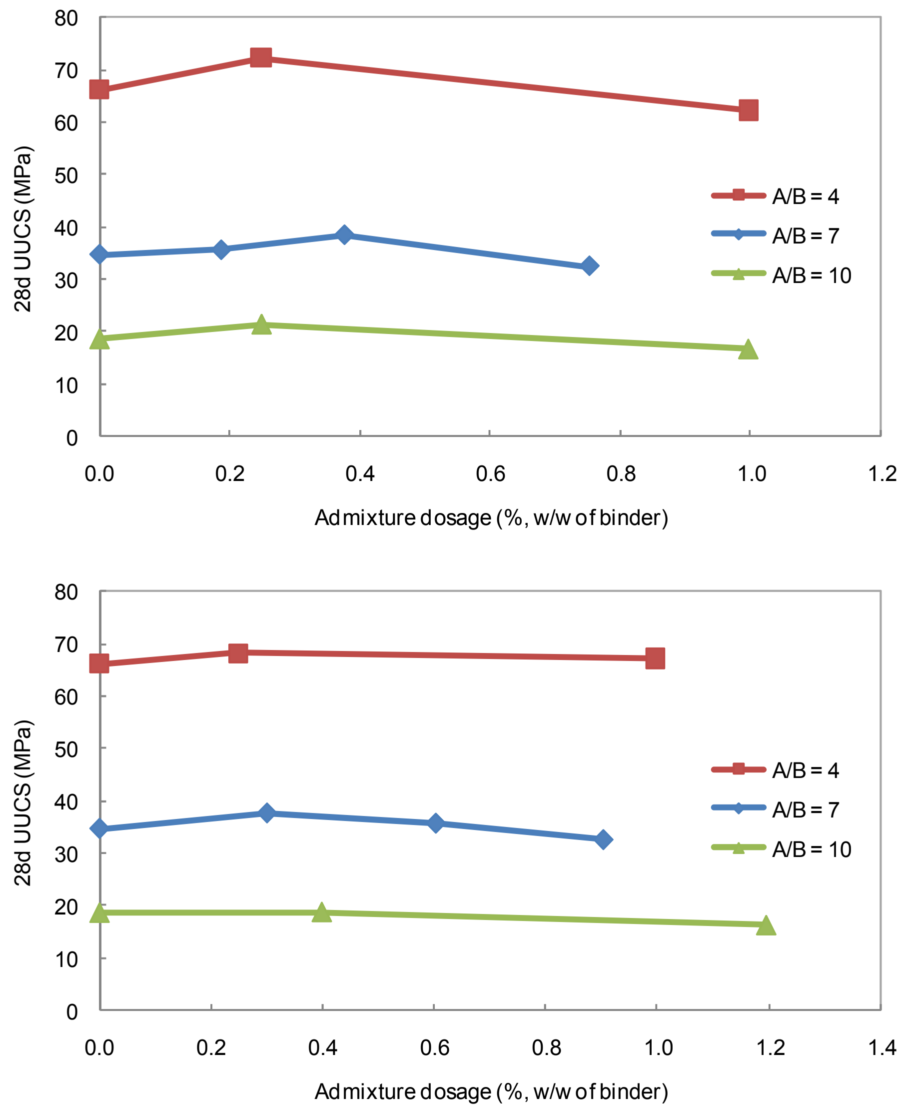


Figure 8-25 Effects of RM dosages on the 28-day strength for various A/B ratios. Top: P-24, Bottom: P-25

8.3 Composite effects of binary admixture combinations

Admixture duets were primarily formulated with an objective of using two admixtures in a complementary way. This means the strength of one admixture is used to overcome the weakness of the other. For example a surfactant based product leads to a better *swipe* or finish with decent water reduction as required in dry cast products. At the same time, and per the on-site requirements, the consistency retention of this admixture is relatively poor. This can be overcome by using a retarder to hold the consistency constant when using the earlier product to overcome the workability loss problem and at the same time improvising the finishibility of the later admixture, when used in combination.

All the admixture duets (five total) were tested on mixtures with A/B = 7 i.e. the intermediate binder content, since this binder content is the closest to the typical pavement mixtures. Since the admixtures could act in different ways at different binder levels, any generalizations or extrapolations of the results to both ends (i.e. A/B of 4 and 10) are not possible.

Example: Ligno-based water reducer and SD based AEA

This admixture combination was used with two objectives as follows:

- To overcome the lack of good finishibility obtained by using the Ligno-based water reducer by extracting the benefit from the SD-based AEA and
- To overcome the lack of consistence retention by using the SD-based AEA alone by extracting the benefit of hydration retardation from the Ligno-based product.

A caution that can be anticipated with the use of such a combination is the air entrainment. Ligno-based products are known for entraining air in concrete and when added with a strong AEA could lead to enhanced air entrainment. Although this may perhaps work in favor of the fresh RCC, but could potential influence the strength in a negative way. The % admixture and their % in total compositions are reported in Table 8-13.

Table 8-13 Admixture compositions for Ligno-based water reducer and SD based AEA duet.

Total dosage		Dosage-1: @ 0.75%, w/w of binder					Dosage-2: @ 2.00%, w/w of binder			
Composition		1	2	3	4	5	1	2	3	4
WR (%)	P-05	0.750	0.562	0.375	0.188	0.000	2.000	1.750	1.000	0.000
AEA (%)	P-19	0.000	0.188	0.375	0.562	0.750	0.000	0.250	1.000	2.000
WR (%)	P-05	100.0	75.0	50.0	25.0	0.0	100.0	87.5	50.0	0.0
AEA (%)	P-19	0.0	25.0	50.0	75.0	100.0	0.0	12.5	50.0	100.0

Note: The last two rows are the % compositions in the total admixtures

Figure 8-26 shows the water reductions by various admixture compositions and at two different dosage levels. It can be seen that the water reduction is highest with the SD-AEA is used alone at a both the combined dosage levels. As the contribution from the AEA increases, the water reducing capacity of the newer compositions increases gradually, pretty much following similar slope at both the dosage levels. At intermediate and combined dosages, the blend produces water reductions between those produced by the WR and AEA.

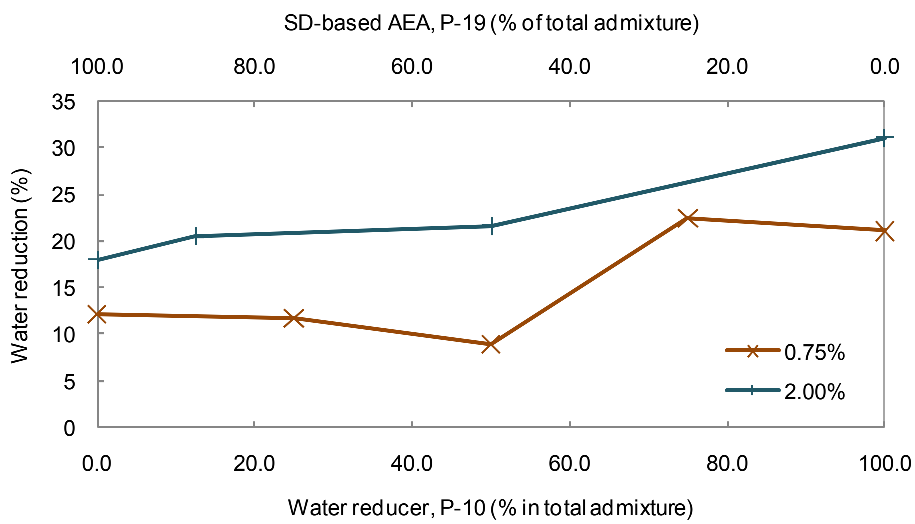


Figure 8-26 Water reduction of the admixture duet: Ligno-based water reducer and SD-based AEA. Total admixture dosage is in percentage, w/w of binder

Figure 8-27 represents the 28-day compressive strength results. It can be seen that the combined dosage does not make a difference in the 28-day compressive strength. The results show a comparable trend as the composition is varied at two different dosages.

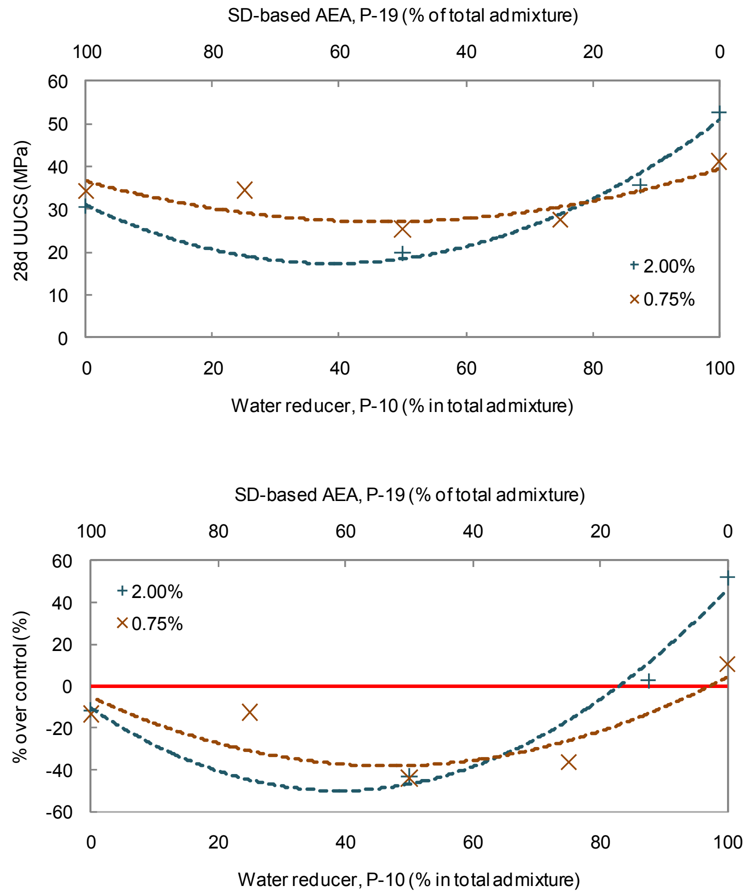


Figure 8-27 28d UUCS of the admixture duet: Ligno-based water reducer and SD-based AEA. Total admixture dosage is in percentage, w/w of binder

Compared with the control mixture, the use of this combination of admixture did not produce any increase and in-fact the strength reduced, except when only water reducer used. The possible reasons of such a manifestation could be the use of a combination of admixtures that have the potential to entrain air. As discussed previously the lingo-based admixtures, although highly refined have a tendency to increase entrained air volume. At lower dosage, the air is entrained only from the AEA. On the other hand, at higher dosages, the air is entrained by both the lingo-based water reducer and the AEA. The effect of increased air entrainment masks the effect of water reduction. The percussions of this could be seen in the fact that the Abrams' law is not followed. This could also mean the increased dispersion is superseded by the increased porosity of the concrete mixture.

8.4 Composite effects of ternary admixture combinations

8.4.1 Background

Admixture triplets were primarily formulated to assess if there are any incremental advantages in using rheology modifiers in RCC mixtures. The benefits would primarily be seen in the terms of fresh properties and it was anticipated that the compressive strength will not be much affected by using the triple blends.

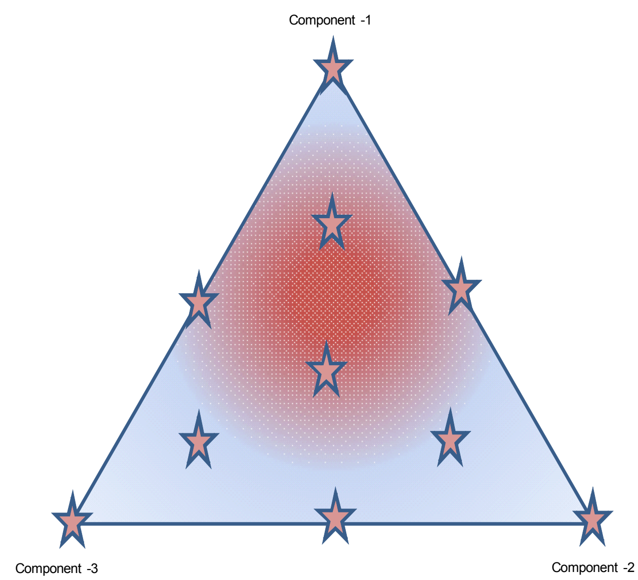


Figure 8-28 Response surface generated by simplex-centroid design augmented by three interior points. Stars represented the point at which the composition is tested for the required property

The *method of mixtures* was used for generating the experimental matrix. The model used was ABCD, generated by JMP; this makes use of ten points on the ternary plot. This design is called as a simplex-centroid design augmented with three interior points. Refer to Figure 8-28. It is said that a good design of mixture experiment should be able to

- generate a satisfactory distribution of information throughout the experimental region (the triangle);
- ensure that the fitted model predicts a value as a function of given combination at all points in the experimental region that is as close as possible to the true value of the response;
- give good detectability of model lack of fit; and
- provide an internal estimate of the error variance [23].

One detailed example is described below

8.4.2 Example combination: PC-based water reducer-hydration stabilizer-rheology modifier (WR-HS-RM)

This combination is typically recommended for pervious concrete and is used at a fixed combined dosage of 1.5%. This combination consists of a PC-based water reducer (P-09) that is comparable to the product P-05, a hydration stabilizer (P-17) that can retain slump for normal concretes for different time durations depending on the dosing and a viscosity modifying rheology modifier (P-26). Table 8-14 presents the individual mixture compositions for this blend.

Table 8-14 Triplet combination-1: Compositions

Mixture ID		A	B	C	D	E	F	G	H	I	J
WR (P-09)	(%, w/w)	1.50	0.00	0.00	0.75	0.00	0.75	1.00	0.25	0.25	0.50
HS (P-17)	(%, w/w)	0.00	1.50	0.00	0.75	0.75	0.00	0.25	1.00	0.25	0.50
RM (P-26)	(%, w/w)	0.00	0.00	1.50	0.00	0.75	0.75	0.25	0.25	1.00	0.50
WR (P-09)	(%)	100.00	0.00	0.00	50.00	0.00	50.00	66.67	16.66	16.66	33.33
HS (P-17)	(%)	0.00	100.00	0.00	50.00	50.00	0.00	16.66	66.67	16.66	33.33
RM (P-26)	(%)	0.00	0.00	100.00	0.00	50.00	50.00	16.66	16.66	66.67	33.33

Note: The last three rows are the % compositions in the total admixtures

The following ternary diagram (Figure 8-29) shows the water reduction contours for this combination of admixtures. It can be seen the sole use of water reducing admixture does not lead to maximal water reduction. A combination of hydration stabilizer and rheology modifier leads to the maximal water reduction. Quite interestingly the use of rheology modifier increases water demand and can be clearly seen by the negative water reduction. Intermediate compositions lead to water reduction to different degrees.

To design a model was run to appreciate the effects of different components on the water reduction of this combination of admixtures. The resulting prediction equation having a R^2 = 0.9482 is as follows:

$$WR\ (\%) = 11.05(WR) + 7.10(HS) + 0.81\ (RM) + 26.73\ (WR{\cdot}HS) - 12.92(HS{\cdot}RM) - 4.08(RM{\cdot}WR) + 50.17\ (WR{\cdot}HS{\cdot}RM)$$

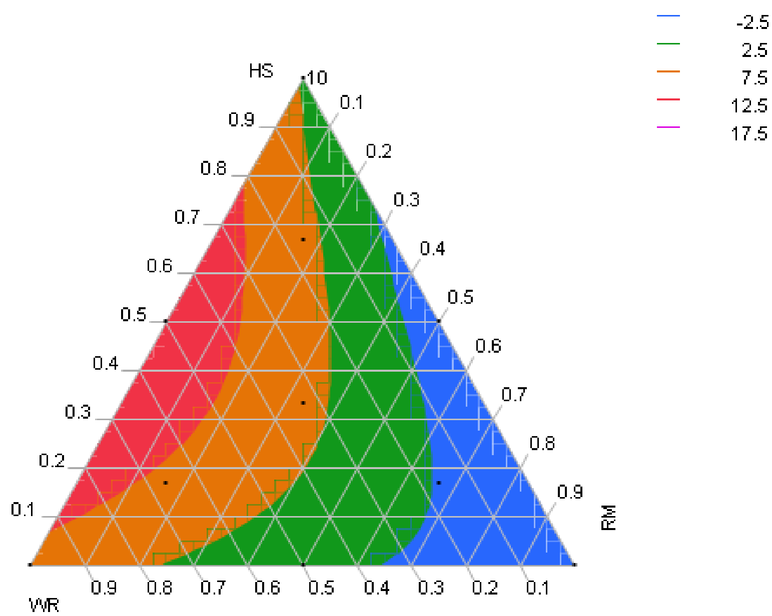


Figure 8-29 Water reduction by ternary combination-1

The equation shows a strong influence of water reducing admixture on the water reduction. Table 8-15 tabulates the parameter estimates. Figure 8-30 and Figure 8-31 show the prediction and desirability profiles.

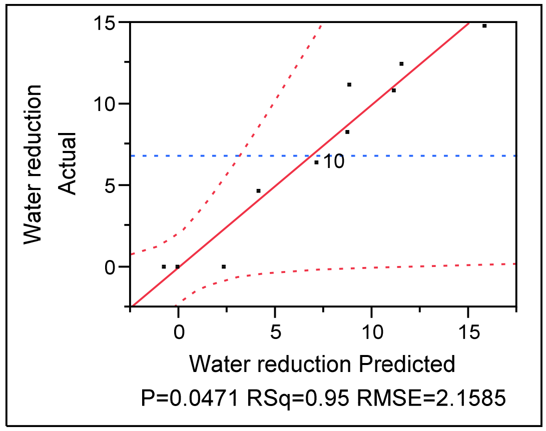


Figure 8-30 Actual by predicted plot of the model for ternary combination-1

Table 8-15 Table of parameter estimates for ternary combination-1

Term	Estimate	Std Error	t Ratio	Prob>|t|
WR	11.05482	2.086555	5.30	0.0131*
HS	7.0884559	2.086555	3.40	0.0425*
RM	-0.807908	2.086555	-0.39	0.7244
WR*HS	26.730551	10.50328	2.54	0.0843
HS*RM	-12.9229	10.50328	-1.23	0.3062
WR*RM	-4.082176	10.50328	-0.39	0.7235
WR*HS*RM	50.167059	69.24477	0.72	0.5212

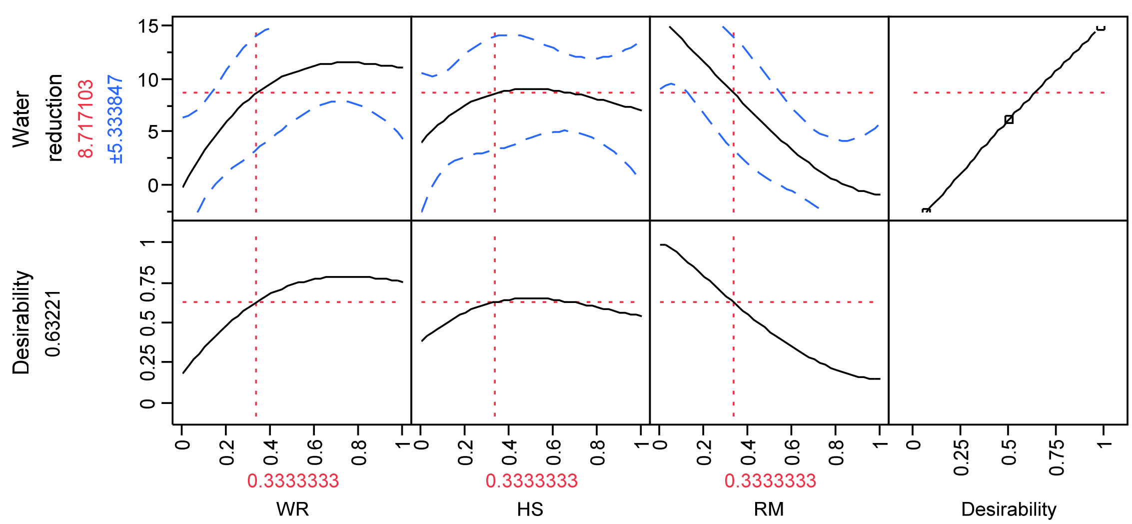


Figure 8-31 Prediction and desirability profiles for ternary combination-1

Figure 8-32 represents the contour plot for the mixture of admixtures used. Being PC based, the water reducer produces substantial water reduction leading to higher strength gains. Hydration stabilizer retards the strength a little bit and with its increase in the admixture composition, the strength reduces. The rheology modifier improves the viscosity of the paste a bit potentially leading to increase in the compressive strength, but to the least possible amongst the three admixtures when used alone. When combined together, there are admixture interactions and their individual and combined interactions with the binders those results into different strengths. The strength produced depends on the dominating action in the admixture combinations.

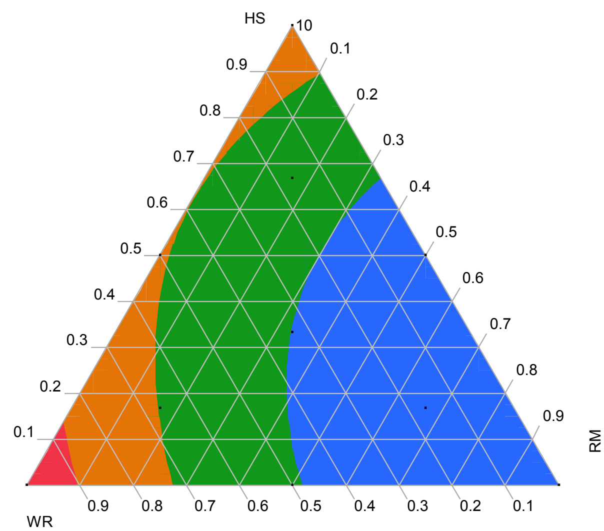


Figure 8-32 Strengths of ternary blends of admixtures. Blue (40 MPa), Green (46.25), Orange (52.5), Red (58.75) and Pink (65)

8.5 Comparative effects

8.5.1 Water reduction

In this section an example of the construction of a composite picture is presented. Different properties show different trends depending on the binder content, and dosage of the admixture. For brevity, only one example for the intermediate binder content is cited here.

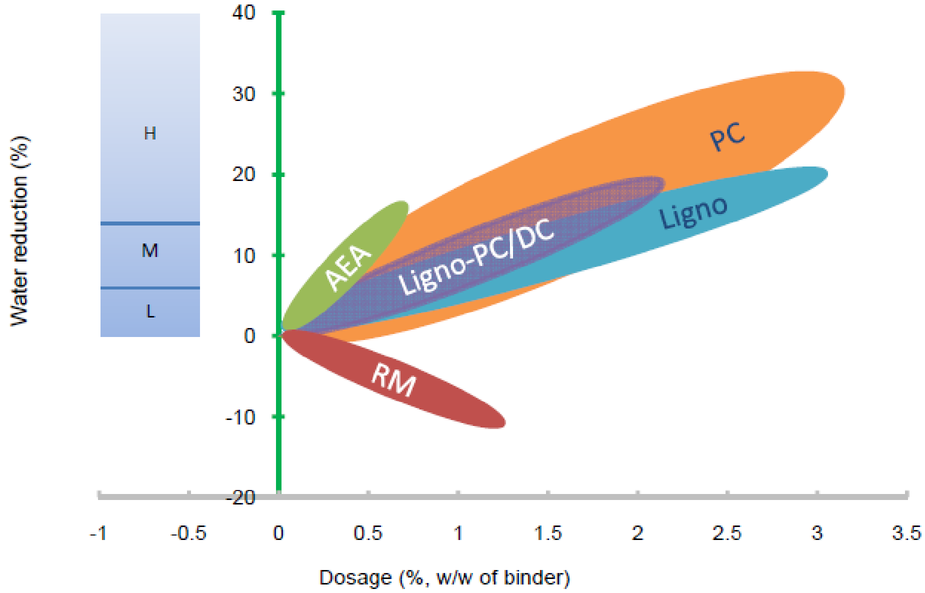


Figure 8-33 Potential water reductions for various admixtures as a function of their dosage for intermediate binder content

The potential for water reduction as a function of admixture dosage for the intermediate binder content is shown in Figure 8-33 presents a summary of different admixture chemistries and admixture types. Due to the broad range families of PC-type water reducers, there could be a wide range of potential variations in their water reducing potential. Purified lignosuphonates can offer comparable water reduction within a certain range, but tend to have reduced potential at higher dosages. Lingo-PC blends offer intermediate water reductions. AEAs have limited water reduction potential, beyond which the entrained air starts having deleterious effects. Rheology modifiers tend to increase the water demand.

8.5.2 Strength gain over control

From the practical perspective, a contractor would be interested in a comparative composite picture that will help him select the most suitable admixture for some specified strength. Figure 8-34 represents the improvement in strength over control for the series of mixtures cast with A/B = 7, binder content of 282 kg/m^3 and water reducing or water reducing cum retarding admixtures. It can be seen that the PC-based product offers a wide range of applicability in terms of dosages and can potentially increase the strength up to the maximum possible within the tested set of admixtures. The Calcium ligno-sulfonate based water reducer and product P-06 offer similar potential, however their abilities to increase the strength are relatively lesser than the PC-product. This is a consequence of the water reducing abilities of these admixtures, which is compared in an earlier chapter.

Retarding/water reducing admixtures, under tested conditions, show a mixed trend. These products exhibit strength improvement over a limited range of dosages, beyond which their effectiveness in reducing the water while overcoming their hydration retarding action is reduced. However, they offer manifold benefits in terms of fresh concrete properties and hence can be applied where reaching minimum strength is not an issue. This comparison assumes that qualitatively mixtures produced with different concretes are similar at the microscopic level. Although the amount of charge stabilization of binder particles achieved by each of these admixtures and the consequent dispersions and their nature could be different. This cannot be elaborated further based on the studied parameters. Since this mixture has an intermediate binder content and is most proximal to typical pavement mixtures, therefore the results of this A/B ratio are presented.

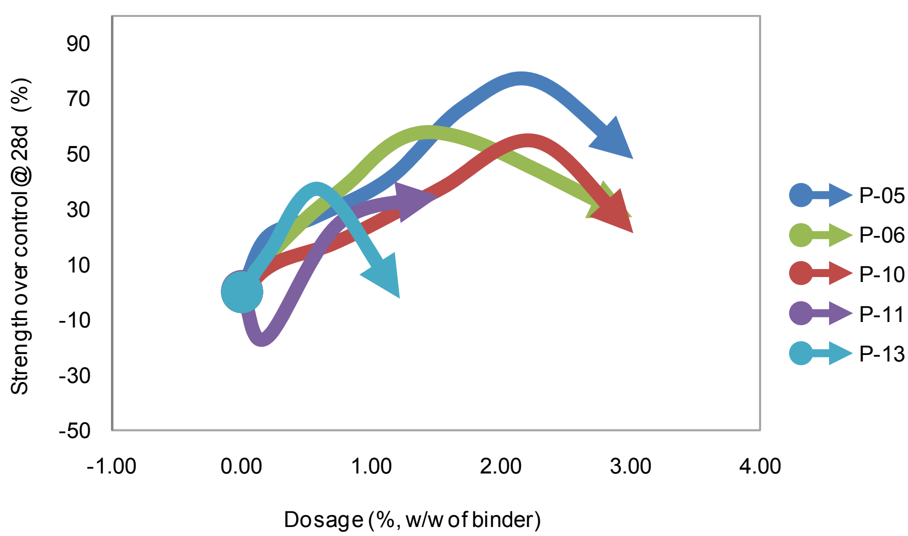


Figure 8-34 Relative strength gain over control as a function of the admixture type (ASTM C494 types A, B, D and for normal concretes) and dosage. Results to be seen vis-a-vis water reduction.

Similar curves can be constructed for other binder contents as well; however, their behaviors are different and are described in one of the appendices. It can also be seen that the water reducing admixtures are relatively more robust in their compressive strength response to dosage than the retarding-cum water reducing admixtures.

8.5.3 Binder savings

From the cost perspective, the additional advantage of using admixtures could be binder content reduction. A simple analysis is presented here with an objective of appreciating an aspect of cost reduction. Reducing the binder content will also make the concrete systems more sustainable by reducing the carbon-footprint. It can be recalled that the binder efficiency is computed using the following formula:

$$Binder\ efficiency\ (\eta) = \frac{UUCS\ (MPa)}{Binder\ content\ (\frac{kg}{m^3})}$$

Say, the target strength is kept constant, that of control mixture. The use of admixtures leads to changes in the binder efficiencies. Using the following symbols:

η_c: binder efficiency of the control mixture at a given age
$\eta_{a:}$ binder efficiency of the admixed mixture at the same age as the control mixture
B_c: binder content of the control mixture
B_a: binder content of the admixed mixture

For a fixed strength, the following equivalence can be established from the above relation

$$(UUCS)_{age} = B_c\eta_c = B_a\eta_a$$

For a given admixture, there is certain binder efficiency at a given age and with this changed efficiency (w.r.t. control); the binder content can be changed. The % change of binder content with respect to control can then be given by the following formula:

$$\frac{(B_a - B_c)}{B_c} \times 100 = \frac{(\eta_a - \eta_c)}{\eta_a} \times 100$$

It should be noted that this is a quantitative comparison based primarily the assumption that the reduction in the binder contents will not produce any unwanted effects of the fresh behavior and compactibility to the extent that it affects the compressive strength.

Above mentioned analysis is presented in the following discussion. 28d compressive strength is considered the base strength. Figure 8-35 shows the potential scope of reduction in the binder content of concrete mixtures due to use of different retarding-/normal-water reducing admixtures. Assuming the finishibility offered by all the admixed mixtures is the similar, the binder content reduction offered by the PC-based and lignosulfonate based water reducers is comparable. Product P-06 is also offers comparable reduction; however, it is effective at lower dosages. Retarding water reducer's offer limited advantage over a relatively narrower dosage range.

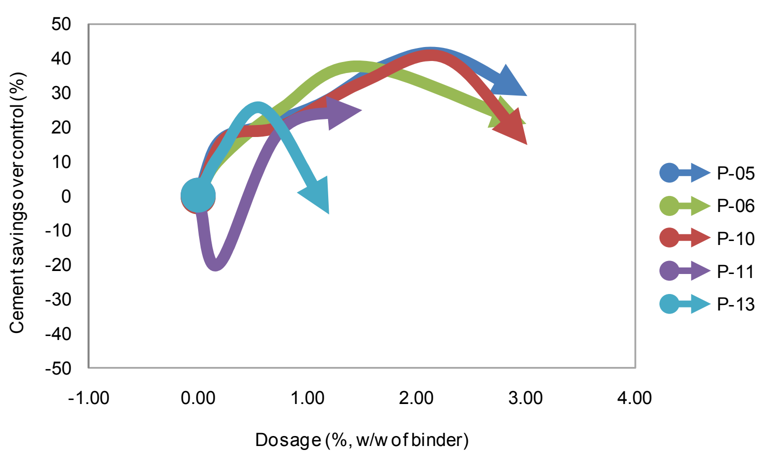


Figure 8-35 Potential for binder reduction with the use of different retarding-/normal-water reducing admixtures conforming to ASTM C494 types A, B, D and F. Results to be seen vis-à-vis water reduction.

Similar plots for binder savings could be constructed for AEA's that have shown water reducing and hence strength improving potential. Again, with a less robust system, the synthetic detergent based system offers a potential case of good cement savings. The other AEA's offer a poor to negative savings potential. This is shown in Figure XX. Other binder contents are shown in one of the appendices. It should be noted that all the comparative composite plots are constructed from the actual data. For the sake of clarity the data points were removed from the plots.

SUMMARY

This chapter presented a synoptic view of the results from admixed concretes. Fresh behavior of RCC was analyzed and quantified in terms of cohesion, angle of internal friction, compactibility, consistency, air content among others. Similarly, hardened properties were described. The reported results include single admixtures and binary and ternary blends. Comparative results are also presented briefly.

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CHAPTER 9 VOLUMETRIC INTERACTIONS AND PASTE: A PROXIMATE DESCRIPTION

SYNOPSIS

This chapter describes sample properties of various mixtures from volumetric and paste perspectives. Initially several ratios are defined and their applications are demonstrated through various examples. The applications include all the properties a few of which are reported. It is noted that the paste quality and quantity has an influential effects on most of the measured properties. These indices can also be used in comparing the performances of different admixtures. Finally a paste quality index is defined and described through an example.

Keywords: voids, paste, volume, properties, paste quality index

CONTENTS

9.1 Important ratios

Table 9-1 shows the nomenclature, per unit volume of concrete as used in this chapter for further analysis of the presented results from paste and other volumetric perspectives

Table 9-1 Nomenclature and definitions

Symbol	Definition
V_B	Volume of binder
V_A	Volume of air
V_W	Volume of water
V_{agg}	Volume of aggregates
V_{adm}	Volume of admixtures
V_{air} or V_a	Volume of air
$V_{voids\ in\ aggr}$ or $V_{V,\ aggr}$	Volume of voids in total aggregates
V_{VFA}	Volume of voids in fine aggregates
V_P	Air free volume of paste
V_m	Air free volume of mortar
α	V_P/V_{VFA}
β	$V_P/V_{V,\ aggr}$
γ	V_W/V_B
δ	V_{agg}/V_B
ξ	V_{adm}/V_P

9.2 Typical relations

This section produces some examples on how volumetrics and the above defined ratios can be applied in evaluating some of the results. An example of fresh properties is provided. A caveat to the contour plots developed from this data is as follows. The number of data points used for developing these plots are limited and as such these plots should be considered as indicative of the trends in general. Moreover, they also have limited resolution. More statistical and intermediate data shall be required to evolve better plots.

Since strength of RCC is a function of the compactibility of the mixture, therefore only strength is described in these examples. If the obtained strength is good, that inconspicuously implies that the compactibility of the mixture and hence the fresh properties were good.

9.2.1 Consistency

Figure 9-1 shows the isoconsistency plot for the control mixtures. This plot, in general indicates that not all the mixture will have good compactibility. Compactibility is a composite function of the relative volume of paste and the volume of water in given system of aggregates. If the volume of water is less than a certain limit, then, just increasing the paste content in a fixed volume of voids in the aggregates is not helpful in increasing the consistency of the mixtures. Similarly having more than required volume would tend to make the mixtures sensitive, easily deformable and moreover the mixture may not have the capacity to hold increased volume of water due to limited surface area of the aggregate and binder. Thus for a given aggregate system, there is a range of volume that would render compactable mixtures.

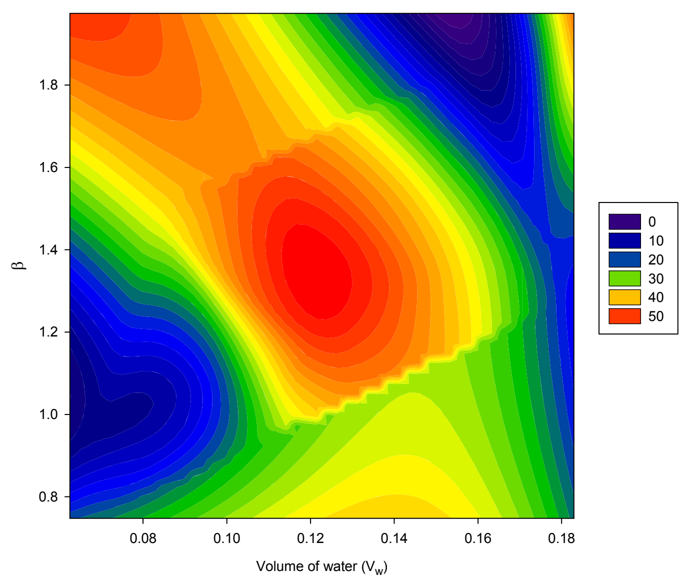


Figure 9-1 Isoconsistency (CSV, mm) plot for control mixtures

Similar to above logic, less paste in a given system of aggregates leads to air entrainment and results in less compactable mixtures. Such mixtures cannot attend maximum potential density because the friction in the aggregates is not overcome because of lack of sufficient quantity of paste. Lesser water in the paste offers higher resistance to compaction, while more water can partially take care of lubricating the system sufficiently, however, due to lack of adequate binder the aggregate system cannot be held together with cohesion. With higher paste content, less water leads to incompactibility and more water leads to dimensional instability and the problem of oozing out of water under sustained/vibratory loading. There is however, a limited range of relative volume of paste in a given aggregate system that leads to most compactable mixtures.

9.2.2 Strength and volumetrics

Figure 9-2 represents the interactions of various parameters and ratios with w/b ratio as a primary parameter on the 28d UUCS. Several interactions and optimizations can be observed. Within the scope of present work, the influences of A/B, w/b, Vp, Vair are represented in these contour plots, which represent iso-strength lines. Similar plots can be obtained at all ages. Note that the paste volume is *air-free paste volume* and consists of only binder and water. It can be seen that not all combinations of cement-aggregate-water-air would produce economical concretes. The following observations are relevant:

1. First quadrant (RHS-Top): For a given A/B, there are ranges of w/b ratios that would produce compactable mixtures. Only a narrow range of w/b will produce optimum compaction characteristics that will in turn manifest in highest strength. Similarly, for a given w/b, only typical ranges of A/B will produce good concrete. From the current study it can be seen (RHS-top quadrant) that the strength is optimized at w/b close to 0.3 for A/B = 4, 0.45 for A/B = 7 and 0.6 for A/B = 0.6. This implies that as A/B ratio increases the optimal w/b ratio from strength perspective also increases. Although the water demand of aggregates systems does not change significantly, the amount of binder changes; thus reflecting in terms of higher w/b ration with increasing A/B ratio. The smudged red area with higher w/b and lower A/B cannot be fully explained based on available data. One explanation could be the presence of higher binder content, which in turn ensures reaching a certain minimal strength level. Juxtaposing this fact with the amount of water that higher w/b in this case would mean tends to overrule this argument at least at higher w/b ranges and also these concretes may be way beyond the regimes of RCC from consistency and compactibility perspectives. Hence, this red-bulb can be ignored while studying these plots.

2. Second quadrant (LHS-Top): It appears that there is a two-way optimization going on. There is an inverse trend observed; higher A/B ratio mixtures have lower volume-of-paste/volume-of-aggregate-voids ratio (β) and vice versa. This fact has an intricate relation with A/B ratio and shall be explained in detail in the following section. It can be seen that the filling up of voids in aggregates by binder paste plays a crucial role in optimizing the strength behavior. It is not required to have the highest β values for an A/B ratio to achieve its potentially highest strength. From the obtained numbers, it can be seen that having paste volumes beyond a certain limit is actually leading to dropping down of strength, thus offering a testimony to the nuisance it creates. This can partially be explained based on the composition of paste. In the present study, the binder contents were kept constant for a given A/B ratio, while the water content was increased. This means that increasing paste volume implicitly means increase in the volume of water (and hence w/b). On the other hand, having lesser paste volume leads to incomplete filling up of aggregate voids and insufficient mobility (not close to optimal) required for full compaction thus restricting the realizing of full strength the existing binder quantity is capable of offering.

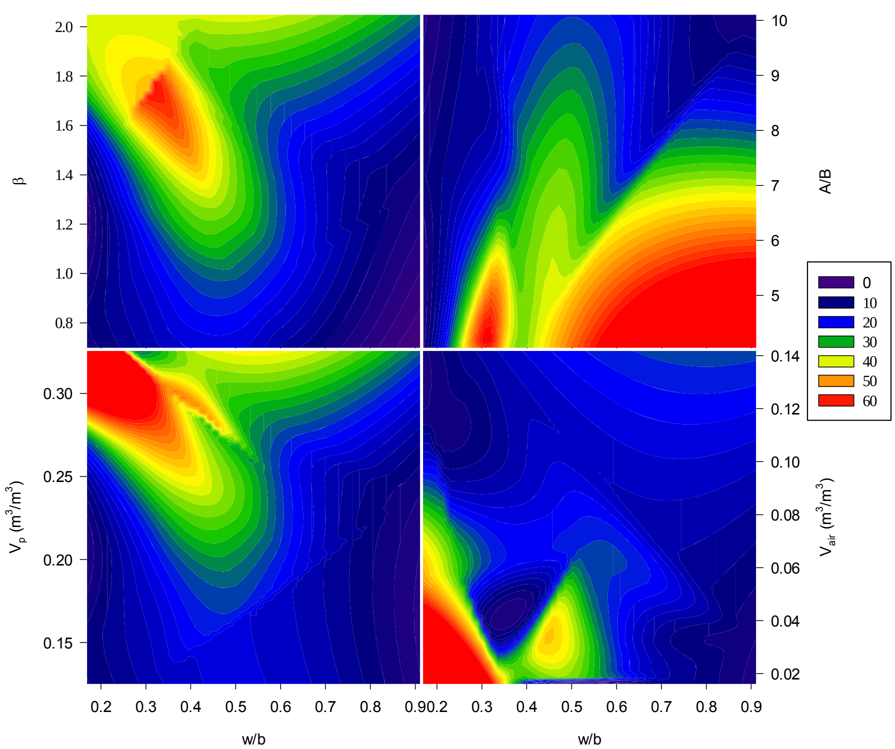


Figure 9-2 UUCS (MPa): Interactions of volumetrics as function of w/b, by mass

3. Third quadrant (LHS-Bottom): The objective of this plot is clarify the role that the amount of water relative to binder content plays in deciding the quality of paste and their composite effect on the strength evolution of concretes. It can be seen that for every paste volume, there are one or more ranges of w/b ratios that would offer optimized strengths. There would certainly be interplay of other factors that would be considered in the subsequent sections. Analyzing this from another angle reveals that having a certain quantity of water in a mixture is not sufficient for achieving compatibility. There has to be commensurate amount of binder that leads to a compactable mixture that could potentially achieve the highest strength.
4. Fourth quadrant (RHS-Bottom): The objective of this plot is to explain the role of air content in RCC mixtures and the sensitivity of strength to air content vis-à-vis the w/b ratio. As expected, higher strengths are obtained at the bottom of the air content axis. Another perspective on this is that every w/b ratio has a range of *tolerable air content* for which the mixture strength will not be affected substantially; once this range is crossed, there will a dramatic drop in the strength. As a response to compaction effort a mixture can be compacted to various air contents, but individually, depending on the binder content and w/b ratio, the mixtures' responses to strength will differ. For example, the higher binder content mixtures (low A/B ratios) will be less sensitive to the changes in the air content than the corresponding mixtures with lower binder contents (higher A/B ratio).

9.2.3 Strength of admixed concrete, some examples

USE OF PC-BASED WATER REDUCER

Different ratios and volume concentrations are plotted as second variables. Refer to Figure 9-3.In terms of the ratio of paste volume and voids in aggregates, it could be seen that less paste is required to produce similar or higher strengths. This is however subject to production of aesthetically acceptable concrete. There are combinations of quantities of water and admixture dosages that would not render any strength. This fact is to be viewed in the light of A/B ratio used for these combinations. With increasing admixture dosages, the corresponding volumes of water reduce. The exact mechanism of these transitions is considered to be beyond the discussion of this work.

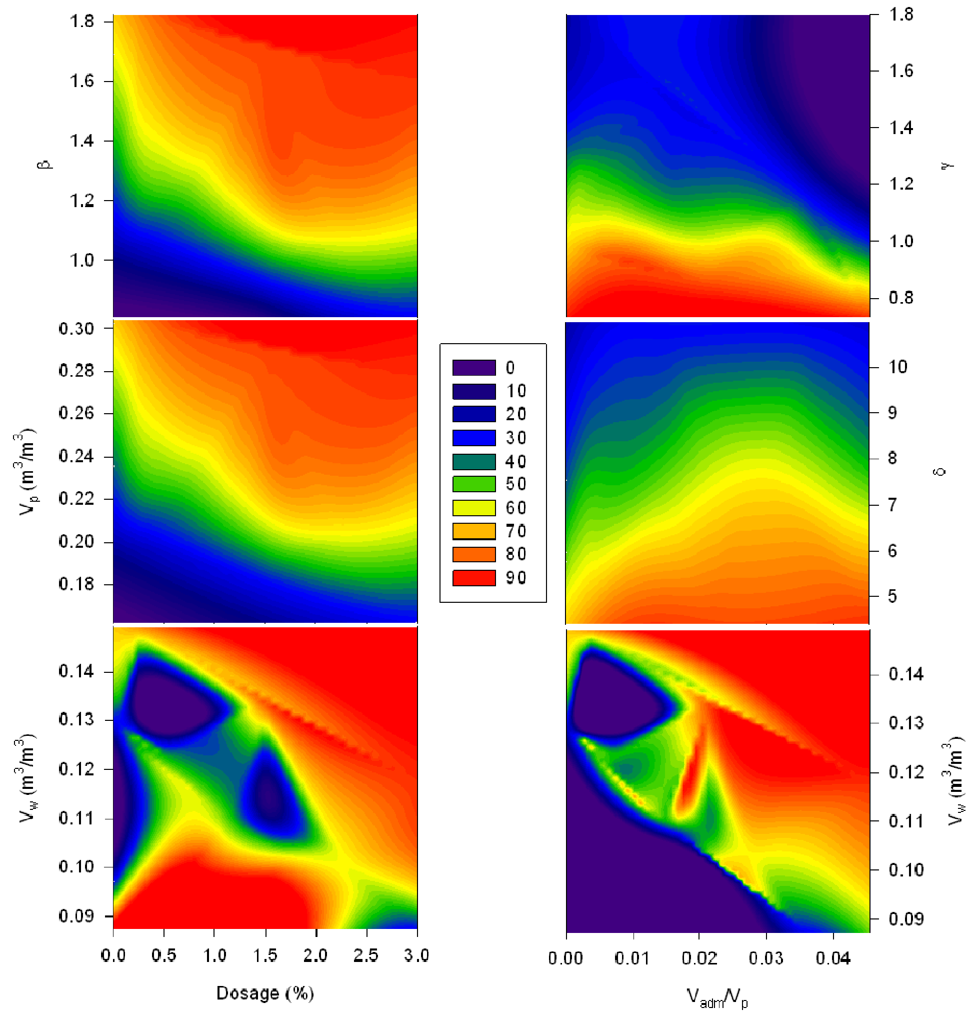


Figure 9-3 Trends of 28d UUCS (MPa) as a function of admixture dosages and relative volumes

The paste composition plays a decisive role in influencing the strength properties of concretes in general. A volumetric ratio of the volumes of admixture and paste, ξ is used in obtaining the second set of plots and to appreciate the transitions in strengths while being cognizant of other ratios and volumes. The following observations are salient:

- For a fixed γ ($V_p/V_{voids\ in\ aggr.}$), there could be more than one combination of admixture volume and paste content that would produce highest possible strengths.
- It is interesting to note that even with γ less than one, much higher strengths can be produced.

- There are optimal combinations of δ and ξ (V_{adm}/V_P) that would render highest possible strengths. There are specific trends and pathways to this optimization. If we consider an iso-strength line in this plot, we could see that there are two pairs of such combinations that would render similar strengths. The first pair will have relatively lower admixture volume when compared with the paste volume and second pair will have a relatively higher admixture volume. This fact needs to be juxtaposed with the volume of water in the paste, since this could have a decisive influence on the strength of concrete.
- One of the interesting things to note from the plot of ξ versus volume of water is the revelation on of the minimum water required for mobilizing the effect of water reducer. From this plot and a corresponding plot on the dosage of the admixture, it can be seen that some combinations of volume of water and admixtures will not produce strength, while slight changes in the relative volumetric composition of admixture and water. Similarly there are distinct combinations for a given paste composition that produce the highest strength thus reflecting on the range of water volumes over which this admixture is most efficient.

COMPARISON OF PC-BASED AND LIGNO-BASED WATER REDUCERS

Figure 9-4 shows a comparison of PC-based and Ligno-based water reducers on the strengths as a composite function of A/B, V_p, ξ and w/b ratio. It can be seen that these water reducers follow distinctly different trends towards optimization. The following are the salient inferences:

- The range of w/b ratios over which these water reducers are effective is distinct. Similarly, the amount of binder relative to the aggregate content over which these two admixtures are most effective is also distinct.
- In terms of the paste volume optimization, the optimal range of effectiveness of Ligno-based superplasticizer is different as well. However, at similar paste volumes, the PC based water reducers tend to produce higher strengths than their counterparts with Ligno-based water reducers did.
- The plot of ξ vs. w/b ratio shows that the PC-based admixture remains effective over a wider w/b ratio range. In case of Ligno-based water reducer, at higher w/b ratio, the effectiveness reduces dramatically. It is also interesting to note that unlike clear trends observed in PC-based admixture, there is a distinct nebula of high strength over a specific zone bound by w/b ratio and ξ.

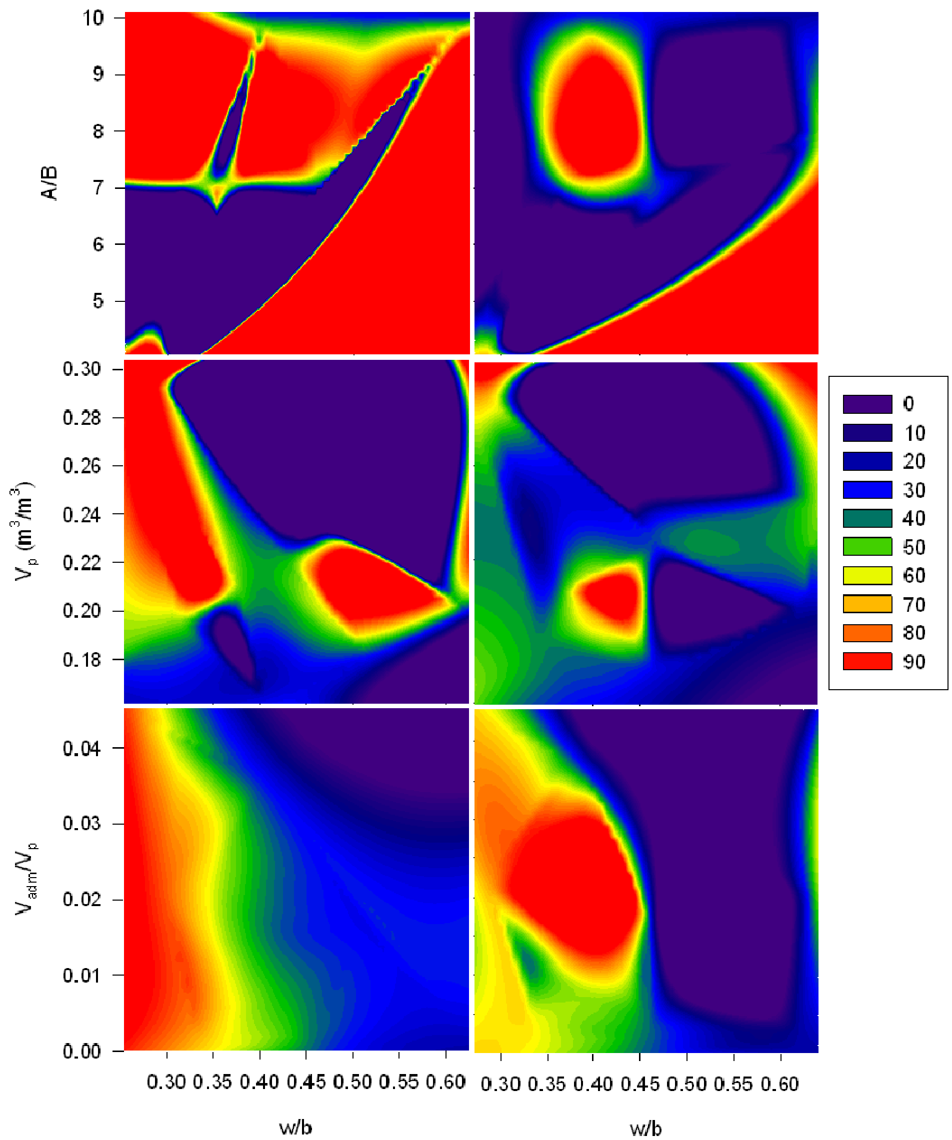


Figure 9-4 Comparison of strengths achieved by PC-based and Ligno-based water reducers

COMPARISON OF AIR ENTRAINING ADMIXTURES (AEAS)

Figure 9-5 shows a comparative plot for the water soluble hydrocarbon, synthetic detergent and modified resin based air entraining admixtures as a composite function of dosage, and other ratios.

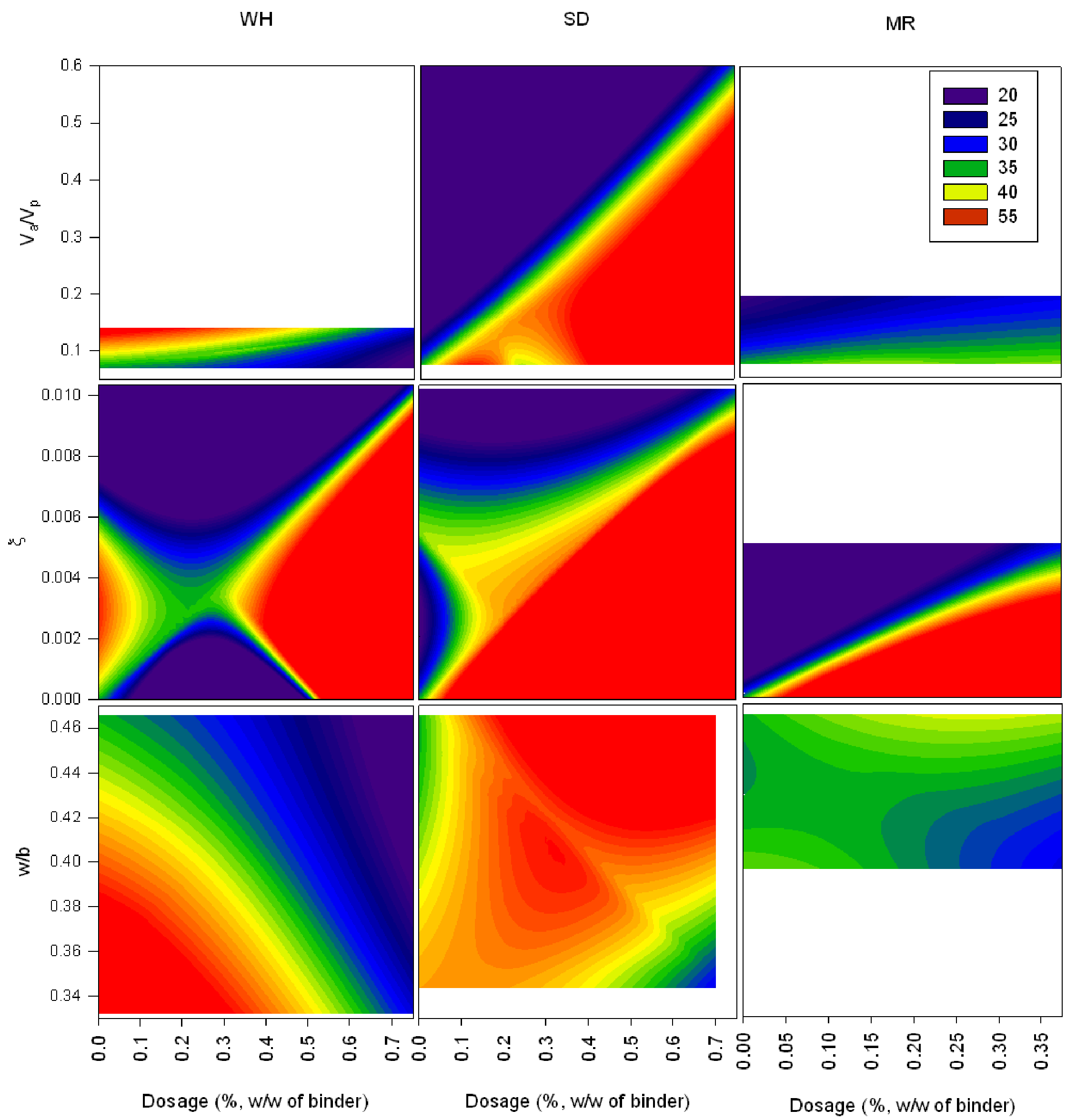


Figure 9-5 Isostrength (MPa) plots as a function of different ratios dosage of AEA's

INTERACTION EFFECTS OF AEA DOSAGE

Figure 9-6 shows 3D plots for the 28d UUCS as a function of SD-based AEA dosage and other ratios. Similar plots can help appreciate the role of relative volumes of paste and voids and other ratios combined with the admixture type and dosage in influencing the strength or other properties of concrete mixtures.

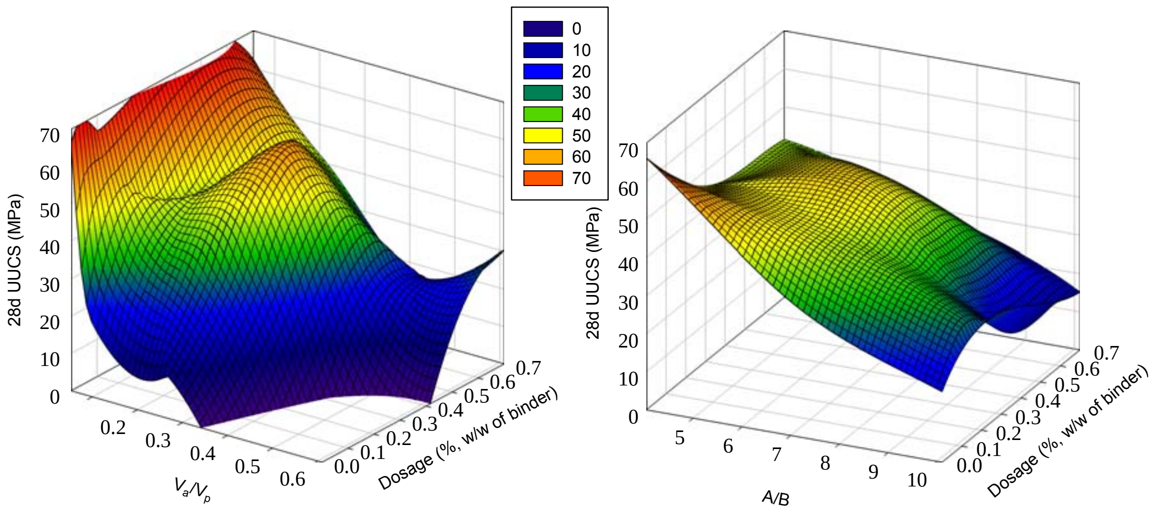


Figure 9-6 Interaction effects of AEA dosage on strength

9.3 Paste quality index

Conventionally and so far for this research, quantitative descriptions of paste and volumetric relations have been presented and discussed. The use of different admixtures in concrete mixtures leads to changes in several properties. These changes are a function of admixture chemistry, dosage and the interaction effects produced by different factors acting together. A qualitative description of paste appears to be less feasible on the basis of this work. However a new index, paste quality index (PQI) is defined as follows:

$$\mathrm{PQI} = \frac{\mathrm{28d\ UUCS}}{\mathrm{V_P} + \mathrm{V_{air}}}$$

The numerator can be any other properties under consideration. This definition can be applied in comparing different mixtures and how admixtures or any other changes affect the quality of the paste, which in turn is reflected in terms of the changes in the property in the numerator. It should be noted that the denominator consists a separate term for the volume of air because the volume of paste is air-free.

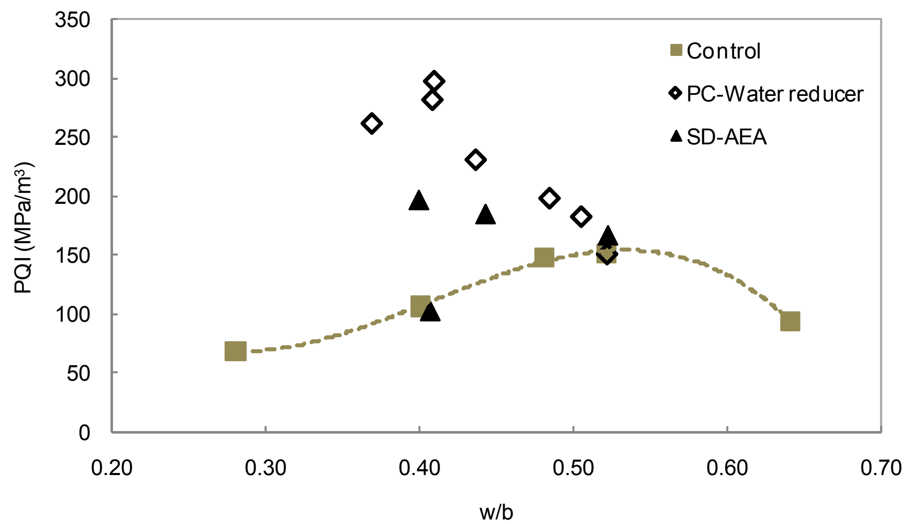


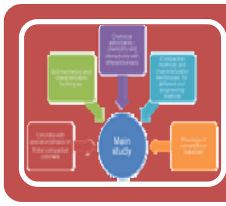
Figure 9-7 PQI for 28 day strength: Control, PC water reducer and SD AEA for A/B = 7

Figure 9-7 shows an application of this concept. This concept basically evaluates the utility and efficiency of a paste system in a mixture for a given performance property. It can be seen that the PQI increases with the use of PC-based water reducer, while the use of AEA leads to improvement only upto a certain limit beyond, which the PQI reduces. This happens because of the excessive air that get entrained.

SUMMARY

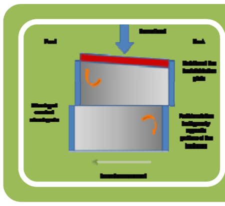
A synoptic perspective on the use of volumetric ratios and paste quantity was offered in this chapter. Due to limited data available extensive treatment of the results was not possible. However, the concepts developed in this chapter can be effectively used for other applications. The paste quality index is a good way of comparing the improvements in the paste through quantification. Further effort is required in this area to better define this term.

CHAPTER 10. SUMMARY AND CONTRIBUTION TO THE EXISTING BODY OF LITERATURE



Unification of concepts and review

Concepts and methods from soil mechanics, rheology, calorimetry, statistics, chemistry, compaction of granular matter - reviewed, documented and applied

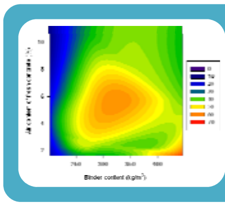


Intrumentation

Various instruments and characterization methods developed, statistically evaluated and applied; appreciation of strengths and weaknesses of each

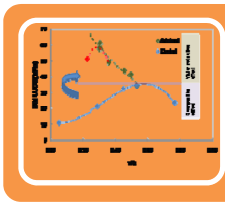
Fundamental work: Workability

Arguments on aggregate selection; explanation of moisture-density plots, cohesion, angle of internal friction and compactibility



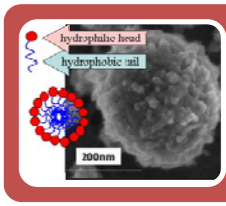
Concepts of paste quality and quantity

Most mechanisms explained from two perspectives - relative paste volume and paste quality



Explanations on strength evolutions

Mechanisms of strength development in various mixtures explained from fundamental perspective



Applied work: Applications of chemical admixtures

A range of chemical admixtures were tested and evaluated for thier performances in fresh and hardened properties

CONTENTS

10.1 Research need statement

An exhaustive literature review was performed dealing with several areas of expertise including concrete behavior, cement-admixture interactions, the state of the art on admixtures, soil compaction and behavior, asphalt compaction amongst others. The following is a brief review of the relevant points that culminated in

- Identification of the voids in the existing body of knowledge and the state of the art;
- The formulation of the research needs statement.

10.1.1 RCC and its applications

RCC has evolved over the past 25-30 years and is a well-used, adequately understood material for hydraulic construction. The body of knowledge for pavement applications is in its early years, thus stipulating research with an objective of having better fundamental understanding of the material. The fundamental material behavior of RCC is quite different from that of the routine and modern concretes. The primary reason being its inherent composition and resulting drier consistency. RCC has a wider range of applicability in various pavement applications. Moreover, it also has a potential to compete and surpass the properties of other cement based pavement materials. Furthermore, considering the sustainability potential of RCC, it appears to be the material of choice for the future. Hence research efforts are required to be invested for furthering the awareness and enhancing the body of knowledge. Figure 10-1 shows the range of applications.

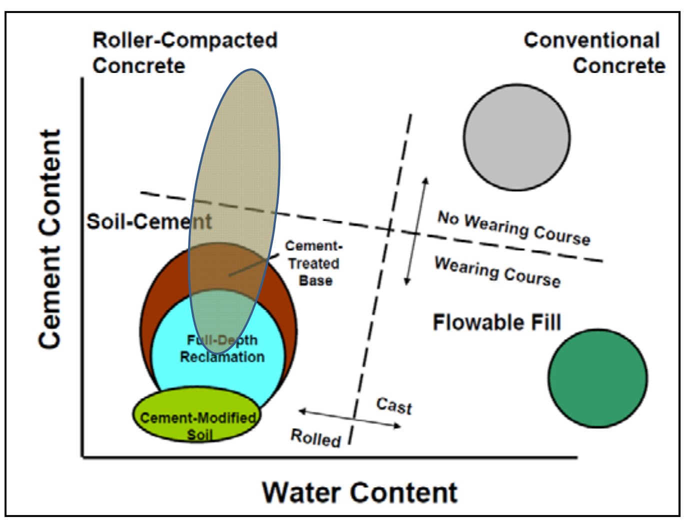


Figure 10-1 Various applications of RCC

10.1.2 Understanding fundamental behavior

Paste volume slightly higher than the voids in the aggregates is required for rendering better fresh, mechanical and durability performances. In drier mixtures, such as RCC, this relative volume of paste becomes exceedingly important. The composition of paste is also important and an understanding about the paste composition, its quality and quantity in a mixture helps anticipate and predict the material behavior. Aggregates play a vital role in filling up the space. Their relative volume when compared to the binder volume offers an interesting interplay that eventually affects most of the concrete properties.

Our understanding about the cohesion in concrete and the relative internal friction of fresh concrete is negligible. Studies pertaining to cohesion, internal angle of friction and compactibility are therefore required. Previously sporadic and scattered studies have been performed on these topics. Figure 10-2 shows an example from one of the previous studies.

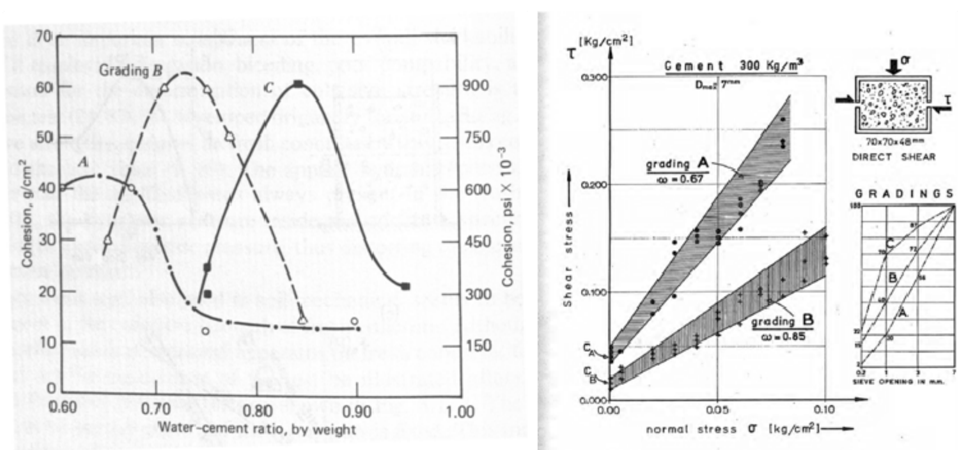


Figure 10-2 Cohesion measurement in concrete

Similarly, our appreciation about strength and limitations of the Abrams' law, which is widely accepted and invariably used in many mixture proportioning philosophies and design guides is rather poor. The caveat in applying this law to drier concretes is not properly understood and spelled out. Although water/binder ratio is invariably used in specifying and ordering concrete, it has its own limitations and should be used with caution. The advent of newer materials is making its use arbitrary. There is thus a need for identifying of proper parameters and/or coming up with new ones for specifying concrete mixtures in more effective ways.

The mixture proportioning strategies could be greatly enhanced with basic understanding of concrete properties in terms of workability and how different components of workability would alter the constitution. Considerations include evolving proper indices for selecting appropriate water/binder, aggregate/binder, and chemical admixture selection vis-à-vis concrete consistency, cohesion, angle of internal friction, compactibility, etc.

10.1.3 Chemical admixtures

Chemical admixtures are becoming essential components of concretes. With rapid evolution of admixture science and our understanding about their interactions with concrete making materials, many of long perturbing questions are being resolved. The study of the interactions of chemical admixtures, which are mostly organic in nature with mostly inorganic binders, is an interesting area of work. Figure 10-3 shows a synoptic overview of different factors affecting the interactions of chemical admixture with other materials factors. However eluding in terms of their physiochemical interactions, our knowledge about applying them is increasing every day. It is a topic of greater interest from sustainability perspective.

ASTM and other standard writing bodies have followed the chronological discoveries and with the pace at which the admixture technology is advancing, it is difficult for them to keep up with that pace. There is thus a need for a comprehensive classification scheme that would last longer than it has been in the past. With the advent of admixtures that can perform multiple functionalities, it is more often than not difficult to classify them.

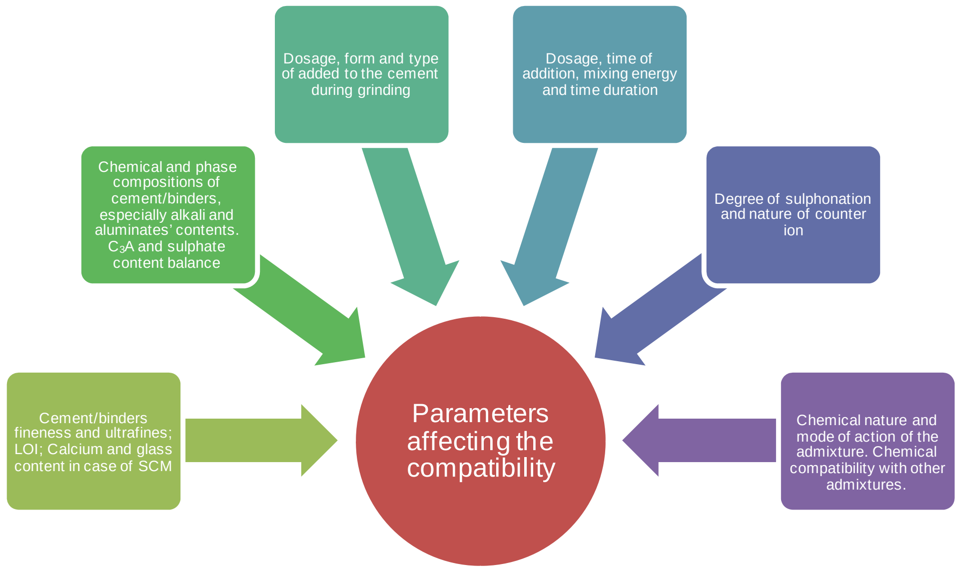


Figure 10-3 Factors affecting the interactions of chemical admixtures

The use of chemical admixtures in RCC is becoming crucial. Due to lack of research and proper and adequate appreciation of the fundamental behavior of RCC, including the apprehension about the dry nature of RCC, the advancements in applications and research on the use of chemical admixtures in RCC has remained more or less limited.

10.1.4 Rheology

Rheology is a study of the flow behavior of matter, under conditions in which they flow rather than deforming elastically. Concrete is a complex system of few materials, so diverse in their chemical constitution, age, behavioral responses, scales of forces and interactions that studying it at narrow range of scale of forces is difficult. Isolating the behaviors of individual material is certainly a solution, but it offers difficulties in letting us build a composite picture from pieces of information. Attempts have been and are being made to overcome this difficult with partial success. Figure 10-4 offers a conceptual merger of shear and rheological parameters.

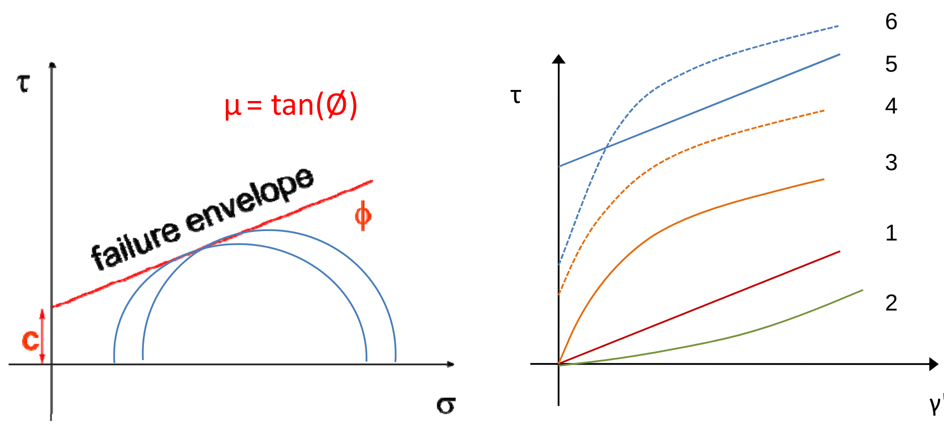


Figure 10-4 Shear measurement in soils and plots from rheological characterization

Pavement concretes are a special family of compositions that have distinct rheological nature. The current state of instrumentation is not geared towards measuring such stiff concretes; while it can to a great degree of refinement estimate mechanistic performance of some types of concretes like self-consolidating. The unique juxtaposition of pavement concretes at the interaction of solid-like and semi-solid behavior makes the study of their rheology quite a challenge. What further aggravates the problem is the transitioning of concretes from one type of behavior to another in response to vibrations. This requires blending of concepts from different areas of expertise.

10.1.5 Gyratory compactor and field compaction

Gyratory compaction method (refer to Figure 10-5) has been used for asphalt concretes for nearly half a century. The associated operational ease, superior consistency and faster sample production have made it the method of choice. The concept of gyratory compactor is said to offer benefits such as proximity to field density, similar aggregate breakdown and simulation of actual process of compaction. Several versions of gyratory compactors are available in the market and there are ongoing efforts in modifying and fine-tuning it.

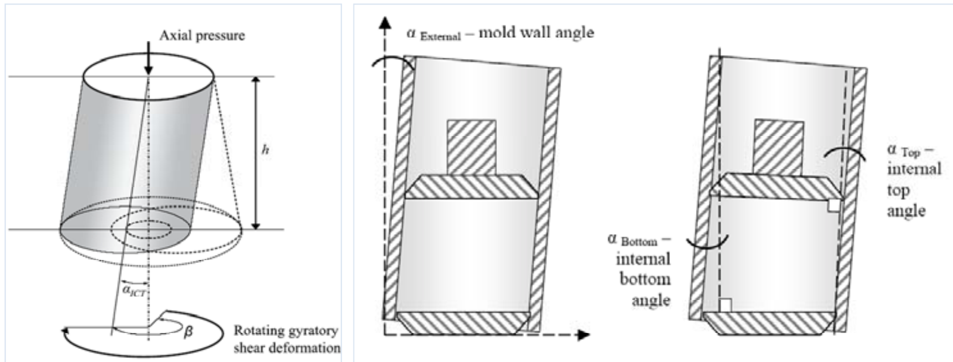


Figure 10-5 Gyratory compaction: Working principle

In recent year's gyratory compactor have been evaluated for soils and have shown good promise. Its application for concrete has been researched and practiced in some parts of Europe for concretes used for precast works. For reliable and satisfactory application of gyratory compactor for concretes, changes in the consolidation pressure, the angle of gyration, rate and number of gyrations have to be adjusted or modified. This establishes the premise for further research on optimization of the compaction parameters for gyratory compactor to be used for RCC.

10.2 Instrumentation

Any experiment needs to take into account the strengths and possible limitations of the instrumentation used. A further complexity arises when instruments that are routinely applied in characterizing materials those are inherently different. This specificity offers several limitations in applying these instruments on other than the materials that are characterized regularly. Change of material not only necessitates adjustments and fine-tuning of some of the instrumentation, but often could require scaling up or down and eventually this change leads to changes in the way the statistics of measurement is distributed. This in turn could change the nature of forces and the mechanisms undergone by specific materials during such testing.

Application of different instruments for characterizing the same property could lead to large-scale variations in the measurements and hence an appreciation of such an artifact needs to be accounted for or at least acknowledged. The statistical data established as a part of this work,

- Indicated a good quality control over most tests;
- The variations caused due to multiple operators were minimal, since most of the work was carried out by the author himself;
- Use of Cabrera slump value is limited to a narrow range of values. There is a need for further evaluation. There are extreme cases offering similar numbers but having different meanings. For example, a drier concrete on a moisture density plot and a wetter concrete might give the same number, but in the earlier care, it is lack of compaction (presence of excess air) and in the second case, there is a tendency to consolidate (presence of excess water). Further studies with this measurement technique need to reconsider some of the strengths and limitations;
- The compacting hammer offered good consistency in most measurements including the air pot sample, the fresh density measurement and sample casting for strength measurement;
- The shear box used in this work needs further modification and sophistication to be able to reduce the noise in the measurements. It did offer a reasonable experimental clarity to offer a trend in the cohesion;

10.3 Studies on the attributes of workability

The dissertation offered several critiques on the existing theories. The following is a sampling of results, inferences and perspectives from current work:

10.3.1 Aggregate grading and correlations to compactibility

Aggregate gradings are conventionally evaluated using the specified aggregate. Furthermore, such evaluation may include a mention of the fineness modulus, which is a rather incomprehensive term, since it does not take into account the finer fractions in an aggregate system. Sophisticated computational methods may not be very helpful at the practice end of engineering. A simpler, comprehensive and quick method or suite of tests are thus required for evaluating and selecting aggregate grading systems that are most compactable. This work evaluated and used such methods, of which a correlation plot is shown in Figure 10-6. This plot shows correlations between the coefficient of uniformity and measured voids content in various aggregate compositions along with the correlations with fineness modulus.

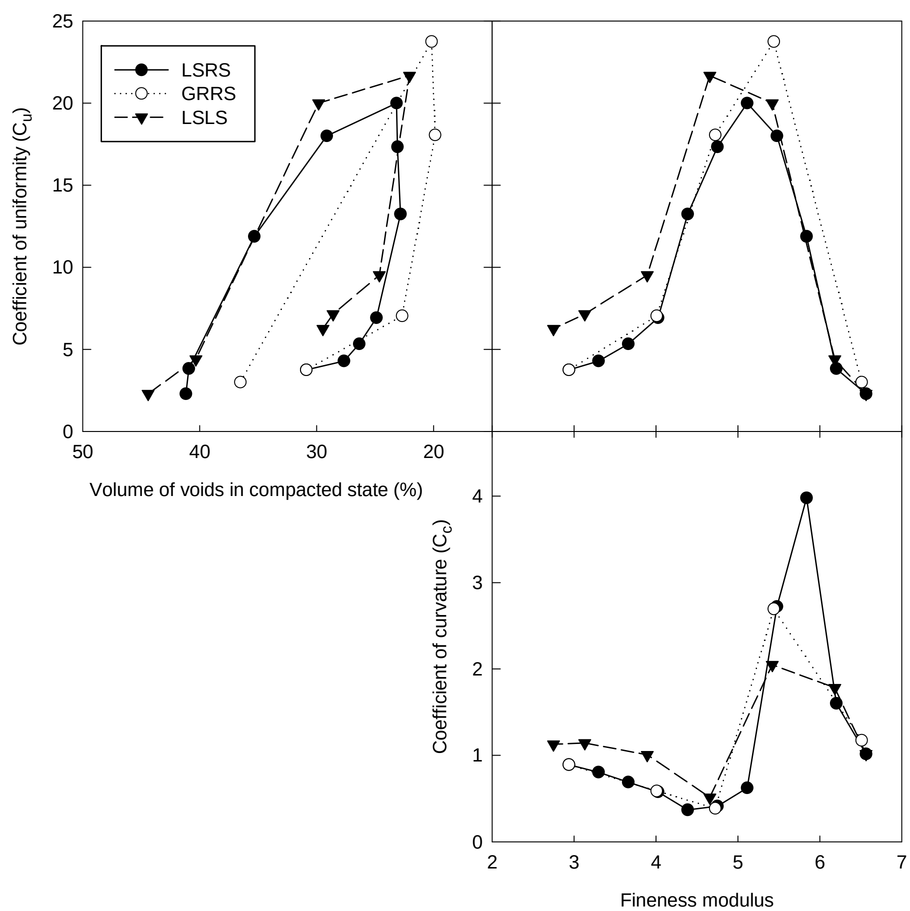


Figure 10-6 Coefficient of uniformity related to other theoretical and measured parameters

10.3.2 Abrams' law

Abrams' law is widely used without a comprehensive appreciation of its potential limitations. The caveat that the concrete has to be compactable is overlooked while evaluating any strength results and relationships are established only with water/binder ratios. This was however critically reviewed and tested in this work. Incomplete compaction is possibly one of the most easily perceptible reasons. Use of water reducing admixtures (provision of artificial water) reinstates this law, however only up to a certain limit. Figure 10-7 shows an example.

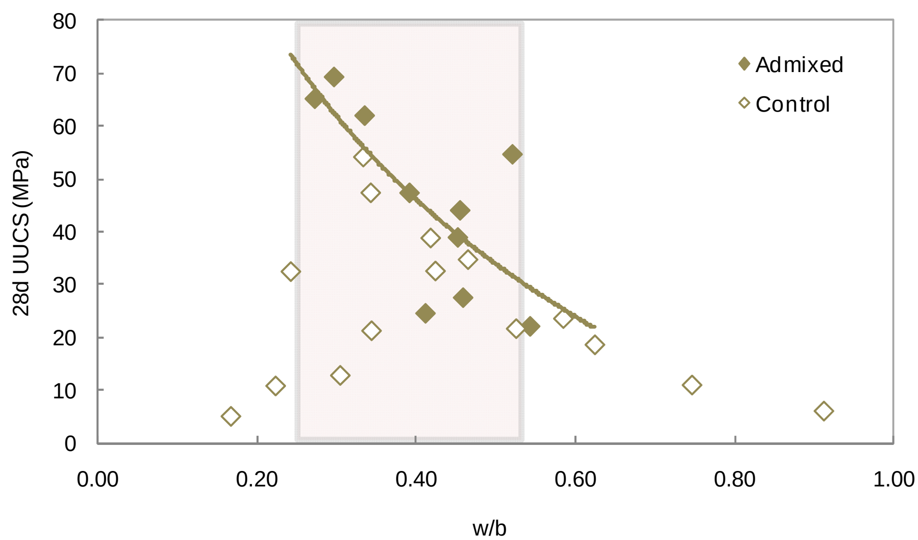


Figure 10-7 Failure of Abrams' law in non-admixed concretes and its reinstatement with the use of chemical admixtures

10.3.3 Compactibility of concretes

The behavior of RCC in response to its material composition is not fully understood. Moreover, the factors that influence compactibility of different mixtures are not appreciated well. This may involve the effects of aggregate grading, relative volumes of water and binder, relative volume of paste, voids in aggregates, effects produced by the air amongst others.

A study on the compactibility of concrete mixtures as influenced by the binder content, the relative volumes of water and binder and aggregate grading is reported in this work. Furthermore, attempts at correlating compactibility with moisture density plots are also made and reported. Figure 10-8 is a sample from such plots.

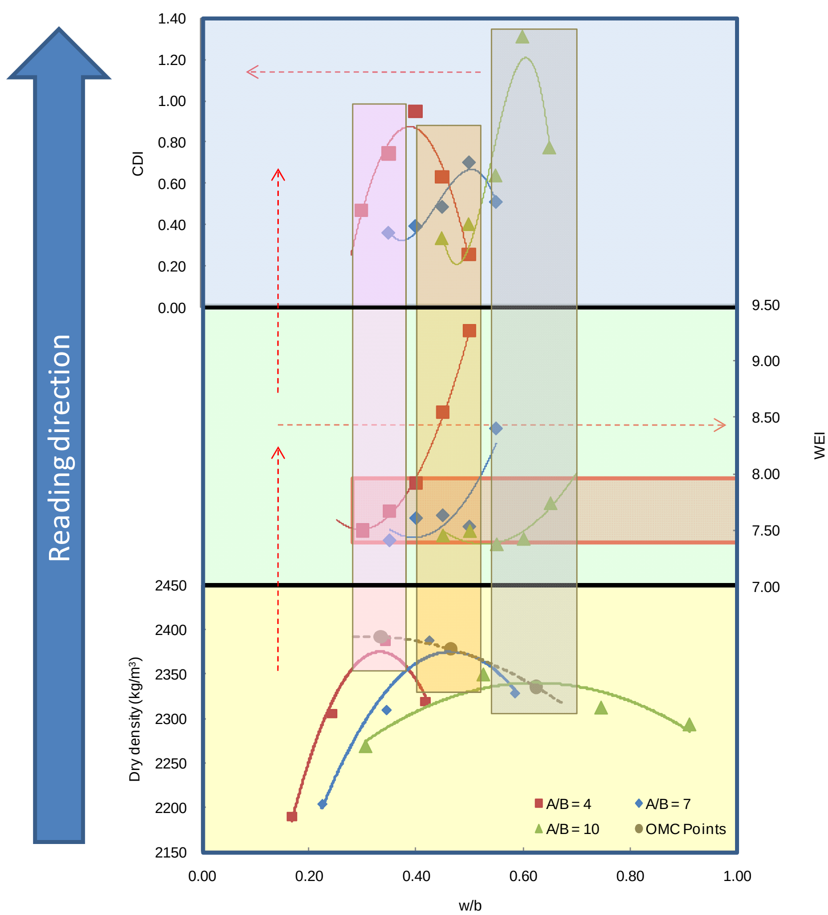


Figure 10-8 Correlation between compatibility and moisture plot

10.3.4 Taking a step forward

Fresh behavior of RCC was further analyzed and quantified in terms of cohesion, angle of internal friction, compactibility, consistency, air content among others. New indices to define the ease with a mixture can be worked with were defined and used successfully.

It was shown how the data obtained from shear test could be manipulated and used in analyzing and comparing different concrete systems. Figure 10-9 represents a sample plot that guides the selection of the right quantity of paste relative to the combined aggregate grading.

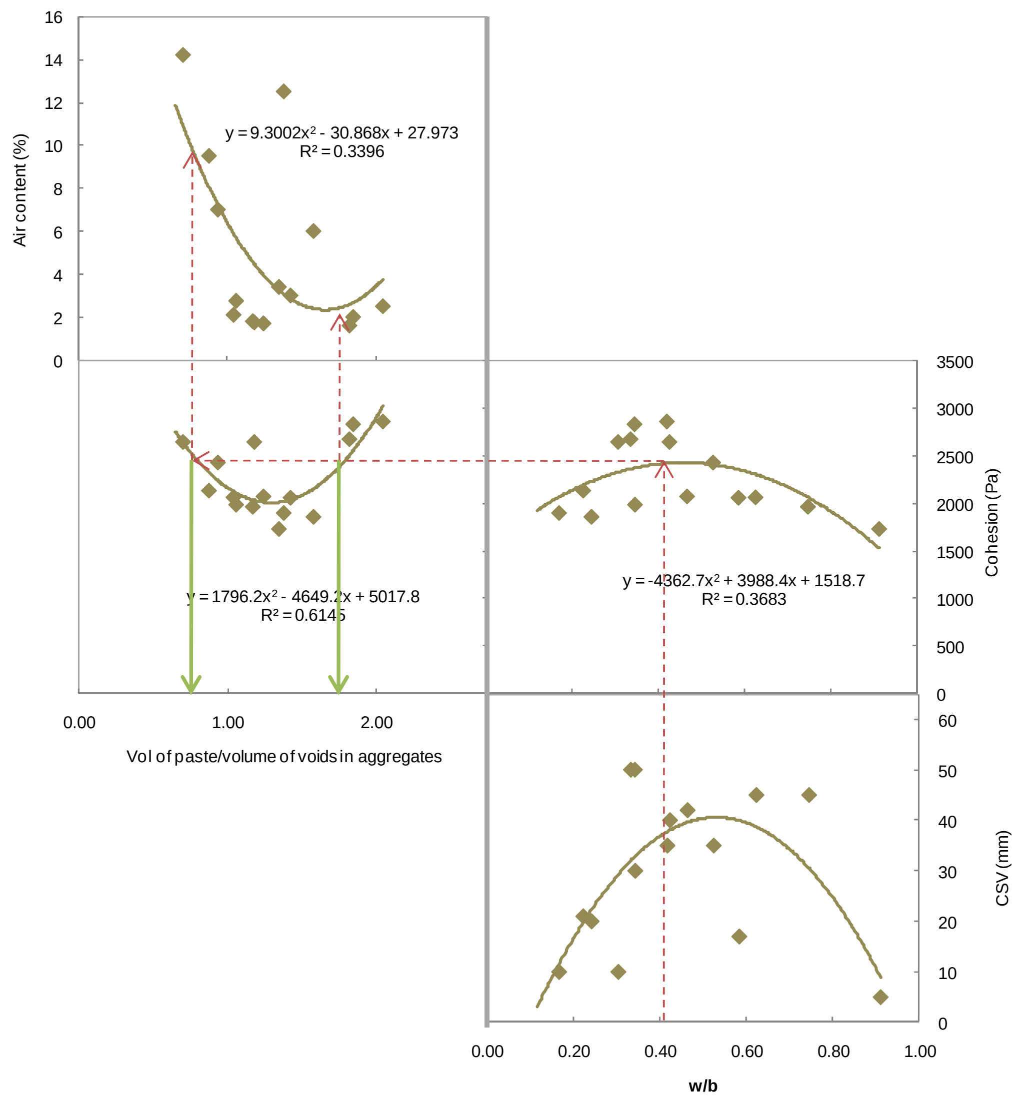


Figure 10-9 Correlating w/b, consistency, cohesion, air content for estimating the volume of paste

10.3.5 Explanations from paste quality and quantity perspectives

One of the interesting aspects of this work has been the description of concrete systems in terms of its paste quantity and quality. The composition of paste plays a decisive role in influencing the properties of fresh concrete and good correlations with most of properties can be established. Figure 10-10 is a sample plot that helps understand the trends and interactions in various material and mixture parameters.

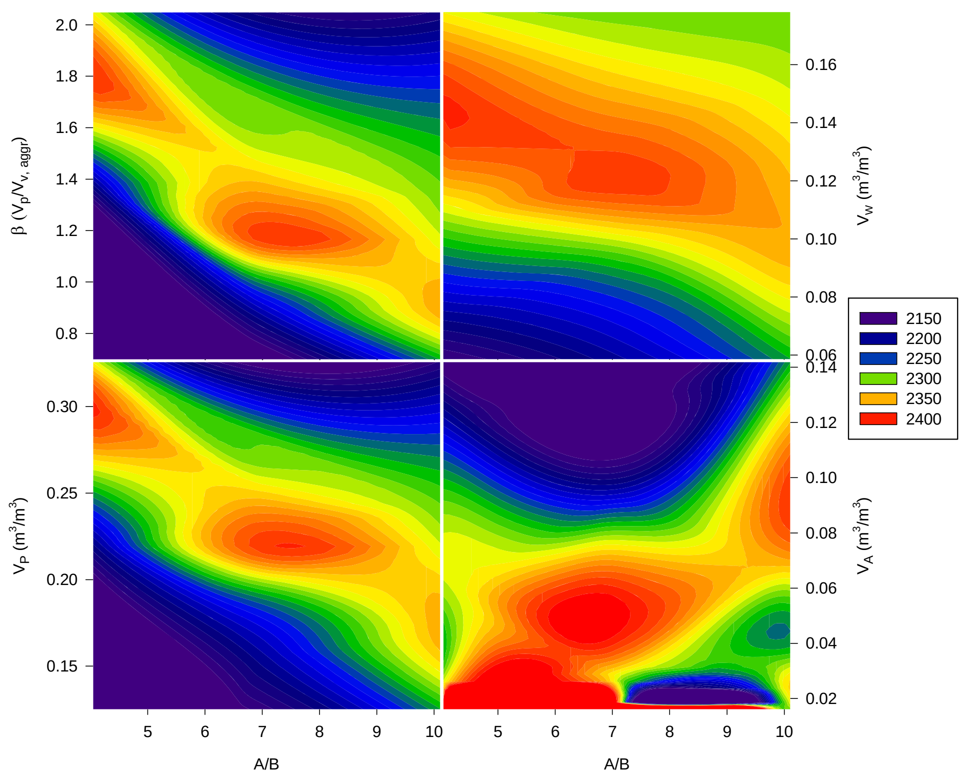


Figure 10-10 Sample trends with various material and mixture parameters

Paste quality was defined in terms of the strength per unit volume of paste including the volume of air. This method can be used in characterizing any other properties of fresh or hardened concretes. The application of this method offers comparative picture and helps evaluate the changes brought by the alterations in the paste quality. Further effort is required to enhance this definition and probably come up with new ones.

10.4 Studies with chemical admixtures

10.4.1 Composite plots

Different chemical admixtures were used to evolve comparative plots to help select the most appropriate admixtures and their dosages. The effectiveness of many chemical admixtures was found to be dependent on the binder content. For each of the admixture tested, there was a specific range of binder content over which the admixture showed optimal performance. Figure 10-11 shows a sample plot.

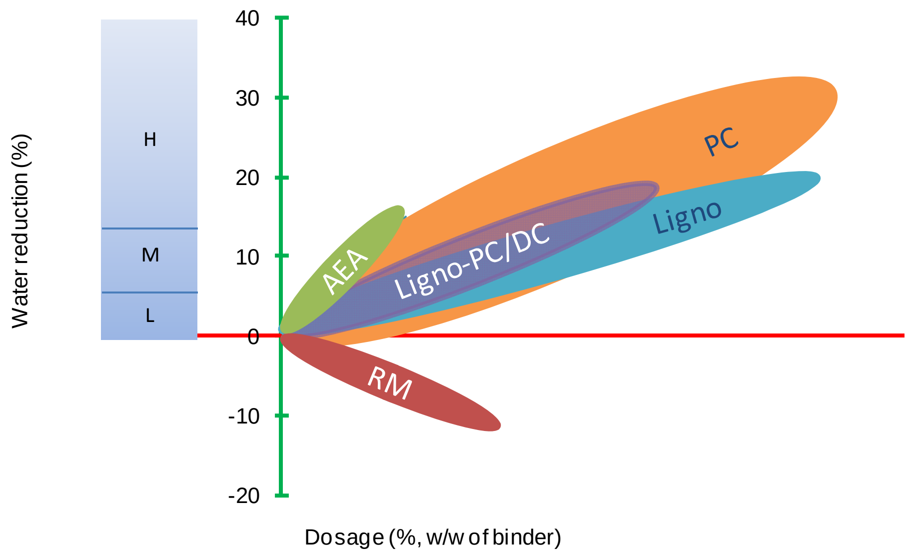


Figure 10-11 Water reducing ability of different chemical admixtures

10.4.2 Choosing the right admixture

The choice of an admixture or a suite is guided by the composition of mixture. Based on a comprehensive study reported in this dissertation evolving a single criteria or a parameter to estimate the relative performances of admixtures seems to be less practical. Based on the study conducted, the author would however like to offer a schematic summary of individual admixtures as is shown in Figure 10-12.

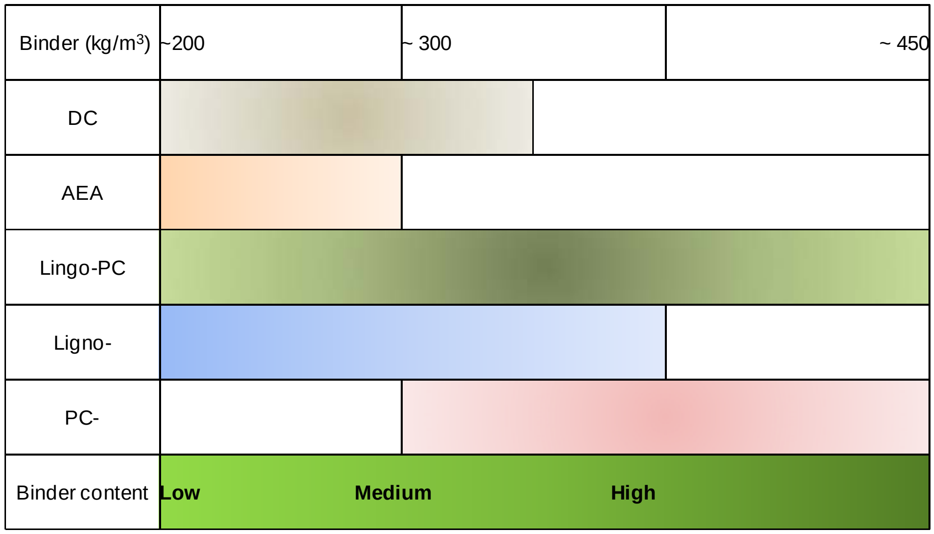


Figure 10-12 Recommended admixtures for different binder content ranges. Only technical considerations taken into account.

The above plot should be read with reference to the shade of the color. Darker shade implies more appropriate applicability, while lighter shade implies less applicability. Table 10-1 offers similar information.

Table 10-1 Binder content specific admixture selection

Admixture type	Binder content range (kg/m^3)	Best performance (kg/m^3)
DC	200-350	250-325
AEA	200-300	Lower end of binder; leaner mixtures
Ligno-PC water reducer	200-450	More towards center, ~300
Lingo-based water reducer	200-375	200-300
PC-based water reducer	300-450	300-375

10.4.3 Explanation of plasticification and water reduction of concrete

An explanation for the plasticizing and water reducing effects of some of the admixtures was offered. Figure 10-13 is reproduced here. Initially the water-reducing admixture is used to plasticize the drier mixture and bring it to a stage of compactibility. After this level is achieved, then the water reduction starts.

Comparisons were made between various water reducing and retarding admixtures and relationships and comparative statements were offered. The PC based water reducers were found to be most effective over a wider range than the other admixtures. Ligno-based admixtures followed closely, although their early age strength development was relatively poorer. The blends of ligno-PC showed intermediate performances. The cost effectiveness of these admixtures was not computed.

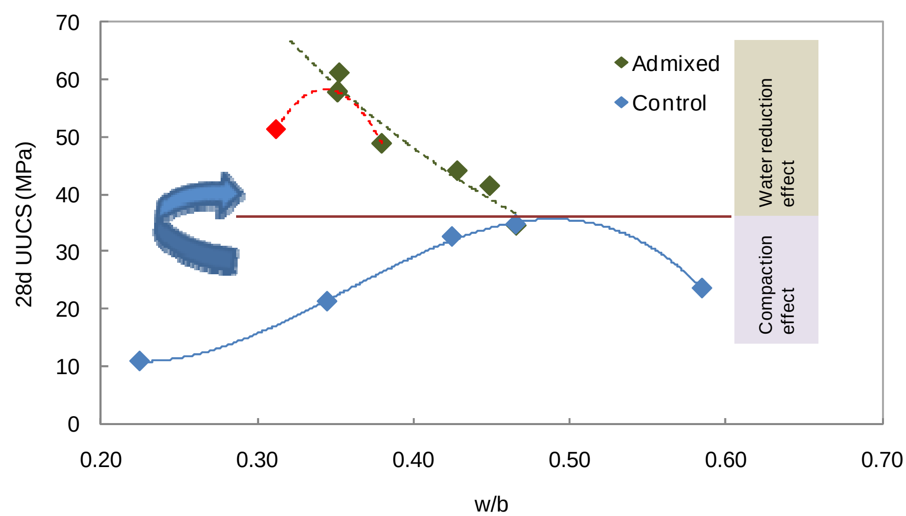


Figure 10-13 Explanation of plastification and water reduction

10.4.4 Explanation for air entrainment and strength development

Mixtures entrained with air followed different trends and had to be analyzed while taking into account the air content in the water/binder ratio. The chemical constitution of AEA decides its air entraining potential. The strength of RCC, in fact increases with some air entraining admixtures. There is a competing tendency between the air entrainment and water reduction by an AEA and the superior of these two manifestations leads to more pronounced effect respectively. A sample analysis is reported in Figure 10-14.

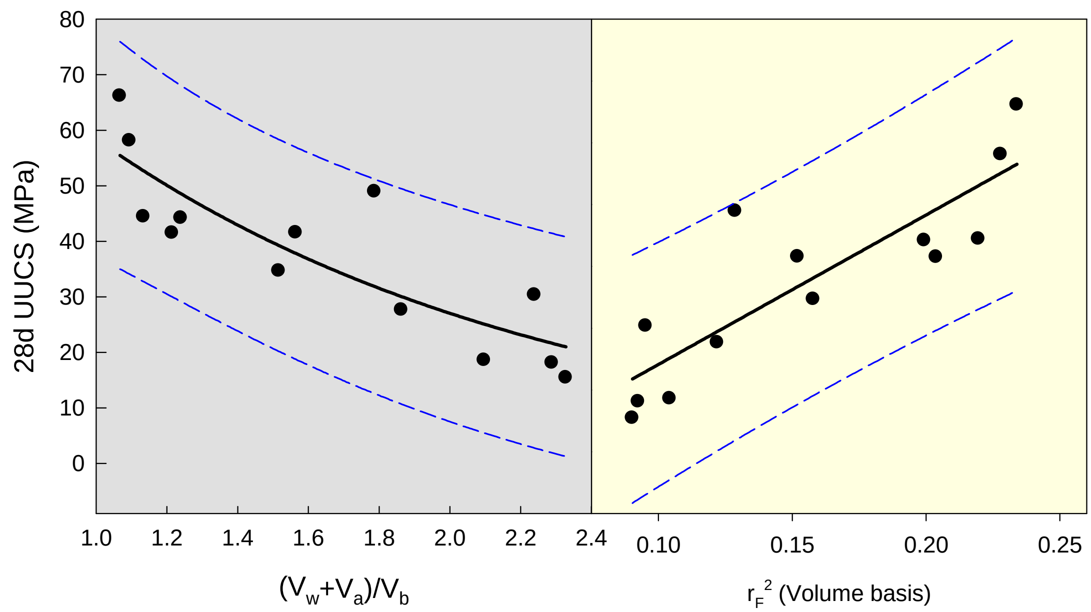


Figure 10-14 Strength analysis for mixtures with different air contents

The results for dry cast and other products were also presented. The results indicate that the rheology modifiers have no significant effects on the strength evolution of different mixtures. Finally composite diagrams to illustrate the relative performances of different admixtures were developed. These diagrams will help choose the right admixture depending on the intended strength goal for a particular site.

10.4.5 Binary and ternary combinations

Binary and ternary combinations of admixtures were tested primarily to improve the fresh properties of concrete. Some of those showed improvements in the strengths of mixtures as well. Ternary plots were evolved in order to offer proof of concepts used for this work. Figure 10-15 shows a sample.

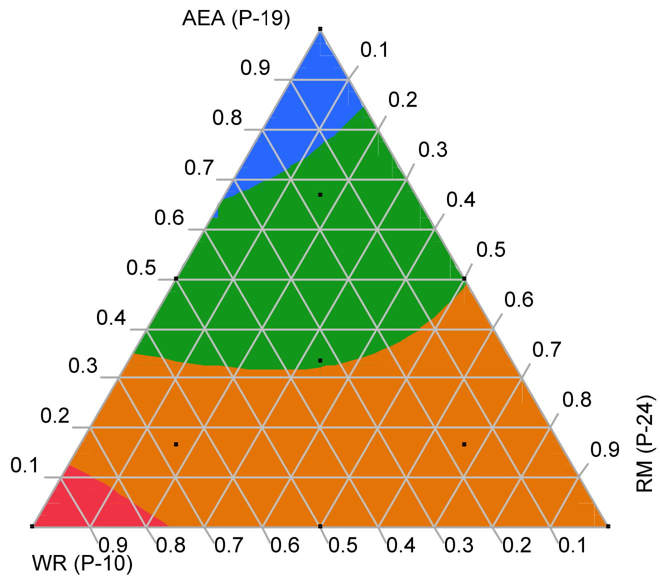
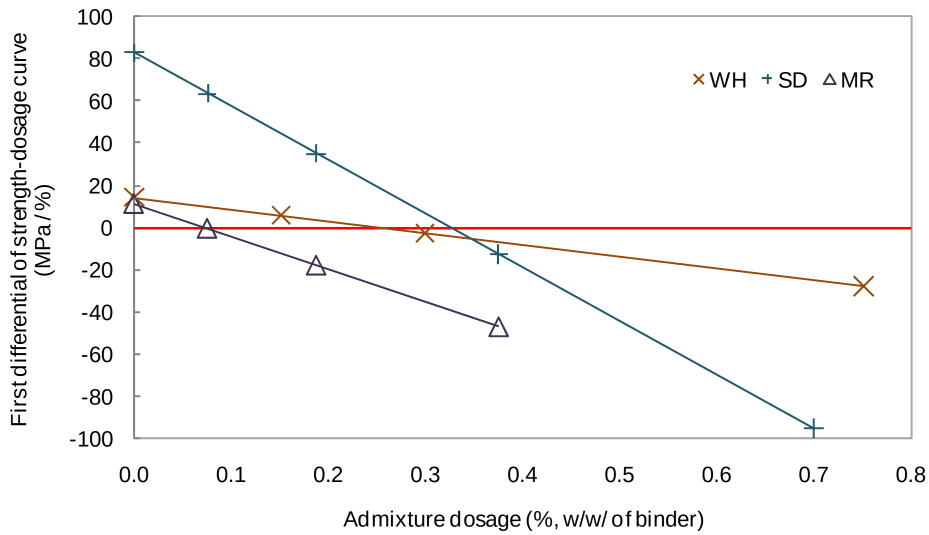


Figure 10-15 An example of ternary plot as obtained by using ternary blend of admixtures

10.4.6 Robustness and effectiveness range of admixtures

One of the important outcomes of this study was the evaluation of the robustness and effectiveness range of different admixtures. Chemical admixtures were found to be robust depending on the composition of concrete (hence the availability of paste). Figure 10-16 shows an example of the set of AEA tested in this work.



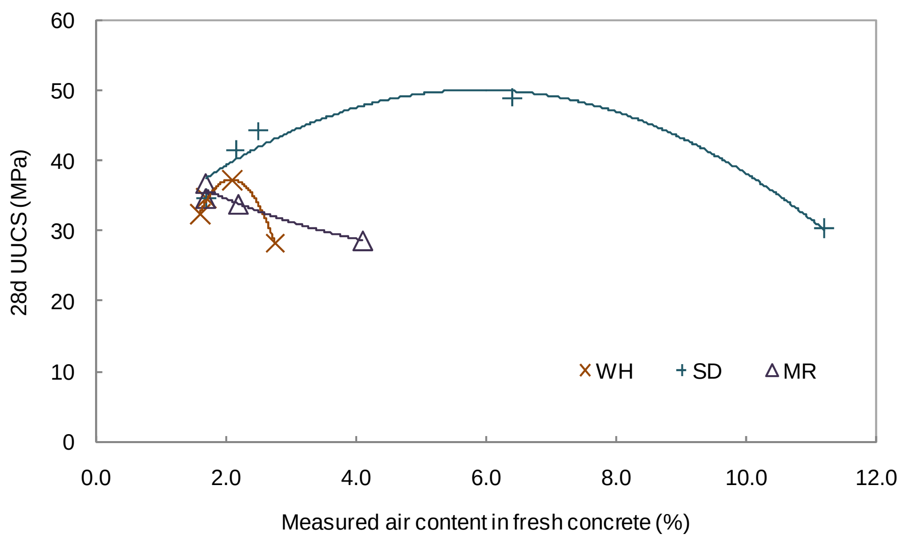


Figure 10-16 Strength-air content and admixture dosage: Robustness

Similarly there are must be some mechanism by virtue of which a given admixture chemistry becomes most effective over a certain binder content range for a binder. This is demonstrated in Figure 10-17. Similar results were presented and discussed for other admixtures as well.

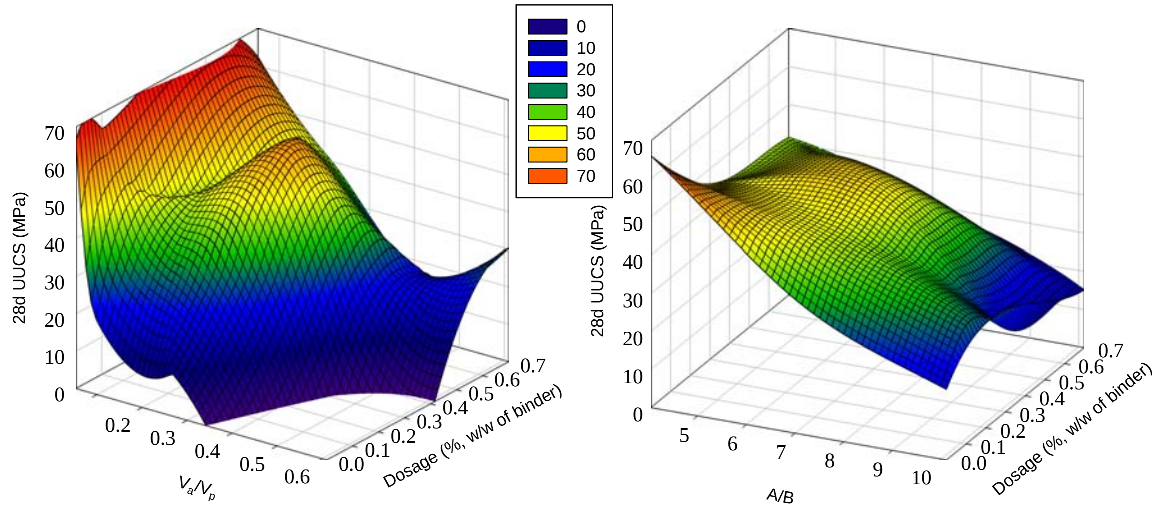


Figure 10-17 Interaction effects of AEA dosage on strength

10.5 Contribution to the existing body of knowledge

A synoptic view of the contribution of this work to the existing body of literature is as follows:

- Concepts related to paste: This work offered perspectives on approaching a mixture from multiple perspectives. Significant amongst these were the use of paste concepts. Paste quality and quantity both were used in describing different manifestations of the properties. This approach is becoming increasingly important considering the fact that we are transitioning from previous generation of materials to a more unpredictable age with multiple choices.
- Different attributes of workability: Workability was characterized into its components including cohesion, angle of internal friction, compactibility and consistency. This has helped advance our understanding about the material parameters that influence these properties individually. Furthermore, this work has initiated multiple new terms and concepts that can successfully be applied in appreciating different aspects of concrete workability.
- Multi-disciplinary research: The intermixing of concepts from other areas of studies and the borrowing of multiple instrumentation techniques have made this work a

cross-disciplinary work. Moreover, the application of these techniques was founded on statistical investigations, thus establishing their validity and precision for their use in concrete.

- Explanation of fundamental mechanisms: This work has explained some of the fundamental mechanisms that control concrete behavior contingent to its composition. Such explanations have opened up avenues for further discussions and research.
- Research on chemical admixtures: Research on chemical admixtures have been a privilege and prerogative of admixture manufacturers. This research has opened new avenues for others related to concrete making materials. Moreover, statistical concepts of blending were applied and demonstrated with success.
- Influence on standards: It is anticipated that some of the findings from this work will influence the ASTM and other international standards.
- Interaction charts and methodologies: The beauty of this research lies in the fact that multiple correlation charts were evolved display the wonderful interplay of several factors taken separately and in congregation. It can be anticipated that these charts when stitched together could evolve a mixture proportioning philosophy

CHAPTER 11. INDUSTRIAL BENEFITS

CONTENTS

This chapter tries to highlight some of the key contributions that would help various industries involved. This includes the cement, admixture and construction industries. Some of the points and arguments are addressed through question and answers.

11.1 Some questions and answers

Is RCC a sustainable material?

The use of RCC can reduce the per unit cement consumption (hence the carbon footprint) in a mixture for a fixed strength. Since it derives a significant part of its strength from the aggregate skeleton, the strength achieved per unit cement content is usually comparable or higher than the conventional pavement concretes. Moreover, due to the aggregate interlocking, the flexural strength per unit compressive strength is also relatively higher. So if flexural strength alone is considered as a criteria for mixture proportioning, then the cement content could be further reduced.

In addition to this, RCC is a robust material in terms of its ability to accommodate wide range of raw materials. These include different kinds of binders and aggregates. As such this makes RCC more sustainable than the other types of concretes.

How can RCC be made more sustainable with the use of chemical admixtures?

Chemical admixtures when judiciously selected and supported by adequate laboratory testing have the potential to render multiple benefits. For instance, the use of appropriate water reducing agent can improve the compactibility and increase the strength. Optimization of binder and admixture dosages could yield enhanced benefits in terms of fresh and hardened properties of concrete. What is interesting from application perspective is a small expense of resources during the initial stages of mixture proportioning resulting in proper appreciation of the interaction effects produced by a binder and an admixture could greatly save on the per unit cost of the mixture. For example for a given binder, just increasing the binder might not render the required properties including strength; a combination of the right admixture chemistry and dosage at a much lower binder content could yield the desired results.

Specially chosen admixture chemistries can enhance concrete's performance in the long run as well. For example, this research proved that air can be entrained in RCC, if the chemistry and dosage are properly chosen. Air entrained concrete becomes more durable in cold regions and thus has extended service life.

Another important aspect of admixed concretes is as follows. With proper optimization of admixture or admixture combinations, RCC can be made paver compacted concrete. It is anticipated that in the presence of certain admixtures a consistent density throughout the depth can be ensured, which in case of non-admixed RCC is difficult to achieve. If good and consistent quality paver compacted concrete can be produced with the use of suitable admixtures, a lot of savings could be obtained in compaction cost.

It is also important to appreciate the fact that the carbon footprint for (organic or inorganic) chemical admixture is much less than the carbon footprint of a unit weight of cement. As such saving a unit weight or volume of cement enhances the sustainability value of concrete by much more than saving the admixtures.

Why do chemical admixtures require higher than manufacturer recommended dosages in RCC?

Roller compacted concrete is a drier consistency mixture. It also has less paste content, which has lower than normal water contents used in regular slump (> 25 mm) concrete. The effectiveness of many chemical admixtures is a function of the paste content and it reduces as the paste volume reduces. This is the first reason that needs to be appreciated well.

Most of the contemporary admixtures are formulated for routine concretes having measurable consistencies. Moreover, these are fine-tuned for some specific applications. This in turn implies that a particular admixture will perform best over a certain range of cement content and water/cement ratio and its effectiveness will reduce if this range is crossed. Evidently this implies that the admixture is optimized over a paste volume and hence composition and if this is crossed the admixture will not work with same effectiveness. This will either require altering the concentration of the active ingredient in the admixture or the admixture content itself in the concrete. Changing the concentration of the active ingredient in the admixture is usually beyond the scope of the end user (contractor or concrete manufacturer); increasing the dosage is however within possible means.

While appreciating above points, it should be noted that the manufacturer recommended dosage is for normal concrete and therefore is not applicable to RCC. The current work has established that using higher than normal dosage is safe and should be encouraged on the basis of adequate laboratory testing.

Can RCC be entrained with air?

Yes! RCC can definitely be entrained with air. It however requires extended dosing as discussed above. Moreover proper selection of admixture chemistries is required.

What process should be adopted for optimizing chemical admixture for an application?

As noted in this research although a chemical admixture might perform a function in normal concrete, the same function might not be performed in RCC. It should also be noted while stepping outside the manufacturer recommended dosage that there are potential side-effects. Hence, an elaborate testing is encouraged.

Optimization is a process that would require comprehensive testing. The following procedure is recommended:

- ► Choose a range of binder content, dividing the range into practically possible binder contents.
- ► Select different admixture chemistries or based on the recommendations from research select one.
- ► For each of the binder content, test a range of dosages, while measuring several relevant properties. It might be necessary to step outside the manufacturer recommended dosage range. The manufacturer should be consulted while doing so.
- ► Each of the measured performance parameters should be evaluated.
- ► The combination of binder and admixture dosage that provides the required set of properties within plausible economic means could be selected.
- ► It is also important to check the sensitivity of and admixture towards a particular mixture and under given construction conditions. For example a particular admixture may be robust at one temperature, but could become less robust (more sensitive) at another.

What are the recommendations and precautions should be accounted while using different admixtures?

The following is a sampling of the recommendations for the use of different chemical admixtures along with the precautions to be taken:

PC based water reducers

- At lower and intermediate dosages, these admixtures offer excellent overall performance. At higher dosages, there are concerns that need to be carefully addressed.
- These admixtures have an excellent potential for saving cement and/or binder.
- The finishibility of the concrete mixture improves.
- The admixture may require longer than normal time to start its activity. As such, the concrete may appear very stiff initially, but after some time (say 15 min or so), the appearance of concrete could dramatically change. In addition, their use in pugmills needs care and pre-screening.
- Higher dosages lead to higher water reduction and strength gain; however, these may entrain excessive air into concrete and make the mixture excessively sticky. Excessive air may not be a critical issue for RCC, although this should be assessed on a case-to-case basis. Presence of stickiness beyond a certain limit may not be something desirable and hence higher dosages should be carefully avoided.
- Care should also be exercised in assessing the setting behavior at various dosages.
- There are multiple formulations and families of PC-based admixtures available in the market. These could behave differently depending on their chemistry and hence detailed comparative investigations should be carried in lab before.
- RCC can be made paver compactable with the use of these admixtures.

Ligno-based water reducers

- This is one of the better admixtures from technical as well as economic perspective. Higher dosages can delay the setting of concrete; hence, care should be exercised while using such dosages.
- These can be used in hot weathers. Their use in mixtures containing SCM should be limited and prior testing is essential. In cold weathers, these admixtures could cause setting delays and poor strength gain.

- ► The compaction window can be extended as a function of the dosage and water reduction.
- ► The finishibility of concrete could be a concern, as this admixture has not shown any improvement in the finishibility.

Ligno-PC based water reducers

- ► These admixtures offer the advantages of both ligno- and PC-based water reducers and hence are a good intermediate solution.
- ► Care should be exercised in selecting the right product with adequate water reduction, improvement in cohesion, workability and finishibility and sufficient setting time. This has to be balanced with economic considerations.

Synthetic detergent based AEA

- ► These are highly water sensitive admixtures. A slight change in the water content could lead to dramatic changes in the entrained air content. Hence, the moisture contents of the aggregates should be monitored with extra care while using these AEA's.
- ► Similarly, it is important to have the batching plant well calibrated so that the dosing is controlled. Negative batching tolerances will not affect the mixture performance as much as the positive tolerances could.
- ► Variations in the dosages could lead to some drastic changes in the workability of concrete mixtures.
- ► Sole use of AEA could be permitted, provided a balance between the water reduction, air entrainment, workability and strength is tested in the lab. Else, it is recommended to use a retarding water reducer for retaining the compactibility of concrete.
- ► Other AEA types can be used with prior testing and evaluation as outlined in this work.

DC products

- The DC products are good solution for RCC, provided they offer adequate retardation.
- The surfactant-based product offers significant improvement in finishibility while not entraining excessive air in the mixture. There is no significant strength gain with its use; however, the workability improvement is significant. This product may turn out to be a cost effective solution.
- The PC-based product offers somewhat comparable advantages to that of PC-based water reducer. The strength gain is however not so significant, and this can be attributed to the relatively weak action of this admixture. Sufficient workability improvement can be achieved with good retention. This type of product may be a good alternative to PC-based water reducers, which are expensive.

What are some of the contributions of this work towards the development of standards?

The following observations are relevant in answering this question:

- Chemical admixtures mostly perform multiple functions and especially in a concrete like RCC.
- The performance of an admixture is a function of dosage and binder content.
- Currently there are two ASTM standards available for chemical admixtures. The first being ASTM C494, primarily for water reducers, retarders, accelerators and their combinations. While the second standard, ASTM C260 for air entraining admixtures. It should also noted that combinations of the materials that make combined admixtures performing functions as prescribed in ASTM C494 and C260 are also available.

Considering the above points and keeping the reported research in context, the following recommendations are offered:

- ASTM C494 defines water reduction on the basis of a fixed cement content. It was observed that water reduction is a function of the aggregate and binder systems and for the same admixture provides different values. Hence, water reduction should be defined based on the individual binder content. It could be possible that ASTM C494 is taking the intermediate binder content from a range of binders widely used in practice.
- There is a need for some broad based classification system in ASTM C494. The standard so far has been updated in accordance with the chronology of discovery of admixtures. In recent years, the admixture technology has been changing at dramatic pace. This has prepared the ground for us to anticipate and prepare this standard for a broad based classification which would accommodate more multi-functional products rather than classifying the products on the basis of their primary role.
- It was observed in the earlier stages that compatibility of different admixtures depends on several factors including materials related, test method dependent and ambient conditions dependent. There are no prescriptions for establishing compatibilities of admixtures under various conditions and with different materials.

How to optimize combinations of admixtures?

The optimization of admixtures should take into account the following considerations:

- In the initial stages ascertain that the admixtures that are proposed for combining are mutually compatible and play a synergistic role in enhancing the desired properties. This can be accomplished by simple testing on paste.
- Once the mutual compatibility is established, trials on mortars or concretes can be conducted depending on the availability of resources.
- The trials on mortar or concrete should take into account the possible range of admixture combinations required for imparting desired characteristics to concrete.
- Practical batching tolerances and mishaps have to be anticipated. This means that the admixtures being combined should possibly be checked over the

complete range i.e. each admixture starting from 0 to 100 % in the combination and at a particular dosage.

- Several dosages should be tested to be comprehensive. This shall ensure that compatibility is assessed over a range of dosage. Various conditions should also be applied for testing.
- The key thing is to capture the window that clearly establishes the range of binder and water/binder ratio over which the admixture is most effective.
- A proof of concept was offered in this work. Optimization of admixture combinations could be achieved through the application of proper statistical methods.

What test methods are recommended to characterize RCC workability?

Workability is a very broad term. For drier concretes like RCC, conventionally compactibility is considered as an appropriate characteristic. The following are some of the considerations to be accounted for in selecting an appropriate method:

- The Vebe test with a surcharge weight could be used, however it is a subjective test.
- The use of Cabrera slump value (CSV) is recommended because it is easy to perform, is less subjective and does not require additional skill or purchase of special instruments for characterizing the consistency and compactibility. It should however be noted that the range of CSV is very narrow and care should be exercised in interpreting the numbers as duplicate set is obtained, one from the dry side, the other from wet side of concrete.
- The use of intensive compactor is highly recommended as it offers realistic information on compactibility. The state-of-the-instrumentation in United States is not adequately geared towards the use of the contemporary gyratory compactors. There are some units available in the market that can be used. The use of gyratory compactor for RCC requires lowering down of the consolidation pressure. Although further work is required for optimizing compaction parameters, the recommended consolidation pressure for RCC is close to 150 kPa.

- Characterization of cohesion and friction angle requires scaling up of shear box. This could also involve capacity addition for pulling mechanism, load measuring devices, etc. Moreover, the concrete industry is not yet calibrated to appreciate cohesion and angle of internal friction for fresh concrete. Hence this set of measurement stands last on the recommendation list.

What is the recommended procedure for aggregate selection?

The recommended procedure for aggregate selection resulting from this work is as follows:

- After ensuring that the aggregates posses the required mechanical strength and long-term durability, the objective should be to choose an aggregate grading that would render the highest possible density and will be easily compactible. These two considerations might sometimes be mutually conflicting.
- Strength is not the only consideration, the finishibility is also important. Moreover a given aggregate system might need a certain minimum binder content to render the required performance characteristics in terms of fresh and hardened properties. A method for constructing the interaction diagram as suggested in the discussions can be used.
- Similar considerations hold for paste content.

11.2 Samples of proofs of concepts

Sample-1: Admixture requirement for a given water reduction and w/b ratio

Figure 11-1 shows a sample interaction chart. This chart shows the procedure for obtaining certain water reduction and the corresponding admixture dosage and reduction in the water/binder ratio. In turn this chart can also be used in estimating the binder content, provided other considerations are properly dealt with.

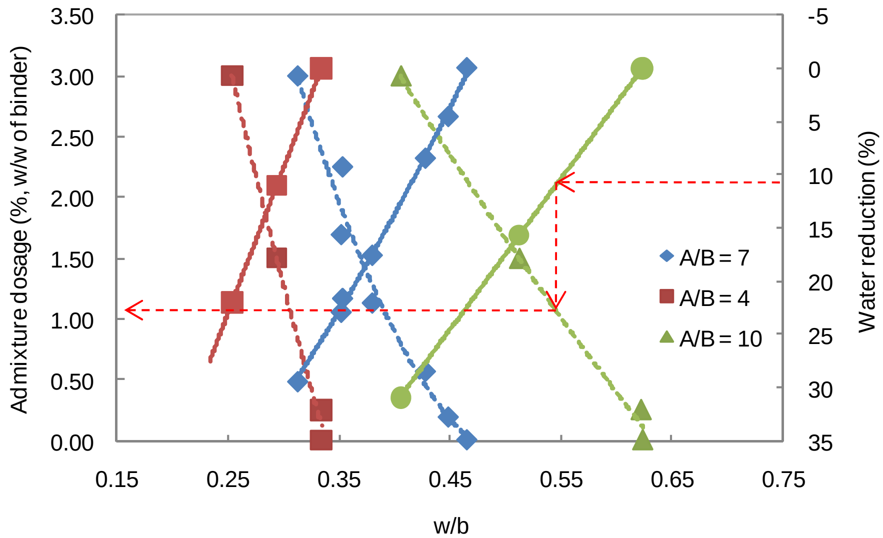


Figure 11-1 Interaction chart for selecting the admixture dosage for a given water reduction

Sample-2: Mixture proportioning chart

Figure 11-2 shows an interaction chart evolved from this study. This chart helps estimate the mixture proportions for a pre-finalized system of aggregates. The following are the salient points:

- ► To obtain the required strength for a given set of materials, there is a requirement for certain compactibility and hence cohesion in the fresh mixture.
- ► For obtaining these properties certain water/binder ratio needs to be chosen so that the required consistency and cohesion are obtained.
- ► For a given system of aggregates, the volume of paste can be estimated from the ratio of volume of paste/volume of voids in aggregates. This ratio should be carefully selected. At the lower end, the mixture will not have enough paste, will have excessive air voids and might end up having rock-pockets.
- ► An area is demarcated by the resulting air content. Lower volume of paste leads to excessive air entrapment and hence should be avoided. At the higher end of the paste, the mixture might tend to become excessively cohesive and uneconomical. Hence, higher end should also be avoided.

- For the two values of paste content there is a corresponding cohesion value which relates to a water/binder ratio.

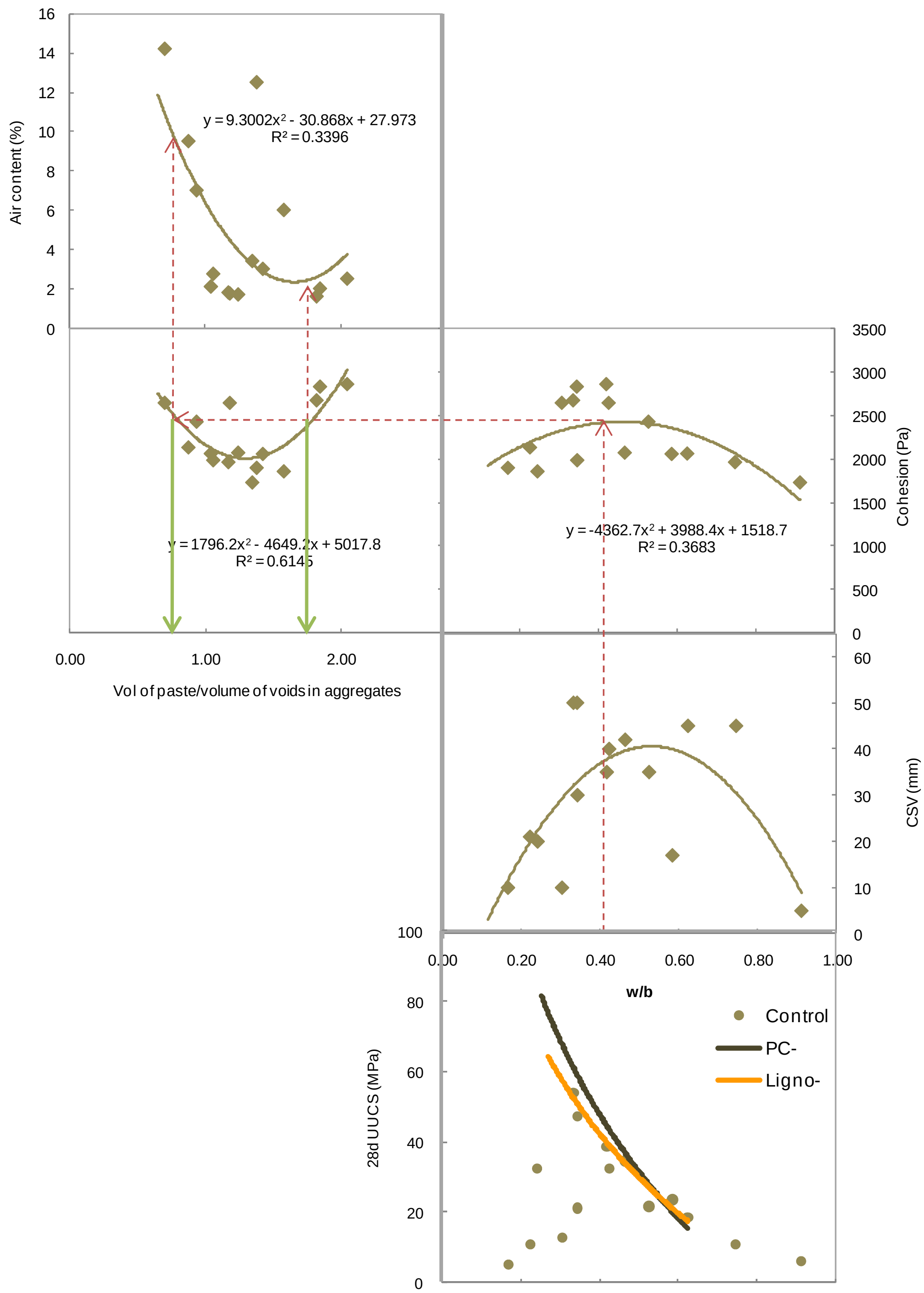
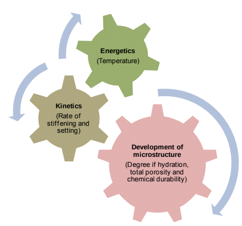
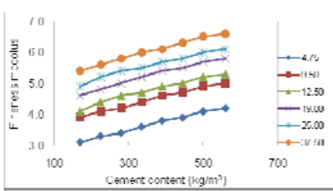
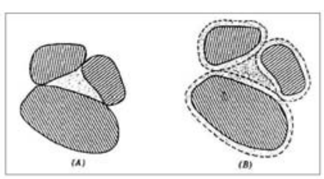


Figure 11-2 Single chart used for predicting fresh properties, material constitution and strength

APPENDIX A FUNDAMENTALS: MATERIALS AND CONCEPTS







SYNOPSIS

This chapter is a primer on the basics of cement chemistry, its hydration, setting and microstructural evolution; some aspects of aggregates in concrete, and water/binder ratio. The chapter starts with discussing the unhydrated cement phases followed by a briefing on the hydration of individual phases. This is then followed by the descriptions of setting and microstructural developments. Subsequent to this, a discussion on the influences of relevant aggregate characteristics on the fresh and hardened properties is offered. A synopsis of the cohesion and friction of fresh concrete, its measurements and typical values then follows. Finally, a critique is drafted on the water/binder (w/b) ratio and its implications is drafted.

Keywords: ordinary portland cement, hydration, setting, pores, aggregate/cement, cohesion, friction, water/binder ratio

CONTENTS

A.1 Introduction

The following sections present a brief summary of the main phases of ordinary portland cement (OPC) along with the hydration reactions, microstructural development and their implications.

A.2 Main phases: anhydrous cement

In terms of its mineralogy, OPC is a complex, multiphase material essentially composed of five phases (in frozen equilibrium, [1]) viz. calcium sulfates (tricalcium sulfate (C_3S)

and dicalcium sulfate(C_2S)), aluminates (tricalcium aluminate (C_3A) and tetracalcium aluminoferrite (C_4AF)) and some form(s) of gypsum ($CaSO_4$). Of these, the calcium silicates are in the greatest quantities while others are present in relatively minor quantities. During the burning operation of cement clinker, calcium combines with the other components of the raw mix to form the first four principal phases that typically make-up for more than 90% of cement mass. Gypsum (4 to 6 %) or other calcium sulfate source is added during grinding, possibly with other grinding aids. Due to the very nature of the raw materials, these mineral phases are always found in impure forms. The impurities exist in crystal structure, and could potentially alter the individual crystal structures of the primary phases. Table A-1 summarizes the four main phases of OPC along with their characteristics as noted in the literature and observed in field surveys. Calcium sulphate may be present as anhydrous calcium sulfate ($C\mathit{S}$), calcium sulfate di-hydrate ($C\mathit{S} \cdot H_2$) or calcium sulfate hemi-hydrate ($C\mathit{S} \cdot H_{1/2}$) [2].

Chemical analyses of OPC are typically reported as oxide equivalents (in addition to other properties and computations), although the elements are not necessarily present as oxides. Major elements as oxide equivalents include calcium (CaO), silicon (SiO_2), aluminum (Al_2O_3), iron (Fe_2O_3) and magnesium (MgO). Sulfate (SO_3) is present to regulate setting, drying shrinkage and strength gain.

Minor oxides (in amount) include, alkalies (sodium (Na_2O) and potassium (K_2O), titanium (TiO_2), and phosphorus (P_2O_5). They are largely included as impurities in the raw materials [2]. The insoluble residue represents a measure of adulteration of cement, largely arising from the impurities in gypsum. Similarly, the loss on ignition (LOI) shows the extent of carbonation and hydration of free lime and free magnesia due to the exposure of cement to atmosphere [1]. Typical oxide compositions of cements are widely available in the standard texts, research literature and can be obtained from cement manufacturing companies.

Table A-1 Main phases of Portland cement [1, 3-9]

Name	Tricalcium silicate	Dicalcium silicate	Tricalcium aluminate	Tetracalcium ferroaluminate
Chemical formula	$3CaO.SiO_2$	$\beta 2CaO.SiO_2$	$3CaO.Al_2O_3$	$4CaO.Al_2O_3.$
(alternate form)	Ca_3SiO_5	βCa_2SiO_4	$Ca_3Al_2O_6$	$Ca_4Al_2Fe_2O_{10}$
Abbreviation	C_3S	βC_2S	C_3A	C_4AF
Composition				
Impure Phase/Mineral name	Alite	Belite	Aluminate	Ferrite
Impurities	MgO, Al_2O_3,	Al_2O_3, Fe_2O_3,	SiO_2, MgO,	SiO_2, MgO,
Common crystalline form	Monoclinic	Monoclinic	Cubic,	Orthorhombic
Specific gravity	~3.15	3.28	3.03	~3.73
Particle size distribution (mass, %)				
< 7 μm	24	32	5.3	6.5
7-15 μm	42	26	5.8	6.6
15-25 μm	52	24	5.9	6.8
25-45 μm	51	28	6.5	7.1
> 45 μm	44	35	7.2	7.5
Typical ranges (anhydrous cement) (mass, %)				
United States	35-65	10-40	0-15	5-15
United States (Mill test reports, 1998)	42-67	9-30	6-14	1-12
Europe	45-65	10-30	5-12	6-12
Typical level (mass, %)				
United States	55	18	10	8
United States, (Average, 2004)	56.9	14.8	8.9	8.2
Europe	57	16	9	10
Cementing action				
Reaction rate with water	Moderate	Slow	Fast	Moderate
Strength	High	Low initially, high later	Low	Low
Heat liberation	High	Low initially, high later	Very high	Moderate
Heat of hydration (for complete hydration) (kJ/kg)	120.4-126.6	262	273.2-399.3	418
For cement at different ages	3 days	7 days	28 days	90 days
United States (kJ/kg)	242.5	303.5	247.8	416.0
Europe (kJ/kg)	255.2	322.7	262.0	434.2

At the particulate level, in its anhydrous state, OPC exists in the form of agglomerates of primary particles held together by forces ranging in magnitudes from very weak to approaching chemical bonds [10]. The grinding of clinker and gypsum results in the development of a greater number of electrical charges on the surface of cement particles; essentially, negative charges on C_3S and C_2S particles and positive charges on C_3A and

C_4AF particles [5]. Figure A-1 shows a pictorial representation of a cement grain and a microscopic image of unhydrated cement.

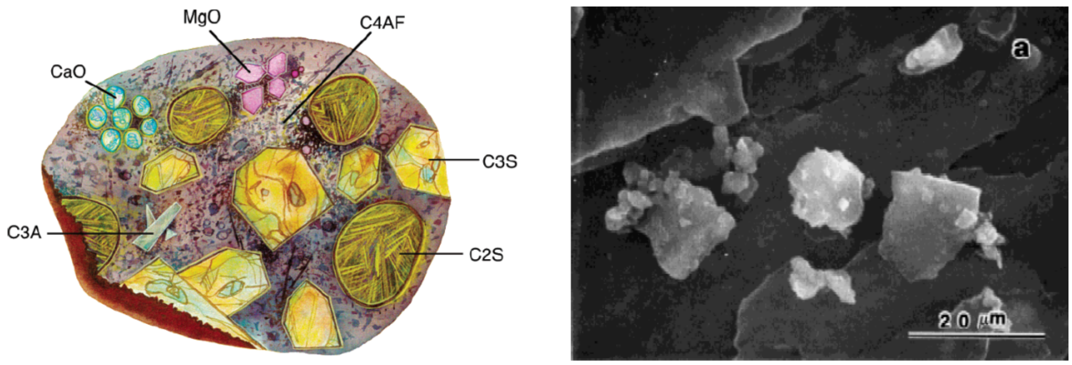


Figure A-1 L: A pictorial representation of a cross section of a cement grain [11]; R: SEM micrograph of un-hydrated cement [12]

A.3 The role of water

OPC is a hydraulically reactive material. It hydrates, sets and hardens to mostly stable and water insoluble compounds. As water is added to the cement powder, the paste undergoes transition from moist to semi-solid to paste-like state eventually rendering a consistency with which it (in its paste form) can be worked with. In this discussion, it is assumed that the water is of good quality.

Water fulfils two purposes, as reagent in reactions with cement particles and as a lubricant making the cement paste workable. At the particulate level, when the charged cement particles are exposed to a liquid, as polar as water, they have a strong tendency to flocculate. These cement flocs trap water that is no longer available to fluidize the cement suspension [5]. In a freshly mixed state, OPC paste is composed of grains of cement in an aqueous solution. The solid products of the hydration reaction occupy more space than the anhydrous particles and result in a rigid interlocking mass whose porosity is a function of the ratio of water to cement (w/c) [1].

Although arbitrary, in a hydrating cement paste, water is usually present in two forms. The first form is the chemically combined water, which is an integral part of the resulting cement gel. The second form is present in two variations viz. chemisorbed water and free water. The chemisorbed water is the adsorbed water at the surfaces of gel particles due to surface reactivity of the gel and this occupies gel pores. Free water on the other hand is the remaining water in a saturated paste and occupies capillary pores [13].

The minimum w/c required for achieving complete hydration of cement has been variously given from 0.36 to 0.44 [3, 14], with most widely accepted value of 0.38 [3]. The lower end of 0.36 is possible when water is available from external sources and of 0.42 when there is no water available from external sources [13]. Aitcin and Neville [15] and Mindess, et.al. [4] on the other hand argue that a w/c of not less than about 0.42 is necessary for full hydration to be possible.

At this point, it is important to note that although water is required for hydration and providing initial mobility to cement paste, it becomes a nuisance after these roles are finished. The basic issue is that of bleeding and can be seen (although on an exaggerated scale) in grouts. When cement grout slows down or stops, cement particles gravitate downwards at the same time as water floats upwards [16].

A.3.1 Process of hydration

Hydration of cement, as discussed in the literature, is a rather complex process consisting of a series of individual chemical reactions that take place both in parallel, and in succession. Consequently, anhydrous phases are transformed into hydrous phases with progressive development of structure in hydrated cement paste, temperature rise, changes in the absolute and apparent volumes of paste and a decrease in the volume of the interstitial solution in fresh paste [3, 5, 17].

There are three key aspects of cement hydration in the presence or absence of admixtures and are represented in Figure A-2. The presence of one type of admixture or the other influences the synergy between these aspects of cement hydration.

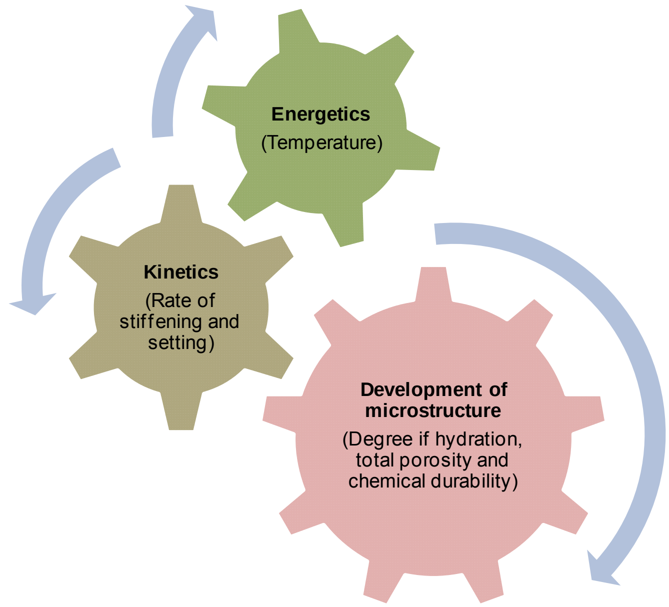


Figure A-2 Aspects of cement hydration

Hydrating cement paste consists of non-hydrated and hydrating agglomerates. Because of its wide variety of morphologically different structures that are changing with time, hardening cement paste is an example of highly disordered matter with a large technical relevance [18]. The following sections present a synopsis of the hydration of the individual phases of portland cement. The discussion excludes the chemical reactions, as these are widely available in standard literature.

ALITE (TRICALCIUM SILICATE, C_3S)

Alite (C_3S + impurities-Magnesium, Iron, Aluminum, Potassium, Sodium and Sulphur ions) is the most important constituent of OPC. To a great extent, it controls hardening and early strength gain [9]. C_3S typically exists in monoclinic form with its hydration essentially generating two types of complex hydrates viz. Portlandite (CH) and calcium-silicate hydrates C-S-H. Portlandite has pseudo-hexagonal crystals of up to 120 µm while C-S-H appears as a micro-crystalline, semi amorphous product (Griesser, 2002). Chemical substances like $CaCl_2$ and other chlorides accelerate hydration whereas phosphates, borates and salts of Zn^{2+} and Pb^{2+} cause retardation. Similarly, some organic compounds, especially different saccharides may retard the hydration of C_3S. Addition of anhydrite or gypsum can accelerate the hydration reaction [17].

BELITE (DICALCIUM SILICATE, C2S)

Hydration of Belite (C2S + impurities-Magnesium, Iron, Aluminum, Potassium, Sodium and sulfur ions) produces structurally similar family of C-S-H along with Portlandite, but varies widely in Calcium/Silica ratio and the content of chemically combined water. On a mass basis, both Alite and Belite require approximately the same amount of water for their hydration, but C_3S produces more than twice as much CH than is formed by the hydration of C_2S [1, 9]. Although the hydration products are similar, the process of hydration progresses more slowly than Alite, eventually leading to better later age strength contribution. The hydration rate can be accelerated by the use of accelerators, however, these seem to be less effective with C_2S than with C_3S [17]. This could be due to the thermal history of this phase and the inherently slow nature of reactivity.

TRICALCIUM ALUMINATE (C_3A)

For practical purposes, it is not the hydration reaction of C_3A alone, but the hydration reactions of C_3A in the presence of gypsum that are important. These hydration reactions and the resulting products play a vital role in controlling the consistency of cement paste after dissolution and hydration commences, and hence the workability of concrete. Depending on the solubility of C_3A, which in turn is depressed in the presence of hydroxyl, alkali and sulfate ions, an initial reaction of C_3A close to the surface takes place immediately after contact with the mixing water. This initial reaction comes to a halt after a few minutes and only starts again after the induction period of four to six hours during which there is practically no further chemical reaction with C_3A [19].

TETRACALCIUM ALUMINOFERRITE (C_4AF)

The composition of the solid solution of C_2A–C_2F may vary between C_2 ($A_{0.7}F_{0.3}$) to C_2 ($A_{0.3}F_{0.7}$) and its hydration results in products analogous to that of C_3A, with or without gypsum. The hydration is slower and evolves lesser heat when compared to C_3A; seldom causes flash set and is significantly affected by the presence of gypsum. The reactivity of ferrite phase may vary in a wide range depending on the Al/Fe ratio and declines with increasing Fe content. Also the reactivity is slowed down in the presence of CH, gypsum or a combination of both in the order of (CH + gypsum)>gypsum>CH [3, 17].

FORMS OF CALCIUM SULFATES

Gypsum is added to cement clinker, where, upon hydration in the presence of C_3A (and due to high Sulfate/Aluminate ratio), a dense, coherent layer of ettringite ($Ca_6Al_2(SO_4)_3(OH)12.26H_2O$, $C_6AS_3H_{32}$) is formed rapidly on the surface of C_3A grains. This layer retards diffusion of dissolving ions and hinders the formation of the hexagonal hydrates, thus preventing flash set. Ettringite is stable when sufficient sulfate is present in the system, and is formed in a through-solution reaction, which then precipitates. This initiates the dormant period [17]. The reaction takes place in the solutions saturated with calcium and hydroxyl ions and the microstructure is observed as short prismatic needles. Else, monosulfate formed by the continued reaction between C_3A, ettringite and water in the absence of sulfate, crystallizes as thin hexagonal plates. The precipitation of ettringite contributes to stiffening, setting and early strength development of concrete [9]. In terms of energetics, this first stage is characterized by a peak in the heat evolution curve during the first 30 min [3].

The rate of hydration of individual compounds proceeds in the order $C_3A>C_3S>C_4AF>C_2S$. This rate will depend on the crystal size, imperfections, particle size, particle size distribution, the rate of cooling, surface area, the presence of admixtures, temperature, among others [14]. The hydration and microstructural development of OPC is significantly different from the individual components because of the interactions between the various compounds and their hydration products [20].

During the induction period, the hydrate-phase formed around C_3A prevents further rapid hydration. The concentration of CH in the liquid phase eventually reaches a maximum and starts to decline, while the concentration of sulfate ions remains constant as the fraction consumed in the formation of ettringite phase is replaced by the dissolution of additional amounts of calcium sulfate. During the acceleration period, the calcium sulfate completely dissolves and the concentration of sulfate ions in the liquid phase starts to decline [17]. During the deceleration phase, when the sulfur/aluminum (or gypsum to

C_3A) ratio falls below 1.5, the deficit caused due to consumption of sulfate leads to decomposition of ettringite (through-solution reaction with additional C_3A yielding monosulfate. This continues until all C_3A or sulfate is consumed.

Monosulfate is a group of minerals called 'AFm' phases. Ettringite is a member of a group known as AFt phases. The general definitions of these phases are somewhat technical, but ettringite is an AFt phase because it contains three (t-tri) molecules of anhydrite when written as $C_3A.3CaSO4.32H_2O$ and monosulfate is an AFm phase because it contains one (m-mono) molecule of anhydrite when written as $C_3A.CaSO_4.12H_2O$ [17].

A.3.2 An account of hydration kinetics

The actual process of cement hydration, for the purposes of modeling the development of microstructure, can be broken down into three parts:

- material dissolves from the original cement particle surfaces;
- diffuses within the available pore space and
- ultimately, reacts with water and other dissolved or solid species to form hydration products through aggregation.

A.3.3 An arbitrary division of timeline

The stages of hydration and the corresponding heat generation are pictorially represented in Figure A-3. The following are brief descriptions of these stages.

STAGE I: INITIAL STAGE (0-15 MINUTES)

Immediately after mixing, the cement powder and water act together to form a gel-like viscous liquid. Cement grains of different sizes are suspended in water. Materials start to dissolve from the surface of the grains and defuse into ions. The sulfate ions (from the gypsum) react with the aluminate ions (from C_3A) to form ettringite as very fine-grained crystals in the solution. These are very small to form bridges between the cement grains so the cement paste remains plastic. Ettringite starts to increase in the solution forming a gel, coating all grains. Some of the ettringite in the solution crystallizes as needle like crystals outside this layer. The rate of dissolving and diffusion of ions on the grain surface decreases as the ettringite gel gets thicker until no water can penetrate the gel to reach the grain surface to dissolve more materials and diffuse more ions.

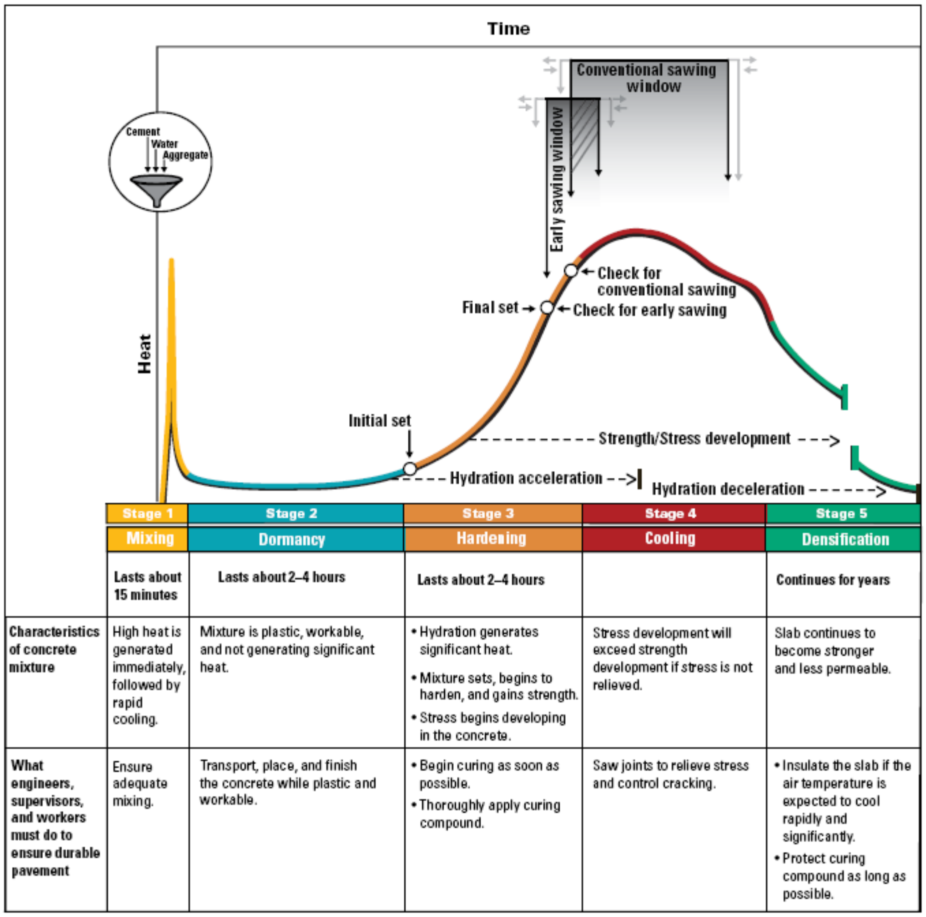


Figure A-3 General cement concrete hydration curve and its implications on concrete construction [21]

STAGE II: DORMANCY STAGE (INDUCTION PERIOD) (15 MIN-4 HOURS)

Because the solution around the gel is supersaturated with the ions, the diffusion of the ions stops. The ettringite gel is very thick now and it stops the water from penetrating the gel to reach the surface of the grain. Because some water already exists between the water and the grain, some materials dissolve and diffuse behind the gel barrier and with time. The ion concentration between both sides of the ettringite gel causes osmosis pressure that finally ruptures the gel.

STAGE III: ACCELERATION STAGE (HARDENING) (4-8 HOURS)

After the ettringite membrane is ruptured, water reaches the surface of the grain dissolving more materials and diffusing them into ions and because the solution around the grain is saturated, hydration products of the ions start to precipitate on the grain. This decreases the concentration of the ions, triggering more ion diffusion of different grains of cement. The dissolving of the grain surface and the ion release starts again increasing the heat generated. The same happens with the C_3A grain. As more ettringite is formed in the needle crystals, these needles interlock with other on the adjacent grains causing the cement to set (initial set)

STAGE IV: DECELERATION STAGE (COOLING) (8-24 HOURS)

Because of the hydration products building up by the minute, the water faces more difficulties in reaching the surface of the grain in order to dissolve more materials resulting in a decrease in the generated heat.

STAGE V: STEADY STAGE (DENSIFICATION)

With time, water is facing more thickness to reach the grain through the hydrates' pores; the reaction slows down but continues as long as there is water available for the ions to dissolve.

The following factors [17] determine the kinetics of hydration process:

- the phase composition of the clinker and impurities;
- the processing history of clinker;
- the quantity and form of calcium sulfate present;
- the fineness of cement;
- technology employed for comminution of cement;
- water/cement ration of the mix;
- curing conditions;
- hydration temperature and
- the presence of chemical admixture in the mix

A NOTE ON THE DEGREE OF HYDRATION

The maximum degree of hydration (α) for a paste with w/c < 0.38 may be computed by equating the total volume of paste to the sum of the volumes of unreacted cement and hydration product and is given by (w/c)/0.38. This assumes unrestricted supply of water is available during curing. If no such water is available, the degree of hydration is limited by the amount of water present initially to a maximum value of (w/c)/0.44 [3]. Further details are available in published literature.

A.3.4 Progression of setting

Setting of cement results from the evolution of cement paste [22] resulting in mechanical interlock of hydration products. The mechanical evolution is conventionally marked by two different stages marked as initial and final setting times. Physically, setting institutes the transitioning of cement paste when it starts loosing its plasticity and starts developing (with conventional measuring units) measurable mechanical properties.

Chen and Odler [23] reached the conclusion that setting in OPC is mainly due to the formation of solid phase built up through the random growth of reaction products. At some point, this growth becomes continuous across the sample mainly due to the formation of C-S-H surface products. This happens as long as the ratio between sulfate and C_3A+C_4AF is balanced. Jiang, et.al. [24] offer a description of the structure formation and setting of cement paste in terms of two fundamental processes viz. coagulation and rigidification. After water and cement are mixed, a weak, mechanically irreversible, thixotropic coagulation network is formed. Following this, the rigidification of the coagulated cement structure is provided by the formation of hydrates near the contact zones. As time progresses, the rigidified structure becomes mechanically more irreversible, and the increase of paste strength at this stage is proportional to the quantity of precipitated hydrates. Percolation theory has also been used to explain the setting of cement paste, but is considered to be beyond the scope of current discussion.

Lately a good description and interpretation [25] of setting of cement paste has been offered by combining various analytical techniques. Such studies were conducted previously as well [12, 26], but for the sake of clarity, the figures have been extracted from a recent reference. The SEM images obtained at various times as the cement paste evolves are shown in Figure A-4.

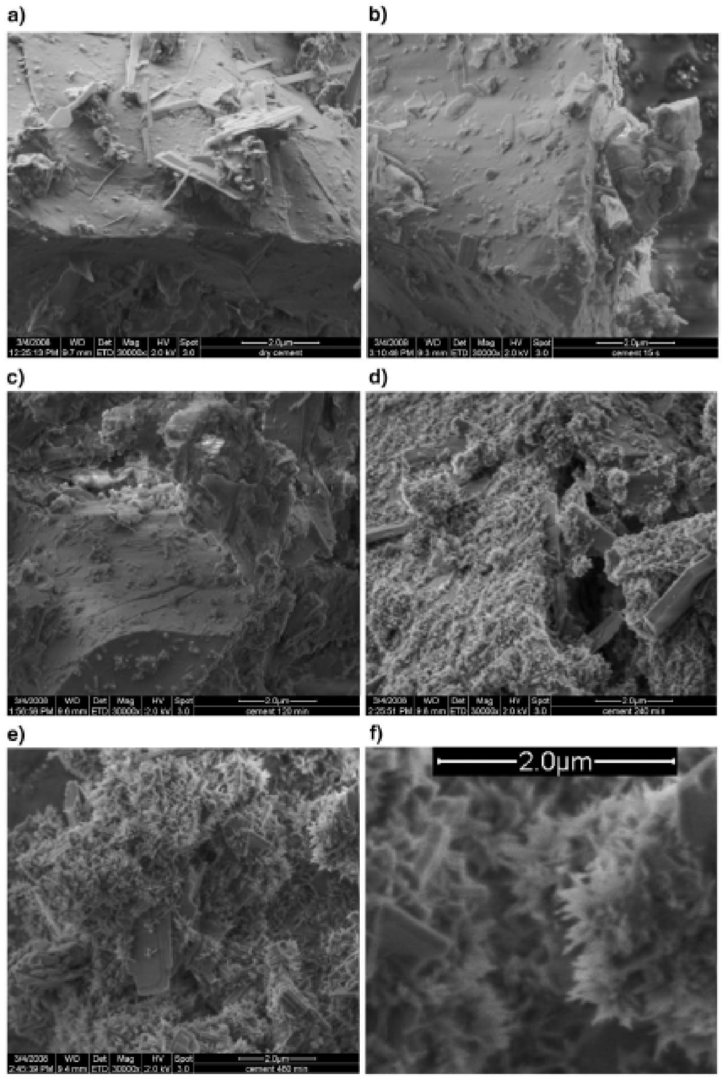


Figure A-4 SEM pictures of cement at different stages of hydration a) surface of unhydrated particle; b) Surface of the particle hydrated for 15s; c) Surface of the particle hydrated for 120 min; d)Surface of particle hydrated for 240 min; e)Surface of particle hydrated for 480 min; f) Surface of particle hydrated for 480 min at larger magnification [25]

A.3.5 Pore structure development

In the acceleratory stage of hydration, chemical bonds (exceeding the weak flocculating forces) develop at the points of contact between the individual cement grains. As the degree of hydration increases with time, the number of contacts increase, eventually growing into a continuous, three dimensional network of solids [17]. These hydration products (having specific gravity much lower than that of unhydrated cement) start building up, gradually occupying the volume approximately twice that of the volume of unhydrated cement [1, 13]. The network of solids and graded pore spaces is made up of cement gel (consisting of hydrates and gel pores) and capillary pores. Table A-2 provides a summary of the pores present in a cement paste.

Table A-2 Pores in cement paste [4, 27]

Type	Category	Diameter (μm)	Role of water	Paste properties affected	Methods for characterization
Gel	Micropores (interlayer)	$\leq$ 0.0005	Strutural water involved in bonding	Shrinkage, creep at all RH	Gas absorption/desorption
Gel	Micropores	0.0005-0.0025	Strongly adsorbed water, no menisci form	Shrinkage, creep at all RH	Small angle scattering, NMR, gas absorption/desorption
Gel / Capillary	Small (gel) capillaries	0.0025-0.01	Strong surface tension forces	Shrinkage between 50% and 80% RH	Small angle scattering, NMR, gas absorption/desorption
Capillary	Medium capillaries	0.01-0.05	Moderate surface tension forces	Strength, permeability, shrinkage at >80% RH	Mercury intrusion porosimetry, electron microscopy
Capillary	Large capillaries	0.05-10	Bulk water	Strength and permeability	Mercury intrusion porosimetry, Optical/electron microscopy

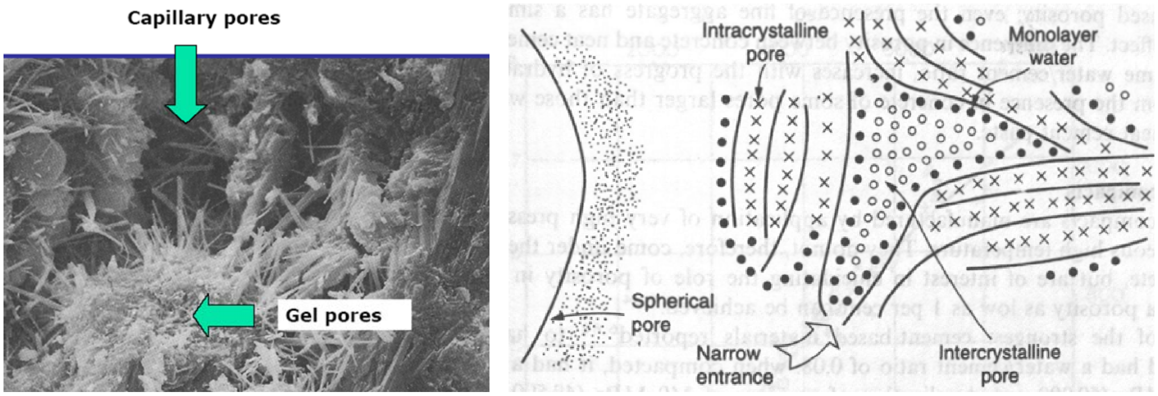


Figure A-5 L: SEM micrograph of pores seen in concrete microstructure; R: a schematic sketch of different pores [1]

Physically the development of pore structure also means that progressively the deformability of cement paste is reducing with time. It is reported that the degree of hydration, w/b ratio, binder composition, and particle size distribution are amongst the primary factors affecting pore structure development [28-29]. Figures A-6 show the changes in the volumes of hydration products at different w/c based on the model proposed in a paper by Jensen and Hansen [30].

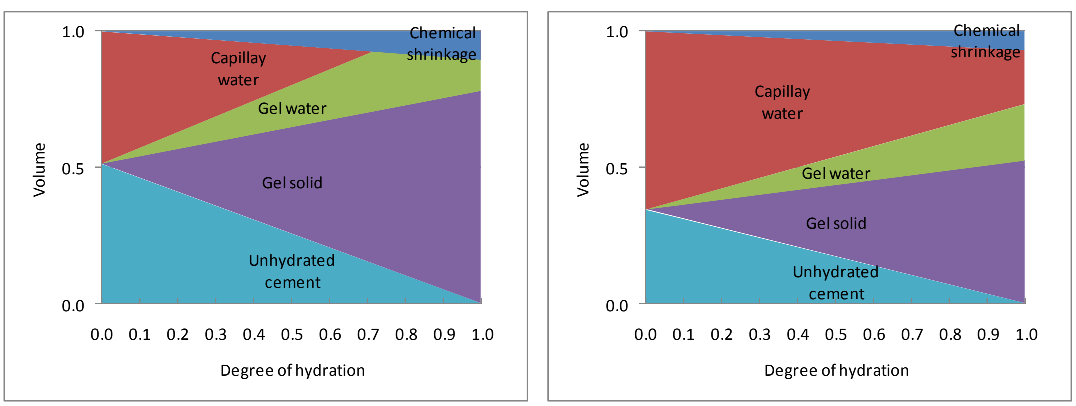


Figure A-6 Volumetric phase distribution of cement paste at w/c = 0.3 (L) and w/c = 0.6 (R)

A.3.6 Composite picture of cement hydration

It has been said [5] that OPC hydration occurs within the eternal triangle: strength, heat and volumetric variations represented in Figure A-7. In summary, portland cement hydration corresponds to:

- a succession of chemical reactions that transform the anhydrous phases of OPC into hydrated phases;
- the appearance of a progressive development of structure in the hydrated cement paste that in the case of concrete, is manifested initially by a more or less progressive slump loss and then a strength increase;
- a temperature rise;
- changes of the absolute and apparent volumes of the paste and
- a decrease in the electrical conductivity of the interstitial solution in fresh concrete.

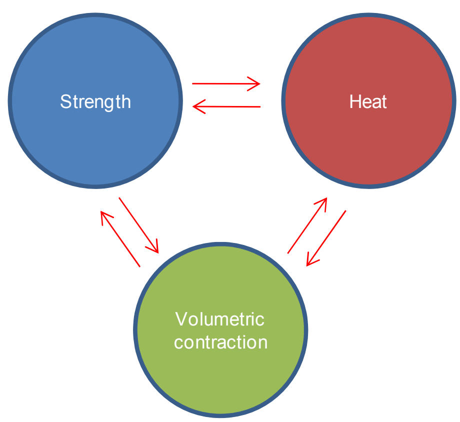


Figure A-7 The eternal triangle of cement hydration

The rate of hydration of cement decreases continuously with time, so that even after a long time there remains an appreciable amount of unhydrated cement [1]. Intimately linked is that fact that the cement paste microstructure is not constant but rather changes over time.

A.4 Role of aggregates

Aggregates play a decisive role in determining the properties of concrete in its fresh, transitional, and hardened states. Aggregates in conjunction with binders and in mutual dependence influence the properties of concrete. The following is a relevant summary of aggregate characteristics influencing concrete properties:

Grading especially that of fine aggregate is important in deciding the water demand. This takes place through the influence of the surface area (to be wetted) and the relative volume of aggregate in a mixture. Specific attention is paid to fractions passing 600 µm. The finer fractions (passing 150 µm and 75 µm) are reported to have significant influence on the cohesiveness and bleeding characteristics of a mixture [31]. The shape of the aggregate influences the water demand and nature of packing of aggregates. As the angularity of the aggregate increases, the water demand of aggregates also increases.

A.4.1 Cement content vis-à-vis aggregate

The desirable conditions for good workability include:

- the average particle size of combined grading should be close to the optimum value and
- the grading should contain a reasonable amount of fines.

Figure A-8 shows the effect of maximum size of the aggregate on the water demand of concrete. Similar trends as shown in the left hand side figure are observed for non-air entrained concrete. Aggregate grading has a non-linear effect on the water requirement of concrete and the water requirement contributions of the individual size fractions vary from one concrete to another. The water requirement values are minimum for optimum grading. The coarser the grading, the lower the water requirement up to a certain optimum coarseness, beyond which the water demand increases rapidly with increase in the coarseness. Small deviations, however, will not cause sizable differences in the water requirements. At the same time, it is important to note that the grading effect decreases with the increase in the cement content [32].

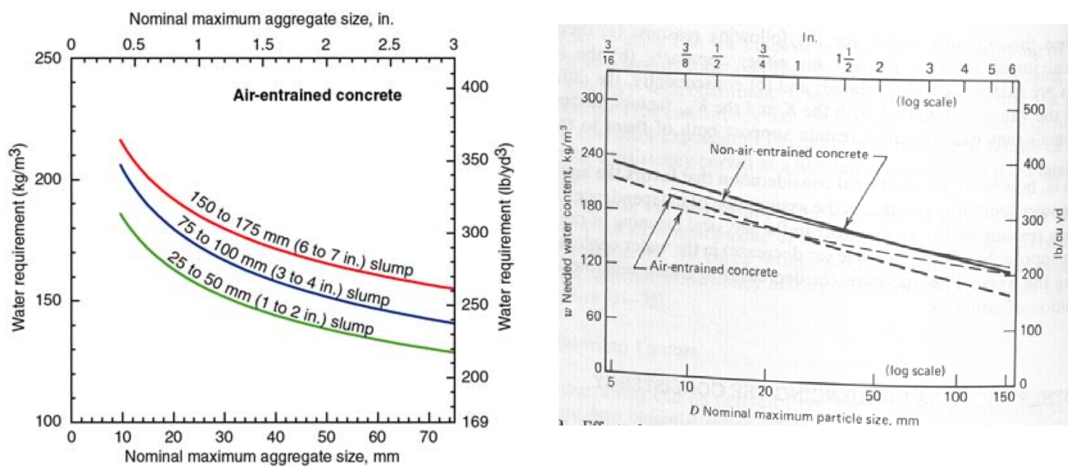


Figure A-8 Effect of the maximum size of the aggregate on the water requirement [32-33]

GRADING AND SHAPE

There are maximum permissible values of the fineness modulus (FM) of aggregates that can be used when producing workable concrete. These have been formulated by different researchers. A sampling is reproduced in Figure A-9. When the FM is considerably less than the minimum value and/or when the amount of the fine particles is excessive, the concrete consistency becomes drier for a given amount of mixing water. When the fineness modulus is greater than the maximum and/or the amount of fine particles is too small, a harsh mixture results, regardless of the amount of water, which in turn is detrimental to the workability of concrete [32].

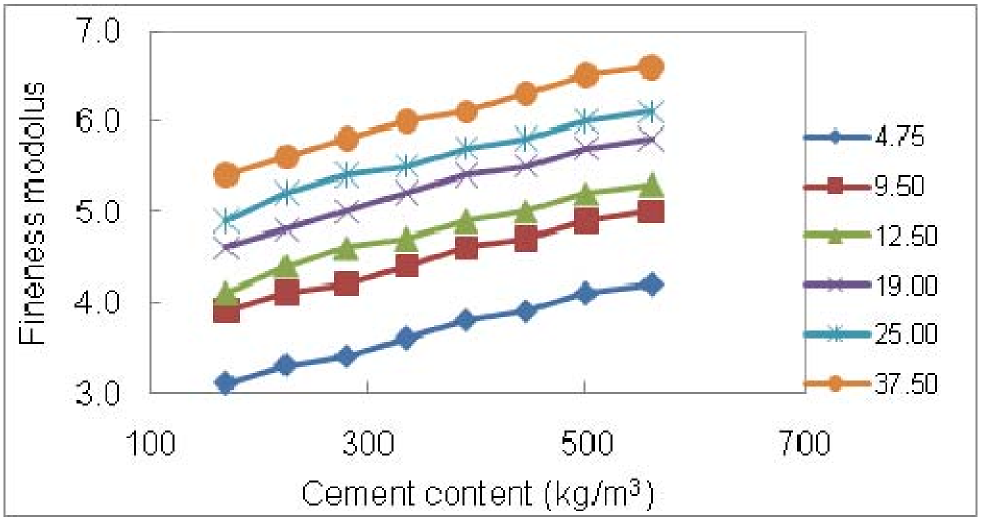


Figure A-9 Maximum permissible (optimum) values of fineness modulus for sand and gravel with different FM [34]

The water requirement of the concrete increases with increasing aggregate angularity, flakiness, and/or surface roughness. Figure A-10 shows an example of the effect of voids content on the water requirement of concrete. It is generally accepted that the angular aggregates tend to have higher water requirements than rounded shaped aggregates. The exact effect will depend on several factors. The particle shape effect decreases with increasing cement content.

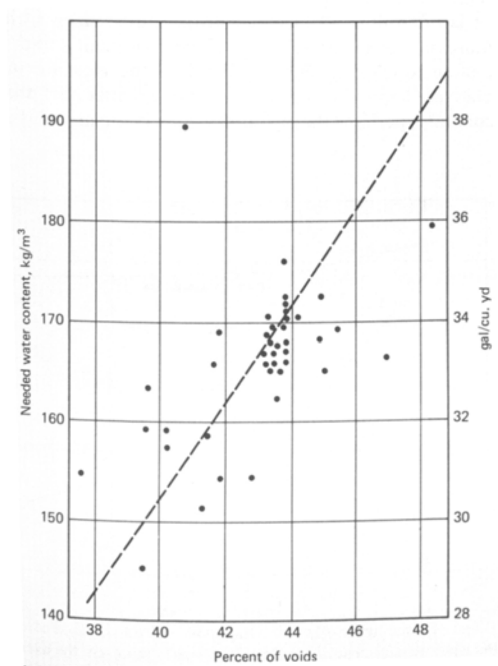


Figure A-10 Effect of particle shape (and hence voids content) on the water requirement of concrete [35]

Although aggregate/cement (A/C) ratio is only a secondary factor, for a given w/c ratio, leaner mixes tend to offer higher compressive strength. See Figure A-11. This is not fully understood; it could possibly be due to lower shrinkage and bleeding and therefore less damage to the bond between the aggregate and the cement paste. Else, it could also be explained on the basis of the fact that leaner mixes tend to have lower volume of water in a unit volume of concrete [1].

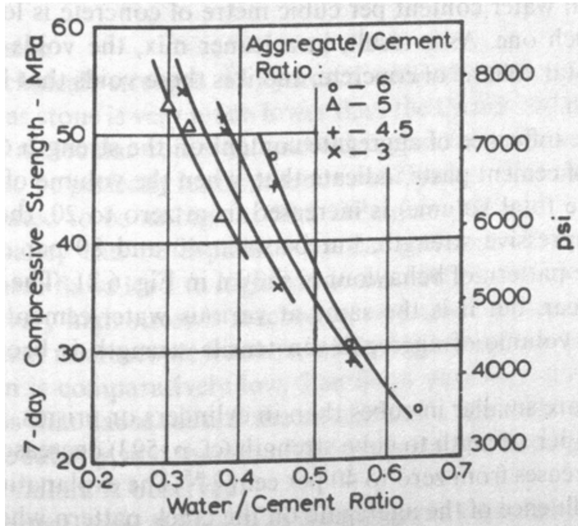


Figure A-11 Effect of the different aggregate/cement ratio on the compressive strength [36]

A.5 Miscellaneous

THE EXCESS PASTE THEORY

Powers [37] defined optimum paste consistency as the consistency at which the solids content of the paste and the paste content of the mix are such that they produce the maximum solids content possible with the given materials. For a concrete mix to become plastic, the volume of the cement paste must be sufficient to fill the interstitial space of the computed aggregate, plus an increment that causes dispersion of the aggregate particles. Figure A-12 shows this pictorially.

The excess paste theory states that the consistency of concrete depends on the following two factors:

- the volume of cement paste in excess of the amount required to fill the voids of the compacted aggregate and
- the consistency of the paste itself.

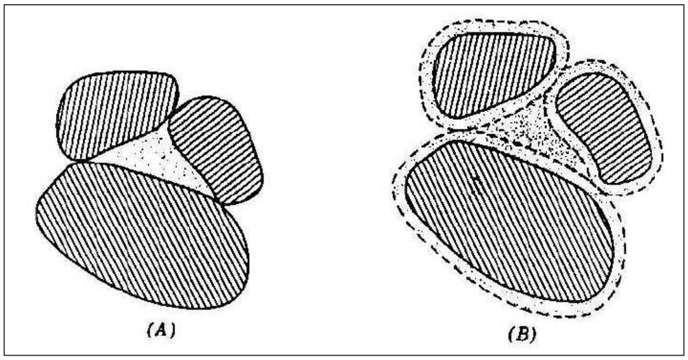


Figure A-12 Transition from dry compacted state of aggregates to dispersed in cement paste

If the aggregate/cement ratio is kept constant, then the workability is governed by the water amount. In addition to this, the air content of concrete is affected by the aggregate/cement ratio. This is shown in Figure A-12.

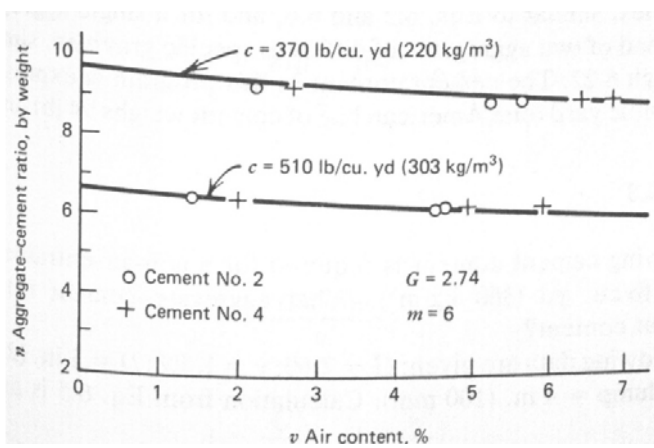


Figure A-13 Effect of A/C ratio and cement content on air content

A/C-W/C-WATER CONTENT

From the mixture proportioning perspective, there are three factors viz. w/c, aggregate/cement ratio and water content that are important and at a time, only two are independent [1]. It becomes critically important to appreciate the fact that there are limits up to which a mixture can be made cement rich or cement deficient and can still render desirable properties. This is often mentioned in terms of aggregate/cement ratio and for a given nominal maximum size of aggregate, there is a range within which workable concretes can be produced. Figure A-14 shows examples from published research. While analyzing any research these facts should be considered.

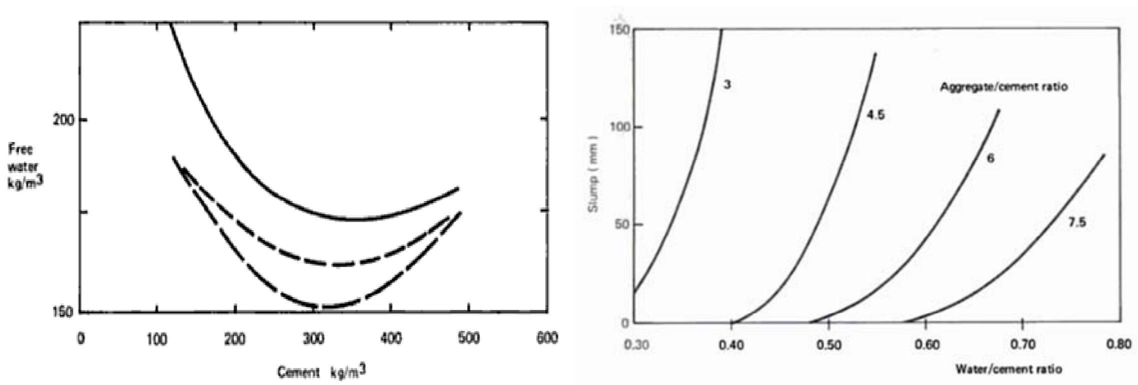


Figure A-14 L: Effect of change in cement content on the water demand at a fixed slump of 50mm; R: effect of aggregate/cement ration on relationship between slump and w/c [38]

COHESION AND FRICTION OF CONCRETES

The methods of determining cohesion and friction for concrete could be similar to those that are applied in soils. Triaxial testing of fresh concrete is reported to render greater than true values [37] and hence is not discussed here.

Direct shear test has been used by L'Hermite [39] and Popovics [40] for assessing the cohesive strength of concretes. Figure A-15 shows a schematic sketch along with resulting stress-strain diagrams. Tassios [41] on the other hand used a special direct shear box on over 500 concrete mixtures.

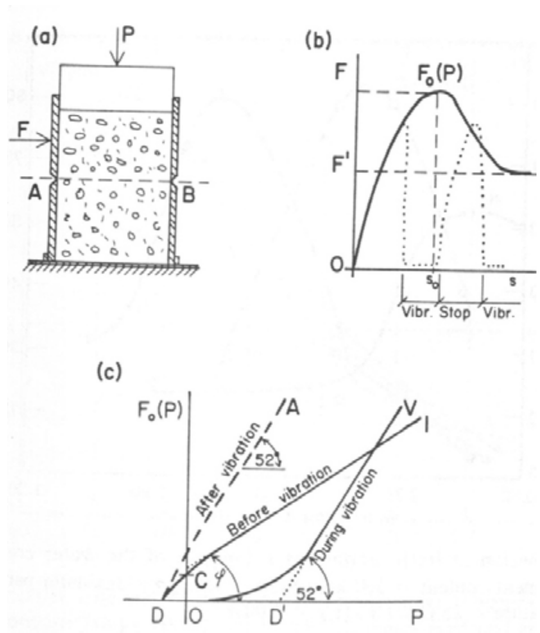


Figure A-15 Direct shear test of fresh concrete, stress-strain curve and interpretation [40]

The following inferences from these studies are relevant:

- when the displacement (s) value is small the shearing force (F) is controlled by the properties of mortar; with large s such as s_0 the interference of the coarse particles is dominant;
- the steeper the first part of the curve, the stiffer the mixture;
- the area under the curve O-F_0(P)-s_0 represents the work required to cause shear rupture;
- the effects of water content and grading are shown in Figure A-16 [39-40];
- cohesion is usually attributable to the surface tensions of fine materials and/or the tensions of the quasi layered structures of cement-gel's microcrystalline sub-stances;
- for every aggregate-grading and cement content, there is an optimum w/c for which maximum cohesion is obtained [41];
- the fresh concrete follows Coulomb's law for internal friction [42];

- the stress-strain diagram of fresh concrete also provides information about the cohesive strength of concrete and this method is particularly useful in case of low-slump concrete [43];
- the internal friction increases rapidly with an increase in the maximum particle size and increases moderately with increasing fineness modulus and angularity of aggregate, as well as with the decrease in the cement content. The effect of water content appears to be relatively small. Fresh concretes with medium cement content and about 75 mm slump usually have an internal friction angle between 28 and 32°. As cited in [32] and
- the shear test does not offer any direct information about the tendency of concrete to segregate, if there is any.

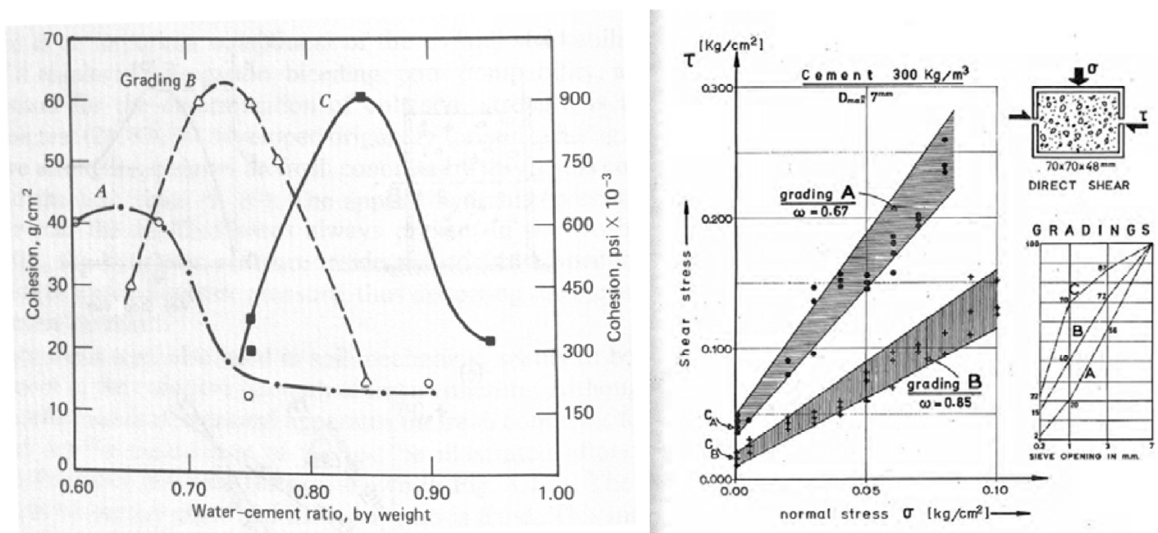


Figure A-16 L: Effect of water content and grading on the cohesion of cement mortar. As cited in [32];
R:Effect of grading on shearing stress of concrete [41]

Based on the above readings, the following interpretations can be drawn:

- for a given set of fine and coarse aggregates, there will be a combination at which the friction angle would be minimum;

- there are two components to characterizing the shearing behavior of concretes following Coulomb's law (acting as plastic solids), one there would be cohesion (shearing stress at zero normal load) and two angle of internal friction and
- for a given aggregate/cement ratio, there would be an optimum water content at which the cohesion would be maximum and there would be another water content at which the angle of internal friction would be minimum. This would be decided by the aggregate grading, shape, geology, cement characteristics and resulting consistency of cement paste.

A.6 Water/binder (w/b) ratio: Appreciations and implications

Based on 100,000 tests, Abrams [44] summarized the following fundamental principles:

- the strength of a concrete mixture depends on the quantity of mixing water in the batch, expressed as a ratio to the volume of cement so long as the concrete is workable, and the aggregates are clean and structurally strong;
- the effect of differences in the quantity of cement is reflected by differences in the water-ratio;
- the sieve analysis of the aggregate is the basis on which proportioning must be done. There is an direct relationship between the size and grading of the aggregate and the quantity of water required to produce concrete of a given workability;
- it is not necessary, or desirable, that the aggregate be proportioned according to any fixed grading; wide variations in grading of aggregate may occur without affecting the quantity of mixing water or the quality of concrete and
- the plasticity or workability is an essential requirement of concrete for structural purposes.

Based on this work and more, Abrams also offered a water requirement formula and maximum permissible aggregate fineness moduli. There has been additional work reported by others in the literature [37]. It is also stated that if adding cement is not accompanied by a reduction in water/cement ratio, it does not serve any useful purpose. The author has conducted some investigations in 2004-05 to test this fact. When the slump or workability of concrete is kept similar, increasing the cement content initially leads to an increment in the strength of concrete, reaches a peak and then starts dropping down.

Amongst others' works (Talbot and Richart, Lyse) and modifications (Thaulow, Swayze and Gruenwald, Walker, etc.) [32, 37], the work by Gilkey [45] merits a mention due to relevancy. His work states that for a given cement and acceptable aggregates, the strength that may be developed by a workable, properly placed mixture of cement, aggregate and water (under the same mixing, curing and testing conditions) is influenced by the:

- ratio of cement to mixing water;
- ratio of cement to aggregates;
- grading, surface texture, shape, strength and stiffness of aggregate particles and
- maximum size of aggregates.

The following is a relevant perspective:

- The Abrams' law and subsequent works are relevant for mixtures that are workable and have measurable consistency as characterized by slump test. Mixtures below a certain w/c ratio will actually show a drop in strength. Similarly, when this ratio exceeds the value of 1.2, the law may not remain valid. Figure A-17 shows an example.

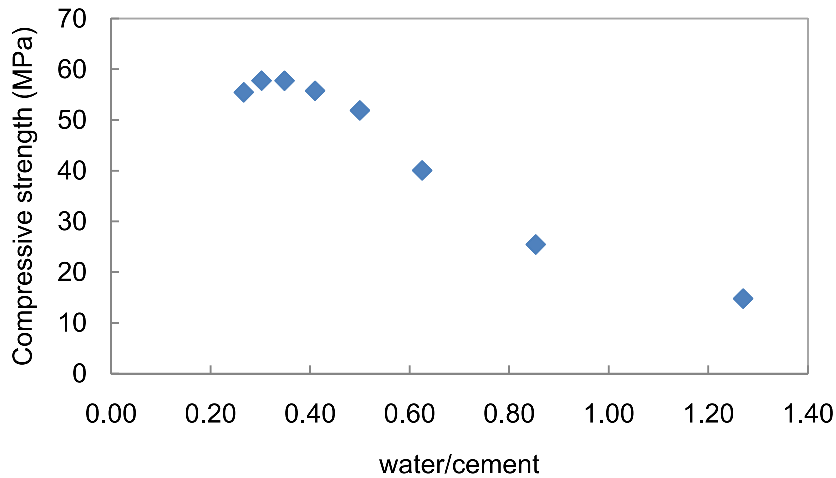


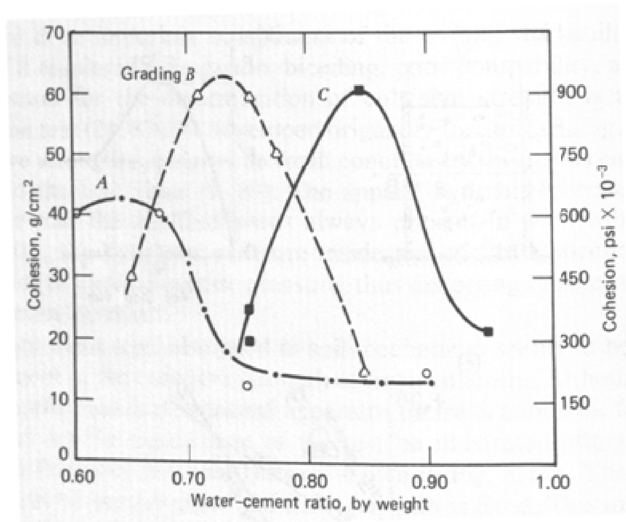
Figure A-17 Deviation from Abrams law [46]

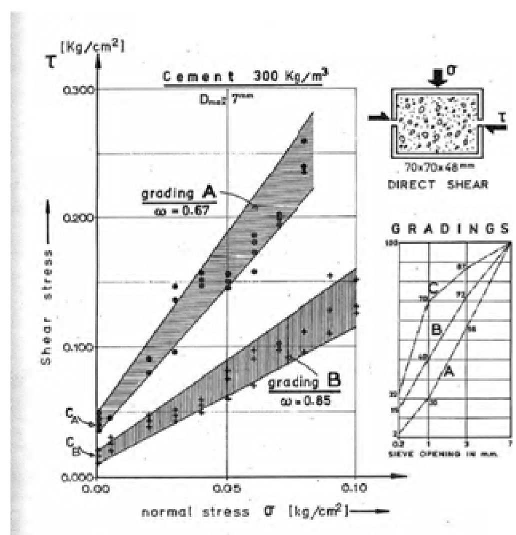
- The concrete is supposed to be fully compactable. It is interesting to think what actually is full compaction or maximum density.
- The reactions actually take place on a volumetric basis.
- The use of only portland cement is concrete mixtures is decreasing, however, since it still exists as the principal component of the binder composition and decides the kinetics of overall hydration and other reactions, we haven't found significant deviations from the Abrams law.
- It is also interesting to observe that over the years, the inclination is towards using higher consistency concretes that cannot be characterized fully by the conventional slump test.
- Similarly, concretes are heavily dosed with chemical admixtures acting by differing physio-chemical mechanisms. The reactivity of these chemical admixtures may not remain the same over all the w/c or w/b ratios and cement or binder contents.
- The role of vibration or method of compaction is an important consideration. Two extreme examples can be considered. In case of very dry mixtures like roller compacted concrete (RCC), the mixture is very dry and if it is compacted with routine effort used for conventional concrete, it would show a strong deviation from the above law. The fact that needs to be considered is that roller vibrations

momentarily reduce the yield strength of fresh concrete and allows the paste to become less viscous. This allows the paste to liquefy and concrete to get compacted in a small duration. Full compaction may or may not be possible in this case. On the other hand, in self-consolidating concrete, the density is governed more by the composition of the paste, which is heavily admixed with SCM's, fillers and chemical admixtures

SUMMARY

A composite understanding of behaviors of different constituent materials of concrete and their interplay is critical in understanding of any material. This chapter presented some fundamental dealings on portland cement, aggregates, water, their relative volumes on the performances of concrete. water/binder ratio is widely accepted and utilized in concrete world.





A critical appreciation required for further discussions was about the excess paste and how it influences the properties of concrete. Paste volume slightly higher than the voids in the aggregates is required for rendering better fresh, mechanical and durability performances. In drier mixtures, such as RCC, this relative volume of paste becomes exceedingly important. The composition of paste is also important and an understanding about the paste composition, its quality and quantity in a mixture helps anticipate and predict the material behavior. Aggregates play a vital role in filling up the space and their relative volume when compared to the binder volume offers an interesting interplay that eventually affects most of the concrete properties.

Our understanding about the cohesion in concrete and the relative internal friction is very meager. Similarly, our appreciation about strength and limitations of the Abrams' law, which is widely accepted and invariably used in many mixture proportioning philosophies, is rather poor. The caveat in applying this law to drier concretes is not properly understood and spelled out. Although water/binder ratio is invariably used in specifying and ordering concrete, it has its own limitations and should be used with caution. The advent of newer materials is making its use arbitrary.

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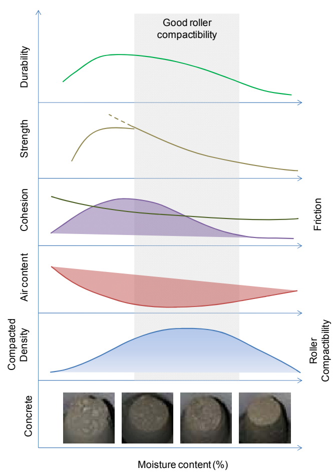
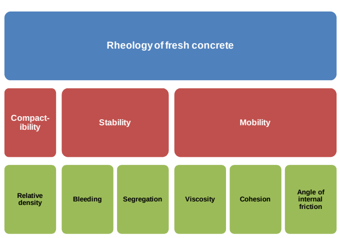
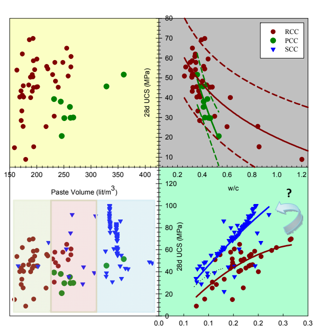
APPENDIX B ROLLER COMPACTED CONRCETE FOR PAVEMENT APPLICATIONS







SYNOPSIS

This chapter presents an overview of roller compacted concrete pavements from a materials' perspective while excluding the structural aspects of RCC pavements. After reviewing the worldwide applications of RCC, the chapter discusses the constructional aspects. This is then followed by discussion on the evolution of this concrete from dry to compactable state. Workability studies are briefly summarized. Main emphasis is given to the application of gyratory or intensive compactor and its applications in measuring consistency. Mixture proportioning strategies are briefly summarized followed by the materials used and researched for RCC mixtures. This section also presents a critique on chemical admixtures and the contemporary perception of their usages in RCC mixtures. Instead of entering into detailed studies, the mechanical properties are compared with conventional concrete in terms of cementing efficiency factors, paste content and water/binder (w/b) ratio. Similarly, the durability and performance attributes are reviewed by reference to the respective studies.

Keywords: RCC, applications, construction, workability, gyratory compactor, Mixture proportioning, materials, chemical admixtures

CONTENTS

B.1 Introduction

A brief history of roller compacted concrete pavements is presented in the ACI 325 committee's state of the art report [1]. RCC is conceived not only as a construction material but also as a construction method and has been widely applied for dam construction all over the world [2-3]. In the last quarter of the last century, RCC has been increasingly acknowledged and used for pavement applications with growing interest [4]. It is also recognized as dry lean concrete [5], no-slump concrete [6] and econocrete. Reported literature describes research and field observations on RCC for pavement applications in United States, Canada [1], United Kingdom [7-9], Turkey [10], Brazil [11], Australia [12-13], Sweden [14-16], Greece [17], Belgium [18], Japan [19-20] India [21-25] and Thailand [26].

As a material, RCC handles initially like a soil and sets up later to be a true concrete or concrete-like material, thus making it a unique combination of soil-concrete. Engineers designing RCC projects therefore come from a diversified background ranging from structural, geotechnical, geological, general civil, transportation and hydraulic specialties [27]. RCC for pavement applications is placed without forms, finishing, and surface texturing and without any requirements for dowelled joint, or other steel reinforcement. Because of its potential ability to accommodate a wide range of materials, this material and method offers engineering advantages in the form of reduced materials' cost, increased placement speed, and reduced time for construction and lower maintenance costs. It is claimed that initial cost savings of 15 to 40% can be expected if RCC pavement is specified as a pavement alternative for projects requiring heavy wheel loading compared to conventional paving concrete [28].

The composition of the RCC mixture is characteristic to its application. The applications include pavement bases (highway construction in India, UK); low maintenance roads and parking areas (General Motors, Spring Hill, TN, USA); industrial access roads surfaced with or without concrete overlay (Tennessee DOT, USA); inlay rehabilitation (City of Murray, Al, Canada); fast track intersections (Calgary, AL, Canada); shoulder constructions (I-285, Atlanta, GA, USA); city streets (Lane Avenue, CO, OH, USA); industrial roads (Plant Morrow, So. Miss. Electric power), heavy-duty pavements for ports (Port of Houston Authority, Houston, TX, USA); airport pavements (Portland airport taxiway).

RCC characteristically differs from the conventionally compacted pavement concrete (CCPC). Therefore, it is important to scan over some of these differentiating attributes. Figure B-1 offers a sampling of this comparison.

Table B-1 Sampling of RCC and CCPC attributes

SN	Point	CCPC	RCC
Materials	Cement content	Decided by the water demand of the aggregate system and w/c ratio of the mix Relatively higher for a given strength	Decided on % by weight basis required to achieve specified strength Relatively lesser for comparable compressive strength
	Aggregate grading	Comparatively less well graded	Very well graded to minimize voids
	Moisture content	Given by w/c ratio by weight	Optimum moisture content (OMC)
	Chemical admixtures	Primarily retarders, water reducers, Air entrainment	Not widely used
Workability	Consistency measurement	Can be measured by slump test, compaction factor etc. Vebe test is not very helpful	Vebe consistometer. Value depends on the surcharge weight used
	Theoretical density (NMSA,19mm)	Usually close to or greater than 98 % depending on mix constitution	Usually close to or less than 98 % depending on the mix proportioning method; could range between 95-98 %
Mixing/ transport	Concrete mixer types	Drum, pan, twin shaft horizontal, transit	Drum, pan, twin shaft horizontal, continuous flow, transit, pug mills
	Mixing energy required	Relatively lower	Relatively vigorous
	Transportation	Dump trucks, transits	By scraper, conveyor, bottom and rear dump trucks or large front end loaders
Construction Field checks	Spreading and laying	Bob cat, concrete pavers	By back hoe, loader, asphalt pavers, concrete pavers, etc.
	Compaction	Usually using internal or external vibrators	Vibratory, rubber tire rollers
	Density checks	Not required on fresh concrete	Required on fresh concretes
	Fresh concrete specified in terms of	Slump, air content and temperature	Vebe, OMC and maximum fresh (dry) density
Mechanical and durability properties	Strength	Relatively lesser for the same cement factor	Relatively more for the same cement factor
	Surface finish	Smooth	Rough and wavy due to roller compaction
	Air entrainment for	Required; Relatively easier to entrain	May or may not be required Quite difficult to entrain at regular doses
	Shrinkage, carbonation, sulfate resistance, Alkali silica reactivity, abrasion resistance	Widely studied and reported in the literature and quite conclusive	Not much studied to be conclusive to report

B.2 Practical considerations

Mixed in various types of mixers (e.g. pug mill, continuous flow, rotating drum, horizontal twin shaft, pan, transit), RCC requires vigorous mixing to ensure proper dispersion of cement, admixtures and to reduce segregation and other losses. Figure B-1 shows a sampling of RCC mixing and mixer selection. The mixture proportioning needs to be considered from these perspectives to ensure a consistently good product. RCC is then transported in dump trucks to the paving site within an acceptable time span (usually 45-60 min) with adequate compensations made for the moisture losses and thus loss of workability before concrete starts getting compacted.

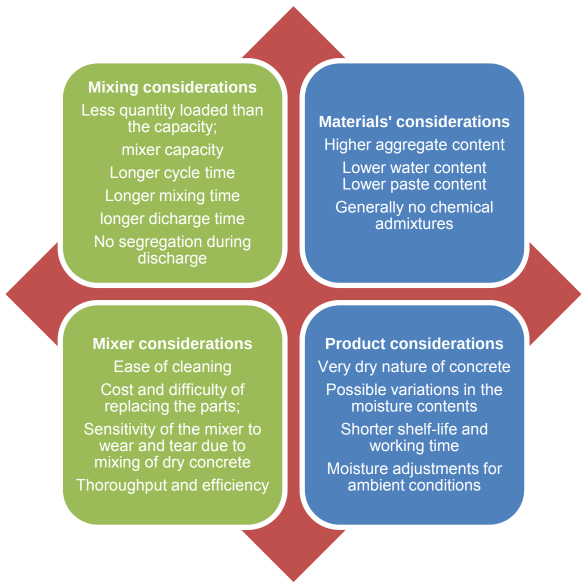


Figure B-1 Considerations for RCC mixing and mixer selection

RCC is paved on well-prepared, clean and lightly moistened sub-grade. When used in concrete pavements as a base layer, a de-bonding sheet [29] or thin asphalt coat may also be used. RCC is usually placed using asphalt pavers (regular, with extra screed, heavy tampers, heavy-duty), or regular concrete pavers (with vibrators either lifted or removed) to the required thickness. One important aspect of hauling cycle is maintaining a coordinated through-put. This is usually achieved by planning, matching and regulating production and paving speeds and by arranging a suitable fleet for transportation while anticipating possible breakdowns and disruptions. Figures 4-2 through 4-6 illustrate sub-grade preparation, production, construction, compaction and curing operations.

Compaction (plain-vibratory-plain passes) is started at a suitable point in time, usually after observing the consistency and compactibility of concrete. The moisture content is monitored during compaction. Concrete on the drier side will tend to consume more fuel as it would demand a greater number of passes and often might not achieve the specified degree of compaction. However, mixtures on the wet side would lead to time losses as the roller will not be able to operate without forming a wavy surface or causing edge slump. Subsequent to compacting the density is checked and verified before concluding the compaction for a given stretch of pavement.

Figure B-2 Sub-grade preparation [30-31]

Saw cutting is usually started within the first 16-24 hours. Depending upon the type of joint (transverse or longitudinal), the joint may be sealed with a suitable sealant. Sometimes the pavement is left without any joints and allowed to crack in an uncontrolled way. Saw cutting may not be required when RCC is used either as a pavement base or is going to be overlaid with asphalt or concrete. However, it is important to install saw cuts at regular intervals (much longer than conventional concrete pavements) to prevent unplanned cracks and associated damage during the lifetime of the pavement.

Figure B-3 RCC loading, unloading and paving [31-32]

Water curing is usually specified for first seven days [32]. This can achieved using water tankers fitted with sprayers or sprinklers, spreading plastic sheet after spreading water or application of curing compounds.

Figure B-4 Compaction, density checking, saw cutting [31-33]

Figure B-5 Curing of RCC [30, 32]

B.3 Understanding the transitioning and anomalous behavior

Clean, well graded, and surface dry sands or fine aggregates are cohesion-less, having laboratory measured friction angles in the range of 20 to 50 degrees. Presence of clayey impurities may impart a negligible cohesion to sand. In addition to the geological process of formation and mining and crushing operations (in case of crushed sands), particle size distribution, moisture content, relative density, method of compaction, confinement and test conditions affect the friction angle. Of relevance for the matter under scrutiny is moisture content and compacted density. Cement particles are angular in shape with weak forces binding them together in addition of the ambient moisture ingress. It can be anticipated [34] and is established [35] that these particles also offer frictional resistance in a dry condition. Particles like fly ash have a measurable friction angle (bituminous fly ash ~ 26-42°) and a very small cohesion.

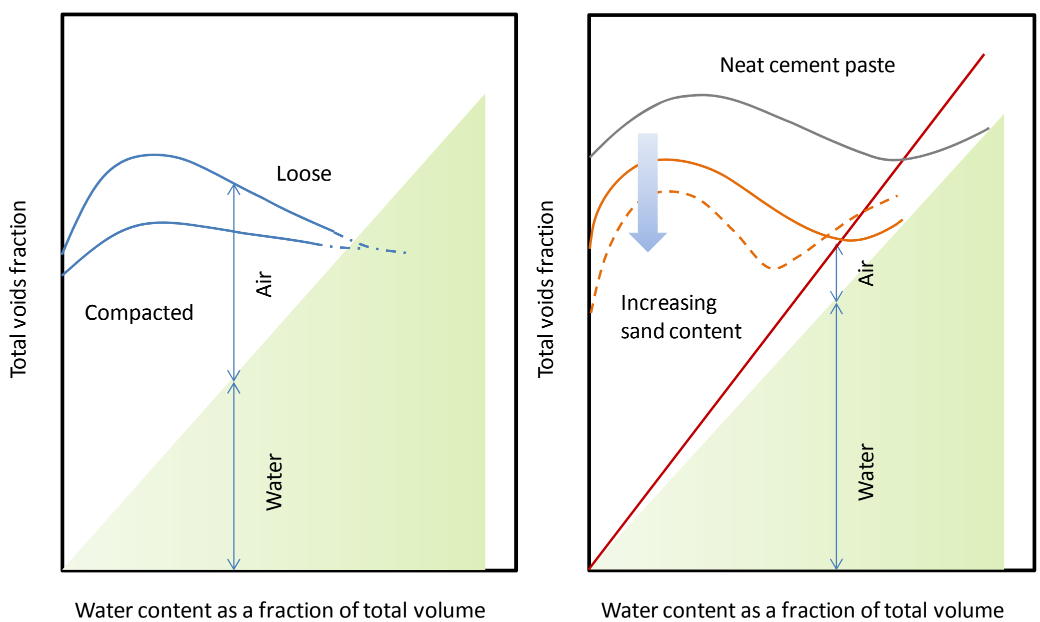


Figure B-6 Transitioning behaviors of aggregate-water systems and comparison with neat cement paste [36]

The primary factors controlling the void-ratio limits or extreme densities of sands are particle shape, particle size range and the particle size distribution (characterized by the shape of grading curve) [37]. Increasing the density of sand increases the angle of friction, while increase in the moisture content leads to marginal reduction in the friction angle.

As the moisture content of sand is increased beyond its SSD condition, water starts forming a layer on the surface and acts as a lubricant while filling the inter-particle voids. Due to surface tension so created by water, sand particles are pushed apart leading to increase in the voids content or bulking of sand accompanied by an increase in the total volume of sand at a constant true sand volume. Bulking increases as the average particle size decreases with negligible bulking in aggregates that do not contain particles smaller than 6mm. This is schematically shown in Figure B-6.

When cement or mixtures of cement and sand are moistened with water (below the normal consistency of cement), initial bulking similar to sands is observed. As water content is gradually increased, the voids content starts reducing reaching a minimum value, subsequent to which the voids content starts marginally increasing. Because of water contacting cement particles, forming a sticky mass along with the initiation of cement hydration, the mixture acquires some cohesiveness. Following compaction (although potentially not to maximum value), the mixture has sufficient self-standing capacity after de-molding. The nature and extent of the hydrostatic tension decides the degree of stability and as such, the mixtures are found to exhibit maximum strength and stability at moisture contents where maximum bulking takes place. The minimum water that renders minimum voids content is called the basic water content. These bulky mixtures are dilatant, and true plastic deformation does not occur. These transitions will vary with cement, sand and their combinations [36]. A schematic is shown in Figure B-6.

The objective of any mixture proportioning is to render a workable mixture of aggregate-cement-water. It has been stated before that the Duff Abrams law is valid above a w/c = 0.3 [38], by weight. Depending on the batching sequence, the aggregate-cement-water mixture renders different forms viz. dry, plastic, extremely plastic, consolidating, etc. Initially, as water is added to a fixed aggregate/cement ratio mixture, the aggregates become wet and it can be anticipated that the cement particles are dispersed to a certain degree. These mixtures contain water; just enough to wet the surfaces of aggregates and cause partial dispersion of cement particles. The mixture is still below the normal consistency of cement. The mixture is not fully compactable and usually renders higher (entrapped) air content in response to vibratory compaction with a surcharge weight. This mixture cannot be hand-compacted.

With further addition of water, cement dispersion increases, paste formation is initiated and thin layers of cement paste starts coating the aggregates. With an increase in the lubricating media, depending on the volumetric composition and other technological factors, several actions at multiple levels occur. At the level of cement particles, water starts reducing the friction while increasing the cohesion. At the composite level of aggregate-cement-water mixture, the cement paste starts coating the aggregate particles. This reduces the interparticular friction in the aggregate skeleton, while building cohesion in concrete. The mixture cannot still be hand-compacted, although with vibratory effort, the mixture is so structured that it can be compacted to a higher level rendering reduced air content and improved finishibility.

As water is further increased, cement particles are surrounded by more dispersing media (although not a media/mediator/catalyst that would increase their dispersing ability), consequently reducing cement paste viscosity, friction and cohesion. At the composite level, depending primarily on the composition and nature of materials, the mixture shows alterations in cohesion and friction values. Increasing water keeps reducing the friction (up to a certain limit), while the cohesion undergoes a transition from a lower value, reaches a peak and then starts dropping down. The nature, extent and duration of such forces depend on the individual composition of materials and constitution of aggregate-cement-water mixture. The mixture is still beyond hand-compaction, but can be compacted to a considerable degree with measurable air contents (not necessarily voids content, through routine lab tests on fresh concrete) quite comparable to conventional, workable concretes.

Analytically, considering the fresh behavior of A-C-W mixture, the density profile follows a trend similar to that shown in Figure B-7. It is interesting to note that there are pairs of two moisture contents that quantitatively render similar densities. However, there is a qualitative difference between each of such pair. One moisture content is on the lower side of optimum moisture content (where maximum compacted density is obtained) while the other lies on the higher side. The phase diagrams of these pairs reveal that on the lower side, the entrapped air occupies a relatively higher volume of the voids, while on the lower side air is expelled out by excess water.

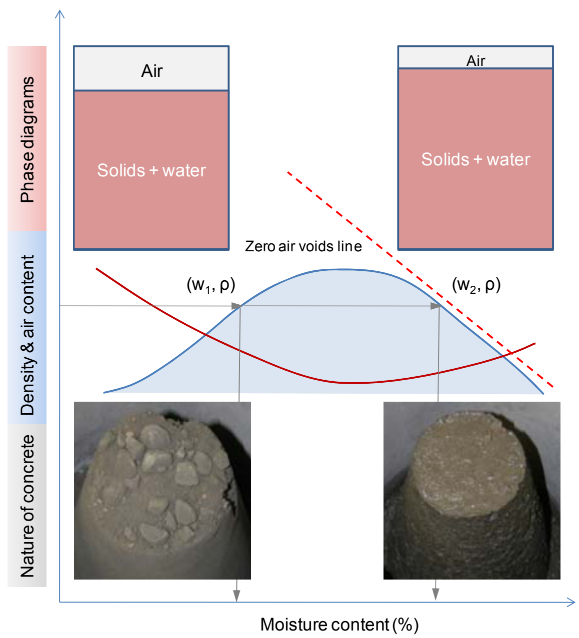


Figure B-7 Influence of moisture content on density and phase composition

Physically and outside the OMC ± 0.5%, on the lower side the mixture is potentially, compactable and placeable, but cannot achieve maximum density. In addition, the mixture will crumble (fall apart) due to lack of cohesion and will not be able to retain an edge. On the other hand, on the higher side of moisture content, the mix can potentially achieve the prescribed maximum density, possess requisite amount of cohesion, but lacks the internal harmony of forces (through surface friction, stiffness) to retain its shape and would thus slump. Additionally, this mixture would show some signs of bleeding and might not be able to carry the roller weights. This mixture can potentially show consolidation (a synonymous, although separate term) as well. At this point, it is important to appreciate that maximum density is a relative term. Theoretically and with excessive compaction, it should be possible to achieve a density that has zero voids and thus on the above figure the density touches the zero-air voids line. With practical compaction methods and within discernable economics of construction this is however not possible, if at all due to in accurate or faulty testing.

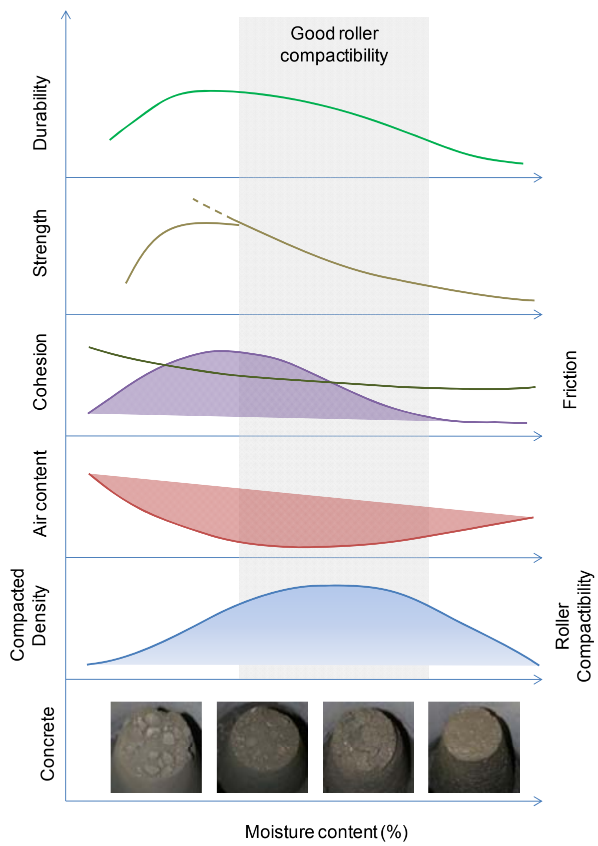


Figure B-8 Schematic representation of variations of properties of A-C-W mixtures (without any chemical admixtures). Figure is not to scale.

Now, what is roller compactable concrete? In addition, what properties are of importance? From engineering and construction perspectives, achieving a concrete structure with least voids content, maximum compactable density in an economical and timely fashion is crucial. This can be achieved when a mixture is properly (technically and economically, with available materials and technology) proportioned and assessed for relevant properties viz. rapid compactibility, ability to retain vertical edges under operating construction loads, good finishibility, less segregation, etc. amongst others.

The Abrams law of strength-w/c ratio losses its legitimacy due to lowering of water beyond workable range (reduced compactibility, excessive entrapped air) or standard/basic water demand [39] and loss of aggregate-paste bond due to introduction of shrinkage stresses and restraining action of aggregate particles [40]. For a given compaction effort, as long as a mixture can achieve its maximum density (meaning the mixture is considerably compactable, approximating the maximum), the strength will vary inversely as the w/c. Lowering water content (hence w/c) beyond a certain limit leads to deviation from Abrams law. It should also be noted that this law is valid over that range of $0.3 < w/c < 1.2$ [38]. Some of the properties are shown as a function of moisture content of mixture at a fixed aggregate/cement ratio in Figure B-8.

B.4 Studies on workability

Workability, per se, is subjectively defined and is quite a controversial [41] term. Neville [40] comments that the technical literature abounds with variations of the definitions of workability and consistency but they are all qualitative in nature and more reflections of a personal viewpoint rather than of scientific precision. Tassios [42] recognizes that workability is an unreliable term and its exaggerated broadness of meaning does not help the expressiveness of the term. Due to diverse demands that different concretes place on some of the qualitative parameters (often quantifiable) that constitute the workability, it can be perceived not as a property but ever-changing optimization of other properties. Therefore, no definition of workability is presented here. A comprehensive summary of fundamental descriptions of workability offered by Ritchie [43] in terms of quantifiable and measurable parameters is shown in Figure B-9.

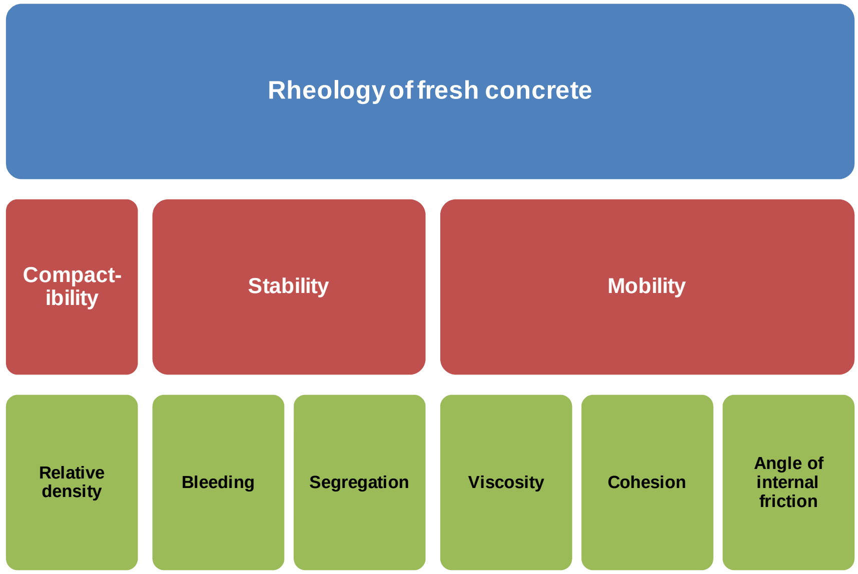


Figure B-9 Factors influencing the rheology of concrete [43]

The author has not come across a study that addresses all these parameters. Tassios [42] presents a summary of workability parameters in terms of concrete behavior and reflects them in terms of desirable rheological properties. Figure B-2 presents a reproduction of the same. In addition to this, he has reported some studies on the measurements of cohesion, friction angle, and yield stress. Shear measurements were determined using scaled-up triaxial and direct shear test units. Herschel and Pisapia [44] report resistance to shear, stickiness, harshness, segregation, adhesion, etc. of concrete mixtures. The deformation behavior of dry concretes can be modeled using Mohr-Coulomb model [35, 45-46] often used for soils. For dry concretes, relative density or compactibility, cohesion, and tendency to segregate are most important [47]. Often the nominal maximum size aggregate (NMSA) in drier concretes is limited to accommodate segregating tendencies for a given construction method. Bleeding and viscosity of concrete are not considered predominant factors. Provided the composition of concrete is designed well, the cohesion of compacted concrete is mostly very good. This often requires the mortar to be 5-10% in excess of the void content in the dry coarse aggregate [48].

Table B-2 Desirable behavior and rheological interpretations of operational characteristics of workability of concrete [42]

	Operational characteristics	Desirable behavior	Desirable rheological behavior
Unreliable term, Workability	Mobility (in conveying and placing)	Small resistance to start flow	Low τ_u yield point of paste on boundary layer
		Small resistance during flow	Low τ_u and η_p of paste of the boundary layer
		Movement without ruptures	Large δ_u
	Stability (homogeneity during transportation and handling)	Water-holding capacity; to avoid bleeding of any kind	High surface tensions, contributing to higher cohesion of the mass
		Capacity of paste to withstand relative movements of coarser particles; to avoid segregation	High critical shear stress of paste within the mass. Especially higher values of cohesion are needed
	Compactibility (facility to overcome internal and surface resistances in order to produce full compaction and desirable surface appearance)	Low cohesion and low internal friction of fresh concrete	Low τ_u of concrete, under compacting method
		Low adhesion and low surface friction of fresh concrete	
		High percentage in cohesive paste	Higher values of cohesion

Note: τ_u: yield stress; η_p: plastic viscosity; δ_u: yield strain

Sorensen [49] presents a comprehensive description of workability properties of fresh dry concretes . These are as follows:

- Dry concretes resemble earth materials. Similar to soils, the workability can be controlled by optimum moisture content and density in compacted and uncompacted condition;
- If cement paste is increased beyond a certain limit the concrete will become unstable;
- In fresh state, the inter-particle forces resist the dispersion of fines and compaction of the granular material, so provide desired stability. The surface forces are due to the air-water menisci and the polarity of fine particles;
- The amount of water required for good workability is very sensitive to the amount and quality of fines;
- There are three principal methods of machine compaction: vibration, dynamic pressure and plain static pressure. Of these, plain static pressure is the least effective method.

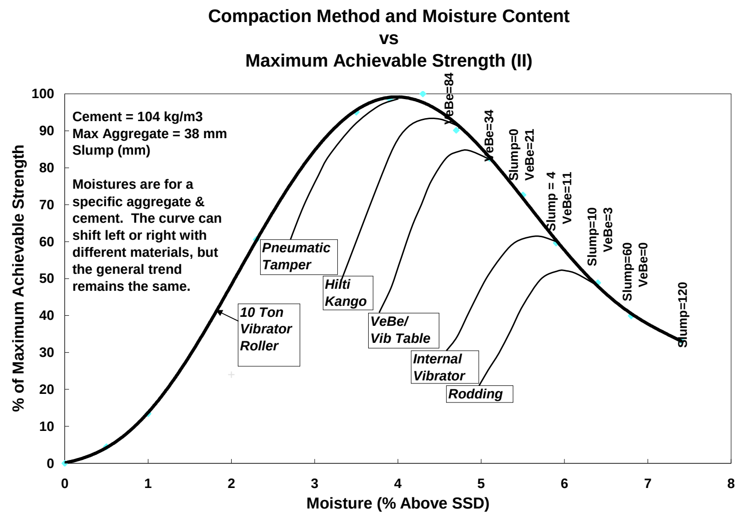


Figure B-10 Compaction method, moisture content and maximum achievable strength (Note: The moisture content is water above SSD divided by the total of all materials including water) [50]

Measuring workability or consistency of no-slump, stiffer and drier concrete mixtures (dry cast industry mixtures, extruded or slip-formed products, masonry blocks, tiles, precast kerbs, pipes, RCC) has always been a challenge. Traditionally, practices have been more or less limited to finding compactibility/relative density of mixtures with different compaction efforts. Although the Proctor test, Vebe test, its modified versions and its derivatives (widely used for dam concretes) [2, 51-53], vibrating hammer [54-55] and Waltz test have been used, these methods are either subjective, lack simulation and/or are cumbersome, tedious, slow, inaccurate, unable to differentiate small differences [47, 56] and show technically poor performance. Vibrated slump value has also been used for characterizing the compactibility of RCC mixtures and has repeatability within ± 5% of the mean value for a wide range of concretes [57]. Figure B-10 presents a summary of various compaction methods for dam concretes. Similar studies were performed for pavement concrete by Nanni and Meamarian [58] and Amer, et.al. [59].

B.4.1 Vebe consistency/time

The procedure for Vebe consistency or time is described in ASTM C1170 [60] and Figure B-11 shows a picture of Vebe consistometer along with the surcharge weights prescribed by different practices. Practices differ according the experience and specifications. For example for if, we take a cross section of surcharge weights used in Vebe test we see quite a range of variation.

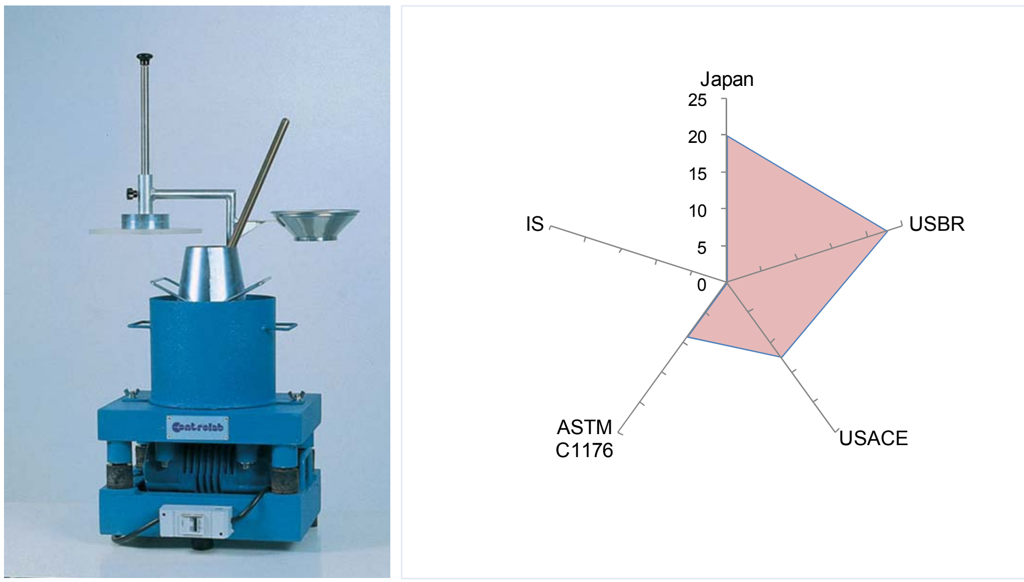


Figure B-11 Vebe consistometer. Comparison of surcharge weights (kg) specified by different standards [2, 53, 61]

Khunthongkeaw and Tantermsirikul [62] in their exhaustive study on RCC for dams report that the free water content affects deformability and Vebe time. Furthermore, they also observed that the minimum free water required for making RCC workable is considered to be directly affected by interparticular surface forces among solid particles. Their prediction model was found to have good correlations with the measured Vebe time. Figure B-12 illustrates a general and a comparative relationship from this study.

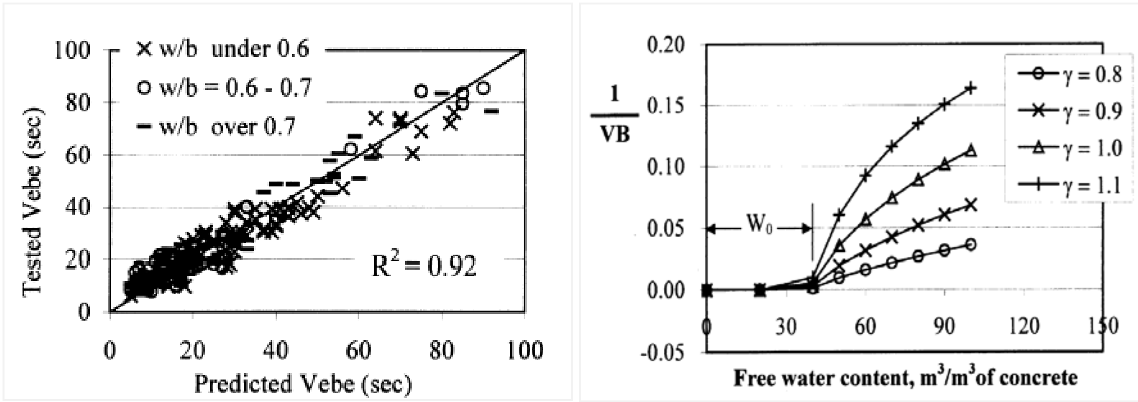


Figure B-12 Relationship between inverse Vebe time (1/VB) and free water content in concrete (where γ is the ratio of volume of paste to the volume of voids in densely compacted aggregates; W_0 is the minimum free water required to make RCC workable). Second figure shows comparison between predicted and tested Vebe time of RCC (Ta Dan Da D Dam) of mixture with different w/b

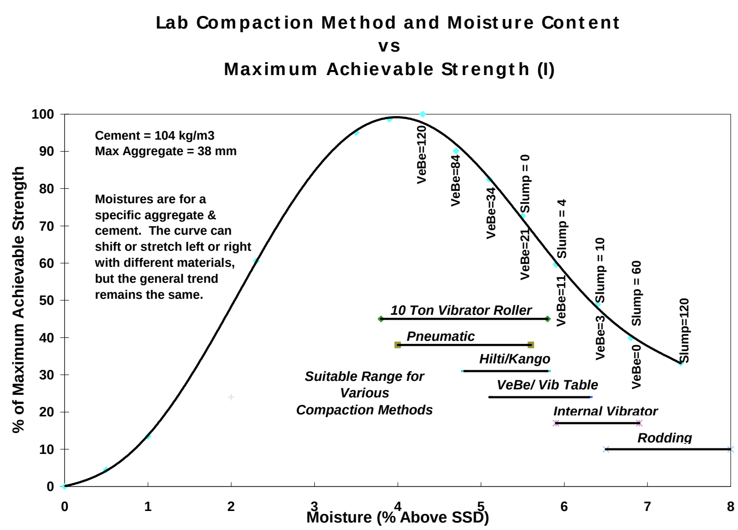


Figure B-13 Applicability of various compaction methods for RCC used for dams [50]

Figure B-13 on the other hand shows the range of applicability of various test methods. Although considered to be the closest test to characterize rheology of RCC, the Vebe test has limited applicability [63]. Relations with other conventional tests have been established [40], but have limited acceptability. Workability being a function of different parameters cannot adequately, satisfactorily and consistently be characterized by Vebe time. Specifications often prohibit Vebe or other tests to determine compactibility. This is because the best test is considered to be the feel and performance of the mixture during laying and rolling and is often left to the supervisor at site [50]. In the pavement market Vebe test is not widely used. Attempts [64-65] have also been made to correlate Vebe time with Waltz, flow, compacting factor and slump tests but are considered to be beyond the scope of the current discussion.

B.4.2 Intensive/gyratory compactor

Paakkinen [66] devised an intensive compaction tester (ICT), which compresses fresh concrete in a 100mm cylinder under a known sustained pressure (100-700 kPa) while it is subjected to a shearing motion (0.7-2.7 rev/s). The reduction in height is recorded as a function of number of cycles and density is plotted against the number of cycles. A schematic of this instrument along with typical datasets is shown in Figure B-14. Furthermore, Paakkinen also found that the point where the moment vs. cycle curve starts to plateau is an indicator of the onset of expression of grout from the sample. Additionally he also observed that for a given mixture, pressure and number of cycles were inversely proportional to each other for a given final density.

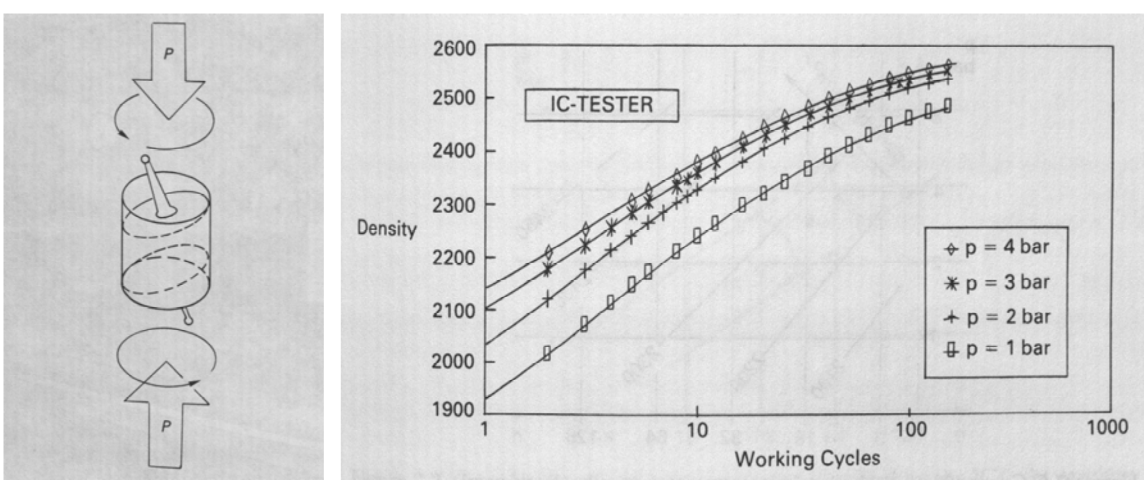


Figure B-14 Schematic of intensive compactor and effect of working pressure on density [66]

Further studies and modifications have been done mainly in Finland. Tattersall [65] reports one such study by Sarja in which he publishes a very useful chart for selecting compaction pressures and number of cylces. This chart is reproduced in Figure B-15. Juvas [47-48, 55, 67] reports further studies on compactibility of no-slump concretes using ICT, where he studied effects of water content, compaction delay, cementitious materials and superplasticizers.

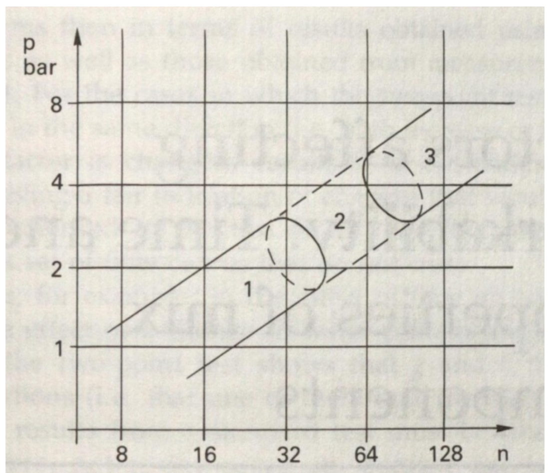


Figure B-15 Concrete production processes as classified by the ICT. By varying working pressure (P) and work cycles, the degree of compaction can be controlled and different production processes simulated. Region 1: Masonry blocks, concrete pipes and roof tile production; Region 2: Masonry stone, hollow core slabs; Region 3: Paving blocks, roller compacted concrete

Kappi and Nordenswan [56] recently reported a summary of industrial practices followed in Finland for no-slump concretes. They report that the internal friction curve, characterized by shear stress has proved to be one of the best parameters to describe the characteristic sand compaction of concrete. Furthermore, this data also offers further information about internal friction and other related phenomena, which can be used for mixture proportioning and optimization. Compactibility retention over a time interval can also be studied using ICT. The repeatability studies showed that the density samples could be compacted with standard deviation of 5.3 kg/m^3. They recommend confining pressure in the range of 80-160 kPa and the angle of gyration up to about 2.3 degrees.

Figure B-16 reproduces a sampling of graphs presented in this publication. Lately, Amer, et.al. [59] have used gyratory compactor for RCC sample preparation with success.

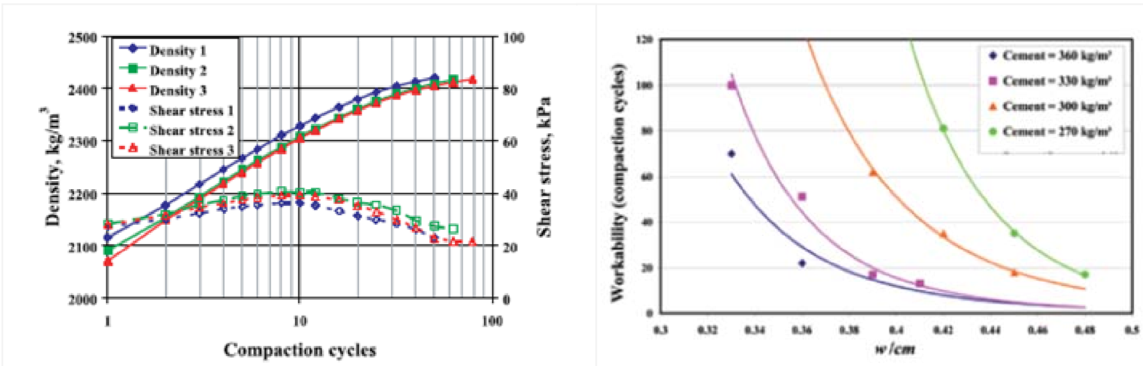


Figure B-16 L: Compaction and shear stress curves; R: Workability and w/cm

B.5 Mixture proportioning strategies

Since RCC was widely used for dams, embankment toppings and spillways, where the degree of compaction of mixture, structural and thermal integrity are of paramount importance, therefore the methods of mixture proportioning are centered around the objectives of achieving economically compactable mixture with least possible heat generation. Clearly, there are two schools of thought for proportioning RCC. The unique origin of this type of concrete inherits one school of thought from its predecessors and competitor materials namely earth materials and granular materials. While the similarity to conventional concrete making materials lead to another school of thought. The approach of the earlier school is known as the soils approach, while those of the latter school are called the concrete approach. Regardless of the approach taken, the primary considerations include constructability (no subsidence under vibratory roller load, no rock pockets), economics, mechanical strength and durability. Figure B-17 summarizes these requirements for pavement concrete and Figure B-3 offers comparison between these two methods of mixture proportioning.

ACI 325 [1] ascribes the methods of mixture proportioning to two broad categories viz.

1. Proportioning by use of concrete consistency tests
2. Proportioning by use of soil compaction tests

Details of these methods can be found in the literature [27, 68] It is criticized that these conventional methods often require production of numerous trial batches to obtain the optimum moisture proportion [69]. Newer methods such as optimal paste volume method and another that uses a solid suspension model have been proposed [70-71]. Of these, the earlier method is well-acknowledged and used due to simplicity, while the other is more theoretical and limited in its theoretical and geographical specificity.

Figure B-17 Factors considered in proportioning RCC mixtures for pavements

Although RCC has existed for over half a century, the mixture proportioning strategies have not evolved much over the years except for some simplification and sophistication. This argument excludes the solid suspension model, which has a stronger experimental footing and theoretical construction. There has not been a consolidated study to appreciate at a fundamental level, the properties of RCC mixtures.

Table B-3 General comparison of factors for RCC philosophies [2]

Factor	Soil analogy (Geotechnical)	Concrete technology
Basis of mix design	Optimum moisture content/maximum dry density	Lowering of w/c and consolidation
Characteristics of voids	All voids not fills-particle to particle contact	Voids filled with paste and excess
Percent theoretical air free density	Usually < 98%	> 98%
Consistency (Vebe time)	45s or more	45s or less
Other names	Rollcrete, stabilized fill, large aggregate soil cement, lean RCC	RCD method (Japan), high paste RCC
Materials	Graded or pit-run	Very well graded to minimize voids
Amount of fines(- 200 micron)	Up to 10% by total weight	Less fines- especially if high fly ash content
Cement + pozzolan content	Usually < 120 kg/m^3	> 120 kg/m^3
Design		
Cohesion	Low value, < 1.4 MPa	Higher values, > 1.4 MPa
Permeability	Void content depends on mix and construction	Depends on properties and amount of paste
Compressive strength	High-per unit weight of cement – greater at top of lift	Decreases with more water – greater at the bottom of lift
Construction		
Mixing	Mostly pugmill	Pugmill or drum
Spreading	Segregation more of a problem	Segregation less of a problem
Compaction	Vibratory or heavy rubber tired roller	Vibratory roller
Primary action or roller	Compaction	Consolidation
Compacted lift thickness	Generally 0.30 m – more possibility of voids at bottom	0.30-0.75 m – possibility of paste at surface and slight chance of voids at bottom

B.6 Materials used for RCC

The strength of RCC is primarily dependent on the quality and gradation of the aggregate, degree of compaction, and proportions of cement, pozzolan and water. The type of cementitious material has a significant effect on the rate of hydration and therefore strengths at early ages [72].

B.6.1 Binders

The selection of binders (composition and quantity) is governed by constructability, strength requirements, exposure conditions, economics and availability. ASTM Type I or

II Portland cements and similar cements are most widely used. Blended cements have been increasingly attempted. These include blast furnace slag cement [73], silica fume blended cement [69], ternary cements [74] and others.

Due to construction requirements, dry nature of concrete, inadequacy of sufficient fines in local materials (especially fine aggregates) and economics, the use of pozzolans and other supplementary cementitious materials is encouraged. Amongst these, the use of fly ash (Type C and F) is accepted widely. Depending on the nature, type and dosage of fly ash used the performance of RCC mixtures will change. Fly ash contents in the range of 15 – 20% [1] of the total volume of cementitious materials are generally specified. Slag, silica fume[75] and rice husk ash[76] can also be used, provided these individually meet the material specifications and contribute well to performance of RCC mixture in terms of its fresh, mechanical and durability.

B.6.2 Aggregates

VIRGIN MINERAL AGGREGATES

Well-graded, uncrushed or crushed aggregates can be used. Changes from the grading or quality requirements of ASTM specification for concrete aggregates, ASTM C33 [77] should be supported by satisfactory laboratory or field test results [72]. The specified requirements, although similar in qualitative sense, vary a bit from grading perspective when compared with conventional concrete aggregates. This necessity originates from the compactibility, least segregation, stability and finishibility requirements. This is quite similar to dense graded bituminous mixtures or granular surface layers used in highway construction. Figure B-18 shows a comparison of RCC aggregate specifications with other similar highway materials. Stricter aggregate specifications may sometimes become difficult to comply with. Moreover, local specifications may be relaxed in order to produce RCC economically. It is also important to take into account the possible role RCC would play in a pavement system.

Good and compactable grading is essential in rendering superior and economical RCC. Several methods can be used for obtaining ideal grading. One important thing to note here is that the optimized or most compactable grading may not simultaneously or necessarily offer good workability. More often, it could produce harsher workability.

Developing decent combined aggregate blends is sometimes influenced by conflicting choices. Influences of increasing sand contents on volumes of coarse and fine aggregate voids could have decisive effects on economic compaction of a mixture [51]. At the same time this combination has a definitive role in deciding the mechanical performance of concretes [78]. The author is intentionally avoiding further discussion on this topic since the reported studies cannot be generalized and experienced engineering judgment is often used in deciding some of these critical factors influencing the mixture proportioning.

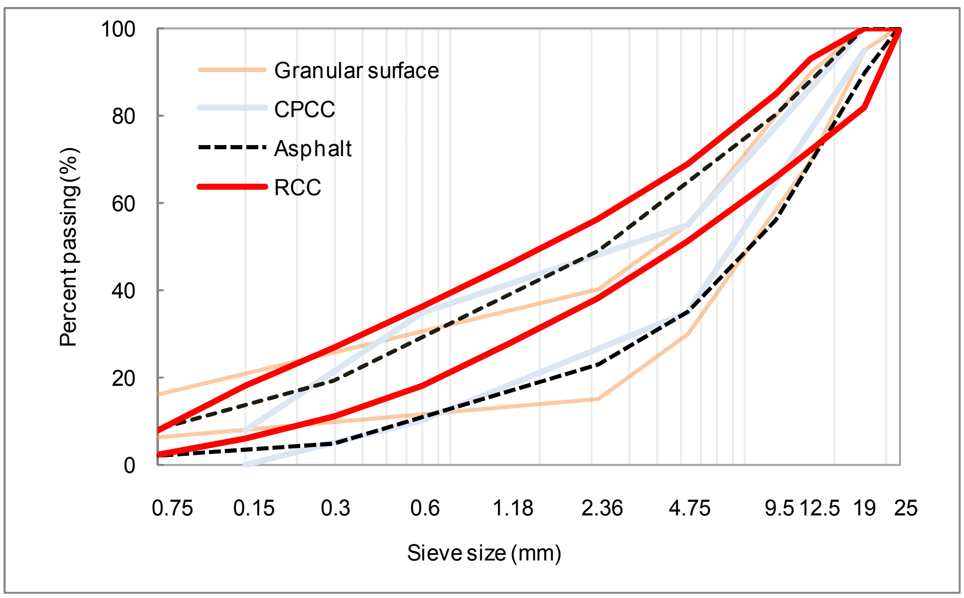


Figure B-18 Comparative chart showing combined aggregate gradations for granular surface and different concretes. The specifications for granular base are ASTM D2940 specifications [79]; dense graded bituminous mixtures are from ASTM D 3515 [80] while that for CPCC are from Neville (Neville 1995)

Evidentially, segregation as perceived for CPCC is inevitable, but is generally counteracted with increased fines and/or higher binder content. Maximum size of aggregate is therefore often limited to 25 mm to reduce the potential for segregation. Shape of aggregates is important from the perspectives of binder cost savings, superior and consistent compactibility, better finishibility and flexural strength. Excessively flaky particles would tend to distort the workability, construction economics and mechanical performance on the negative side.

Increased sand content (contingent to grading and fineness modulus) may sometimes be required for providing cushioning for the larger aggregate, minimize breakage from compaction, minimize segregation and to aid in compaction [81]. To produce a compact and well-finished surface, increased non-plastic fines (passing 75 μm) are required. This can be accomplished through good quality sand and/or using SCM's. The allowable amount of fines in the aggregates shall depend on the amount of plastic limit of fines in the sand.

OTHER AGGREGATES

Other aggregates like limestone crusher-run and tailings from quarry screen [78], marginal aggregates [82-83], aggregates containing shale, dune sand, silt, clay, etc. [84], dry bottom ash [85], recycled concrete aggregates [86-88] have been tested in lab for potential usage in RCC for pavements.

B.6.3 Chemical admixtures

Air entraining admixtures as well as water reducing and set retarding admixtures have been tried in RCC for dams with the mixtures proportioned on soil-analogy basis. It is claimed that due primarily to the dry consistency and fines content of these mixtures, a proper air-void system has not been achieved at any application rate using normal batching or proportioning procedures. For mixtures proportioned using the Japanese RCD method, AEA and water reducing admixtures are invariably introduced, although at higher dosages and with success [2].

Chemical admixtures are not widely used in RCC for pavement applications. Limited research has illustrated the use of water reducers [69, 89], viscosity modifying agent [90] and retarders. Commonly used chemical admixtures in practice include water reducers, retarders, accelerators and superplasticizers. So far, most usage has been in the central batch and transit mixer type operations where improvement in the cohesiveness of the mix and the discharge rate has been observed. They are not commonly used in "pug mill" type operations[91].

A small amount of air in dry/semi-dry lean mixes improves cohesion and eases finishing. While acting as a lubricant, it reduces water and significantly enhances compaction [92]. Contradictory results pertaining to air entrainment have been reported in the literature, although it is generally agreed that entraining (quantifiable) air in RCC is quite difficult [93] and may require much higher dosages [94]. Recent studies by PCA [69], Hazaree [89, 95] using scanning electron microscope have established the possibility of entraining air in RCC, when mixtures are properly proportioned, mixed and admixtures aptly selected. In addition, when correct AEA (chemistry and dosage) is selected the workability and the strength can also be improvised along with savings in binder content [96].

The author would like to offer the following critique on the improperly conceived notion of effectiveness of chemical admixtures in RCC.

- Successful introduction of chemical admixtures is first a function of the water content of the concrete mixtures, RCC having less water to mobilize the activity of admixtures. Mostly RCC for pavements is proportioned using soil analogy method that renders less paste to work with.
- The practices are inclined towards using less powerful mixer technology viz. pug-mill, tilting drum mixers, truck mixers, continuous-flow mixer, etc. These mixers have shorter mixing cycle times and are less efficient in mixing when compared to mixers like horizontal twin-shaft mixers, which are very efficient and powerful in mixing concrete. Proper introduction and dispersion of all ingredients including chemical admixtures demands improved mechanization (power, speed and mix shearing ability).
- With respect to entraining air in RCC, it is the action of mixing which entrains air. The amount of energy required is inversely proportional to the size of the bubbles. The number and share of the blades also have a very significant influence [93].

- Research so far has been focused on using chemical admixtures with similar chemical activity to that used for routine concreting, albeit it could easily be conceived that higher activity chemical admixtures would be required to produce significant alterations in the mixture properties.

B.7 Mechanical and durability performances

Rather than reporting the published literature values, the author intends to offer a comparative statement between RCC, CCPC and self-consolidating concrete (SCC). Appreciating the fact that RCC, relatively, has lower binder and water contents and the water requirement for 20 mm nominal maximum size aggregate (NMSA) may be much lesser than the value, 190 kg/m^3 quoted in ACI 211.1 [97] for normal concrete and also the general range, 145-225 kg/m^3 for SCC [98-99]. On the other hand it also needs to be appreciated that the binder contents (RCC < CCPC < SCC) in the later two types of concretes are relatively higher than those used in RCC. Moreover, the composition and quality of the paste is markedly different, although, a comprehensive meaning of this is not fully understood while covering the full spectrum of concretes. Entraining air in RCC is much more difficult than in CCPC and SCC; the dispersion of cement grains is difficult due to lower consistency [100] and could potentially lead to micro-structural heterogeneity if proper dispersants are not added.

Figure B-19 represents a general sampling of these three types of concretes as obtained from published and unpublished works (of the author). Following are some salient observations:

- As discussed before, Abrams's law may not remain valid, especially for RCC at lower w/b ratios due to incomplete compaction and consequent shrinkage stresses [40];
- The paste volume (consequent to simultaneous reduction in the binder and water contents) is lower than CPCC and SCC for a given strength;
- A fact to be noted here is many of RCC mixtures used in this analysis were without any chemical admixtures, while the SCC is heavily dosed with blends of several mineral and chemical admixtures (powerful polycarboxylate families, other superplasticizers, viscosity modifying agents, etc.). The question then

arises, whether it will be possible to make a transition from a stiffer, aggregate rich RCC to higher binder efficiency; while simultaneously enhancing and improving the workability attributes of RCC;

- Juxtaposing this fact with cementing efficiency, it can be seen that despite of lack of powerful cement dispersants and hence chemical enhancers, RCC mixtures are showing better performance. It is quite possible to positively alter the cementing efficiency in RCC mixtures;
- The left-bottom quadrant clearly distinguishes the paste content ranges.

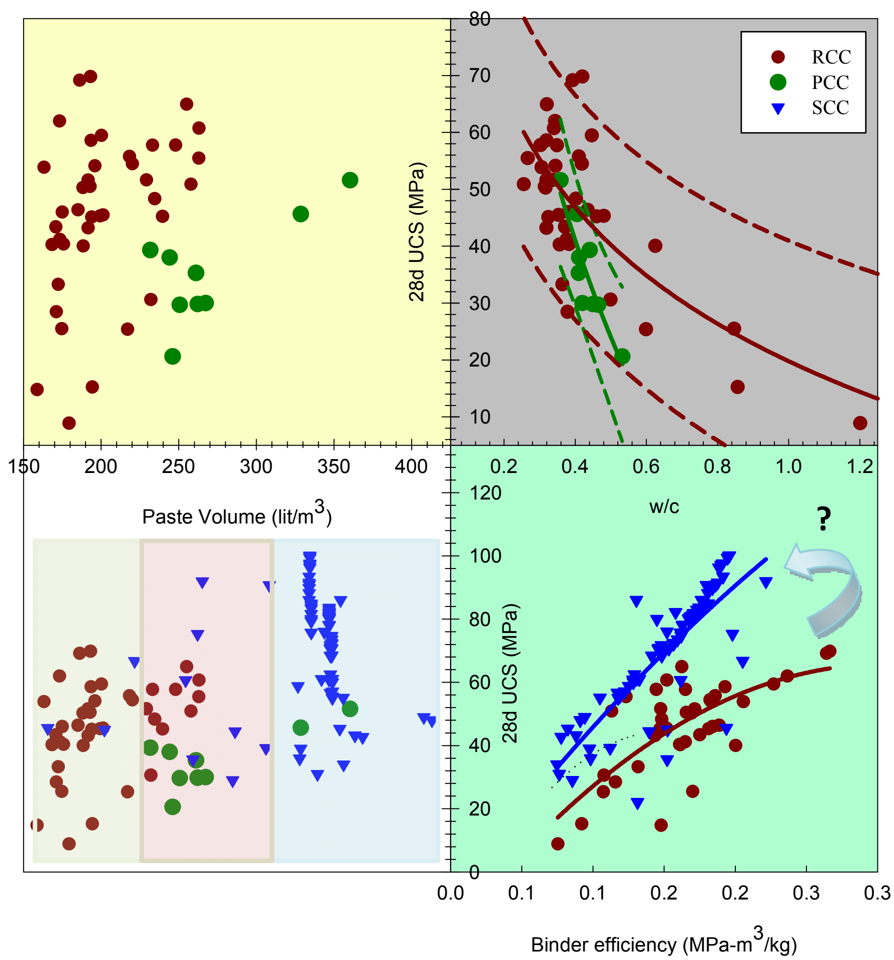


Figure B-19 Comparison between RCC (pavements), PCC (pavements) and SCC (Structural) [10, 59, 69, 76, 89, 100-106]

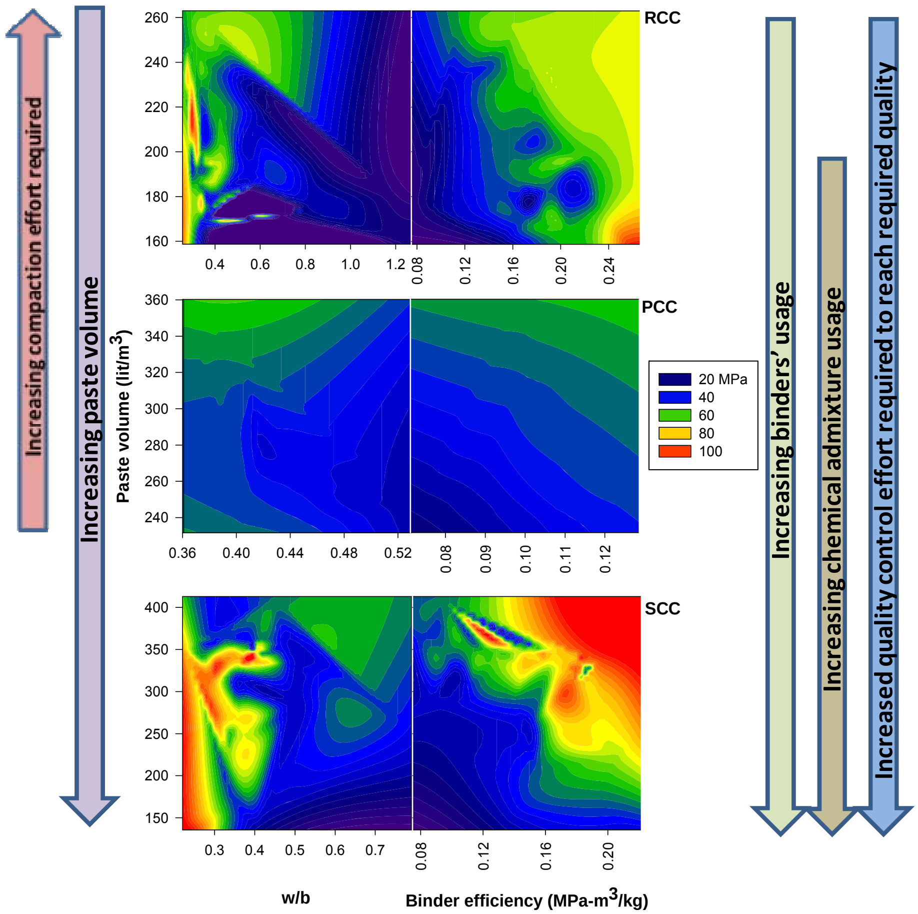


Figure B-20 Contour plots and other comparisons between RCC, CCPC (PCC) and SCC. Values are taken from the above data analysis.

Figure B-20 offers another perspective on this data. Observing just the paste volume could lead to incomplete inferences, since the paste volume is composed of binders and water and with alterations in compactive effort (in case of RCC and CPCC) and/or the use of pertinent chemical admixtures, the volumes of either or both could be altered. Therefore, the above figures are sketched to understand the interplay of these factors on the compressive strength.

Now, it is also important to recognize that due to the natures of these concretes (aggregate packing, cement dispersion, etc.), the flexural strength (nature and extent) may also differ. Further comments on this point are not possible due to incomplete nature of published literature on one topic or the other. ACI 325 [1] reports the following relationship with compressive strength (9 ≤ C ≤ 11):

$$f_{third\ point\ flexure} = C\sqrt{f_{compressive}}$$

It should be noted that the recommended range of C could differ from this recommended relation depending on the aggregates, in addition to the regular factors that affect this property.

Notes pertaining to modulus of elasticity, bond strength, splitting tensile strength and bond strength are offered in ACI 325 [1] document on RCCP and since these properties were planned not to be a part of the study matrix, therefore are not dealt with elaboration here.

Since no durability studies were to be performed as a part of this study, limited discussion is offered in this chapter. However, to be comprehensive, the following is a sampling of the research and field observations on durability and performances pertaining to the following have been reported:

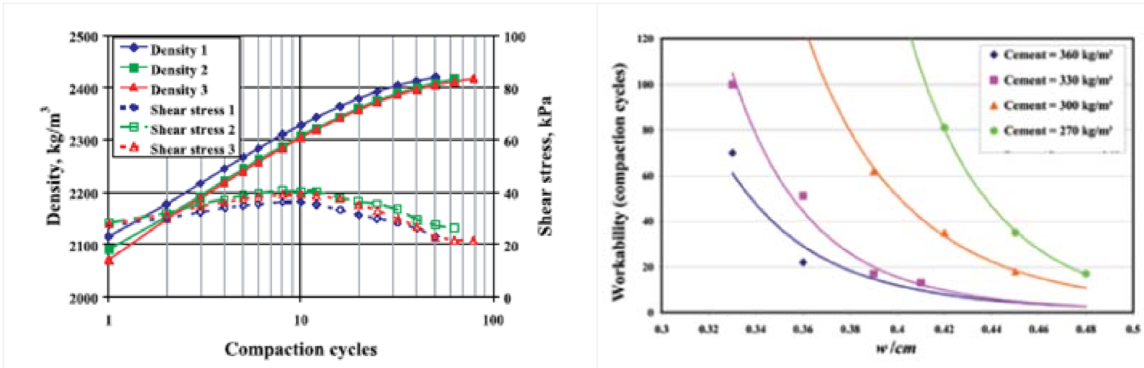
- Air entrainment and freeze thaw durability [6, 69, 89, 93-94, 107-111]. There has been a mixed opinion about the possibility and need for air entrainment in RCC. It is also believed and proven that without air entrainment, RCC could perform well;
- Permeability [112-114]. Mixed opinions exist pertaining to water permeability, but these observations should be juxtaposed with the fact that there is a lack of detailed studies;
- Sorptivity, desorptivity, voids content [89] . The sorptivity was found to be comparable to conventional concretes;
- Sulfate resistance [115]. In this study good resistance to sulfate was observed;

- Shrinkage [116]. The study found that moisture content and aggregate grading in combination affect the shrinkage; the range of values obtained were observed to be lower than the conventional concrete;
- Abrasion resistance [72, 115, 117-119]. The abrasion resistance was observed to be dependent upon the cement content and moisture conditions, but overall the performance cannot be compared in the light of lack of detailed studies; Higher performance RCC showed better performance than the conventional concretes; quality of aggregates affect the abrasion resistance; field observations suggest excellent performance;
- Skid resistance

SUMMARY

RCC as a pavement material is being applied worldwide with different eagerness. There is a growing awareness in the United States, thus inviting research. As compared to the conventional pavement concretes, RCC enjoys greater technical benefits, effective cost savings and can offer itself as a better sustainable material. A perspective on binder efficiency in comparison to pavement and self-consolidating concrete is presented with an intention of comparing different concretes.

The compacted density is one of the most important properties of RCC and has far-reaching influence on all its properties. The compactibility is influenced by the volumetric composition of concrete, which in turn influences the workability of concrete. Studies pertaining cohesion, internal angle of friction and compactibility are required in order to better understand and apply the concept of workability in real life. Previously sporadic and scattered studies have been done on these topics and this chapter has attempted at unifying these with a critique



The mixture proportioning strategies could be greatly enhanced with a basic understanding of concrete properties in terms of workability and how different components of workability would alter the constitution. Considerations include evolving proper indices for selecting appropriate water/binder, aggregate/binder, chemical admixture selection.

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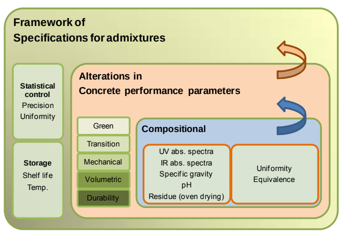
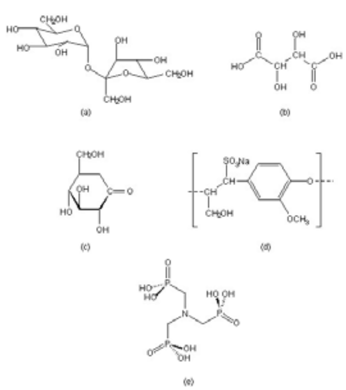
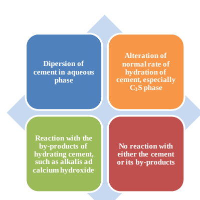
APPENDIX C CHEMICAL ADMIXTURES: ORIGINS, MECHANISMS AND USES







SYNOPSIS

The primary objective of this chapter is to present a discussion of the present day chemical admixtures used in concretes in general. Initially two classification schemes are discussed followed by a critique on the standards used for classifying water reducers, retarders and accelerators. Subsequently, the origins, general chemical compositions, mechanism of action and uses are discussed for water reducers, hydration kinetics modifiers, air entraining admixtures, and viscosity modifying agents. Following this is a discussion on admixture-admixture and admixture-cement compatibility. Finally, a perspective on using chemical admixtures in dry concretes is presented.

Keywords: chemical admixtures, water reducer, plasticizers, superplasticizer, retarder, air entraining admixture, viscosity modifying admixture, compatibility, dry concrete

CONTENTS

C.1 Chemical admixtures

Chemical admixtures are ingredients other than water, aggregates, cementitious materials, and fiber reinforcement, added to the batch before or during its mixing to modify its freshly mixed, setting and hardening properties [1]. Unlike supplementary cementitious materials, these are non-pozzolanic, mostly organic, physio-chemical in their actions and are normally supplied as water based solutions and suspensions (but could also be in powder form, dispersions and emulsions [2]), with typical active chemical content of 35-40%. The dosage rate is generally less than 5% on cement, albeit, the majority of admixtures are used in the typical range of 0.3-1.5% [3]. Although added in small quantities compared to the other constituents in concrete (Figure C-1), these are of great value in economically enhancing several concrete properties and play a decisive role in sustainable development. Conventionally made from industrial by-products, the contemporary trend is shifting towards making chemical admixtures from synthetic polymers especially produced for the concrete industry [4].

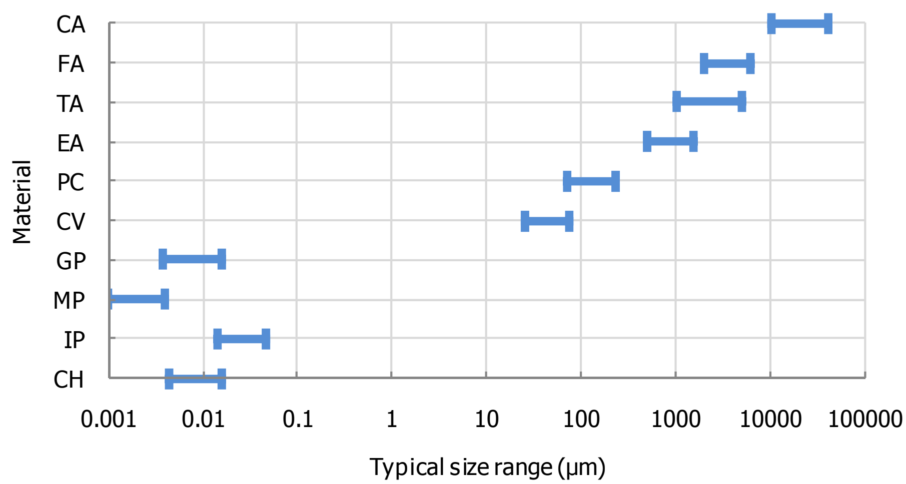


Figure C-1 Size comparison of concrete constituents (CA: coarse aggregate, FA: fine aggregate; TA: entrapped air voids; EA: entrained air; PC: Portland cement; CV: capillary voids; GP: gel pores; MP: micropores; IP: interparticle spacing; CH: chemical admixture)

National and international standards, by and large, identify two primary sets of requirements to be fulfilled by the chemical admixtures that are properly stored and tested within their specified shelf life. The basic framework is shown in Figure C-2. The first set covers the uniformity of composition of an individual admixture and is more or less related to the characteristic attributes, benchmarked on the approved admixture. These attributes include pH, specific gravity, solids content, ash content, InfraRed (IR) or UltraViolet (UV) absorption spectra/signatures. Tolerances and measurement precision statements are also incorporated in the standards. The second set of requirements, called physical requirements, deal with anticipated alterations to be brought to a concrete mixture's performance in terms of its fresh, transitional, mechanical and durability properties and consistency thereof. These alterations are benchmarked with a control concrete and include percentage change in the water requirement to achieve similar consistency, retention of consistency over time, setting properties, compressive and flexural strength development over time, volumetric stability and relative durability factor.

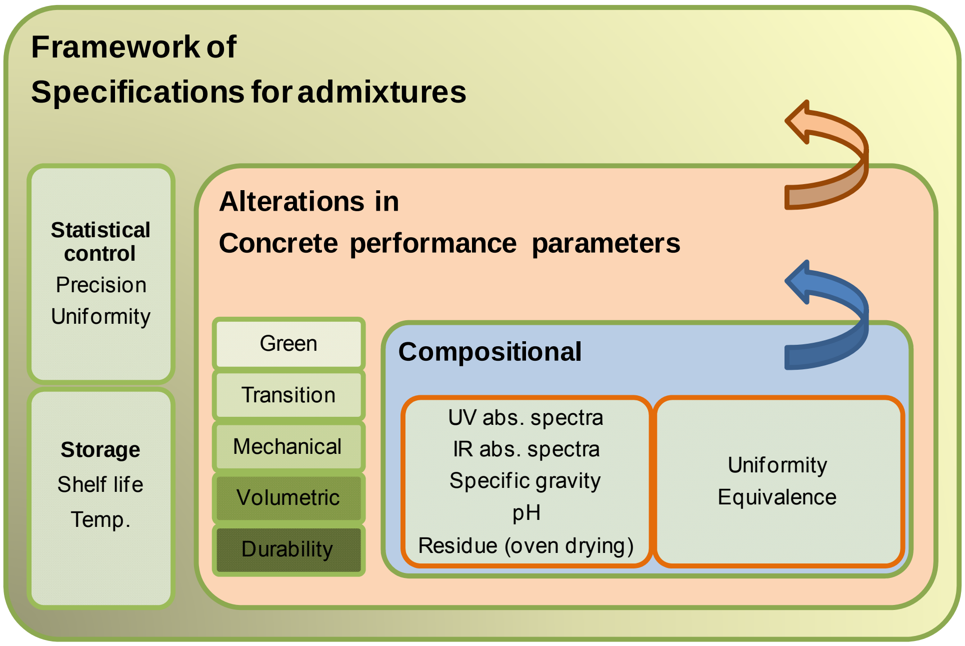


Figure C-2 Framework of specifications on chemical admixtures

C.1.1 Dodson's classification and an account of ASTM C494

Figure C-3 shows Dodson's [5] classification of chemical admixtures based on their physio-chemical mechanism that affect the fresh and hardened properties of concrete. Although there exists an apparently complicated and confusing terminology embedded into standards, mostly these four mechanisms will describe the actions of admixtures in cementitious mixtures. Physically, the usage of admixtures alters the water demand, rheology of fresh concrete (stability, compactibility and mobility), quality and quantity of air, rate of cement hydration and resulting pore structure and hence the consequent properties.

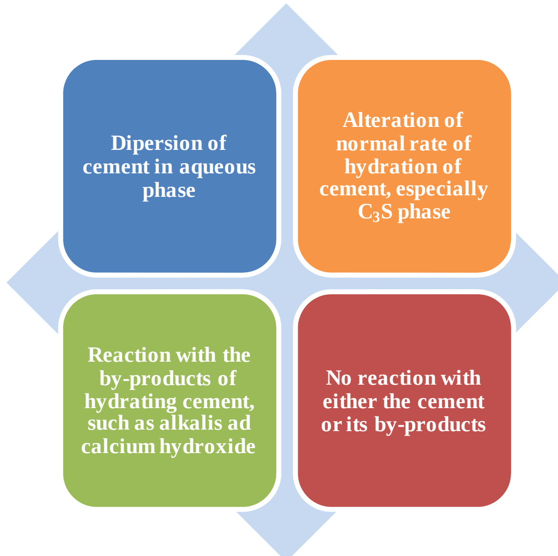


Figure C-3 Dodson's classification of admixtures based on their physio-chemical actions

ASTM C494 classifies water reducing, retarding and accelerating chemical admixtures into seven types depending on the role they play in concrete. Of relevance are types A, B, D and F. Type A and D are expected to have a minimal water reduction of 5% while, type F of 12%. Type B is a retarding admixture. The initial and final setting time requirements are summarized in Figure C-4.

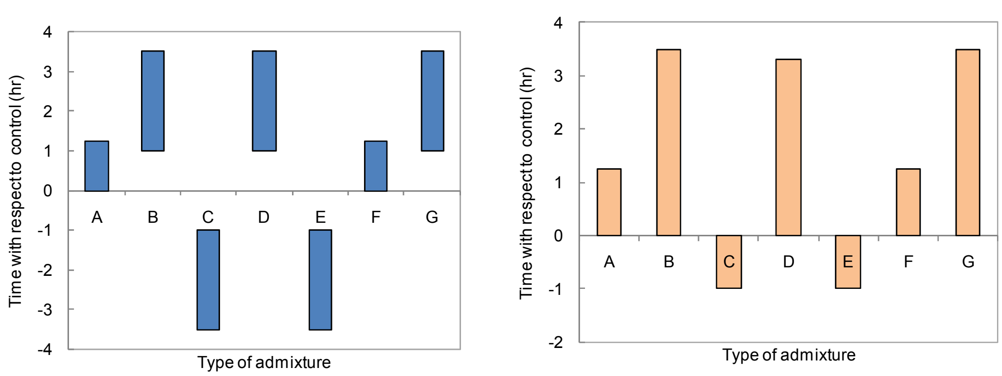


Figure C-4 Initial and final setting time requirements w.r.t. control mixture

Apart from these requirements, the standard sets minimum requirements for compressive and flexural strength. Figure C-5 depicts the strength requirements for the four admixtures. The initial requirements set for type F admixtures are quite high (40% over control or 140% of control mixture) when compared with control concrete. On the other hand, for retarding admixtures, ASTM allows a strength (UUCS: unconfined, uniaxial compressive strength) reduction of 10% at all ages except at 1 day. Considering the scope of this work, other requirements are not discussed further.

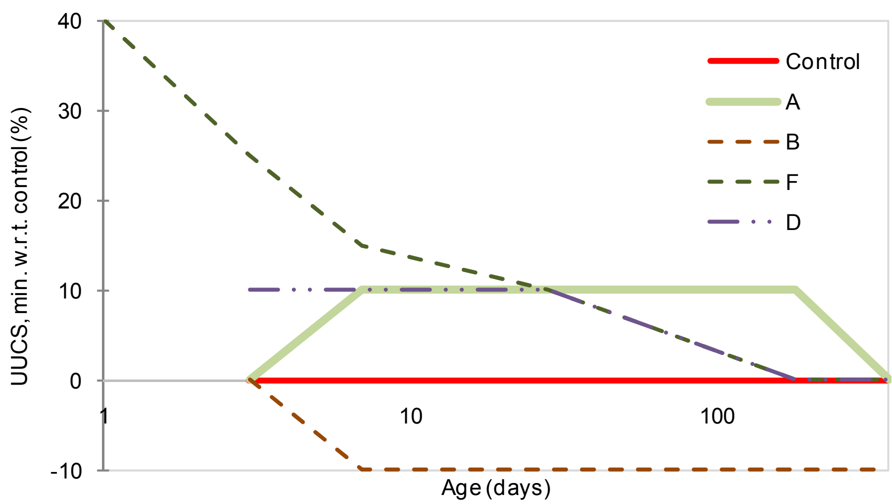


Figure C-5 Compressive strength requirements set by ASTM C494

C.1.2 An introspection on ASTM and other standards

ASTM C494 primarily covers water reducers, accelerators and retarders and covers their requirements in terms of water reduction, setting time, temporal evolution of compressive strength (up to one year), flexural strength (up to 28d), shrinkage and relative durability. The following points (revisited in the results section) relevant from the perspective of this investigation:

i. The developments in the area of admixture technology are taking place at a much faster pace than previous years. It is proved rather difficult to change the standards at a matching pace. This fact has to be considered while assessing new admixture chemistries.

ii. The author feels that the classification offered by Dodson is appropriate, comprehensive, and less complicated. With growing types of concretes, newer admixture chemistries are developed to cater to specific needs. Accommodating all the admixtures in ASTM C494 may not be possible.

iii. The determination of water reduction w.r.t. control mixtures is accomplished using a standard mix with a slump range of 90±15 mm. The admixtures covered by this standard are sensitive to the volume of water in concrete in the sense that they need a certain minimum amount of water to mobilize their action and produce perceptible results. Moreover, with higher water content mixes the efficiency and effectiveness of these admixtures could change.

iv. So many blends of admixtures are used and developed every day that it may not be possible for all the admixtures to fit into one category or the other. There is thus a need of a simple yet comprehensive set of specifications.

C.2 Admixtures that disperse cement and reduce water

Primarily non-pozzolanic [6], organic [7], hydrophilic surfactants, water soluble or insoluble (solid particulate, liquid dispersion, liquid emulsion), the fundamental function of a cement dispersing agent (CDA) or water reducing agent (WRA) is to deflocculate and disperse the cement particles thus reducing the water demand of a cement paste, mortar or concrete mixture at a particular consistency [2]. These organic molecules strongly reduce or even destroy the flocculation of cement particles so that all the water introduced during the mixing of concrete gets efficiently used to give plasticity and workability to concrete [5].

Depending on the range of water reduction w.r.t. the control mixture, these are classified as low range (LRWR, 5-10%), mid (MRWR, 10-15%) and high range (HRWR, 12-30+ %) water reducers. Since one of the roles these play is plasticizing the mixtures, therefore the first two water reducers are also called as plasticizers, while the last is called as superplasticizer (SP). Admixtures have undergone significant changes in not only their formulation but also in their modes of action. Three generations of admixtures are noted in the literature [8-10]. Table C-1 summarizes their formulations, modes of action and effects on cement-based systems.

Table C-1 An account of generations of admixtures

Generation	Mode of action	Effects and drawbacks
First	Creation of negative charges leading to repelling of cement particles through reduction of surface friction	• No effect on hydration • Short period of workability or large loss of slump
Second	Adsorption on cement particles producing plasticity. Electrostatic repulsion is the primary mode of action.	• Hydration affected leading to allowing of reduction in w/c ratio • Plasticity enhanced and workability loss reduced
Third	Electrosteric effect	• Very less loss of slump • High reduction in w/c

C.2.1 Chemical descriptions

Water reducing admixtures (Refer to Figure C-6 for typical molecular structures) are normally based on

i. Salts of lignosulphonic acids (Ca, Na or NH_4);
ii. Modified and derived lignosulphonic acids. Modification is achieved using hydroxylated polymers or other cement dispersing polymers;
iii. Salts of hydrocaroxylic acid (Na, NH4 or tri-ethanolamine salts) and their modified and derived versions [11];
iv. Other compounds.

Superplasticizers (Refer to Figure C-7 for typical molecular structures) are broadly classified [4, 12] into the following four major groups viz.

i. Polymelamine sulphonates
ii. Polynapthalenes

iii. Lignosulphonates
iv. Polycarboxylates

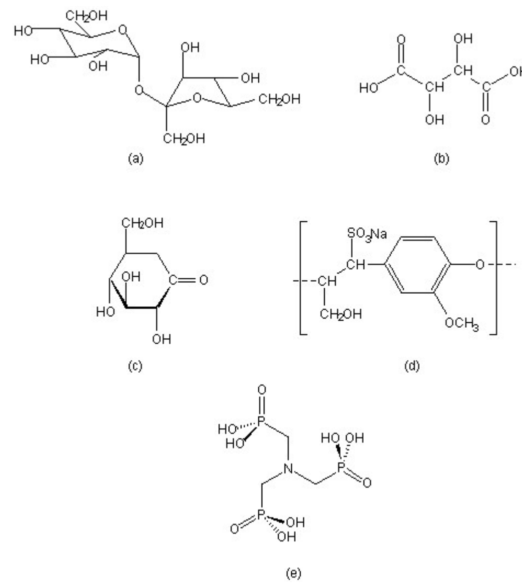


Figure C-6 Structural formulae of common plasticizers/retarders. (a) sucrose, (b) tartaric acid, (c) gluconic acid, (d) sodium lignosulfonate, and (e) phosphonic acid [13]

In addition to these superplasticizer groups, polyacrylates and phosphonates and other copolymers are also manufactured [4]. Nowadays many proprietary products are blends of two or more active chemicals and the distinctions have become blurred [2]. Blends are also available with normal water reducing admixture to give admixtures with carefully targeted properties. These can also be blended with other chemicals to increase retardation, workability retention, air entrainment and other properties [3]. The individual chemistries and historical development is amply discussed in published literature.

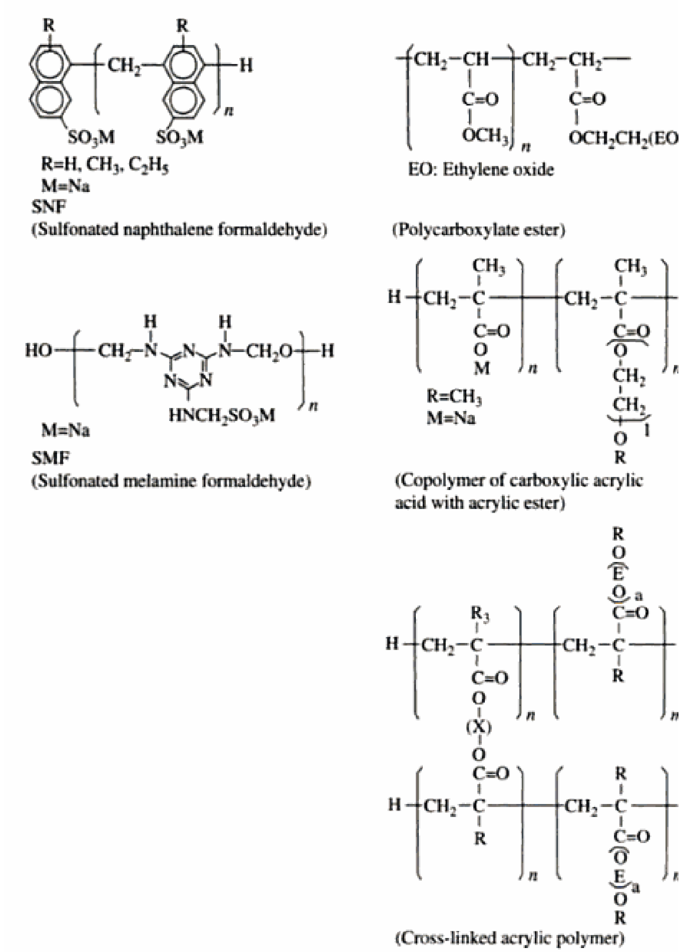


Figure C-7 Typical superplasticizer molecules [8]

C.2.2 Nature of physio-chemical reactions

As reviewed before, cement particles are weakly bonded during early hydration, this state leads to locking up of water between cement particles and reduces the available surface area for hydration reactions to progress. This in turn leads to inefficient usage of cement in concrete. A water-reducing admixture is adsorbed on to the cement particles with a consequent lowering of inter-particular attraction so that agglomerates of cement break up. This produces a uniform dispersion of cement grains reducing the amount of water required to achieve a given consistency. This is schematically shown in Figure C-8.

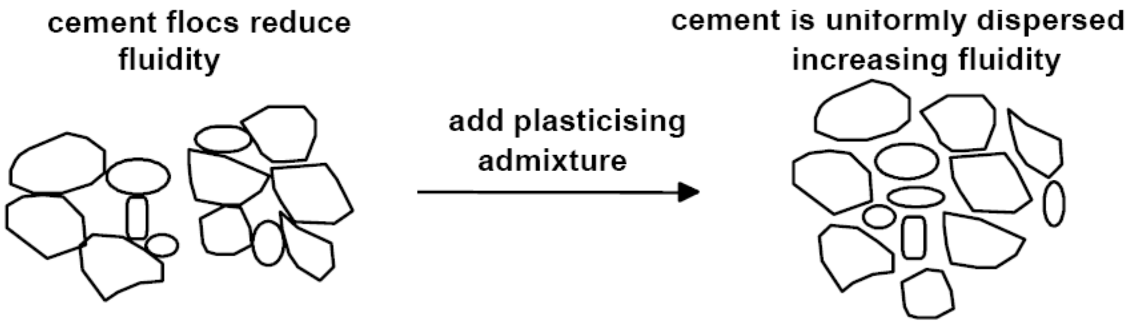


Figure C-8 Schematic of plasticizing mechanism [14]

Many mechanisms have been suggested to explain the fluidizing effect of plasticizers added to concrete at a given w/c ratio. Amongst the primary mechanisms suggested and accepted are the reduction of interfacial tension (Prior, 1960); multilayer adsorption of organic molecules (Young, 1972; Banfill, 1979); increase in the electro kinetic potential (Ernsberger, 1948; Cook, 1967); protective adherent sheet of water molecules (Prior, 1960); release of water trapped in cement clumps (Collepardi, 1980) and change in the morphology of hydrated cement compounds (Massazza, 1980; Odler, 1978).

The cement-SP interaction can be viewed as a colloidal stability problem. SPs improve the dispersion of cement particles, thus increasing their flowability by two mechanisms viz. the electrical repulsion and the steric hindrance effects. With the development in concrete science and technology, the theory of dispersion mechanism of cement particles, based on electrical repulsion phenomena, cannot fully explain the behavior of the new generations of plasticizers, which eliminate such disadvantages of traditional admixtures as their consumption during the hydration of cement [9]. Figure C-9 shows both of these mechanisms of action.

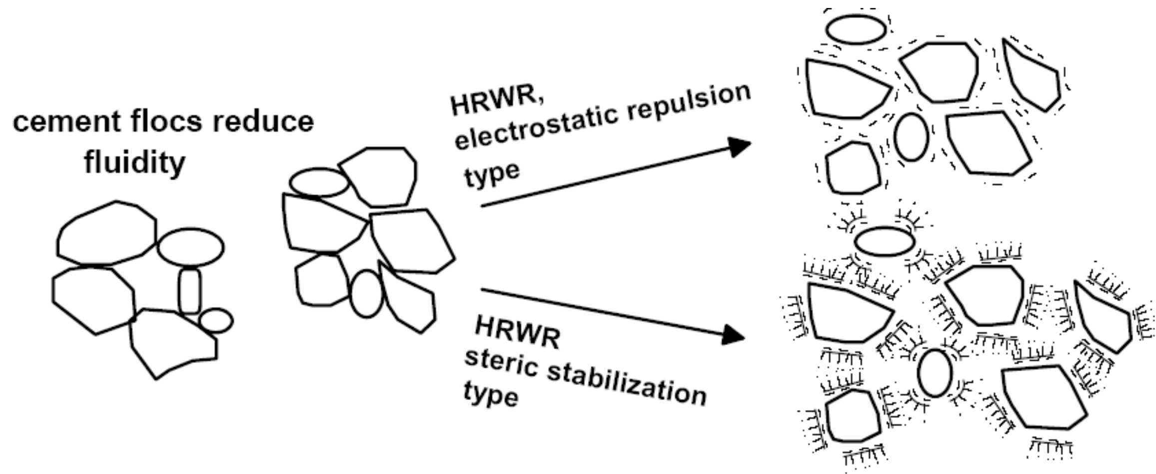


Figure C-9 Schematics of colloidal stabilization (electrostatic and electrosteric) [14]

According to Jolicoeur, et.al. [15-16], in order to achieve the dispersion of cement particles and fluidization of cement pastes, a superplasticizer must perform the each of the following four functions:

A. Physical effects:
   i. Interfacial adsorption through electrostatic and van der Waals forces
   ii. Surface charging and electrostatic screening of interparticle attractive forces and induction of repulsive forces
   iii. Steric hindrance leading to short range interparticle repulsion
B. Chemical effects
   i. Surface binding to reactive sites, inhibiting early hydration reactions

Considering the fact the initially hydrated surfaces are dominated by calcium oxide, the surface charge (or zeta potential, ζ-potential) can be considered probably positive [9]. However, ettringite (4.15 mV) and to a less extent monosulphate (2.84 mV) and syngenite (0.49 mV) show positive ζ-potentials, while portlandite (-4.4 mV) and gypsum (-0.06 mV) show slightly negative ζ-potentials [17]. Research [18] however notes that cement suspensions are always coagulated and the degree of flocculation does not vary with the ζ-potential and ionic strength (although both change with the degree of hydration), which in turn means that the ionic strength is always above critical value of flocculation. Hence, the degree of flocculation is not sensitive to variations in the ζ-potential, at least for values less than 20 mV.

The SP supplies negatively charged hydrophilic groups (SO_3^-, OH^-, COO^-, etc) that are selectively adsorbed on the hydrating phases rather than unhydrated phases (Rossington, 1989). This adsorption is influenced by chemical constitution and molecular weight of SP, C_3A-, sulphates-, SO_3^- content, SSA of cement, silicates phase ratio (C_3S / C_2S) and aluminate phase ratio (C_3A / C_4AF) amongst other factors [12]. These adsorbed superplasticizers hinder the diffusion of water and ions to the cement grain surface causing shielding or screening effect (Mollah, 2000) and leading to inducing of negative ζ-potential much larger in magnitude than that of cement particles [19]. The magnitudes of such changes depend on the chemical architecture of the SP and cement chemistry along with the ambient conditions of observations. This mechanism is the primary stabilization mechanism of SPs like SNF [20]. Further details can be found elsewhere in the literature [21]. All mineralogical components of cement show negative ζ-potential when dispersed in solution with SPs (β Naphthalene sulphonate, polysulphonic acid, PC-based). Therefore, it is expected that the fluidity of cement paste in early age is improved by hindering accelerated coagulation [22].

Darwin, et.al. concluded that electrostatic repulsion cannot be the main dispersion mechanism for polymers [23]. It is critical to point out that in the cementitious systems, where the ionic strength is high (~0.1 mol/l), electrostatics alone are not sufficient and it is thus expected that extending the layer thickness of adsorbed SPs should improve their rheological performance in such systems [21]. Polyelectrolyte species when adsorbed on inorganic surfaces can impart electrostatic and steric stabilization to the resulting system, known collectively as electrosteric stabilization (Hunter, 2001). This has been further explained on the basis of DLVO theory (2008; Griesser, 2002) and further modifications [20] presented in the literature. The combined action of electrostatic and steric actions yields much smaller ζ-potential (< 10 mV), thus providing an enhanced level of fluidity to cement pastes. The molecular architecture of these new generation SPs plays an important role in their performance [24]. PC-based admixtures primarily function through adsorption, but their efficiency is mostly determined by the steric effect (Ferrari, 2000)

C.2.3 Uses and benefits

Plasticizers are used in the dosage range of 0.2-0.8% by weight of cement and typically have water reduction in the range of 8-15% for conventional concrete. These are available in a range of types optimized for particular cement blends, aggregate sources or other properties. Apart from the basic benefits of water reduction (hence enhancement of workability and/or reduction of cement), Lignosulfonate types usually give some enhanced air entrainment, that in turn improves cohesion and reduces bleed in many mixes. Hydrocarboxylic salts can reduce air entrainment and hence cohesion, which may be useful in high cement content mixtures [7].

Table C-2 Pros and cons of using different superplasticizer chemistries [4, 14, 25]

Family	Pros	Cons
Polymelamine sulphonates	• Good early strength at low temperatures • excellent surface finish • Very cohesive mix • Lower air entrainment when compared to Naphthalenes • Easier to obtain a stable air system • Lower solids content makes these more robust	• Can loose workability quickly, especially at high temperatures • Prone to bleed and segregation in low cohesion mixtures
Polynaphthalenes	• Good water reduction • Good early strength • Very cost effective all-round superplasticizer • Higher solids content makes these economical	• Poor retention especially at higher temperatures, but better than melamines • Tend to increase the entrapment of larger, unstable air bubbles
Lignosulphonates	• Good water reduction • Good retention of workability	• May have problems with entrained air • Poor finishibility, especially at lower w/c
Polycarboxylates	• Maximum water reduction and early strength • Offer excellent fluidity and retention • Good finishibility • May lack of robustness	• Could be expensive due to addition of air detrainment

The typical dosages for Naphthalene and Melamine based SPs range between 0.7-2.5% by weight of cement and offer water reduction in the range of 16-30%. Polycarboxylate ethers are typically used in the dosage range of 0.3-1.0% by weight and offer water reduction in the range of 20-40+% water reduction. The choice of right chemistry for a construction site will be governed by materials related, technological and economic considerations. Of relevance is the market availability of a particular admixture. During the course of this investigation, the author was informed that the current market trends in North America are driven towards the usage of ligno-based, PC-based and their blends. Although other formulations are still being used, but they are not predomint the market, at least in case of SPs. Table C-2 presents a comparative application summary of different SP chemistries.

C.3 Admixtures that alter hydration kinetics

C.3.1 Retarders

Retarders are water-soluble chemicals that have little or no effect other than to delay the setting of cement paste. These by themselves do not plasticize significantly and have little or no effect on the water demand or other properties of the concrete [14]. Another definition of retarders are the chemicals that extend the time for the mix to change from the plastic to the hardened state by at least 90min but not more than 360 min at the compliance dosage [3]. Consequences of this delay in rate of hardening, or setting include a delay in the development of the early strength of concrete and an increase in the later strength. Usually it is observed that the strength is greater than the strength of non-delayed concrete [4], however it is interesting to note that ASTM C494 allows for a 10% reduction in strength for pure retarders.

Salts of carboxylic acids are the most dominant type of retarders. Pure retarders (like that of ASTM type B) are occasionally applied and are infrequently available in the market. Instead, bi- or multi-functional admixtures (Type D, G) offering water reduction and/or plasticizing effect and retardation are quite popular. The basic chemistry of water reducers and retarders is similar in many aspects [5, 7, 26]. Refer to Figure C-6. The main types of chemicals used for retarding admixtures are sucrose, other polysaccharides, citric acid, tartaric acid, salts of boric acid, salts of poly-phosphoric and phosphonic acids. In addition to these, the main types of chemicals used for retarding-water reducing admixtures are hydroxyl-carboxylic acid salts, hydroxylated polymers and ligno sulfonic acid salts [3, 14].

Retarders temporarily block the hydration of C_3S and C_3A by delaying the precipitation of $Ca(OH)_2$, by covering cement particles with a thin layer. The interaction of retarder with hydration products continues over time, eventually embarking breaking down and allowing normal hydration reactions to continue. When a retarder preferentially acts on C_3A or C_3S, it delays setting and hardening respectively. On the other hand, if it acts equally on C_3A and C_3S, it delays both setting and hardening [4, 27-28]. Factors that affect the water reducers also affect retarders in largely similar ways. The alteration interference with the hydration kinetics could be explained on the basis of one of the following five models:

- Calcium complexation
- Nucleation poisoning
- Surface adsorption
- Osmotic bursting
- Dissolution-precipitation

Retarders are effectively applied for hot weather concreting, for reducing the rate of workability loss, to increase the compaction and finishibility time window, etc.

C.3.2 Hydration stabilizers

Hydration stabilizers retard the concrete for a desired amount of time by adsorbing and coating the cement particles and hydration products and suspending the hydration reactions. Unlike conventional retarders, the stabilizer can be used at high dosages without the attendant adverse effects such as flash set and poor strength development resulting from the use of normal retarders. Amongst other factors, the dosage of hydration stabilizer is influenced by mix proportioning, time required for stabilization, average ambient temperature.

C.4 Admixtures that entrain air

Air entrainment (primarily in paste; could also be in the aggregate-paste interphase) achieved through the stabilizing action of air entraining admixture results in the formation of a discrete, spherical, uniformly distributed air-voids or bubbles (ranging between 10 to 1000 μm) dispersed throughout the mixture. These admixtures are specified in ASTM C260 [29]. The process of stabilization takes place through one or combined actions of the following:

i. Infolded and mechanically enveloped during mixing
ii. Dissolved in mix water
iii. Originally present in the inter-granular spaces in the dry cement and aggregate
iv. In the pores of aggregates [5]
v. Through reaction with calcium hydroxide solution to form insoluble calcium salts which accumulate at the interfaces between air, water and cement, and stabilize the air bubbles. This happens in case of vinsol resin, sodium adipate, sodium oleate. [30]

C.4.1 Chemical origins

AEA's have traditionally been based on Vinsol resin (abietic acid salts) and fatty acid salts. These have now been largely replaced with synthetic surfactants based on blends of alkyl sulphonates, olefin sulfonates, diethanolamines, alcohol ethoxylates and Betains [31] Table C-3 presents a summary of commonly used AEAs.

Table C-3 Classification and performance characteristics of common air-entraining agents[32]

Classification	Chemical description	Notes and performance characteristics
Wood derived acid salts , Vinsol resin	Alkali or alkanolamine salt of a mixture of tricyclic acods, phenolic and terpenes	Rapid air generation, especially in low slump mixes. Minor air gains some air loss possible with continuous mixing. Mid-sized air bubbles. Compatible with all admixtures. Some air loss possible.
Tall oil	Fatty acid-major component; tricyclic acids-minor component	Slower air generation, air may increase with prolonged mixing. Smallest air voids among common agents. Compatible with all admixtures
Vegetable oil acids	Alkali and alkanolamine salts of coconut fatty acids	Relative to wood rosins, slower air generation, both air gain and air loss possible with continuous mixing. Small to mid-sized air voids, and compatible with all admixtures
Synthetic detergents	Alkyl-aryl sulfonates and sulfates	Rapid air generation. Minor air loss with mixing. Coarser bubbles. Not compatible with SNF. Applicable for cellular concretes
Synthetic workability aids	Alkyl-aryl ethoxylates	Primarily used in masonry mortars
Miscellaneous	Alkali and alkanolamine of lignosulfonates; oxygenated petroleum residues; Protenaceous materials; animal tallow, Saponin	Older technologies not currently used as concrete air-entraining agents.

C.4.2 Physio-chemical actions

AEA's are surfactants, which are materials whose molecules are adsorbed strongly at air-water or solid-water interfaces. Such molecules are amphipathic meaning having dual nature, one portion of which is polar (head) and other non-polar (tail). Figure C-10 shows a schematic sketch of the same. Depending on the charge the head of the molecule carries, the surfactants are classified as anionic (ex. Carboxylates, sulfontes, sulfate esters), cationic (ex. substituted ammonium ion) and nonionic (ex. Polyoxyethylenated compounds). The tail on the other hand is frequently straight or branched chain of hydrocarbon group and for it to produce significant surface activity; it has to be long enough. The details of these portions can vary enormously.

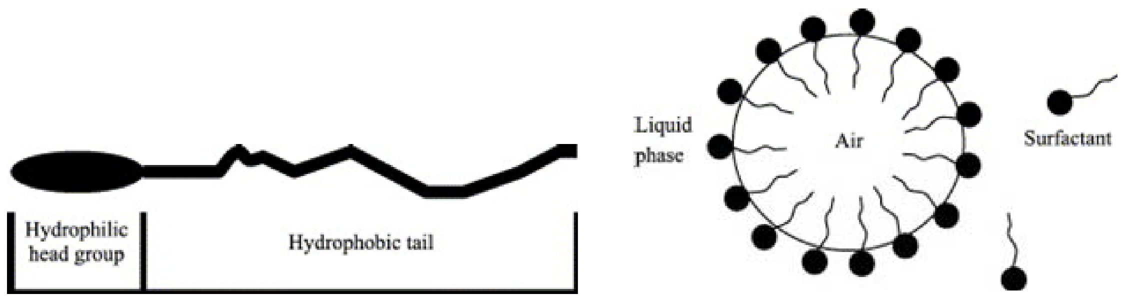


Figure C-10 The basic chemical nature of surfactant based AEA and the distribution of surfactant molecules at the water-air interface [33]

The orientation of surfactant molecules in bulk solution is random. However, the adsorbed molecules have preferred orientations. The hydrophobic tails of surfactant molecules stick out of the solution to reduce the distortion of water molecules by the hydrophobic sections and thus lower the overall free energy of the system. Figure C-10 shows this schematically for a monolayer. The mutual repulsion between the hydrophilic heads of surfactant molecules reduces the attraction of the bulk liquid phase and a lower surface tension is resulted. The nature and concentrations of the surfactants determine the physical and chemical properties of the interface at the air bubble surfaces, including surface tension (equals to free surface energy) and stability. Because of the electrostatic component of the repulsion force of ionic surfactants, their effectiveness to reduce surface tension is more significant than nonionic surfactants. The electrostatic and steric repulsions between surfactants help stabilize air bubbles in the paste phase [33]. Table C-4 summarizes the factors influencing air content.

Table C-4 Factors influencing air content [2] (and PCA book)

Increasing air content	Decreasing air content	Example change	Estimated effect (target 5% air content)
Low temperature	Higher temperature	10-20 C	Reduction 1-1.25%
High slump	Lower slump	50-100 mm	Increase of 1%
Sand grading coarser	Sand grading finer	BS 882 zone 3 to 2 (one zone width)	Increase < 0.5%
Sand content increased	Sand content decreased	35-45%	Increase 1-1.5%
Decrease in sand fraction <150 m	Increase in sand fraction <150 m	-50 kg/m3	Reduction of 0.5%
Decrease in cement content inclusive of sand content adjustment	Increase in cement content inclusive of sand content adjustment	-50 kg/m3	Reduction of 0.5%
	Inclusions of organic impurities	Inclusion	Positive and negative effects reported significant reduction linked to carbon in ash
	Inclusion of fly ash	Inclusion	Significant reduction linked to carbon in ash
	Increase in hardness of water	Increased hardness	Reduction
Increases with increasing dosage of lignin-based materials or retarders		Spacing factor may increase when water-reducers are used	
Moderate increase in air content when formulates with lignosulfonated based HRWR		Spacing factors increase	
With increased w/c		Decrease the AEA dosage as w/c ration increases	
Increase in mixing efficiency	Decrease in mixing efficiency	Better mixing efficiency	Increase linked to dispersion of admixture
Increases with slumps upto about 150 mm	With very high slumps		
Positive dispensing tolerance	Negative dispensing tolerance	± 5%	± 0.25%
Cement introduced at the beginning of mixing cycle	Simultaneous batching lowers air		
Air increases as mixer capacity is approached to its maximum		Overloaded mixers will entrain less air	

Air content increases upto a mixing speed of 20 rpm	Air content may de-crease at higher mixing speeds		
	Prolonged agitation	1h	Reduction of 0-0.25%
		2h	Reduction of 1%

C.4.3 Implications and uses

The following are the possible application areas where benefits from using AEA can be harnessed:

i. AEA can be applied in zero slump mixes, mixes with very low cement content, harsh mixes to enhance compaction under vibration, preserving dimensional stability in fresh concrete and occasionally improve the finishibility;
ii. The overall workability of the mix improves. AEA minimizes or eliminates segregation and bleeding tendency;
iii. Due to improvement in workability and their ball bearing like action, the water demand of the mixture goes down and thus there is a reduction in the effective w/c;
iv. AEA usage reduces concrete density;
v. The strength is a function of w/c and air content and the effects of air entrainment cannot be perceived in solitude. The strength will be decided depending on the type of AEA used, it's potential to reduce water demand and ability to entrain air;
vi. Air entrainment with specific configuration (air void spacing, grading, etc.) will beneficially impact the freeze-thaw durability of concrete.

C.5 Rheology modifiers

Rheology modifiers [also known as viscosity-enhancing admixtures (VEA's) or viscosity modifying admixtures (VMA) or anti-washout admixtures (AWA)] were developed to improve the integrity of concrete place underwater and so to reduce the impact that washed out cementitious material can have on the marine environment. These admixtures are generally recognized by their highly pseudoplastic flow behavior. When used these admixtures enhance the cohesiveness of concrete, reduce segregation and often in the presence of adequate binders compensate for poor grading of aggregates.

Rheology modifiers are mostly high molecular weight polymers with high affinity to water. Inorganic materials based VMA's (ex. Colloidal silica) are also available. Table C-5 summarizes a classification scheme for these admixtures

It is said that cement contents above 400 kg/m^3 are desirable when using VMA's. VMA's generally do not affect the other properties of concrete. Applications include self-consolidating concretes, pumped concrete, underwater concrete, etc.

Table C-5 Categories of VMA's [25]

Class/description	Mechanism	Examples
A (water soluble polymers)	Increase the viscosity of mixing water	Cellulose ethers, pregelatznized starches
B (Organic water soluble flocculants)	Increase viscosity by promoting inter-particle attraction after adsorbing on cement particles	Natural gums, styrene copolymers
C (Emulsions)	Increase interparticle attraction and supply additional superfine particles in the cement paste	Acrylic emulsions, aqueous clay dis-persions
D (Inorganic material of high surface area or unusual surface properties)	Increase the water retaining capacity of the mix	Bentonites, condensed silica fume
E (Fine inorganic materials)	Increase the thixotropy by increasing the fineness	Fly ash, hydrated lime

C.6 A note on admixture blends

With the growing number of applications in which concrete can be used, the demands on admixtures to cater to ever diversifying and challenging needs are also increasing. The following is an account of the needs for using admixture blends:

i. To reduce cost while simultaneously combining the benefits of a superior and expensive admixture with a relatively cheaper admixture. For example is combining a HRWR with a plasticizer;
ii. To reduce or to counteract the ill effects of one admixture. An example includes usage of Triethanolamine with ligno-sulfonates to reduce extended retardation;
iii. To extract multiple, but quite distinct benefits. For example, viscosity-modifying agents are added with SP's to enhance the cohesiveness of self-consolidating concretes;
iv. To overcome material limitations in terms of undesirable properties or performance. A surfactant-based admixture may be combined with a water reducer in dry cast applications. The water reducer provides better strength and microstructure, while the surfactant improves compactibility and finishibility;
v. Three or more admixtures could be combined to achieve synergistic or discrete effects. For example, a water reducer, hydration stabilizer and rheology modifier are used in combination for pervious concrete. Here a proper selection of rheology modifier is required; else, undesirable results shall be produced.

C.7 Physio-chemical compatibility

As more chemicals are added to mix, compatibility with cement and other admixtures becomes a critical parameter governing selection. Side effects or reactions among chemicals attributable to the sequence of addition, cement type, temperature change, and batching equipment can all affect the performance [34]. Correct combinations of admixtures can produce custom-made concrete for particular jobs. Serious problems may result from the use of mixture of chemicals in concrete. Hence, it is of critical importance to understand the compatibility of various chemical admixtures to produce the desired results. Moreover, it is important to understand the admixture-cement and admixture-admixture interactions so that optimal use of materials can be achieved; admixture-cement incompatibility can be prevented; better trouble-shooting of field problems is enabled; and more accurate prediction of concrete properties is made possible [8, 35]. The primary factors that control compatibility could be categorized into those that are related to materials (for example cement fineness, binder composition), ambient conditions (for example temperature, humidity, wind speed, etc.) and construction technology related. A materials related compatibility issue in one climatic condition may not exist at all in another. Figure C-11 provides a synopsis of the materials related factors affecting cement-admixture compatibility. A detailed discussion concerning this issue is beyond the scope of this document.

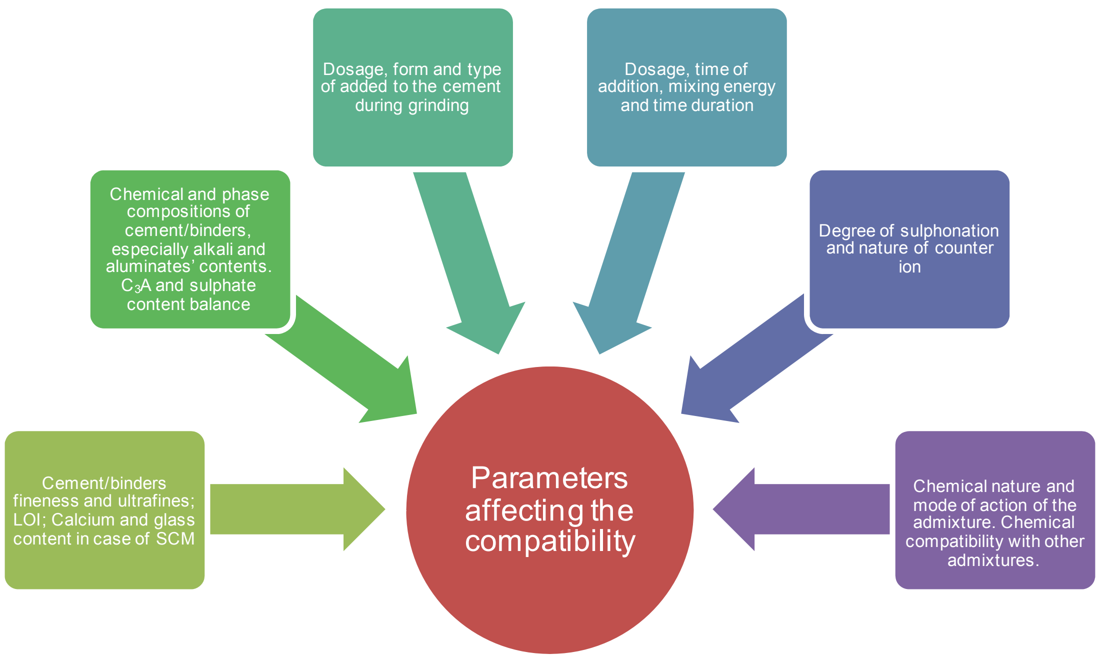


Figure C-11 Factors affecting cement-chemical admixture compatibility

Admixtures have a selective effect on the elementary steps of cement hardening, influencing the rate and duration of the processes involved in early hydration, when the technological aspects are of particular importance. A significant difference in the rates of hydration reaction and the surfactant adsorption may substantially reduce the efficiency of admixture. As such, compatibility can be thought of as the ability of an admixture to ensure the desired level of process parameters (in terms of hydration kinetics) over a preset period. Associated with the interaction (and hence hydration) of admixtures with cement and mineral admixtures is an underlying process of kinetic selectivity. Utilizing the thermokinetic parameters and a cement-admixture compatibility index the efficiency of admixtures for cements differing in characteristics and properties can be assessed. The cement-chemical admixture interaction problems can be roughly classified into two groups:

- Problems caused by the effect of admixture's addition on the hydration reaction of cement and
- Problems caused by the adsorption of the admixture to the cement particles [36].

It is important to note that the incompatibility is in terms of progress of hydration, hydration kinetics and thermodynamics, which results in products and/or manifestations that lead to failure of concrete in fulfilling its intended purpose. Incompatibility between materials may arise from chemical and physical causes. Some combinations of cement, supplementary cementitious materials, and chemical admixtures often at elevated temperatures cause chemical incompatibility; while physical incompatibility may arise from the mix proportions of concrete. Thus, chemical incompatibility may be evaluated in cement paste and physical incompatibility in concrete [37].

C.8 The predicament of drier concretes

Due to the drier nature and hence presence of low water, drier concretes offer unique set of challenges to the effective use of all chemical admixtures. Less water makes it difficult for the admixtures to initiate their actions and effectively influence the properties for which they are intended. As such, higher than normal admixture dosages are required in drier concretes. This point should always be considered with the contention that the manufacturer recommended dosages are for normal concretes and no admixture manufacturer wants to step outside the boundaries of safe dosages for multiple reasons, some being technical, others being ethical, societal and legal. Since there is no dedicated research reported on this matter, it is difficult to say whether or not it is the lack of appropriate chemistry or the a dosage issue.

It is also important to note that admixture manufacturer's fine tune their products to suite a particular range of applications. These applications are mostly geography specific, which in turn means the natures of the constituent materials are more or less known within a reasonable estimate. This helps tailor the product for specific applications where the range of binders, their composition and quantity, the ratio of water to binder and the aggregate properties are well known. Eventually this helps fix the molecular weight and solids concentration in a particular admixture. Using similar formulation might not work in drier concretes with equivalent efficiency.

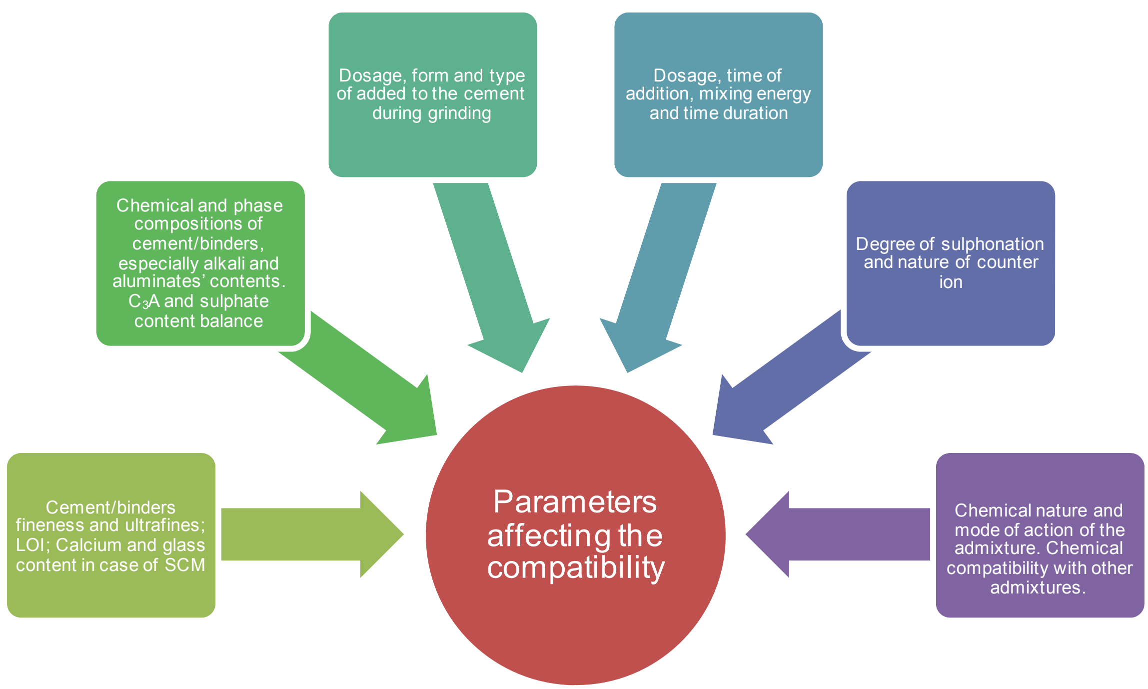
The mixer technology is critical in admixing some of the chemical admixtures in typical concretes. Drier concretes like RCC are a family of such concretes that demand special mixing requirements for effective use of chemical admixtures in them. For example entraining air is a challenging task and cannot be effectually achieved using pugmills. Higher mixing energies, longer mixing cycles and reduced batch sizes are essential for admixing such concretes.

SUMMARY

Chemical admixtures are increasingly gaining the position of essential components of concretes. With rapid evolution of admixture science and our understanding about their interactions with concrete making materials, many of long perturbing questions are being resolved. The study of the interactions of chemical admixtures, which are mostly organic in nature with mostly inorganic binders, is an interesting area of study. However eluding in terms of their physiochemical interactions, our knowledge about applying them is increasing every day. It is a topic of greater interest from sustainability perspective.

ASTM and other standard writing bodies have followed the chronological discoveries and with the pace at which the admixture technology is advancing, it is difficult for them to keep up with that pace. There is thus a need for a comprehensive classification scheme that would last longer than it has been in the past. With the advent of admixtures that can perform multiple functionalities, it is more often than not difficult to classify them.

The chemical interactions of various admixtures are difficult to understand and research is always being conducted to advance our understandings about their mechanisms of action. However, the complexity of interactions involved and the level of variability associated with civil engineering materials makes this task a bit challenging. Moreover, the manufacturers have mostly kept the body of knowledge about different chemical admixtures with them and have self-indulgently engaged themselves into the fancies of discovering newer molecules. Consequentially, there is not enough and prolonged dissertation offered to the understanding of the mechanisms. At the contractor and engineering end, we have been happy with the results that the market available admixtures have produced and have never enquired further.



Drier concretes present a different family of distinctly different nature leading to many misconceptions about the use of admixtures. We have calibrated ourselves on conventionally available concretes and have attempted to use similar candidates into a different office – drier concretes. There is thus a need for detailed studies on searching for appropriate chemistries, chemical formulations, dosing requirements for us to be better able to tell what admixtures can be used in drier concretes

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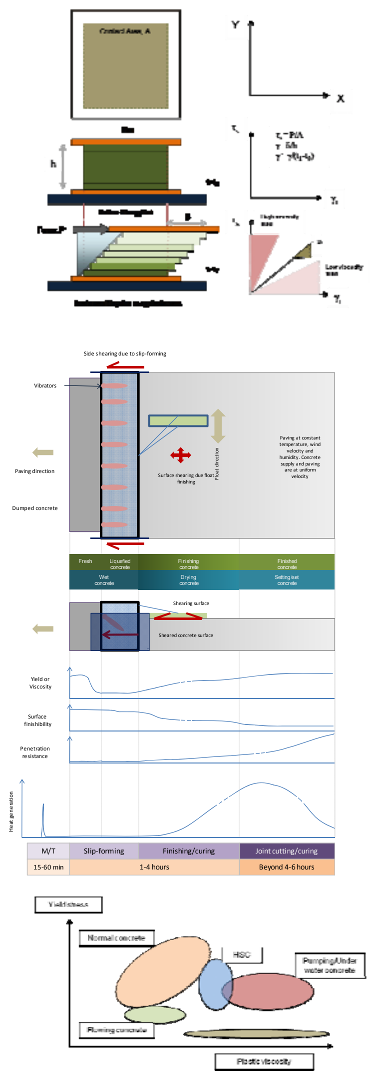
APPENDIX D RHEOLOGICAL CHARACTERIZATION



SYNOPSIS

This chapter presents the conceptual discussion on rheology as applied to cementitious materials. Clarifying the definitions and describing the basic systems, this chapter then talks about cement-water systems. A review of the factors affecting the Bingham parameters of cement-water systems is subsequently presented. Influence of aggregates on the Bingham parameters for mortar and concrete are discussed further. Appreciating the fact that most rheological studies were conducted for self-consolidating and flowing concretes, the chapter further defines and describes the shear strength of fresh concrete with special emphasis on paving concretes. Under vibration, the fresh concrete behavior is altered and is effectively used in compacting concrete, which is discussed further. Finally, the effects of measuring techniques on the measured Bingham parameters are discussed along with few technical notes.

Keywords: rheology, paste, mortar, concrete, vibration, test conditions, rheometer, shear strength

CONTENTS

D.1 Conceptual development

Rheology is the study of the flow of matter, mainly liquids but also soft solids or solids under conditions in which they flow rather than deform elastically [1]. More often than not, rheology is usually associated with liquids/fluids alone; however, it actually unites the seemingly unrelated fields of plasticity and non-Newtonian fluids by recognizing that both these types of materials are unable to support a shear stress in static equilibrium. In this sense, a plastic solid is a fluid. Granular rheology on the other hand refers to a continuum mechanical description of granular materials [2]. Although there is jargon [3] that is distinctively used in various fields of applications, rheology concerns itself with the mechanical descriptions in terms of strain-stress-time. Figure D-1 shows a schematic depiction of the primeval definition of rheology based on a parallel plate model.

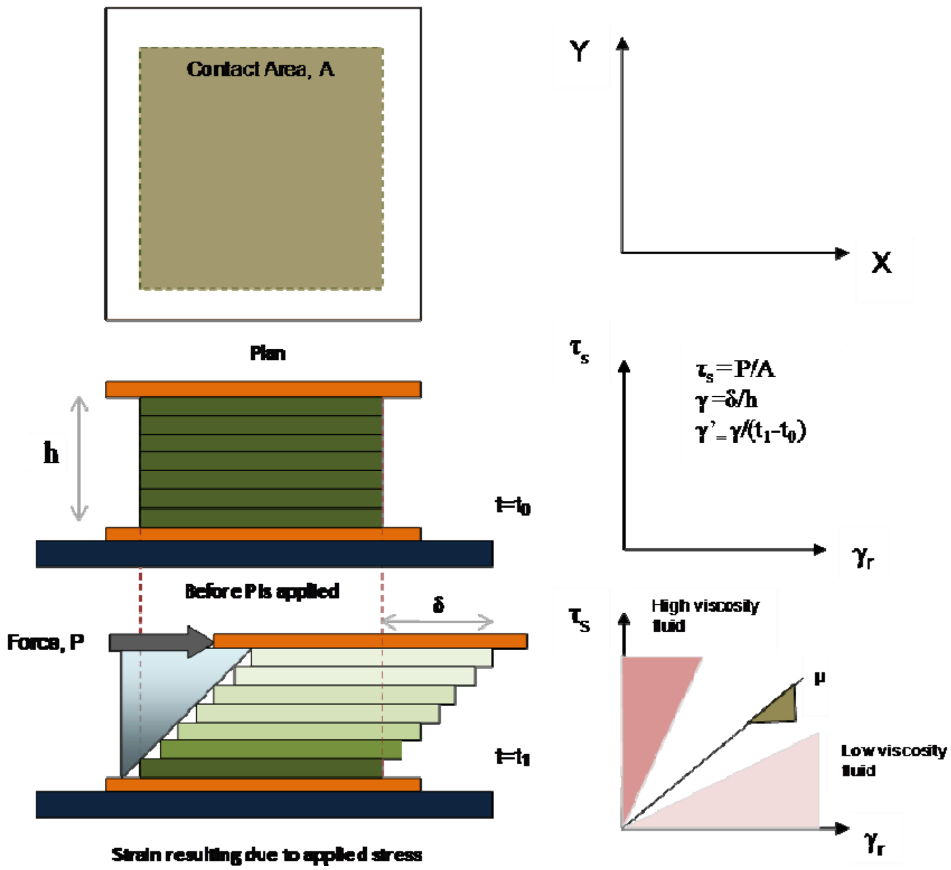


Figure D-1 Parallel plate model

The simplest Newtonian behavior is characterized by a linear relationship between applied shearing stress (τ_s) and the shear strain rate (γ'). The proportionality constant is called the coefficient of viscosity. A positive, non-zero, threshold value of stress called yield stress (τ_y), beyond which the flow initiates, usually characterizes Bingham behavior. A later section summarizes various behaviors exhibited by concretes.

D.2 Fundamental descriptions of the systems [4]

Materials in which hydrodynamic interactions (which develop only after some flow) prevail can be considered as Newtonian fluids, the viscosity of which in general increases with the volume fraction of elements. If the potential energy (PE) is considered as a function of the separation distance between neighboring elements, then the following types of interactions (apart from hydrodynamic) may be differentiated:

i. Soft interactions, in which the PE continuously varies (mainly increases) with the separation distance between the centers of elements. Examples include interactions between colloidal particles, bubbles, droplets. Pastes primarily show such behavior.
ii. Hard interactions, in which the PE abruptly increases from zero when particles come into contact. There are mainly between non-colloidal solid particles. Granular materials primarily show this kind of behavior.
iii. Depending on the flow conditions, a third type of behavior comprising both, with either dominating the behavior, is also observed. Granular pastes and slurries are examples of this kind of behavior.

Pastes, with a wide range of particle sizes, shapes and interaction types can be considered to be in a highly disordered state. Under small deformations, at macroscopic level, the paste system can be considered as linearly elastic. Any relative motion will be associated with hydrodynamic interactions implying viscous behavior. Hence, as long as the deformations remain below a critical value, there is no irreversible configuration change and the paste is considered a viscoelastic solid.

Yielding can be conceived as a solid-liquid transition, which occurs when the initial configuration is irreversibly broken. Macroscopically this behavior can be considered as plastic, possibly with some elastic or viscous effects. For plastic solid materials, the yielding in simple shear is associated with critical deformation (γ_c) which is enabled by a minimum shearing stress (called critical or yield stress, τ_y). For extremely slow flows, the shear stress (τ) required for maintaining the flow remains equal to the yield stress (τ_y) and such a flow is called perfectly plastic flow. On the other hand, at high flow rates, the shearing stress required to maintain the flow depends on the flow rate. This is a combination of plastic and hydrodynamic behavior. For describing such a behavior, that combines plastic behavior at low flow rates and the viscous behavior for larger flow rates, combined models are used. These materials are called as viscoelastic fluids.

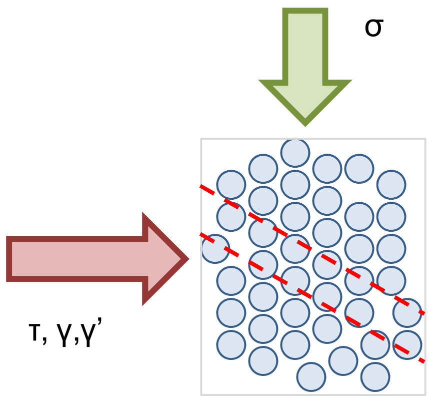


Figure D-2 Shear localization along the surface where Coulomb criterion is reached in granular materials

In case of granular materials, the rheological behavior depends on the configuration of particles, and more precisely on the spatial distribution of direct contacts, which may change in time as a function of macroscopic flow properties and boundary conditions. Depending on nature of the particles, their characteristic energies (kinetic and viscous), frictional displacement, and types of flow behaviors viz. frictional and collisional, regimes can be described. In the frictional regime, the frictional interactions dominate where pure elastic effects are unlikely with negligible thixotropic effects thus representing Coulomb-like behavior. It is important to recognize that the coefficient of friction will depend on the flow history. The coulomb criteria (with some assumptions) states that the tangential stress (τ) needed to shear the material is proportional to the normal stress (σ) and the proportionality constant (μ) is called the coefficient of friction of the material. Generalizing the results to any flow conditions, the Coulomb criterion is said to be reached when,

$$\gamma' \neq 0,\ \tau = \mu\sigma$$

When this condition is reached, the flow initiates, whereby due to localization of shear along the surface the particles move in mass without relative motion, and the shear occurs mainly in this region. This is shown in Figure D-2 with the region encapsulated by dotted lines. Physically, for a given material and a given flow type (with sufficiently low velocity) the coefficient of friction initially acquires a higher value, which reduces with time to reach a constant value at some critical stress. This co-efficient of friction increases with the rate of flow and ageing.

In granular pastes, both soft and hard interactions play a major role depending on the flow regime. At low flow rates, contacts of long duration giving rise to friction may dominate within the granular phase. At larger flow rates, the interstitial fluid can lubricate the grain interactions.

D.3 Cement-water systems

D.3.1 From suspensions to paste

Portland cement suspensions are high solids content (>30 volume %) colloidal suspensions [5], although the cement particles are much coarser than conventional colloid size [6]. These are typically used as cement slurries [7], direction coagulation casting of ceramic pastes [8], cement grouts [9]. Table D-1 offers a synoptic view of the parameters influencing the Bingham rheological parameters (yield stress and viscosity) and setting time of cement suspensions.

Although a clear demarcation between suspensions and pastes is not established, pastes can be considered to be highly concentrated, thixotropic suspensions [10], the rheology of which is quite complex [11-12]. Their colloidal behavior can be traced back to high density and high viscosity characteristics, which combined together hinder sedimentation [6]. It is considered as a viscoelastic material, since it shows both elastic and plastic properties. As time progresses, a hydrating cement paste encounters many physical and chemical changes that lead to qualitative and quantitative changes in the rheological characteristics.

Table D-1 Effects of different factors on the rheology of cement suspensions

Factor or additive	Effect on yield stress	Effect on viscosity	Effect on setting time
Decreased w/c ratio	+++	+++	-
Increased specific surface	++	++	-
Decreased temperature	++	+	++
Addition of bentonite	++	++	+-
Addition of SF	+++	++	-
Addition of SP	---	---	++
Addition of sodium silicate	+++	+	-
Addition of calcium chloride	+	+	---

Notes:

+++: Large increase; ++: Moderate increase;+: small increase; +-: indifferent

---: Large decrease; --: Moderate decrease; -: Small decrease

D.3.2 Factors affecting paste behavior

When water is added to cement powder, there are several physical-chemical-microstructural phenomena taking place concurrently, consequentially and successively. Up to approximately two hours following mixing under normal conditions (20°C and 50% relative humidity), the extent of the growth of the hydration products is usually considered too small to govern flocculation of cement particles. Depending on the particle sizes, inter-particular distances between cement grains in this condition are subjected to the following forces that establish equilibrium:

- Mainly repulsive: electrostatic, coulomb charges;
- Attractive-repulsive: unbalanced electric charges and zeta potential
- Attractive: Van der Waals, capillary [13]

MATERIALS RELATED

The flow of concrete is very sensitive to the flow characteristics and volume fraction of cement paste. Cement paste, not subjected to vacuum, essentially consists of three main phases viz. suspended cement particles (solid-like) in water (liquid) along with entrapped/entrained air. Chemical admixtures may be present in dissolved or suspended form. Gradually, but not at a uniform rate, it transitions from a semi-solid or fluid-like material into a solid. Following is a sampling of the significant factors affecting the rheology of cement paste. Each point is supported from the literature.

BINDERS

With high variability (Bartos, 1992), the following properties of cements affect the yield stress and viscosity:

- the nature of interparticle interactions between cement particles (dispersion coagulation characteristics);
- PSD and concentration which influences the particle packing; formation of hydration products,
- the rapid hydration of aluminate phases [14] ;
- beginning of acceleration period of alite hydration [15];
- flocculation of the aluminates and retardation of their hydration by sulfate [16],
- C_3A content and temperature [17-18].
- For a constant w/c, the rheological behavior of the paste is influenced by the amount and morphology of the hydration products on the surfaces of cement grains. Yield stress and plastic viscosity are reported to hold power-law relationships with the specific surface (S_v) of cement.

$$Yield\ stress = k_1 S_v^{3.83}$$
$$Plastic\ viscosity = k_2 S_v^{2.47}$$

Factors k_1 and k_2 depend on the w/c of the cement paste [19].

Figure D-3 shows a combined effect of the Aluminate content, specific surface area and water reducer type on the rheological properties of cements

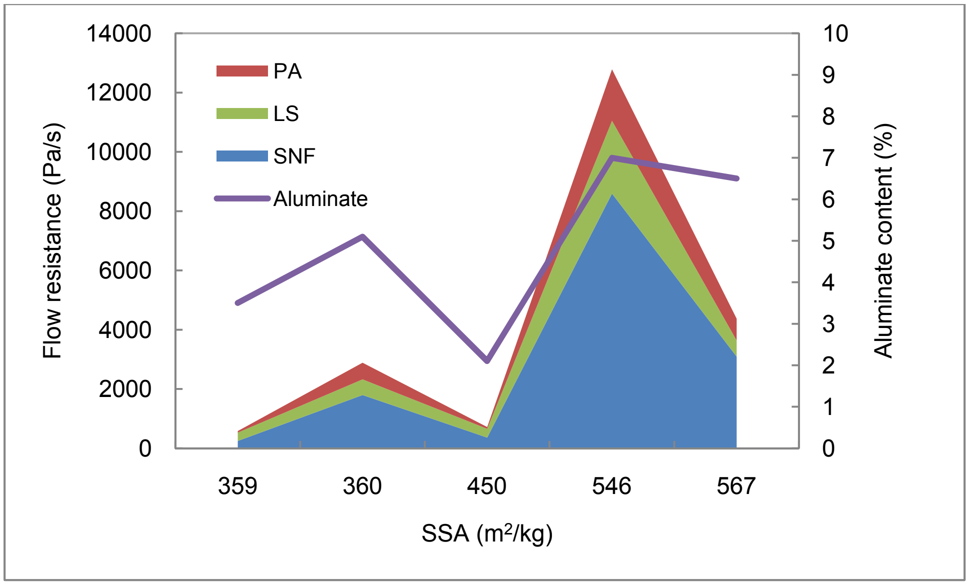


Figure D-3 Flow resistance offered by Polyacrylate-, LS- and SNF-based SPs for cements with different finenesses, specific surface area [20]

Sybertz and Reick [21] observed that the changes in the rheological parameters caused by substitution of the same volume of fly ash for cement are linear, i.e. the effects of fly ash and cement are additively superimposed. The liquefying effect of fly ash will depend on its properties. Park, et.al. [22] observed that addition of fly ash reduces the yield stress while simultaneously increasing the viscosity. Domone [23] on the other hand states that the viscosity reduces. Discussions on other SCM's is considered to be beyond the scope of this work and hence not reported.

w/c RATIO [23]

The w/c is the most influential parameter that affects the rheology of cement paste. Figure D-4 shows that both the yield stress and plastic viscosity reduce with increasing water content. The behavior is, however, somewhat different when the fluidity of the cement paste is increased with a superplasticizer.

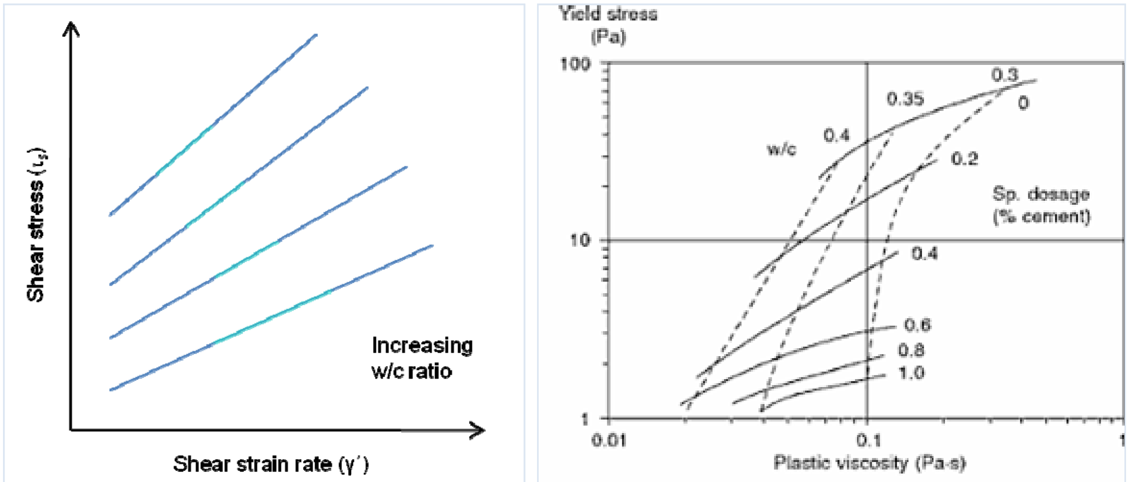


Figure D-4 Flow curves for cement pastes with varying w/c ratio and typical effects of Naphthalene formaldehyde superplasticized cement paste [23]

CHEMICAL ADMIXTURES AND SURFACTANTS

Water reducers exert the following two microstructural effects on the cementitious system:

- the geometrical effect: plasticizers and SPs create better flocculation between fine particles, which increases the packing density of the system and
- the mechanical effect: it lubricates the solid surfaces, decreasing the friction stresses between the particles [24].

While plastic viscosity is moderately influenced by plasticizing admixtures (essentially through the virtual packing density of the fine particles), yield stress is fundamentally changed by plasticizers/SP. Interactions between cement and admixture not only affect the fluidity of cement paste, but also causes a stiffness like pseudo-setting, or remarkable retardation of setting. The flow behavior of cement paste is strongly altered and influenced by admixture chemistry [8, 25-26]. This is demonstrated in Figure D-5.

Research on usage of retarders, plasticizers and SP has been amply reported in the literature (Refer to CANMET/ACI International conferences third through eighth; RILEM conferences). Depending primarily on the quantity of the active ingredient in the chemical admixture and the mode of action (electrostatic or steric or electrosteric), alterations in the yield and viscosity will be observed.

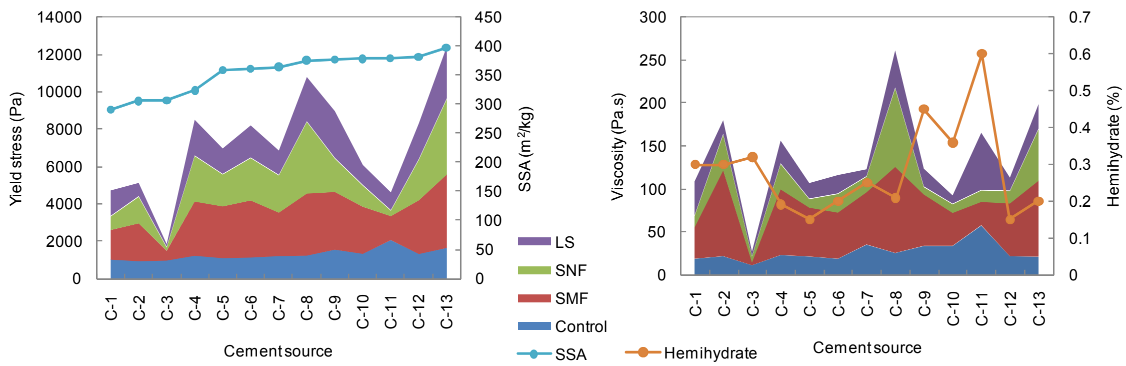


Figure D-5 Effects of cement compositions and chemical admixture type on Bingham parameters.Cements collected from different countries; w/c 0.5 (control, 0%), 0.4 (SMF/SNF, 0.3%) and 0.45 (LS, 0.3%); other details to be found in the reference; variation of different forms of sulfates (anhydrite, gypsum and hemihydrite); Vane type rheometer; measurement @ 8min at room temperature [27]

Viscosity modifying agents (VMA), viscosity enhancing admixtures (VEAs) (Khayat, 2002) or anti-washout admixtures (AWA) (Sonebi, 2001) are incorporated to improve the ability of highly flowable cement-based materials to maintain homogenous suspension (cohesion) in the plastic stage thus increasing the cohesion and stability of the system [28-29]. Use of rheology modifiers affects both viscosity and shear yield stress. An increase of VMA content leads to an increase of rheological parameters without affecting the saturation dosage of SP [30].

The level of air entrainment depends on the surface activity of the surfactant available in the solution, while the air void stability depends on the colloidal phenomena taking place at the solid-air interface [31]. Increasing air content increases the paste viscosity [32-33]. Kikukawa and Lisaka [34] observed that the plastic viscosity of a neat cement paste containing AEA linearly increases over time after mixing and abruptly increases beyond a certain time period departing from linear relationship. The linearity of the relationship was temperature dependent.

MIXING

The following observations made in the literature are relevant:

- Cement paste in fresh concrete is very probably in a structurally broken-down condition [35-36];
- The rheological behavior of cement pastes during the first two hours is strongly influenced by mixing methods. Agglomerates initially existing in the cement powder, and later remaining in the paste due to insufficient mixing, are responsible for the higher and faster increase in the peak shear stress and are potential sources of microstructural defects. It is also recommended that intensive type of mixer would be advantageous in mixing cement based systems [37].
- Mixing for longer times (4 and 5 min.) was observed to provide a better workability and stability for cement pastes [27]. Researchers [38-39] have shown that a minimum mixing time of approximately 5 min is required for obtaining constant properties of both yield stress and plastic viscosity. Using a simple mechanical stirrer, Banfill [40] confirmed that the yield value and plastic viscosity decreased as the time of stirring increased;
- Continuous shearing accelerates hydration and high shear mixing results in rapid hydration [41];
- Mixing with high speeds (> 1100 rpm) gives high workability (Claisse, 2001). Similar conclusions were obtained by Roy and Asaga [42] who observed that the yield and viscosity can be lowered by about 60% with an increase in the severity of mixing. However, care also needs to be exercised to simulate the real life mixing in laboratory studies such that proximity to actual shearing history can be achieved.

TIME AND TEMPERATURE DEPENDENCE

Cement paste, even at reasonably high water contents exhibits yield strength and hence possesses mechanical strength as soon as mixing ceases. The microstructure often formed due to flocculation is responsible for high yield stress, while the plastic viscosity depends on the volume of the solid particles and density of their packing. The yield stress thus represents the extent of flocculation and the strength of the attractive interparticle forces responsible for flocculation [43]. With the on-going build-up of the structure, the rheological responses of cement pastes and hence concrete change with time. As hydration proceeds through the induction period, the slow processes taking place in the paste cause the paste to stiffen, and both yield value and plastic viscosity increase. After the end of induction period the stiffening accelerates as the paste sets and both the parameters increase more rapidly. This behavior critically depends on the mixing method and the shear history associated with each measurement [32]. Figure D-6 explains this behavior graphically.

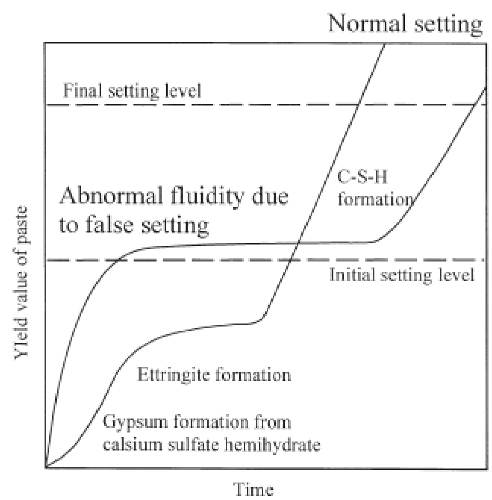


Figure D-6 Effect of setting on the yield strength [44]

Greater or faster loss of consistency is the practical manifestation of higher temperatures [45]. Accordingly, the rheological properties shall be affected and this would be reflected in the faster growth of yield value and plastic consistency. A possible mechanism of action under higher temperatures has been explained elsewhere [46].

D.4 Cement-water-aggregate systems

The constituents of concrete (cement particles, 1 to 100 μm; aggregates, mm to few cm and water) are energetically blended for a short time in a mixer in order to get a uniform mass. After this mixing, the aggregates can be considered to be embedded in cement paste, which is a dense suspension of cement particles in water. The workability of concrete depends on parameters related to the aggregates, but is also highly related to the rheology of cement paste which constitutes that matrix [47].

D.4.1 Nature of particles and change in scale

Introduction of fine aggregates in mortars and coarse and fine aggregates in concrete leads to introduction of forces, different in range and nature of manifestation from those acting on cement particles. Table D-2 provides a review of such forces at different levels. These forces affect the rheological behavior of cement paste, which in turn manifests itself in the form of effects on concrete rheology.

Table D-2 Different kinds of forces acting in particle suspensions, such as concrete [48]

Particle size (mm)	Type of particle	Kind of predominant force
>1 mm	Coarse sand, gravel	Shear, gravity
0.1-1 mm	Sand	Capillary
10^{-6} -0.1 mm	Cement particles, hydrates, aggregate fines	Colloidal forces (electrostatic & van der Waals)

D.4.2 Formation of mortars

Research substantiates Bingham plastic behavior of cement mortars [48-51]. Toutou and Roussel [52] noted a shear thickening behavior of mortars similar to that of the cement paste; they also remarked that the thixotropic behavior of cement (state of flocculation) has an influence on how the presence of sand particles increases (or not) the yield stress of corresponding mortar. When the sand volume fraction increases above a given value that depends on the sand particles size and probably on the mixing procedure (shearing history), the yield stress of the mortar becomes higher than the yield stress of the cement paste as the thickening effect of the sand particles becomes higher than their deflocculating effect. Research [49, 53-57] is reported on the effects of the following materials on the rheological behavior of mortars along with the effects of temperature mixing methods, and measuring techniques:

- Cement type;
- Mineral admixtures (ex. fly ash, silica fume);
- Types of natural/crushed (mineral) fine aggregates;
- Chemical admixtures (SNF, PNS, PC-based)

Table D-3 reports a summary of effects of changes in the properties of these constituent materials on the rheological properties of mortars.

Table D-3 Mix parameters affecting Bingham parameters

Change	Effect on	
	Yield stress	Plastic viscosity
Increase in water content	↓	↓
Increase in sand content	↑	↑
Increase in cement content	↑	↑
Increase in fineness of sand	↑	↑
Addition of plasticizer	↓	↑/No change
Addition of AEA	Little change	↓
Cement replacement by		
Fly ash	↓	↓
SF	↑	↓

Notes: ↑: Increases; ↓ reduces

D.4.3 Formation of concrete

Coarse aggregates add another component to the concrete system in addition to the mortar. The addition of coarse aggregates takes the Bingham parameters to another level. It is important to note that the effect of the aggregate volume fraction on the rheological behavior of concrete is still very unclear from a quantitative point of view [58]. Table D-4 presents a schematic synoptic summary of relative values of these parameters for various types of concretes.

Table D-4 Rheology of cement paste, mortar and concrete [59]

Material	Cement paste, grout	Mortar	Flowing concrete	SCC	Concrete
Yield stress (N/m^2)	10-100	80-400	400	50-200	500-2000
Plastic viscosity (Ns/m^2)	0.01-1	1-3	20	20-100	50-100
Structural breakdown	Significant	Slight	None	None	None

The following report on the influence of aggregate is relevant:

- Aggregate volume

  The volume and proportions of different fractions of aggregate play an influential role on the Bingham parameters of fresh concrete. Apart from the influence of grading on the surface area of aggregates, water demand for a given consistency, the relative yield stress and relative viscosity (defined as rheological parameters of concrete over those of mortar), both significantly increased with the increase in the coarse aggregate volume fraction, irrespective of the type of aggregate volume [60]. Figure D-7 demonstrates this fact. There is an optimal combination of fine and coarse aggregate at which the Bingham parameters individually reach their minimal values [24] .
- Aggregate shape

  The aspect ratio, angularity and surface texture of aggregates affect the yield stress and viscosity differently. Round and smaller aggregates tend to have lower Bingham parameters than the angular ones [60].

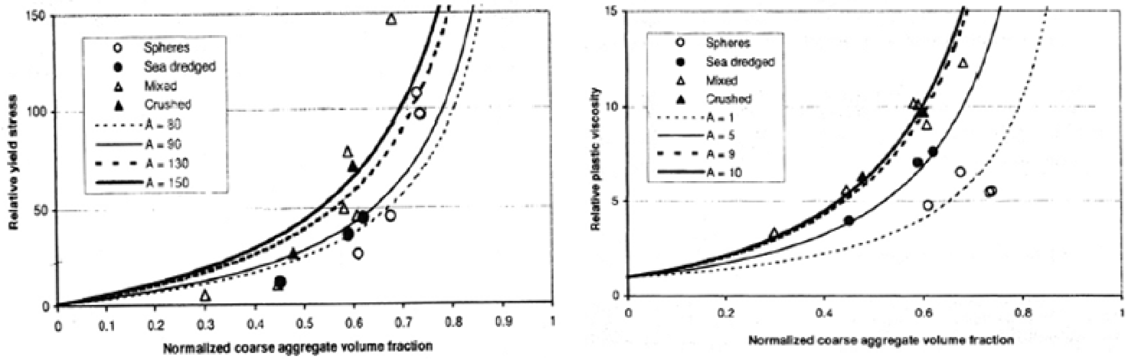


Figure D-7 Influence of coarse aggregate volume on the relative yield stress and viscosity [60]

Rheological modeling of concretes has so far been widely applied for flowing and self-consolidating concretes. The models generally accepted for concretes are summarized in Table D-5. Figure D-8 shows relative ranges of yield stresses and viscosities for various concretes.

Table D-5 Generally accepted equations relating shear stress and shearing rate

Model name	Equation	Remarks
Newtonian	$\tau = \eta\dot{\gamma}$	
Bingham	$\tau = \tau_0 + \eta\dot{\gamma}$	
Hershel-Bulkley	$\tau = \tau_0 + \eta\dot{\gamma}^n$	
Power	$\tau = \eta\dot{\gamma}^n$	
	n = 1, Newtonian flow	
	n > 1, Shear thickening	
	n < 1, Shear thinning	
Vom Berg	$\tau = \tau_0 + B\sinh^{-1}\frac{\dot{\gamma}}{C}$	[61]
Eyring	$\tau = a\dot{\gamma} + B\sinh^{-1}\frac{\dot{\gamma}}{C}$	A, a, B, b, C, K, α, β, δ = constants
Robertson-Stiff	$\tau = a(\dot{\gamma} + C)^b$	
Atzeni, et.al.	$\dot{\gamma} = \alpha\tau^2 + \beta\tau + \delta$	
Casson	$\tau = \tau_0 + \eta_\infty\dot{\gamma} + 2[\tau_0\eta_\infty]^{0.5}\dot{\gamma}^{0.5}$	[62]
Generalized Casson	$\tau^m = {\tau_0}^m + [\eta_\infty\dot{\gamma}]^m$	η_∞: viscosity at very high shear stress
Papo-Piani	$\tau = \tau_0 + \eta_\infty\dot{\gamma} + K\dot{\gamma}^n$	
Sisko	$\tau = \mu_0\dot{\gamma} + K\dot{\gamma}^n$	[63]
DeKee	$\tau = \tau_0 + \eta_{pl}\dot{\gamma}e^{-\alpha\dot{\gamma}}$	

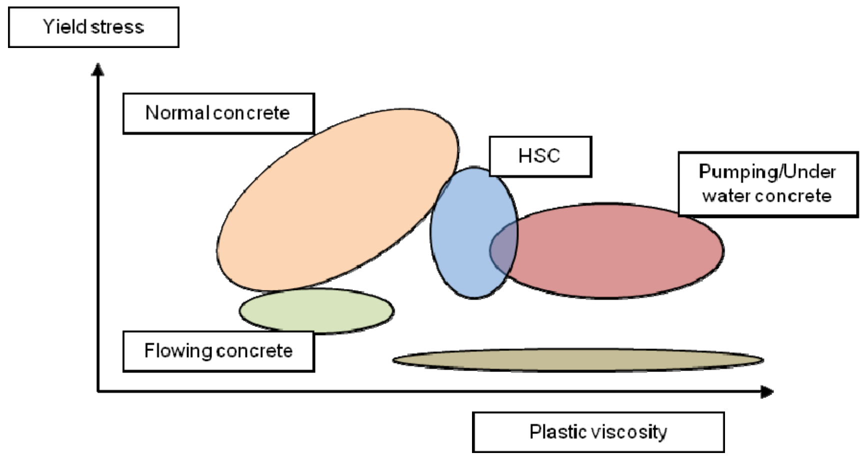


Figure D-8 Relative values of yield stress and plastic viscosity. Inspired from [23]

With attention mainly focused on concretes with sufficient fluidity, little effort has been made toward characterizing the flow properties of other stiffer types of concretes, in terms of flow parameters. Moreover, methods of characterizing concretes of different consistencies are different. Table D-6 provides a general summary of testing applicable testing methods and the ease with which the model parameters can be achieved.

Table D-6 Application of different models for characterizing rheological properties of concrete [64]

Model	Constants	Measuring methods	Facility	Concrete
Mohr-Coulomb	Internal friction angle, adhesive force	Three axes compression test	X	Dry
		One side shear test	Δ	
Bingham	Yield value and plastic viscosity	Rotational rheometers	X	Flowable
		Dragging ball viscometer	Δ	
		Parallel plate viscometer	Δ	Dry
		Inclined pipe test	O	Flowable
Combined model (includes the first two)	Varying yield and plasticity values	Shear box test	Δ	Option

Notes: X: very inconvenient; Δ: inconvenient and O: convenient

D.5 Shear strength of fresh concrete: Perspective on slip-forming

When concrete is paved, it undergoes vibration, liquefaction, compaction, finishing, setting. Figure D-9 shows a schematic sketch of the paving operation with areas that undergo shear and the hypothesized nature of yield, viscosity, and finishibility and penetration resistance.

Fresh concrete is a material that instantaneously undergoes shear strain when stress is applied. When the shear stress is below the yield value, the concrete behaves like an elastic solid. With higher shear stress, the bond strength between the particles is insufficient to prevent flow and the concrete will gradually change to a more liquid like consistence. The fresh concrete can be assumed to follow a linear elastic model below the yield value. Hook's law for linear elastic behavior is stated as follows:

$$\tau = \gamma G$$

where, G is the shear modulus. On the other hand, when the applied stress is above the yield value, the concrete will start to flow. The Mohr Coulomb flow model can be used to describe the shear strength related to the effective pressure at failure

$$\tau = \tau_y + ptan\varphi$$

τ_y is the cohesion while the p is the effective pressure at failure [65]. Since the shear force can only be transferred through particles, therefore the effective pressure, p is used. A caveat to following this relationship is that the concrete has to be stiffer in consistency, at least capable of bearing the normal stress applied during testing. The materials related factors that affect the Bingham parameters can be postulated to have similar effects on the yield stress.

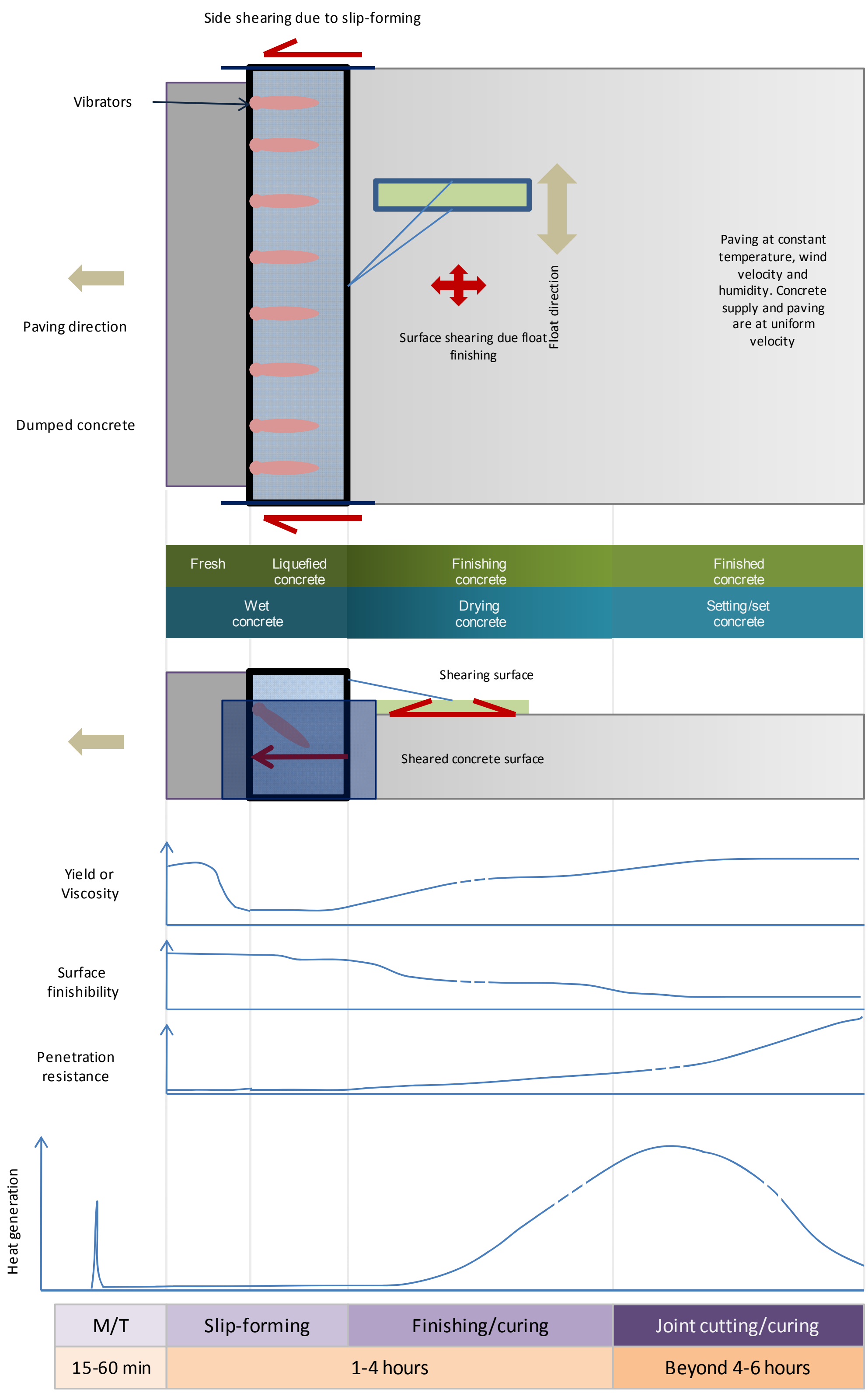


Figure D-9 Schematic sketch of paving operations and temporal evolution of concrete properties

Cohesion mainly manifests due to the chemical bonding resulting due to the ongoing hydration reactions. The shape of the particles, their grading, packing and the friction coefficient when sliding between particles takes place will decide the amount of frictional resistance offered to flow. The angle of friction and hence the second component of above equation will increase with increased sharpness and roughness of the particles, increased packing and increased friction coefficient. The internal friction will also increase with increasing effective pressure. Alexandridis observed that the chemical bonding will be small when the concrete is fresh and increases with time as hydration proceeds, while internal friction remains constant with set time and temperature [66]. This study was performed in drained triaxial loading conditions where pore water pressure is allowed to dissipate. Moreover, this test is performed under conditions that does not simulate slip-forming, where the concrete is shearing at the surface and where vibration is applied.

Recently instruments used for soil strength testing, viz. triaxial, shear, Vane, etc. have been used for characterizing fresh properties of mortars and concretes [67-69]. It is quite interesting to observe that at least partially and at macroscopic level, the direct shear test used for soil testing is quite similar to the paving operation. Figure D-10 shows a simulation.

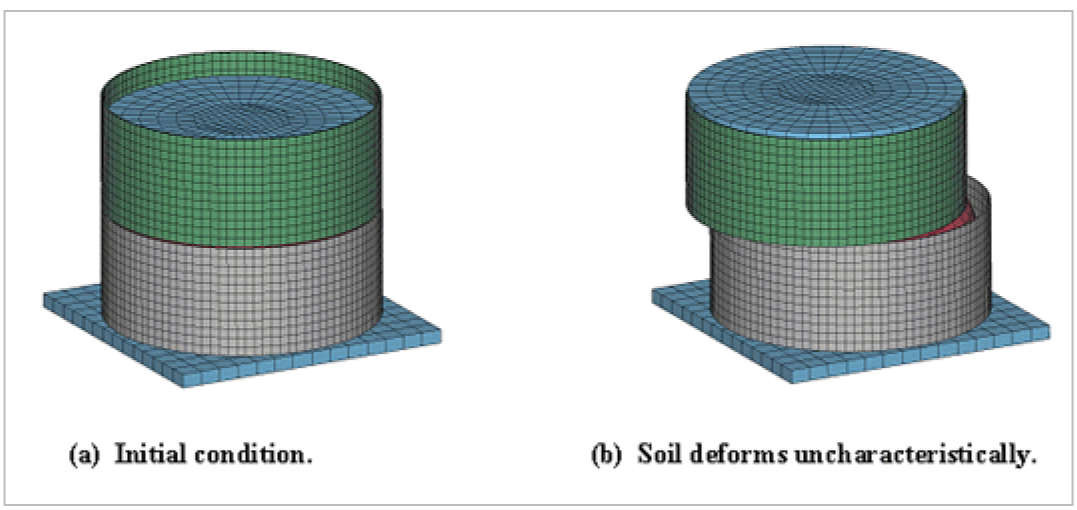


Figure D-10 Simulation of direct shear test for soils [70]. Note that in soils, usually the cross sectional area changes with time and is proportional to the strain

Although applied to materials that mechanically behave differently, a comparison between the Bingham model and Coulomb's failure criteria will help in enhancing the appreciation of the nature of measurements. Rewriting these equations as follows,

$$\tau = \tau_0 + \eta\dot{\gamma}$$
$$\tau = \tau_y + ptan\varphi$$

we can see that the cohesion and yield stress are analogous. The nature of equation changes when we consider the second part of right hand side. Bingham model uses shearing rate and obtains viscosity as a constant. For composing this model, experiments are run at different shearing rates. On the other hand, Coulomb's model varies the normal load or effective pressure and obtains the coefficient of friction as a constant. For composing this model, experiments are run at a fixed shearing rate. Figure D-11 juxtaposes the two models to elucidate the different perspectives of seeing the same of similar yield stress.

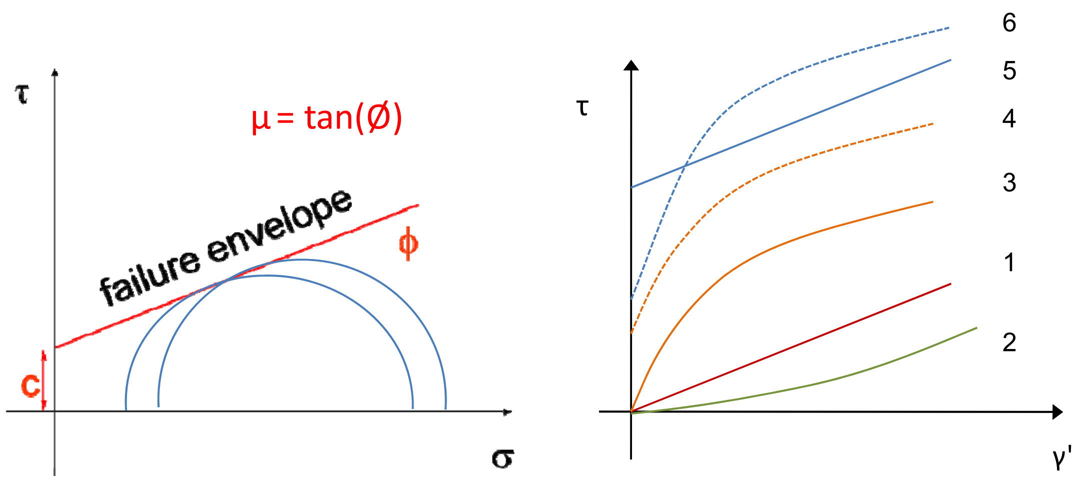


Figure D-11 Comparison Coulomb and other rheological models. Graph on right: 1: Newtonian; 2: Shear thickening; 3. Shear thinning (pseudo-plastic); 4: shear thinning with yield response; 5: Bingham plastic, ideal; 6: Bingham plastic, non-ideal.

D.6 Concrete under vibration

Without any vibrations, cement pastes are viscoplastic in behavior. Vibration periodically breaks the bonds and tends to decrease the initial yield value. It can even suppress the yield stress and at the same time the time dependent response of the material [71-72]. It is reported that a right combination of frequency and oscillating shear can reduce the shear resistance of cement. In addition to this, a right combination of amplitude and frequency can enhance the fluidity of concrete or reduce the viscosity (Banfill, 1996). Additionally the flow behavior of concrete under vibrations may be approximated to that of simple Newtonian fluid at low shear rates [32]. The yield stress drops down, with the viscosity remaining almost the same [23]. Figure 34 shows such behaviors.

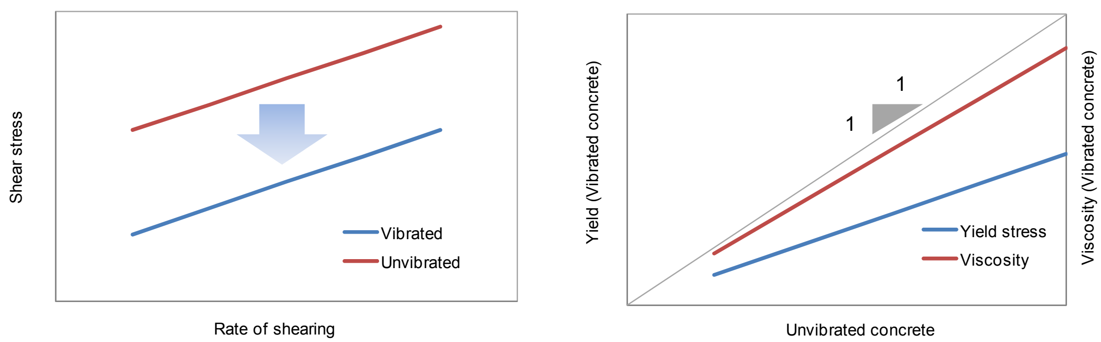


Figure D-12 Effects of vibration on Bingham parameters. Inspired from [23, 32]

The magnitude of reduction of yield stress is dependent on the amplitude and on the period of the vibration. Acceleration of at least 0.5g must be applied to produce a substantial effect on concrete placement [73]. The optimum range is 1g-4g; accelerations greater than 4g provide no additional improvement. The efficient range of values for vibrating frequency is between 50 and 100 Hz[74], while that in use may range from 50 to 200 Hz.

Other research found that the flow curves of concrete under vibration show quasiviscous or pseudoplastic behavior and the flow behavior is related to the acceleration and pore water pressure (Kakuta, 1990). Hu [75] on the other hand observed that the behavior of fresh concrete under vibration doesn't change its basic Bingham behavior, but there is a reduction in the yield stress by half ($\tau_{0vibrated} = 0.52\tau_{0unvibrated}$), while the plastic viscosity ($\mu_{vibrated} = 0.62\ \mu_{unvibrated} + 80$) was not much affected [[75]as cited in[74]].

Nishibayashi, et.al. [76] tested plasticized concretes (OPC-w/c, 0.35, 0.40-soft and stiff consistency) under constant frequency and constant acceleration. They observed that the plastic viscosity grows larger and the yield value goes down with an increase in the acceleration when vibrated, but this tendency varies with the type of admixture used. On the other hand, with an increase in the frequency, plastic viscosity goes down and the yield becomes larger.

D.7 Test method dependence

Experts have cautioned that the interpretation of cement paste rheology needs watchfulness since there are large variations in measured parameters by different researchers. For example at very low shear rates, flow is mainly controlled by yield stress, while at very high shear rates, the flow is mainly controlled by plastic viscosity [77]. These cannot be fully explained by the variation of the materials alone; hence, the unexplained variations can be related to the measuring techniques [32]. Figure XX clarifies this point. The behavior of cement paste can be sub-divided into two categories viz. shear-rate dependent and time-dependent. Quantitatively speaking and in terms of the experimental measurement the rheology interpretations depend on the following three relationships:

i. The rate of shear
ii. The shear stress
iii. The duration of shearing at a given shear rate [13].

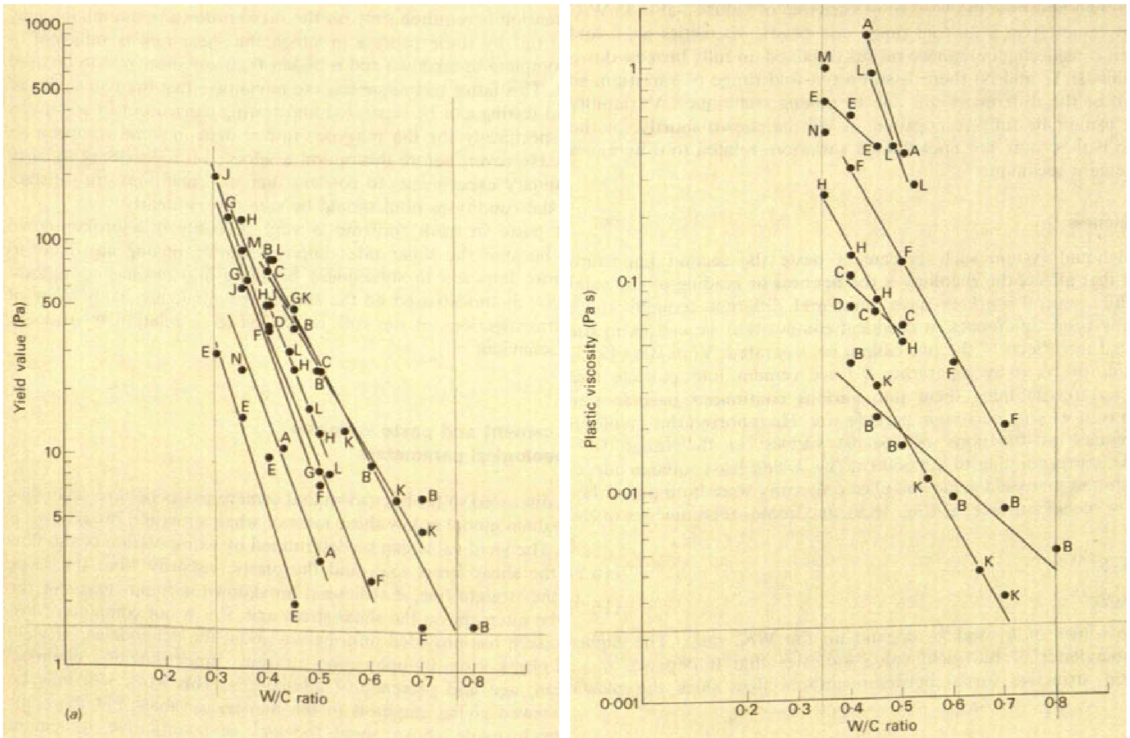


Figure D-13 Effect of rheology measuring apparatus on the measured rheological parameters of cement pastes. A, B, C, F, G, H, J, K: Coaxial cylinder type; D: tube viscometer; E: Cone and plate; L: mini-helical mixer; M, N: helical/cylindrical [35].

Recently a study was undertaken to appreciate the correlations and differences arising due to the usage of different rheometers by Ferraris and Brower [78-79]. Figures XX present a summary of the data obtained from these studies. The salient conclusions of these studies are as follows:

i. All the rheometers ranked the mixtures in the same order both for plastic viscosity to a good degree of statistical confidence;
ii. The degree of correlation of both yield stress and plastic viscosity measurements between any pair of rheometers proved reasonably good;
iii. Differences in absolute values given by various rheometers may be attributed to several causes, such as slip at the instrument wall, interference with the concrete or the confinement of concrete between moving parts of the rheometers

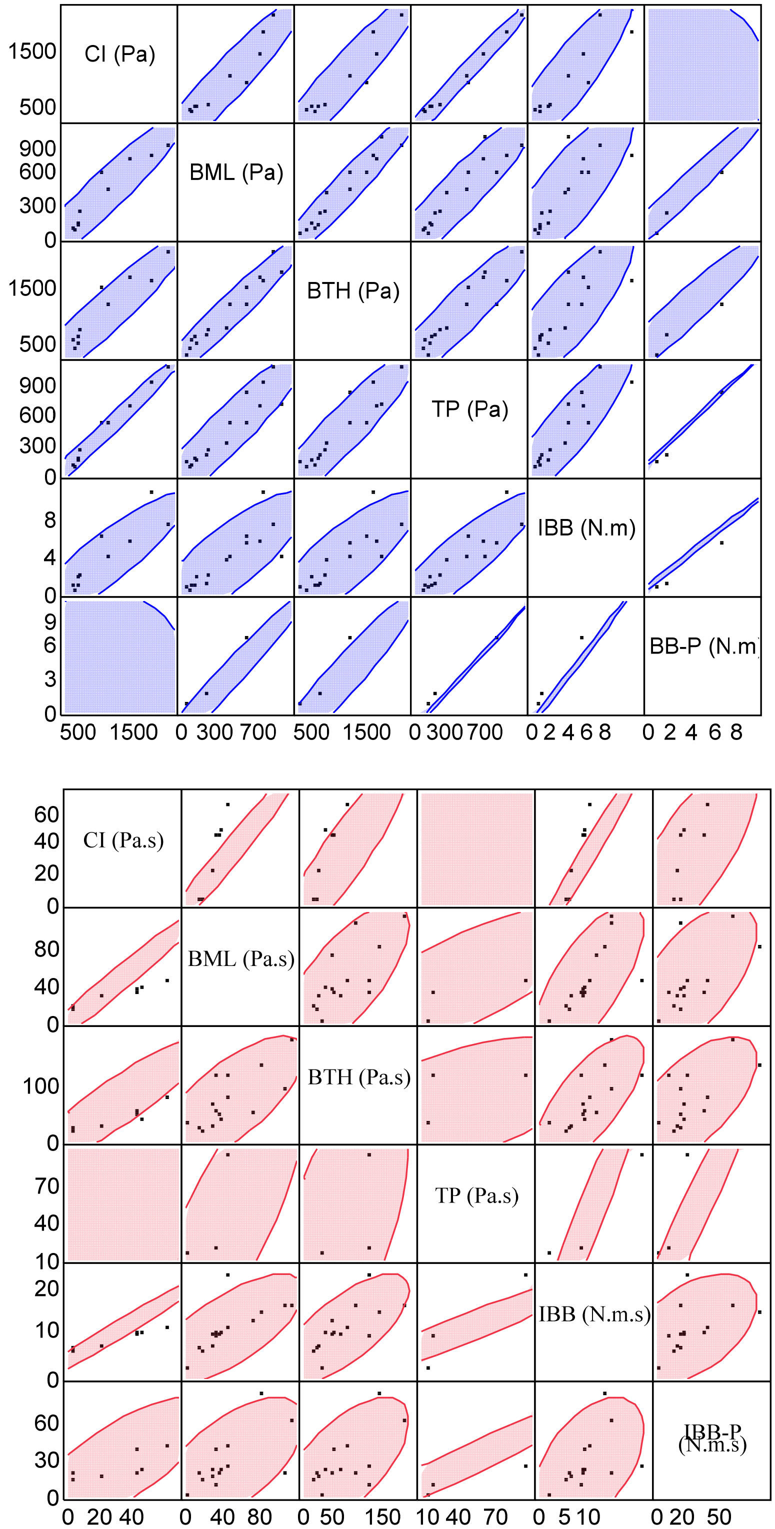


Figure D-14 Comparisons of different rheometers. CI: CEMAGREF (France); BML (Iceland); BTH: BTRHEOM (France); TP: Two point (UK) IBB: Canada; IBB-P: IBB Portable (Canada) [78-79].

D.8 Miscellaneous notes

i. It is reported that cement paste has been subjected to many rheological examinations because flow is very sensitive to the volume fraction of paste. At the same time, it is well acknowledged that establishing a connection between concrete rheology and cement paste rheology is far beyond our abilities. Limited research on this topic claims that neither the properties of paste nor its volume fraction alone are able to reliably indicate the flow behavior of concrete (Ferraris, 1992). However, research by Kishitani, et.al. [80] indicates that there is close relationship between the yield value of cement paste and the slump of concrete. They further indicated that in case of uniform aggregates with fixed aggregate content, the larger the yield value the smaller the slump.

ii. Testing concrete is resource intensive and quite expensive. It is much easier and faster to test cement pastes, mortars, etc. Similar properties of mortar and concrete can then be correlated. The concept of performing tests on mortars has been applied with varying success [81-83].

iii. The standard workability tests such as the Vebe time, compacting factor, slump, flow,. that aim to quantify the ambiguous property of workability can only compare concretes that display approximately the same consistencies. Therefore, it is more correct and realistic to evaluate the workability based on rational characteristic parameters of viscous materials. These parameters are the rheological constants[84]. A table (Table D-7) has been generated to illustrate the kind of relationships that have been derived between flow parameters and fundamental rheological parameters and/or material properties.

iv. Computational modeling is reported to be as a potential tool for understanding and simulating flow and rheological behavior of mortar and concrete as a function of its mix proportions [81, 85].

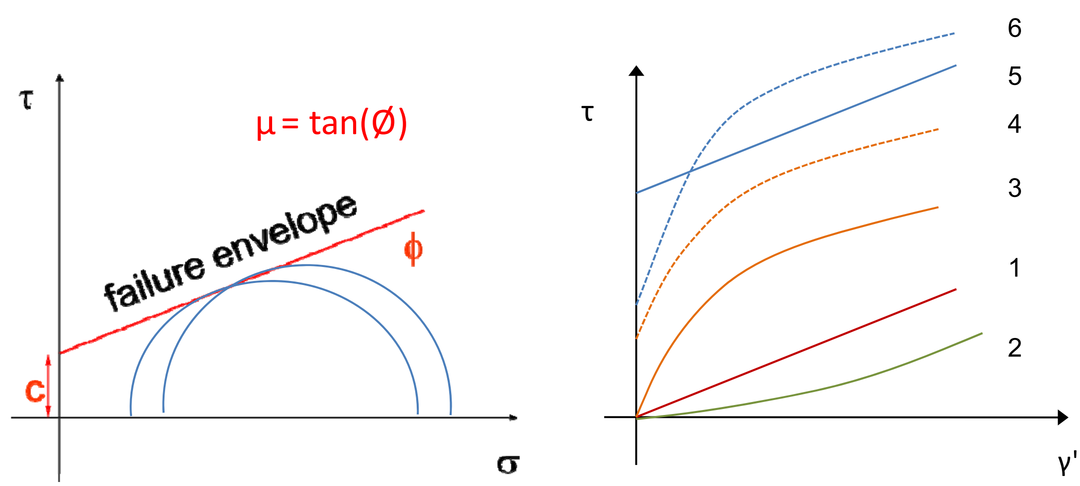
Table D-7 Sampling of conventionally measured concrete properties and Bingham parameters

Mixture			Relationships	Reference
Binders	Admixtures	w/b		
OPC	SP, PL	0.40-0.60	$\tau_f\left(\frac{gf}{cm^2}\right) = -4.83\,Log(slump) + 7.29$; $\eta_{\Delta y} = 0.0048(Slump)_{\Delta}^2 + 0.13(Slump)_{\Delta} + 1$; $\eta_{\Delta y}$: rate of decrease in plastic viscosity $(Slump)_{\Delta}$: Slump increment with time (cm)	[86]
OPC, GGBS, LS	SP, PL, AEA	0.3 and 0.35	$log\eta_{r,mor} = -2.38 \times 10^{-2} Fp + 1.06$; $log\eta_{r,cct} = -0.290 Fm + 1.59$; $\eta_{r,mor}$: relative viscosity of mortar $log\eta_{r,cct}$: relative viscosity of concrete Fp and Fm: thickness of excess paste and thickness of excess mortar respectively	[87]
OPC	SMF, SNF, LS	0.40-0.50	$\tau_0(Pa) = -1259 + 1352(\%\,hemihydrate) + 6\,(SSA)(Pa \cdot \frac{kg}{m^2})$; $\eta\,(Pa \cdot s) = 77 + 50(\%\,hemihydrate) - 14Al_2O_3$;	[88]/ Cement pastes
OPC	SR, VMA	0.45	$ln(\tau_0) = -0.23\,(spread) + 8.0518$; $\upsilon_{\dot{\gamma}} = A(\dot{\gamma})(flow\ time) - B(\dot{\gamma})$	[89]
OPC, FA	SP	0.34-0.43	$Slump\ flow = -1793 + 2.054\,(binder\ content) + 5.9456(fly\ ash\ content) + 710.476(SP\ content) + 2648.08(\frac{w}{b})$	[90]/SCC
OPC			$\tau_o = \frac{\varrho}{0.347}(0.3 - S) + 212$; ϱ: density of fresh concrete	[91]

SUMMARY

Rheology is a study of the flow behavior of matter, under conditions in which they flow rather than deforming elastically. Concrete is a complex system of few materials, so diverse in their chemical constitution, age, behavioral responses, scales of forces and interactions that studying it at narrow range of scale of forces is difficult. Isolating the behaviors of individual material is certainly a solution, but it offers difficulties in letting us build a composite picture from pieces of information. Attempts have been and are being made to overcome this difficult with partial success.

Chemical admixtures apparently occupy minor space in concrete, but have the potential to dramatically change the behavior of concrete to such an extent that the alterations in the forces at cement particle level manifest into dynamic changes at the concrete level. The intricacy of such delicate reactions is not known fully. We have calibrated ourselves with empirical or semi-empirical tests through the yester-years of advancement in concrete technology; lately to realize the gap we have evolved ourselves into by not having mechanistic measurements. Attempts are now being made to establish correlations between the two.



Pavement concretes are a special family of compositions that have distinct rheological nature. The instrumentation that is at our disposal is not geared towards measuring such stiff concretes; while it can to a great degree of refinement estimate mechanistic performance of some types of concretes like self-consolidating. The unique juxtaposition of pavement concretes at the interaction of solid-like and semi-solid behavior makes the study of their rheology quite a challenge. What further aggravates the problem is the transitioning of concretes from one type of behavior to another in response to vibrations. This requires blending of concepts from different areas of expertise.

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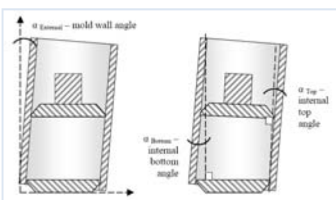
APPENDIX E EVOLUTION OF GYRATORY COMPACTION METHOD



SYNOPSIS

The objective of reviewing the time evolution of and research on, gyratory compaction is to appreciate the ways in which this methodology can be adopted for concrete under consideration. An account of the historical development is offered in the earlier section. The working principle and the governing parameters controlling compaction characteristics are then discussed. Subsequently, evaluation of critical material and compaction parameters, their selection and the implications on the measured properties of tested materials are summarized. Although widely accepted for asphalt concrete and researched for unbound-, granular- and other geotechnical materials, gyratory compaction method, in its current form has limited acceptability for use with cementitious systems.

Keywords: gyratory compaction, subgrade, soil, asphalt, vertical pressure, angle of gyration, number of gyrations, rate of gyration, compacted density

CONTENTS

E.1 Introduction

Gyratory compaction (GC) methods have evolved over the past 50 years and are widely accepted in United States, Europe and Australia with an estimated number of 3000 units in use all over the World [1]. GC has excellent reproducibility for compacted density, offers compaction profiles (in terms of relative density) w.r.t. effort, shear strength and workability information and thus offers a comprehensive tool to the asphalt concrete (AC) world. With minor adjustments and modifications, parameters like the vertical pressure, angle of gyration, time rate of gyrations, number of gyrations, mold size. can effectively be varied if an appropriate gyratory compaction machine (GCM) is available. This offers greater flexibility and freedom in assessing some of the properties of AC while simultaneously and efficiently simulating the field conditions.

E.2 Need statement

In case of asphalt or any other material compacted in field, the evolution of well-proportioned mixtures in the lab is a function of the evaluation procedures (and protocols used) and their precision and proximity to field conditions. Attributes of the mixtures to be considered include their workability, compactibility and ability to meet the end specifications. Next to mix design, construction, homogeneity and degree of compaction must be considered the main quality parameters of an asphalt mixture. A well designed and well produced mixture performs better, has better durability, and has better mechanical properties when it is well-compacted [2]. Compaction is considered the single most important factor affecting the performance of asphalt pavements [3] and it is emphasized that the density of laboratory-compacted specimens should approximate the density obtained in the field in terms of (a) the structure of the mix and (b) the quantity, size and distribution of the air voids [4]. The underlying principles [5] on which asphalt compaction methods simulating the field conditions are based on the following:

- Direction compression
- Impact hammering
- Kneading action
- Gyratory shear vibration and
- Simulated rolling

Earlier methods including the Marshall's, the Hveem's, and other local methods utilized their own unique method of specimen compaction [6]. The details are offered in the literature [7]. Albeit a few of these methods were widely used and assimilated in the standard procedures, yet there was inadequacy of proper simulation.

Some of the key considerations [8-10] that govern the selection of a particular type of compaction method are as follows:

- A good laboratory compaction method should be able to be used for field quality control;
- The compactor should yield essentially the same density as the pavement density after some years of traffic. This is usually assessed in terms of compacted density, voids ratio;
- The compaction method should cause similar aggregate degradation as under the field conditions;
- The compactor should able to simulate increasing loads and tire pressure and should have the flexibility of varying the controlling factors;
- The method must be equally adaptable to the field control of the mix as to the design;
- The time for completing a compaction test should be short enough

E.3 Historical evolution

Realizing the limitations of the earlier methods and the necessity for field-simulation, researchers started evolving newer methods of lab compaction in 1940's. Thus, methods based on kneading compaction with vertical (and sustained) stresses analogous to traffic loads were being developed. Harman, et.al. [10] summarize the historical development of the contemporary gyratory compactor. Figure E-1 reproduces photographs of different gyratory compactors, while Table E-1 illustrates the timelines of the evolution of gyratory compaction. It is reported [11] that today there are three general types of gyratory compaction:

i. Texas gyratory compactor (four and six inch),
ii. Corps of Engineers gyratory compactor and
iii. LCPC (French) gyratory compactor

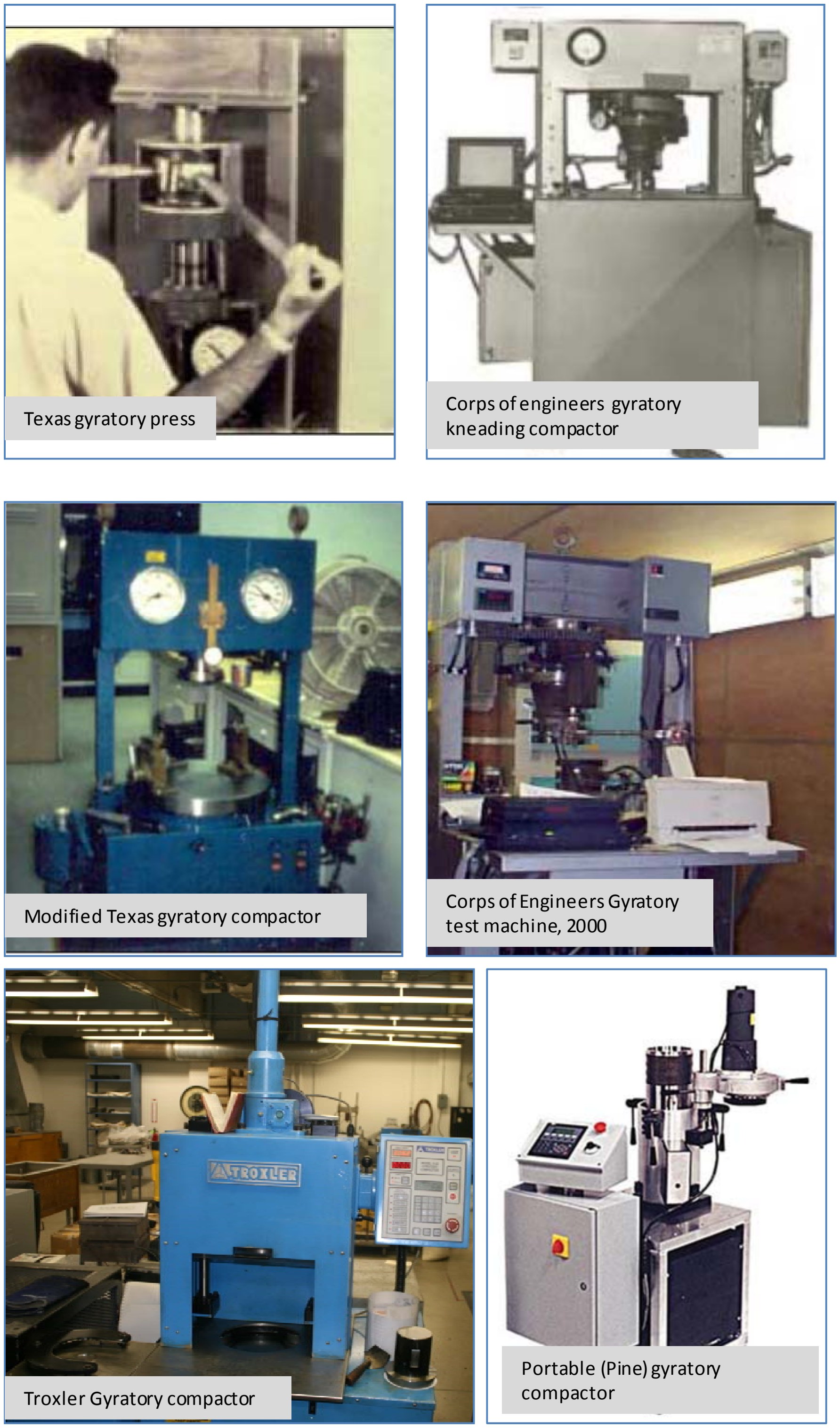


Figure E-1 Gyratory compactors (taken from the personal collection of the author and [12-13])

Table E-1 Evolution of gyratory compaction [12]

Timeline	Device/Agency	Specimen Size	Compaction Effort
1939	Concept TX Highway Department	D – 4” H – 2”	P – Unknown A – Manual S – Manual
1946	TX Highway Department	D – 4 & 6” H – 2 & 3”	P – Variable A – Fixed 6° S – 60 rpm
1957	US Corps Engineers GTM	D – 6” H – Variable	P – Variable A – Floating 0 to 3° S – Variable 12-18 rpm H – Heated mold
1960’s	First Prototype Texas at LCPC, France	D - ? H - ?	P – Variable A – Variable S – Variable
1968	Second Prototype Texas at LCPC, France	D – 80 or 120 mm H – Variable	P – Variable A – Floating 0.5° to 5° S – Variable H – Heated mold
1974 to 1985	PCG1, PCG2 at LCPC, France	D – 160 mm H – Fixed 80 to 300 mm	P – 600 kPa A – Fixed 1° to 4° S – Fixed 6 rpm to 30 rpm H – Heated mold
1991	Modified Gyratory Shear Test Machine, FHWA	D – 4” H – 2.5”	P – 600 kPa A – Fixed 0.5° to 3° S – 30 rpm
1991	Modified TX Highway Department, SHRP	D – 6” H – 3.75”	P – 600 kPa A – See History S – Variable H – Heated mold
1993	SHRP/Superpave Gyratory Compactor in USA	D – 150 mm H – 115 mm	P – 600 kPa A – Fixed 1.25° S – 30 rpm
1996	PCG3 at LCPC, France	D – 150 mm H – Fixed 100 to 160 mm	P – Fixed 500 to 800 kPa A – Fixed 0.5° to 2° S – Fixed 6 to 30 rpm

E.4 Operational features

E.4.1 Working principle

A gyratory compactor applies an axial pressure and a rotating gyratory shear deformation to a sample of material contained in a cylinder. Both the axial pressure and the shear deformation are applied through plates that are at a slight angle to the longitudinal axis of the cylinder. As the end of the plates rotate, the angle of the end plates produces a kneading action that compacts the sample in a reproducible manner. As the sample is compacted, reduction of volume is continuously calculated by measuring the height of the specimen. This also makes it possible to calculate the rate of volume change (rate of compaction) during the test. The rate of compaction can then be modeled as a function of the parameters listed above. As the density increases, the rate of compaction continuously decreases [14]. The working principle along with the definitions of angles is depicted in Figure E-2.

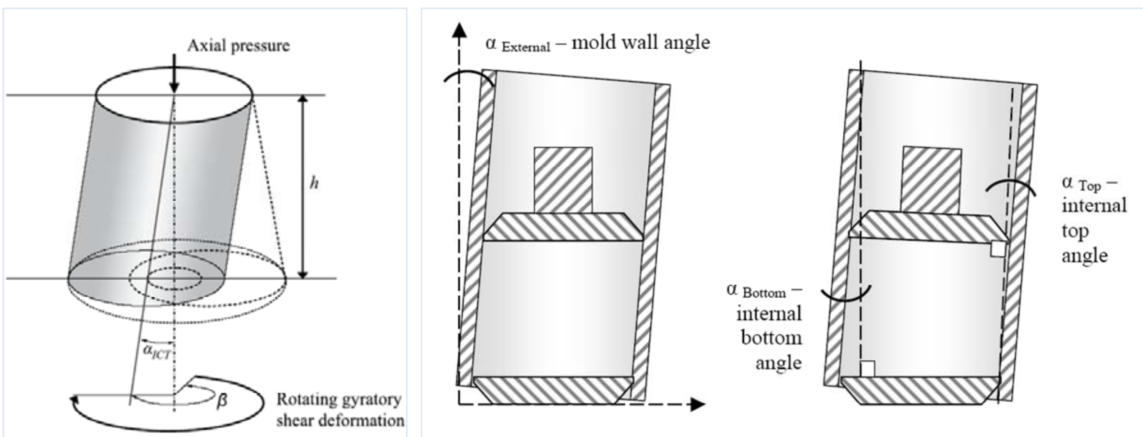


Figure E-2 A schematic representation of the compaction process in GCM [14] . The external angle is the tilt of the mold with respect to the vertical axis; the internal angles are usually less than the external angle, given that the end plates deflect to non-parallel rotations as shown in the schematic sketches [1, 10].

E.4.2 Controlling parameters and Effects on measured properties

There are two groups of parameters affecting compaction characteristics. These are equipment variables and material related factors. Axial or vertical pressure, angle of gyration, rate of gyrations, total number of gyrations and to a limited degree the mold sizes can be varied in some specific makes of GCM . Depending on the material type, the nominal maximum size of the aggregate, the material stiffness and temperature-, moisture-specific properties the above-mentioned parameters affect the compaction characteristics. Table E-2 presents a summary of the most widely used GCMs along with their specifications.

Table E-2 Operational specifications for gyratory compactors

Make	Model	Range of gyrations (No.)	Rate of gyrations (Gyration/min)	Vertical pressure (kPa)	Angle of gyration (°)	Mold diameters (mm)	Speci. height (mm)
Troxler [15]	4140	1-999	30 ± 0.5	200-1000	0.5-2.0	100, 150	50-225
	4141	0-300	30	600	1.25	100, 150	50-225
	5850	1-999	30 ± 0.5	90-1000	0-1.5	100, 150	50-317.5
Pine Instrument [16]	AFG1	0-999	30	600	1.25	100, 150	0
	AFG2	0-999	30	200-1000	0.5-1.5	100, 150	0
	AFGB1	0-299	30	600	1.25	150	10
Servopac [17]	--	0-999	3-60	800-1000	0-1000	100, 150	50-170
LCPC [18]	--	NA	30	600	0.5-2.0	150	NA

The following is a sampling of some of the studies pertaining to these variables:

- Research shows that a wide range in the number of gyrations [14, 19-23] depending on the type of material compacted. Invariably the compacted density increases with the number of gyrations up to a certain point and then the rate of increase becomes negligible. The number of gyrations used for asphalt depend on the traffic level, bitumen grade and the simulation to field density. The number of gyrations required to obtain the ultimate in-place density, targeted as 96% density is called as N_{design}. N_{design} values depending on the traffic level are researched [22] and specified in ASTM D6925-08 [24];
- Speed or rate of gyrations have little effect on density of asphalt specimens [11, 25]. LCPC method uses a steady gyration rate of 6 gyrations/min, but the Strategic Highway research program (SHRP) choose a rate of 30 gyrations/min to reduce testing time [10];
- An increase in the vertical pressure causes a consistent increase in the unit weight for a given number of gyrations. It is one of the critical factors for obtaining consistent compaction results and is predominantly decided by the truck traffic level [11] and material type [23, 26]. The SHRP researchers have recommended a vertical pressure of 600 kPa [10]. For soils a vertical pressure of 200 to 600kPa

is recommended [23, 26-27], while the value can be lowered to the range of 80-160 kPa for Portland cement concrete [14];

- A nominally constant effective internal angle of gyration is applied when the samples are compacted at constant pressure [28]. The angle of gyration has an impact on the internal structure, aggregate orientation of the compacted specimen and is decided by the stiffness of the material [23, 29-30]. It can be observed from Table E-1 that a wide range of angles have been used in reported studies. Cominsky et.al. [3] concluded that a variation in the angle of compaction of ± 0.02 degrees resulted in an air voids variation of 0.22% at 100 gyrations and this research formed the basis of SHRP specification of 1 to 1.25 degrees. Prowell [31] concluded that increasing the angle of gyration leads to an increase in the density of compacted samples;
- Caution needs to be exercised while using and interpreting results obtained from 100 mm diameter samples instead of 150 mm. This will primarily depend on the NMSA, grading and hence the stiffness of the aggregate system. Mixed opinions (although clearly leaning towards 150mm diameter) about the preference of one over the other exist [32-34]. It is recommended that a minimum sample size of 3500 g is required for obtaining rugged and consistent compaction characteristics in terms of volumetrics and compaction properties [35].

E.4.3 A note on precision and bias

ASTM D6925-08 [24] offers estimates for precision in obtaining relative densities with gyratory compactor tests. These will be referred to in a later section. Table E-3 reproduces the precision estimates

Table E-3 Precision estimates [24]

Operator	NMSA (mm)	Relative density (%)	
		1s limit	2s limit
Single	12.5	0.3	0.9
	19.0	0.5	1.4
Multilaboratory	12.5	0.6	1.7
	19.0	0.6	1.7

E.5 Applications

Published studies have demonstrated good utility of GC in the following civil engineering application areas:

1. To establish and evaluate density requirements, compacted densities for unbound materials, subgrade and base of pavements and establish correlations between field and lab compacted samples [26, 36-37];
2. Compaction characteristics of cohesionless materials, aggregates, marginal aggregates, [38-42] and soils [19, 23, 27, 43-44];
3. Studies on Bitumen based materials
   i. Studies on compaction parameters such as vertical pressure, angle number of gyrations, angle of gyration, gyratory shear. [22, 30, 45-49] and constituent materials [50-53]
   ii. Comparing various methods of sample preparation for asphalt concretes [5, 54-59];
   iii. Establishing the design values for compaction (hence number of gyrations) for simulating field densities and evolving mixture proportions [22, 46, 60-62];
   iv. Establishing correlations between lab and field samples [30, 59, 63-66];
   v. Evaluating mixture performance in labs while simulating field compaction using gyratory compactor; These studies include temperature studies, resilient modulus determination, analysis of air void structure, rutting prediction and performance of mixtures, tensile and fatigue properties, deformation characteristics. [30, 58, 67-75].
4. Studies on different types of portland cement concretes such as no-slump [14], roller compacted [76] and pervious concretes [77]. One important point to be noted in the case of concretes and soils containing higher moisture contents than the amount that the mixture can physically hold under a sustained load is that the gyratory compactor is open ended at both the ends. Application of continuous compaction leads to the removal of water mixed with solid particles and this could potentially damage the GCM.

SUMMARY

Gyratory compaction method has been used for asphalt concretes for nearly half a century. The associated operational ease, superior consistency and faster sample production have made it the method of choice. The concept of gyratory compactor is said to offer benefits such as proximity to field density, similar aggregate breakdown and simulation of actual process of compaction. Several versions of gyratory compactors are available in the market and there are ongoing efforts in modifying and fine tuning it.

In recent years gyratory compactor have been evaluated for soils and have shown good promise. Its application for concrete has been researched and practiced in some parts of Europe for drier concretes like precast concretes. For reliable and satisfactory application of gyratory compactor for concretes, changes in the consolidation pressure, the angle of gyration, rate and number of gyrations have to be adjusted or modified.

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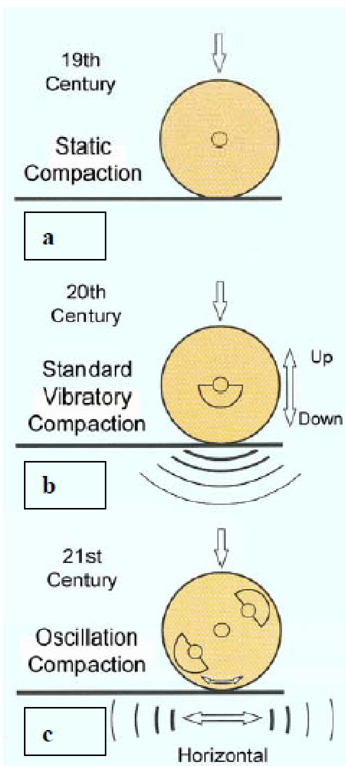
APPENDIX F A BRIEFING ON COMPACTION



SYNOPSIS

The objective of this chapter is to offer a comprehensive perspective of compaction in soils, granular materials for pavements, asphalt and roller compacted concrete. Initially a definition of compaction along with a discussion on its physical significance is offered. Subsequently, the chapter discusses relevant aspects of compaction in soils, aggregate or granular systems used in pavement layers, asphalt concrete and roller compacted concrete. Finally, important tables on lift thickness and compaction equipment selection are summarized.

Keyword: compaction, compactibility, soils, aggregate, asphalt concrete, roller compacted concrete, paver, roller, lift thickness

CONTENTS

F.1 Compaction and compactibility

Compaction for soils is defined as a process by which a mass of soil consisting of solid soil particles, air and water is reduced in volume by momentary application of loads, such as rolling, tamping or vibration. Compaction, thus involves an expulsion of air without significantly changing the amount of water in soil mass [1]. Moreover, during compaction there is no significant change in the gradation of material. In soils and unbound granular materials, the soil type, moisture content, gradation, particle shape (particularly in granular materials) and the subsequent environment of the compacted product influence compaction. On the other hand, compaction of an asphalt mixture is affected by such factors as asphalt grade and content, mix design, temperature, type and configuration of the compaction equipment, etc. [2].

Grain size is one of the key indicators of the likely compactibility of a layer for specific application. Figure F-1 offers a comprehensive summary of the grain sizes used for different compacted fills. Grain size also decides the test methods used for evaluating and specifying quality control schedules apart from influencing the lift thickness, placing and compaction procedures.

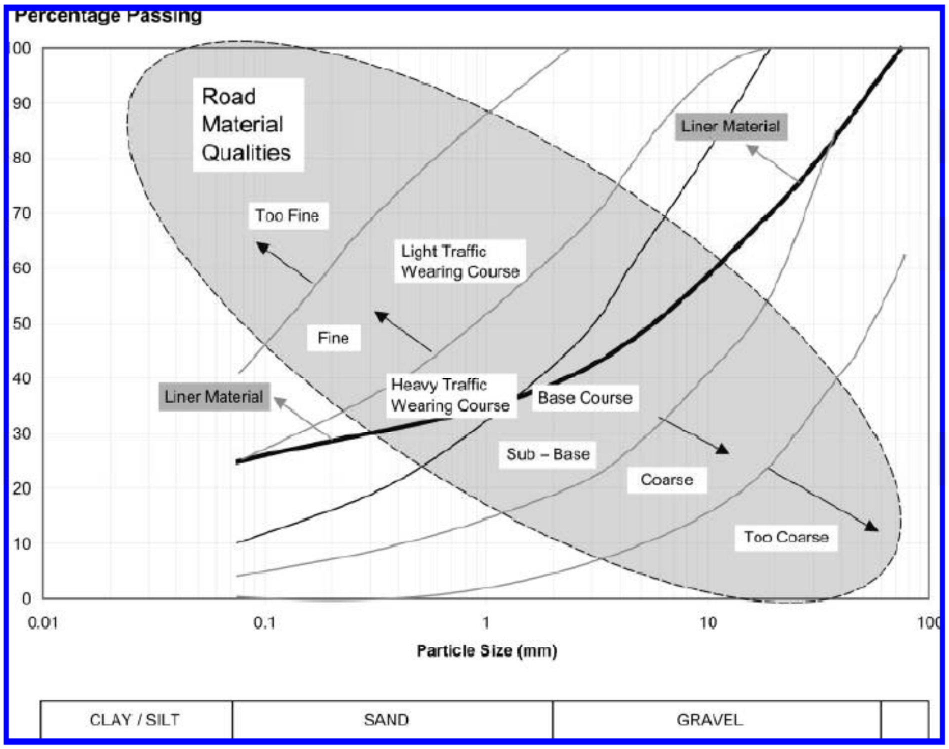


Figure F-1 Grain sizes as used for different applications [3]

Compactibility is not widely described or used in civil engineering materials. Most definitions associate themselves with the expulsion of air and leave it at that point. An interesting clarification as used for pharmaceutical powders is therefore referred as follows. The compaction properties of pharmaceutical powders are (for clarity) separated in two distinct terms, i.e. the compressibility, as the ability of the powder to deform under pressure and the compactibility as the ability of a powder to form coherent compacts [4]. Compactibility is the process of volume reduction and bond formation in a powder bed during compression, which produces compacts of a certain mechanical strength. When pressure is applied to a powder bed, particle rearrangement occurs first, followed by particle fragmentation and deformation (plastic and elastic deformation), and bond formation on the contact surfaces [5]. Plastic deformation is an irreversible process of particle shape changing that contributes to stronger tablets, while elastic deformation is reversible and leads to elastic recovery of compacts in the decompression phase and the breakage of some previously formed bonds, which results in lower tablet strength and capping problems [6]. The nicety of this description is that it encompasses the process of compaction and the ability to hold that compacted mass together.

F.2 Compaction in different materials

F.2.1 Soils

Compaction of soil generally increases its shear strength, decreases compressibility, and decreases its permeability [1]. It should be noted that since compaction involves reduction of volume of air at constant water content, the degree of saturation increases. Other properties getting affected include shrinkage and swelling characteristics (volumetric stability), the stress-strain response, pore water pressure, and the structure of the soil.

COHESIVE SOILS

In case of cohesive soils, the compacted density is sensitive to the moisture content and every soil has its own characteristic compaction curve (moisture versus density). The moisture content at which maximum dry density is achieved is called as the optimum moisture content and the corresponding density is called as the maximum dry density. This density (considering construction tolerances) is specified for field compaction. The shape of a compaction curve is a reflection of the four stages of wetting of soil viz. hydration, lubrication, swelling and saturation [1]. These are pictorially shown in Figure F-2.

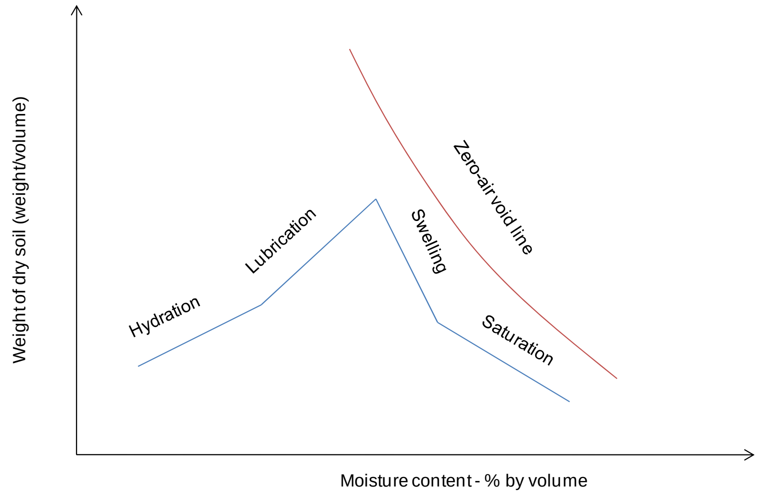


Figure F-2 Four stages of soil compaction

COHESIONLESS SOILS

Compaction curve for sands and gravels (or soils having negligible plasticity and freely draining) is of little practical importance. Typical curve is shown in Figure F-3. The density initially reduces with the increase in the moisture content due to bulking (close to minimum density). With further increase in water, lubrication leads to increase in the density as shown.

It should be noted that the dry density is not a direct measure of soil properties and may not reflect similar engineering properties. Density is just a quantification of the amount of mass that can be fitted in a given volume.

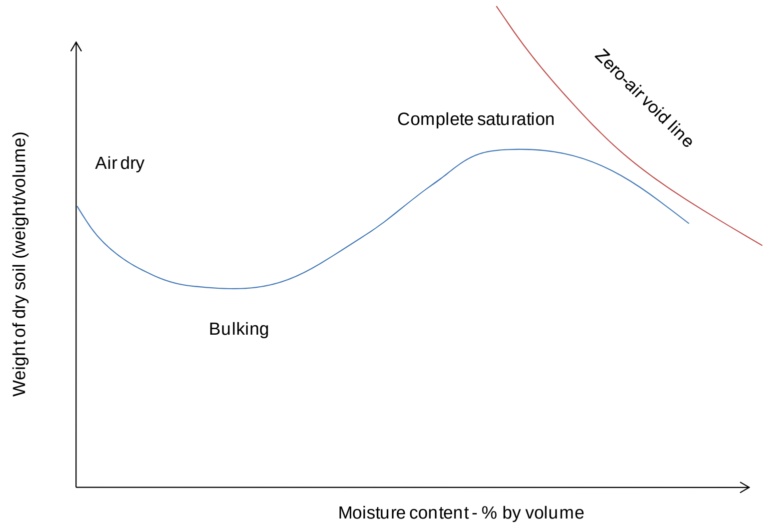


Figure F-3 Compaction curve for cohesion-less sands

EVALUATION OF THE DEGREE OF COMPACTNESS

Depending primarily on the soil type, appropriate method of evaluation and field control are specified. For primarily cohesive soils, standard [7] or modified Proctor [8] test specifying the optimum moisture content and maximum dry density are specified with a tolerance window. For cohesionless soils, the concept of relative density (D_r) is used. The formula for relative density is as follows:

$$D_r = \frac{(e_{max} - e)}{(e_{max} - e_{min})} = \frac{\gamma_{d,max}(\gamma_d - \gamma_{d,min})}{\gamma_d(\gamma_{d,max} - \gamma_{d,min})}$$

where,

e is the void ratio with the subscripts representing the maximum and minimum values while e is the in-situ voids ratio and similarly γ_d is the dry density. Another term that can be used for characterizing compaction is the compactibility (F) of sands [1]. It is defined as follows:

$$F = \frac{(e_{max} - e_{min})}{e_{min}}$$

The void ratio and hence the resulting density will depend on the grading. Figure F-4 shows a pictorial representation of the effect of grading on the inter-granular seating or packing of different particles. In uniform soils, the difference (e_{max}-e_{min}) is less and the e_{min} is large resulting in smaller F value or lower compactibility, while in well-graded cohesionless soil, the difference (e_{max}-e_{min}) is large and the e_{min} is small resulting in large F or higher compactibility.

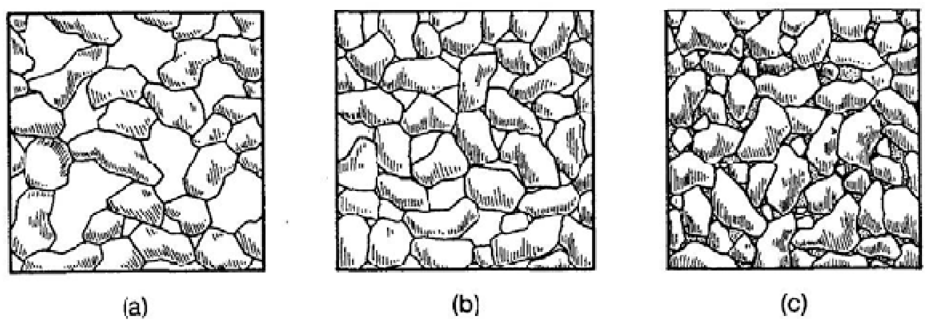


Figure F-4 Inter-granular seating and gradation of coarse grained particles

In addition to the above methods, gyratory compactor [9] and vibrating hammer test applied by the United States bureau of reclamation [10] and specified in ASTM D7328 [11] are also used in assessing compaction trends. The compaction control of mixed-grained soils containing gravel, sand, silt and clay in various proportions should be decided by the cohesion of the soil [12].

F.2.2 Aggregate systems used in pavements

Materials typically encountered in subgrades are characterized by their strength and their resistance to deformation under load (stiffness). In the United States, the California bearing ratio (CBR), Resistance value (R-value) and resilient modulus are commonly used to characterize subgrade materials. Although each method is useful, the resilient modulus is most consistent. Modulus of subgrade reaction (k) is the subgrade characterization used in rigid pavement design. It can be estimated from CBR, R-value or elastic modulus, or calculated from field tests like the plate bearing test [13]. Table F-1 offers a comparison of different pavement layers in terms of tensile strength and failure mode as a function of the cement content used.

Table F-1 Comparison of soil properties with concrete vis-a-vis the cement content [3, 14]

Stages	Soil	Modified soil	Cemented soil	Lean mixture	Concrete mixture
Cement content	0%	< 5%		> 5%	> 15%
Tensile strength	< 80 kPa			> 80 kPa	
Failure mode	Plastic --► Brittle				

F.2.3 Asphalt concrete

BACKGROUND

Asphalt binders are thermoplastic materials and their rheology is highly sensitive to temperature. They exhibit semisolid behavior at ambient temperature but can be made fluid by heating. High temperatures make them fluid enough to coat aggregates and they need to remain hot enough to minimize resistance as the asphalt-aggregate mixture is compacted in the lab or on the road. Compaction is affected by asphalt viscosity because moving of aggregates requires flow of asphalt binder films connecting the aggregates. Higher viscosity results in more resistance to packing. Due to the inherent complexities of chemical composition and its temperature dependent behavior makes modifying asphalt flow (rheology) a complicated process [15].

The factors affecting asphalt compaction can be categorized into three factors viz. environmental, mixture and construction related. Figure F-5 shows these factors in a summary form.

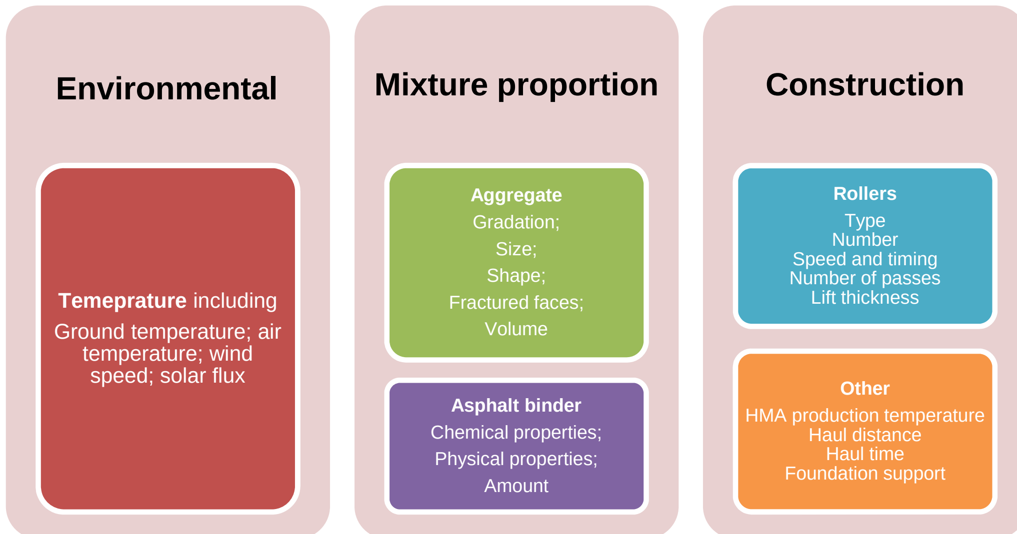


Figure F-5 Factors affecting asphalt compaction [16]

GYRATORY COMPACTION

The laboratory compaction properties are presently widely characterized using gyratory compactors. These have been discussed in the previous chapter. An important note related to assessing workability is presented as follows. The compaction curve obtained from the measurements using gyratory compactor has two distinct portions. The first or earlier portion represents the initial phase, which is characterized by a steep slope where excess air voids are removed under initial, short-term compaction, while the second or latter portion represents the later phase, which is characterized by a small change in slope resulting from particle rearrangement under further applied compactive effort. The initial phase depends on intrinsic workability while latter phase depends on the resistance of mixture once a significant volume of air is expelled. This is schematically shown in Figure F-6.

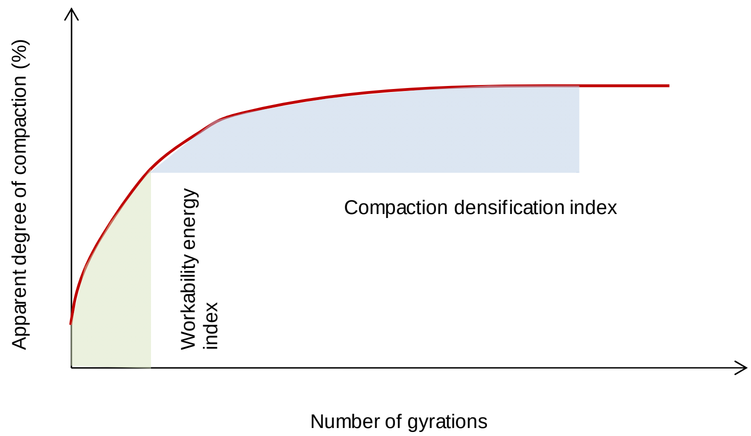


Figure F-6 Workability indices from gyratory compaction plot. The consolidation pressure is fixed.

In the asphalt industry, the initial compaction level is computed between six and eight gyrations, depending on the design traffic level [17]. Kevern [18] uses eight gyrations for characterizing the initial workability for pervious concrete. Table F-2 offers a summary of the ranges of the pervious concrete gyratory values for these two indices. These indices are abbreviated as workability energy index (WEI) and compaction densification index (CDI).

Table F-2 Range of gyratory compaction indices [19]

Workability (WEI)	
Behavior	Range
Highly workable	> 640
Acceptable workability	Between 640 and 600
Poor workability	< 600
Compactibility (CDI)	
Explanation	Range
Self-consolidating	< 50
Normal compaction effort required	Between 50 and 450
Considerable additional compaction effort required	> 450

FIELD COMPACTION

There are three basic pieces of equipment available for HMA compaction:

- the paver screed;
- the steel wheeled roller and
- the pneumatic tire roller.

Each piece of equipment compacts the HMA by two principal means. The first by applying its weight to the HMA surface and compressing the material underneath the ground contact area. While the second by creating a shear stress between the compressed material underneath the ground contact area and the adjacent uncompressed material. The paver screed: the most critical feature of the paver is the self-leveling screed unit, which determines the profile of the HMA being placed. Figure F-7 shows screed forces and a picture of actual screed.

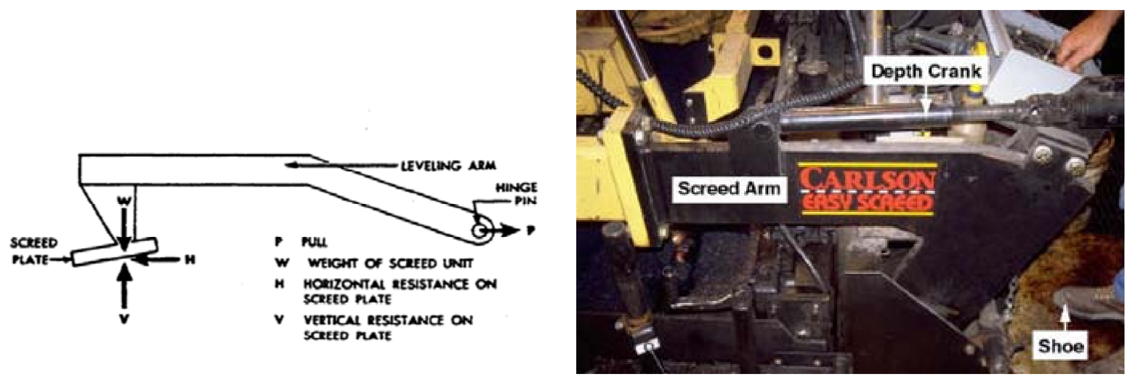


Figure F-7 Screed forces and picture of screed in asphalt paver [16]

Vibratory rollers have been used for compacting hot mix asphalt concrete mixtures for nearly 40 years and further modifications and automations are researched and tried in practice [20]. The compactive effort is a function of the roller weight, the amplitude (or height) of the roller movement and number of vibrations per minute (frequency) of the drum. Advances have also been made in the compaction technology. Figure F-8 shows a schematic of the chronology. The newly evolving oscillation compaction technology, when applied to asphalt concretes, has proved to be extremely valuable [21].

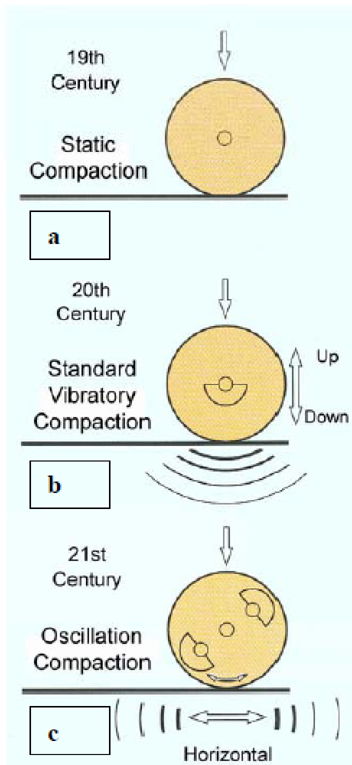


Figure F-8 Three compaction systems for asphalt pavers

Nuclear density gauges and electrical density gauge are routinely used for field control of compaction apart from extracting cores and testing in laboratory.

F.2.4 F.2.3 Roller compacted concrete

Roller compacted concrete is usually placed with asphalt pavers in layers up to 150 to 200 mm. Two lift RCC construction is also possible and is reported in published literature [22]. One of the concerns with roller compaction of concrete is the differential in the compacted density with depth [23] and is discussed previously. New generations of asphalt pavers equipped with high-power compaction screeds eliminate the need for roller compaction. It is now possible to achieve high quality in terms of strength, durability, and surface finish at relatively low device and personnel costs [24].

F.3 Other considerations

F.3.1 The role of lift thickness

The compaction layer thickness depends on the material type and equipment being used. The operating space for equipment also needs consideration. There is usually a "compact to 200 mm thickness" fixation in many specifications. This assumes only light equipment is available and presence of clay material [3]. The achievable compaction depends on the subgrade support below, which could act as a limiting factor for achieving the required degree of compaction. Typical depending on the material type and layer thickness, the relative compaction could be anywhere between 90 to 102% of standard Proctor density. Table F-3 offers a summary of the compaction layer thicknesses for different road materials

Table F-3 Compaction layer thickness [3]

Equipment size	Compaction layer thickness (mm) depending on material type			
	Rock fill	Sand and gravel	Silt	Clay
Heavy (> 10 tonne)	1500	1000	500	300
Light (< 1.5 tonne)	400	300	250	200

In case of asphalt concrete pavements, apart from dependence on local materials, weather, paver configuration, crew knowledge and training and individual experience, the lift thickness is a function of the maximum size of aggregate. Table F-4 shows an example of minimum lift thickness requirements.

Table F-4 Washington DOT minimum lift thickness requirements [16]

WSDOT Mix Class	Minimum Lift Thickness
25 mm (1 inch Superpave)	75 mm (0.25 ft)
19 mm (0.75 inch Superpave)	60 mm (0.20 ft)
12.5 mm (0.5 inch Superpave)	36 mm (0.12 ft)
9.5 mm (0.375 inch Superpave)	25 mm (0.08 ft)
Class A or B	36 mm (0.12 ft)
Class D	18 mm (0.06 ft)
Class E	60 mm (0.20 ft)
Class F	36 mm (0.12 ft)
Class G	18 mm (0.06 ft)

F.3.2 Compaction equipment

There are multiple options for compaction equipments. The selection on the most appropriate one depends on material type, layer thickness, volume of compacted fill and other construction considerations. Table F-5 shows a summary of the appropriate compaction equipments or different types of soils, granular materials and rocks.

Table F-5 Suitability of compaction equipment [25]

Compaction plant	Principal soil type							
	Cohesive		Granular				Rock	
			Well-graded		Uniform			
	Wet	Others	Coarse	Fine	Coarse	Fine	Soft	Hard
Smooth wheeled roller								
Pneumatic roller								
Tamping roller								
Grid roller								
Vibrating roller								
Vibrating plate								
Vibro-tamper								
Power rammer								
Dropping weight								
Dynamic consolidation								

Table F-6 on the other hand shows a summary of interaction of static weight of the rollers and lift thicknesses for two pavement layers.

Table F-6 Practical maximum layer thickness for different roller types [26]

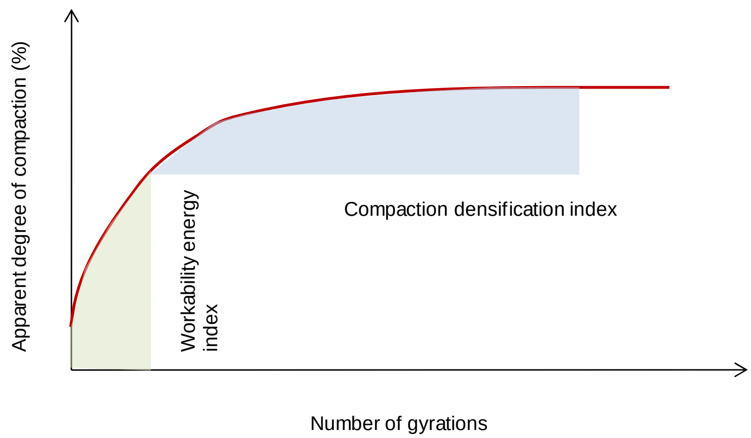
Roller type static weight		Practical maximum layer thickness (m)	
		Pavement	
Type	Weight (tonne)	Subbase	Base
Towed vibratory rollers	6	-0.40	+0.30
	10	-0.60	+0.40
	15	-0.80	-
	6 Padfoot	0.40	-
	10 Padfoot	0.60	-
Self-propelled roller	7	+0.30	+0.25
	10	+0.40	+0.30
	15	+0.60	+0.40
	8 Padfoot	0.30	-
	11 Padfoot	0.40	-
	15 Padfoot	0.60	-
Vibratory tandem rollers	2	0.20	+0.15
	7	+0.30	+0.25
	10	+0.40	+0.30
	13	+0.45	+0.35
	18 Padfoot	0.60	-

Notes: + indicates most suitable application

SUMMARY

Compaction is the expulsion of air from a material under one form of loading or another to achieve a higher degree of compactness. Civil engineering materials used for infrastructure construction are routinely compacted to different densities depending on the type of material, availability of compaction equipment and the importance of a project. Different materials behave differently, each having its characteristic traits in response to a given compaction mechanism.

Field compaction is variable due to inherent nature of material variations, the possible degree of control and supervision in civil engineering construction, amongst other factors. The quantification of compaction is mostly based on density measurements. Although we could reliably predict the compaction attributes of field compaction from lab tests, the nature such of correlations varies from material to material and from one site to another.



Roller compacted concrete compaction is not routinely characterized in the lab. The only attempt made is to establish a moisture density profiles for a given set of materials. Apart from construction and environmental factors that influence compactibility, the most important is the material composition.

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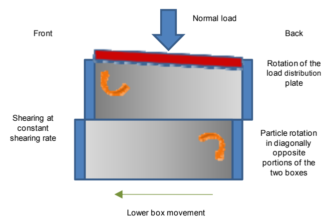
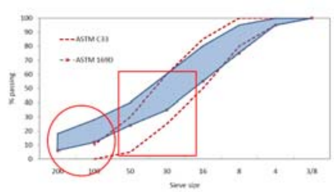
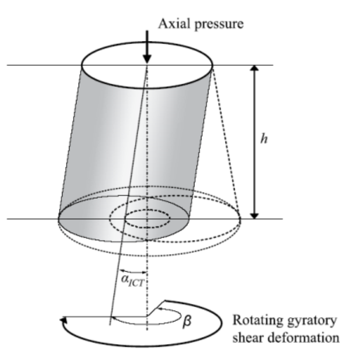
APPENDIX G STATE OF ART AND INSTRUMENTATION: A CRITIQUE







SYNOPSIS

The design of any experimental device will always be a compromise between the theoretically possible and practically feasible. This is the main theme of this chapter. This chapter presents an account of the candidate tests used in this work. At first the external tests are reviewed, which includes only the cement particle size distribution. Descriptions and critiques are offered on the in-house tests performed for this work. These include the cement paste mixing, mini-slump cone test, vibrated slump test, soil shear box test and setting time tests. Subsequently mixer selection criteria and an account of the compacting hammer used for casting cylinders is offered. Finally, miscellaneous considerations like aggregate grading procedures, sample size selection and the statistical design and analysis procedures are summarized.

Keywords: cement particle size distribution, mini-slump test, Marsh cone, Cabrera slump value, shear test, setting time, calorimetry, aggregate grading, mixture models, cement, soil, aggregate, concrete.

CONTENTS

G.1 Introduction

This chapter is divided into three major sections. The first one talks about the external tests, the results obtained from which would have an impact on this work. The second section talks about the in-house tests performed and comments on them. The final section discusses the matters pertaining to aggregate evaluation procedures, sample size and statistical methods employed in concrete mixture design with a special reference to mixture modeling.

G.2 External tests

G.2.1 Cement particle size distribution

Properly stored Portland cement (PC) in its dry state and at room temperature is in a state of weakly bonded particles, often called as flocs. This floc formation is a function of the age of the cement, and the storage history. Granules (10-100 µm) may also be formed if proper care is not taken. For example, coring or plugging takes place in cement silos, which if note aerated and cleaned properly could enhance granule formation. As discussed before and quite like other ceramic powders, PC is a multi-phasic, multi-mineral powder whose chemical constitution, sintering and cooling histories primarily decide clinker's ability to grind to a fine powder when admixed with gypsum.

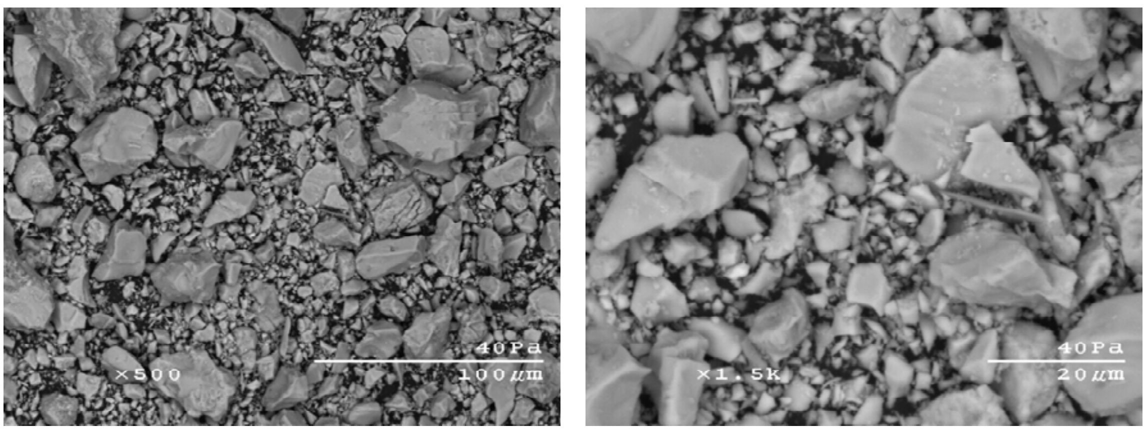


Figure G-1 Wide range of cement particles as seen under a scanning electron microscope.

Courtesy: Dr. Warren Straszheim

The particle size distribution, particle shape [1], resulting specific surface area, uniformity factor [2] are reported to have definitive effects on the particle packing, rheology, setting and strength gain characteristics amongst others. Figure G-1 shows some images. These granulometric properties can be characterized in terms of particle size and distribution, particle shape, degree of agglomeration, surface area, density and porosity [3]. The extent of characterization will depend on the application [3]. Other parameters are gaining importance in recent years considering the level of refinement we are investing in controlling the properties of the resulting cementitious materials, our involvements in computer modeling of cement hydration and enhancement in quality control management. For PC, the specific surface area (Blaine fineness, Turbidimeter, air permeability, etc.), and percent passing 45 μm are routinely specified in the standards and issued through mill certificates. Researchers often use Rosin Rammler distribution [4]. Ferraris, et.al. [5] offer the following comprehensive summary in their paper:

- The potential sources of difficulty with PC arises from the fact that the particle size distribution is extremely broad (sub-micrometer to 100 μm), while the existing techniques are optimized for a limited size range.
- The protocols for dispersing agglomerated cement particles in dry state are not standardized.
- There is no material artifact (i.e., reference material) or universally accepted measurement method exists for cement powder PSD determination. They also established a standard reference material for PSD.
- Of the four methods viz. laser diffraction, electrical zone sensing, sedimentation and scanning electron microscope summarized in this paper, the first one is most widely used in the industry. The report did not publish results from all the four different techniques.

Different methods for obtaining particle size distributions would tend to offer different results. In a personal communication, the author was informed that the PSD obtained using different techniques would yield different results. And guaranteeing the accuracy of the results was difficult [6]. This fact is relevant for this research and will be revisited in one of the later chapters. The choice of the method will also be governed by the importance of such measurement, availability and overall economics of testing.

G.3 Internal tests

G.3.1 Cement paste mixing

Cement paste mixing actually represents the shearing history, which in turn would decide the nature of the rheological behavior. Various methods have been used and reported in the literature. Table G-1 presents a summary of the typical methods as used by different researchers.

Hand mixing, although labor intensive and time consuming is a good technique if experienced operators are available. Using Hobart mixing method is quite common. Although high shear blenders are potent of providing consistent and reproducible results, they need temperature control and cooling down. Else, high shear blending might result into excessive thermal energies that in turn could lead to misleading results about the cement paste, and cement-admixture compatibility [7].

Table G-1 Typical cement paste mixing methods

Reference	Mixing method				
	Hand	Hobart	Blender	High shear	Other
Struble and Sun [8]					■
Struble and Lei [9]	■				
Yang and Jennings [10]	■				
		■			
			■		
					■
Cyr, et.al. [11]	■				
Roncero, et.al. [12]		■			
Aiad and Hafiz [13]					■
Rehman and Nehdi [14]	■			■	
Toutou and Russel [15]		■			
Kuder, et. al. [16]		■			
Ferraris, et.al. [17]			■		

G.3.2 Mini-slump test and Marsh cone

Perenchio [18] developed a miniature slump cone test for the cement paste. The basic idea was to simulate a slump test similar to that of concrete by simply scaling down the apparatus for cement paste testing. Similar to the slump test for concrete, this test is easy and quick and offers estimates about the relative yield values of pastes. Figure G-2 provides a schematic sketch of the mini-slump cone, test protocol and Marsh cone.

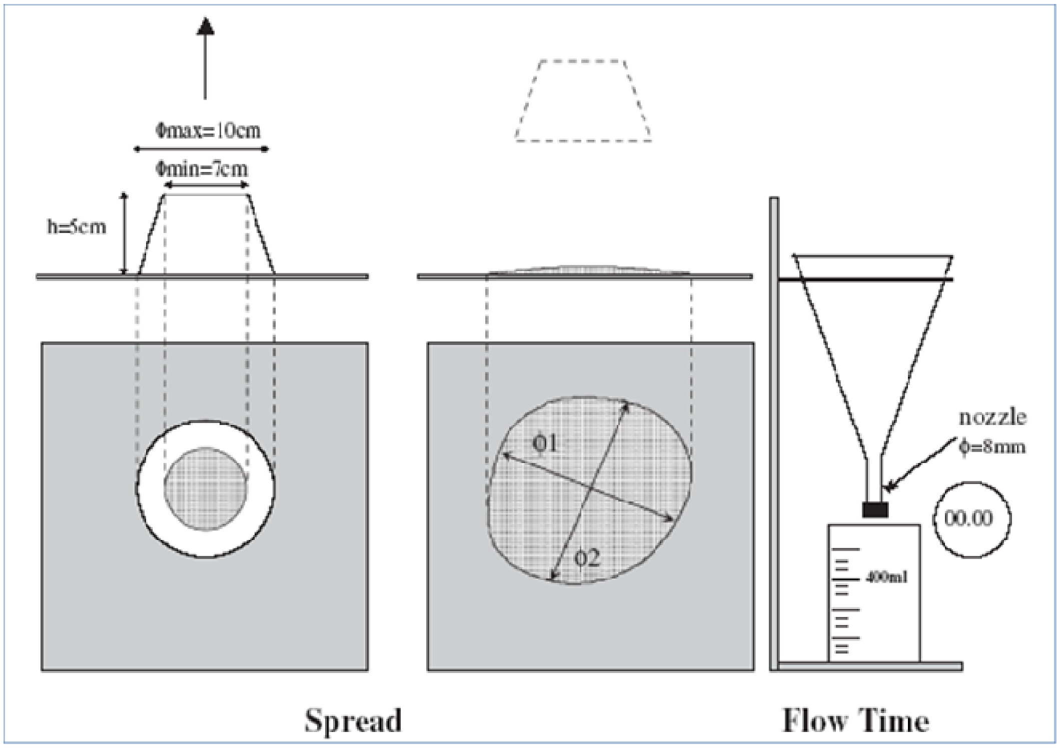


Figure G-2 Characterization of cement paste using empirical tests [21]

It is interesting to note that researchers have tried different dimensions with mini-slump cone. Table G-2 provides a summary of the mensurational details of typical cases. Ferraris, et.al. [19] argue that the mini-slump cone test and the Marsh cone tests are less sophisticated and cannot be relied upon in screening the mineral admixture types and dosages, since they do not relate well with the rheological parameters. Sahmaran, et.al. [20] made more or less similar conclusions for the cementitious grouts prepared using mineral admixtures. They observed that mini-slump flow can be very well related (R^2 = 0.83) to the yield stress while the Marsh cone flow time shows a wider scatter of data with the plastic viscosity.

Table G-2 mensurational details of typical cases of mini-slump cone

Reference	Dimensions			Ratios		Volume (cm^3)
	d_{top} (mm)	d_{bottom} (mm)	h (mm)	(d_{top}) / d_{bottom}	(h) / d_{bottom}	
Chinese standard GB 8077 [21]	36	64	60	0.5625	0.9375	120.83
Perenchio, et.al. [18]	19	38	57	0.5000	1.5000	37.69
Kantro, [22]	19	38	57	0.5000	1.5000	37.69
Sun, et.al [23]	70	100	50	0.7000	0.5000	286.53
Gay and Constantiner [24]	50	152	102	0.3289	0.6711	886.21
Roussel, et.al. [25]	35	50	50	0.7000	1.0000	71.63
Kwan and Wong [26]	70	100	60	0.7000	0.6000	343.83
Cho and Suh [27]	19.1	38.1	57.2	0.5013	1.5013	38.08
Schwartzentruber, et.al. [21]	70	100	50	0.7000	0.5000	286.53
SSD cone for sand [28]	40	90	75	0.4444	0.8333	261.01

On the other hand it is interesting to note that Schwartzentruber, et.al. [29] observed an exponential relationship (R^2 = 0.97) between the yield stress measured by vane shear test and straight lime relationship between viscosity and flow time. Moreover, they advocated the usage of simpler and empirical tests for characterizing the rheological behavior of cement pastes for a given set of constituents. The results are reported in Figure G-3.

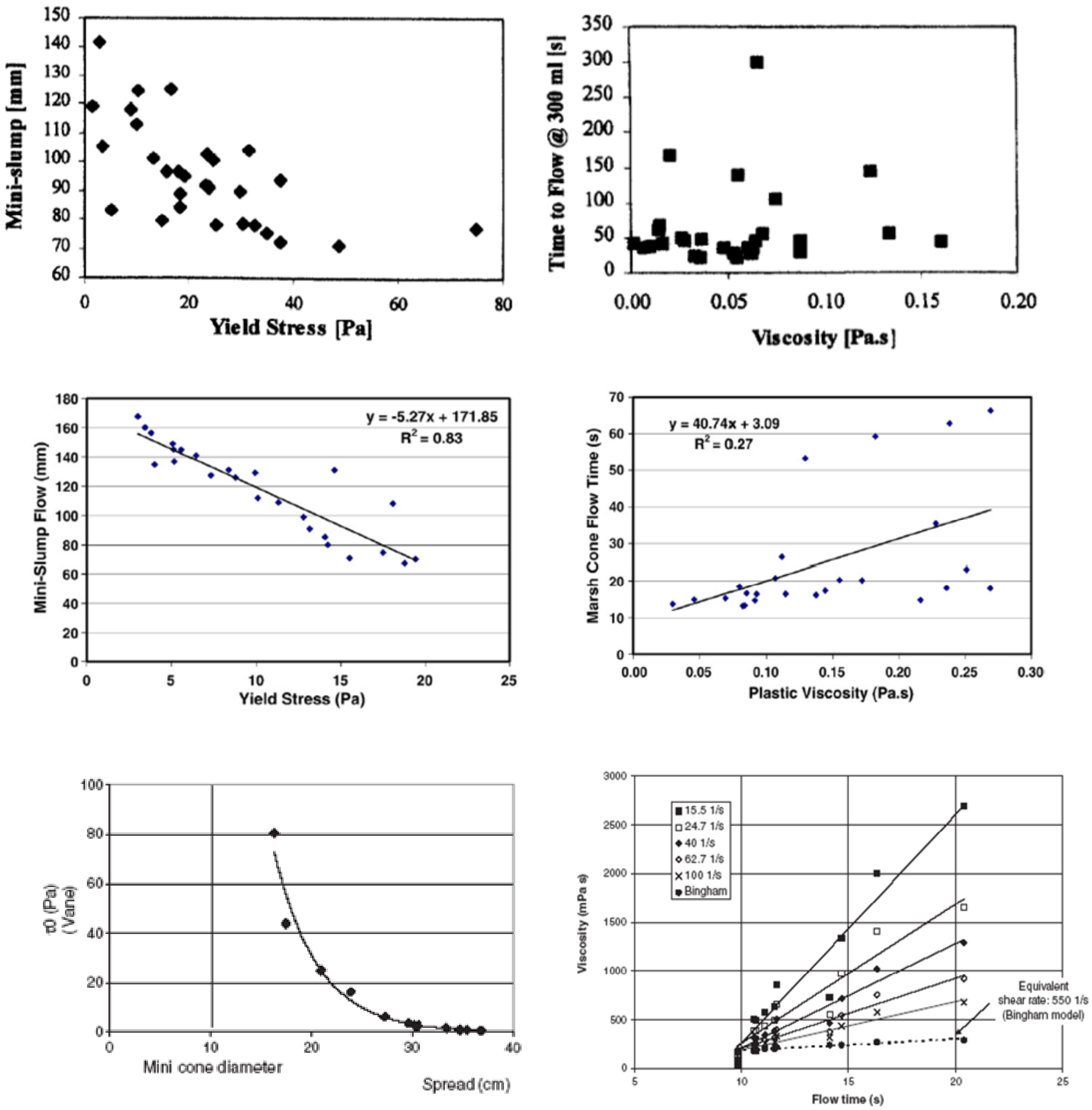


Figure G-3 Comparisons between empirical mini-slump cone test and Bingham parameters. First pair of graphs is from Ferraris et.al. [19]; second from Sahamaran [20]; third from Schwartzentruber [21]

G.3.3 Cabrera slump value

Depending on the measured slump value (reported to the nearest 5mm), ASTM C143 [30] offers certain range of acceptable results along with SD values. Figure G-4 summarizes these. This kind of information is important while writing specifications, evaluating results and for quality control purposes.

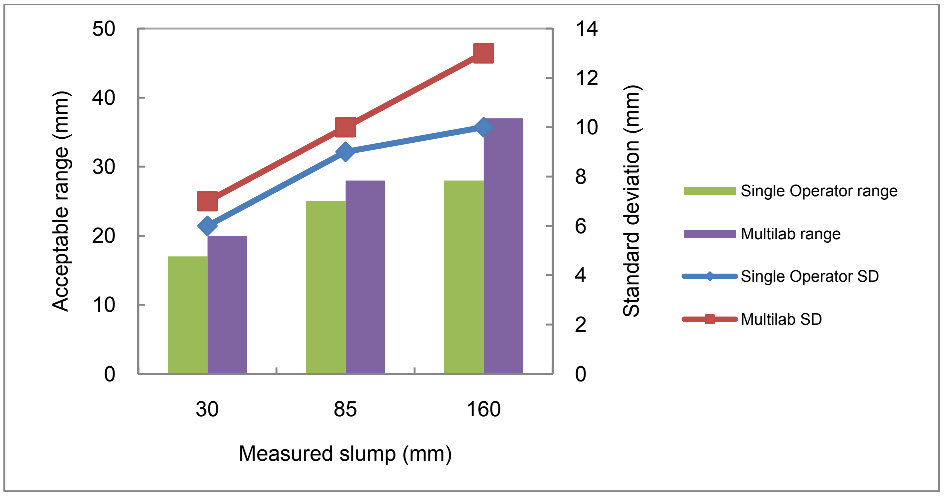


Figure G-4 Allowable range and standard deviations for slump tests

As discussed in the chapter on roller compacted concrete, the Vebe test is criticized for several reasons. Briefly, vibrating slump test consists of vibrating the slump cone filled with concrete (rodded in the same way as conventional concrete) and vibrated for 20 seconds. The drop of the concrete surface (slumping) is measured while retaining the slump cone. This reported slump is expressed in mm and is called as Cabrera slump value (CSV). One of the methods used for this work is vibrated slump test. The developers of this test have reported a repeatability of ±5% for this test [31-32]. It is important to appreciate the fact that concretes of very drier consistencies are tested using this method and the possible range of measurements could be very narrow (zero to 50-60mm).

G.3.4 Direct soil shear (DSS) test and Mohr Coulomb failure criteria

Soil strength is largely a matter of resistance to shearing. Essentially the soil particles slide or roll past one another, the force required for which may be external or from the self-weight of the overbearing soil. Thus, shearing stresses always exist everywhere within soil, although externally and macroscopically stable. The maximum value, by virtue of which a soil's strength is mobilized is the shear strength. The very nature of transferring stress to the adjacent particles when acquires a maximum or critical value leads to the formation of a slip surface.

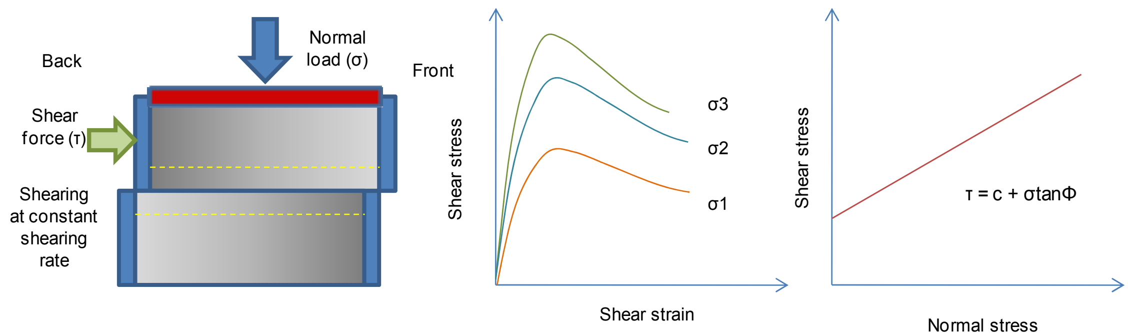


Figure G-5 Schematic sketch of DSS, test results and Mohr-Coulomb failure criteria. NTS

There are many tests to characterize the shearing strength of soils; direct shear strength (DSS) is one amongst these. Refer to Figure G-5 for a schematic sketch and data analysis. DSS is a strain controlled, plane strain, laterally confining test in which a constant normal (vertical) force is applied and the upper half of the soil sample is sheared relative to the lower half, thus shearing takes place along a pre-defined plane. While shearing the shearing area continuously reduces, since the cross-sectional areas of upper and lower boxes are the same. This is often neglected in computations, due to the complexity in estimating the shearing area, especially in circular boxes. It is widely accepted as a simple and quick test for estimating the shear strength (τ) and the angle of friction (Φ) of soils. However, DSS is criticized for not being able to offer reliable estimates of stress-strain behavior, cohesion, friction and anisotropy [33] since their exists extreme progressive failure, difficulties in controlling the drainage, unknown stress state [34].

At this juncture, it is important to recognize the fact that the generalized Mohr-Coulomb failure criteria actually represents

- the limiting envelope along which all the largest principle stress circles and

- the point of tangency of the major stress circles along the enveloping curve, $\tau = f(\sigma)$ must represent in abscissas (σ) and ordinate (τ) the normal and shearing stresses in the planes of slip [35].

ASTM D3080 [36]

The following is a summary of relevant points from testing and instrument design perspective:

- Since the shear stresses are non-uniformly distributed within the specimen, therefore stress-strain relationships or associated quantities like modulus cannot be determined from this test
- The test is suited for relatively rapid determination of consolidated drained strength properties
- It can be used on all soil materials including undisturbed, remolded or compacted
- Since the failure is forced to occur on or near a horizontal plane at the middle of the specimen, failure may not occur on the weak plane
- Minimum specimen dimensions will be decided by the maximum size of the particle of the material to be tested. The shear box dimensions are to be adjusted accordingly.
    - Width for square specimens shall be 50 mm or not less than 10 times the maximum particle size diameter, whichever is larger.
    - The minimum initial specimen thickness shall be 12 mm, but not less than six times the maximum particle diameter.
    - The minimum width to thickness ratio shall be 2:1
- The weight of the top shear box should be less than 1 % of the applied normal force.
- The shearing rate (within ± 5%) shall be between 0.0025 to 1 mm/min.
- The range of normal stresses, rate of shearing and general test conditions should be selected to approximate the specific soil conditions being investigated

Laboratory testing of coarse granular material is an issue with regular DSS (four in. in width) used in geotechnical engineering. Appreciating the fact from the dimensional limits that ASTM D3080 specifies vis-à-vis the maximum grain diameter, it can be concluded that the maximum allowable grain size in a 100 mm square shear box would be 5 mm. There are two ways for getting around this problem viz. either exclude the oversize particles or scale up the direct shear box. The first approach might tend to offer unrealistic and less holistic estimates, while the second approach would tend to be expensive and considering the long history of the conventional small size shear box, would rather cause inconsistencies in accepted and applied design values.

LARGE SIZE SHEAR BOXES

The state of the art in testing is ever expanding [37]; with growing challenges, incorporation of newer technologies, desire for increasing computational accuracy, engineers are forced to expand testing technologies further. DSS with different sizes have been applied by different researchers [38-43] for different geotechnical materials. In general, the widths have been varied between approximately 60 mm to 500 mm.

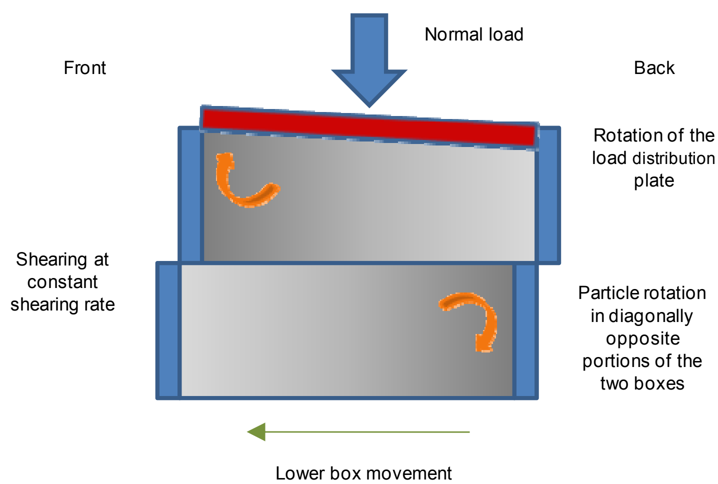


Figure G-6 Particle-box interaction in large-scale shear boxes. Reproduced and inspired from [42]. NTS.

The following observations are relevant:

- The size of the shearing device can influence the direct shear test results. Generally, the boundary effect and device friction are more significant for a smaller shear box and this could influence the distribution of stresses and hence the nature of failure.
- The particle box interaction is far more significant in large-scale boxes caused due to shear banding of larger number of particles. This intensive particle rotation causes rotation of the load distribution plate. Figure G-6 shows the phenomena pictorially.
- The results also depend on the maximum grain size, median particle size, the fractional composition of material (relative quantity of gravel and sand).
- For a given material, in general as the box size increases the friction angle decreases. This inference should be derived in light of the maximum grain size. Linear relation exists between friction angle measured by small and large boxes. Figure XX represents these two facts from published literature.
- The repeatability of larger shear box was found to be ± 0.45°.
- There is not much discussion about the shearing strain rate effects.

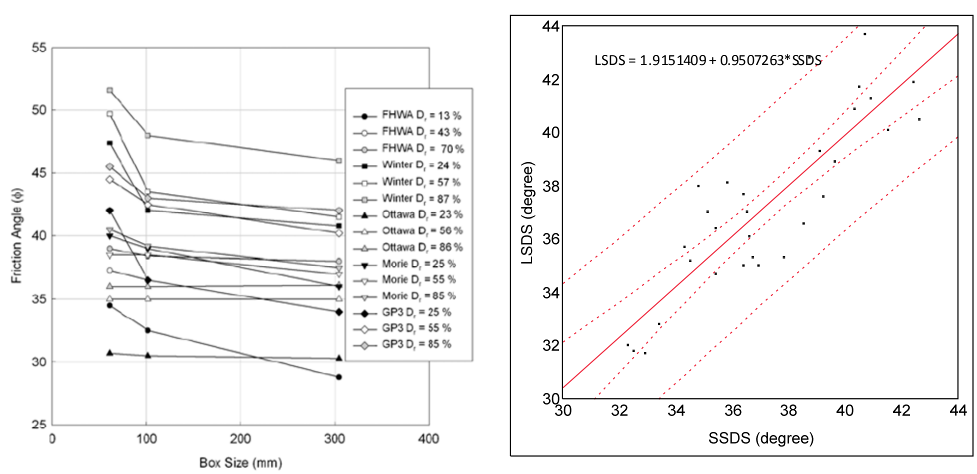


Figure G-7 Effect of box size on the measured friction angle [38] and correlations between angles measured with LSDS and SSDS (data re-plotted from [42]).

OTHER CONSIDERATIONS

The factors that bear relevance to this work and affect the measurements of soil shear parameters are summarized below. The following is just a sampling and not an exhaustive review.

- Geological processes affect the granulometry and surface texture of sands. The compacted density, the diameter having 10% material passing through (D_{10}) in turn affect the measured angle of internal friction [44]
- In a review on the friction angles for sand, gravel and rock-fills, Duncan [45] points out the following:
  - Friction angle reduces with the increase in the normal stress on the slip surface
  - Relative density is the most important single factor governing friction angles of granular materials
  - The Unified soil classification system [46] is not a good guide with respect to the influence gradation on friction angles
  - Higher coefficient of uniformity (C_u) results in higher angle of friction
  - The friction angle decreases as the maximum particle size increases
  - At the same void ratio, material with angular particles has higher friction than material with rounded particles, while at the same compactive effort, material with angular particles has very nearly the same friction angle as material with rounded particles
  - For most sands, moisture reduces the friction angle
- The angle of repose and angle of internal friction can be linearly related [47]
- Researchers testing mixtures of clay silt and sand observed that increases in the gravel size (maximum size of particle) increased shear strength. They also found that the density of clay-rock mixtures reached a maximum at approximately 50% gravel content and decreased rapidly with increasing gravel content.
- Miller and Sowers [48] in their experiments on cohesive soil-rock mixtures observed that the cohesion and friction values remained more or less constant with increases in cohesion-less materials up to a certain level in the total material. Beyond a certain replacement level, the cohesion and friction angle values gradually changed; the angle of friction increased after a certain rock content level, while cohesion decreased and the dramatic change occurred at different

rock percentages. Figure G-8 shows the experimental results. Similar results were reported by Simoni and Houlsby [41] as a function of minimum voids ratio and are reproduced in Figure G-9.

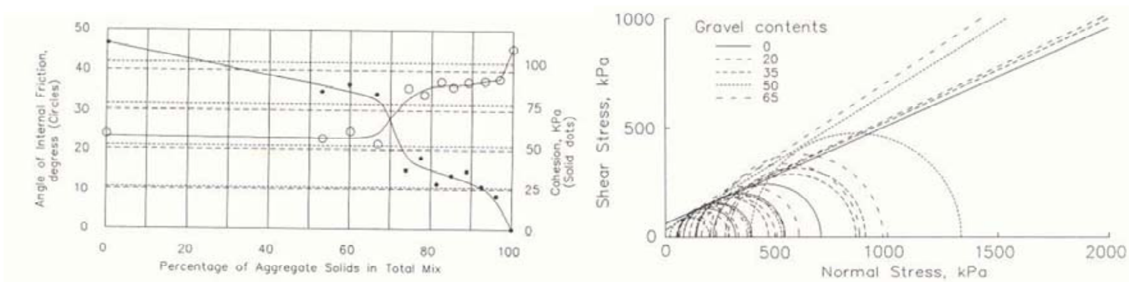


Figure G-8 Shear strength of soils having cohesion friction parameter imparting fractions

- In another interesting study revealing the influence of the soil composition (cohesion and friction imparting fractions), it was observed that the relative concentrations of each of the fractions influence the overall shear-cohesion value. This is shown in Figure G-10. It can be seen from this figure that shear resistance of the mixtures was governed by
    - frictional resistance of sand between sand contents 80 to 100%;
    - combined action of the shear strength of Kaolinite clay and frictional resistance of sand between sand contents 50 to 80%;
    - Kaolinite clay below sand content levels of 50%

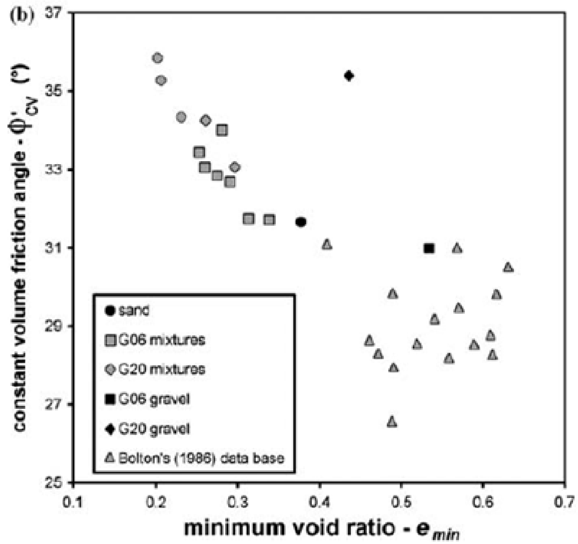


Figure G-9 Critical state friction angle as a function of minimum void ratio [41]

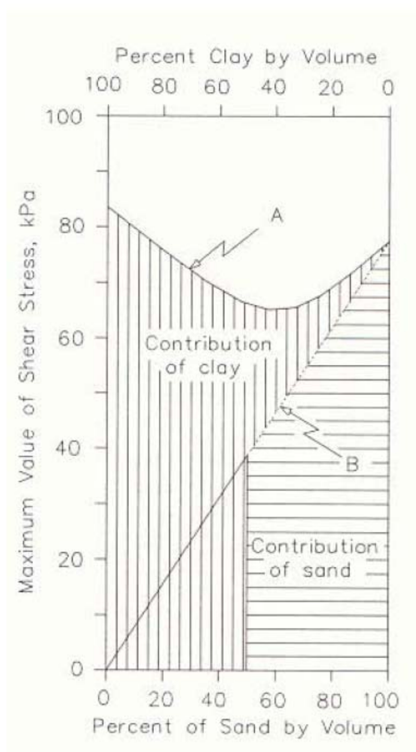


Figure G-10 Contributions to shear strength by different fractions of soil

- The effect of strain rate on mechanical soil properties can have important engineering implications. Achieving a harmony, simulation and relevance between lab measured (for example, strain rate = 0.5-5%/hr) or in-situ characterized (for example, strain rate = 10^3-10^5)%/hr) strength parameters and practically encountered geotechnical engineering systems (for example, strain rate = 10^{-2} to 10^{-3}%/hr) [49] is always difficult. Another potential difficulty arises from the fact that there are spatial heterogeneities found at the field scale [50]. Relatively few investigations have been done on the influence of strain rate on the mechanical properties of rock and other geomaterials primarily due to the difficulties encountered at high strain rates in the instrumentation and the prohibitively large costs to acquire necessary testing facilities [51]. This precludes computer modeling. Figure G-11 offers a testimony of a study on the strain rate dependence of cohesive soil.

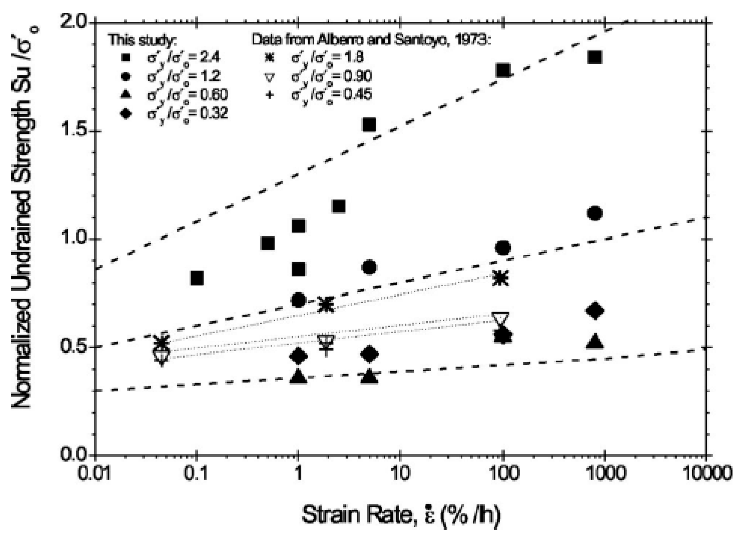


Figure G-11 Strain rate effect on the normalized strength of Mexico City clay

The relevance of above discussion shall be revealed in later chapters on results and discussions. RCC resembles soil in many aspects and it was anticipated during the design phase of this work that the cohesion and friction aspects of RCC could be extracted from similar testing. Factors discussed about were found to be relevant in designing the instrument and planning the protocol of tests performed on RCC.

G.3.5 Approaches to estimating setting times, temperature measurements

The objective of this section is not to review the widely reported factors that affect the setting times of cements and concretes, but to critically appreciate and assess the possibilities of applying the existing techniques to roller compacted concrete. Traditionally the setting time of concrete is estimated on the basis of the penetration resistance offered by the mortar derived from mixed concrete. This is covered by ASTM C403 [52]. Ultrasonic method has been reported to offer better estimates of setting times for RCC for dams [53-54].

Quite unlike the conventional pavement concrete, RCC is water deficient, drier consistency, mortar deprived, and higher aggregate content mixture. Extracting sufficient quantity of mortar from a concrete mixture is often difficult or may not be possible due to the meager mortar the mix possesses and the same is utilized in coating the coarse aggregates. Practitioners agree that the traditional methods of determining setting types as used for conventional concrete fail to provide good results for RCC [53].

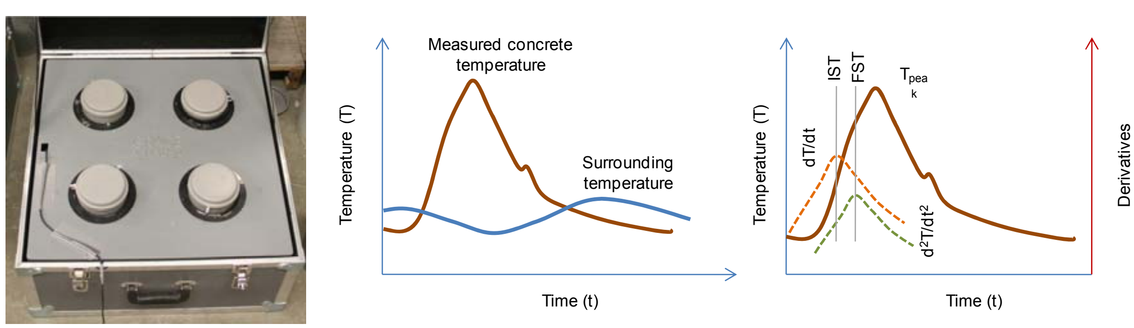


Figure G-12 Semi-adiabatic temperature measurement, obtained and processed data

In recent years, measuring the temperature profiles of cement paste, mortar and concrete over a certain time period is gaining popularity. The temperature measurement and monitoring offer many potential benefits right. This includes optimizing material design [55], assessing compatibility of binders and chemical admixtures [56-58], appreciating the actual on-site thermal gradients (and hence the degree of hydration) in concrete structures, quality control [59], estimating concrete cracking potential [60], etc. Of the three principles viz. isothermal (constant temperature), adiabatic (no heat gain or loss, sample temperature same as the surroundings) and semi-adiabatic (some insulation from the surroundings) used in practice, the semi-adiabatic is relevant for this discussion. Because of its handling ease, less skill demand, applicability to mortar and concretes, easy accessibility to data, in-lab and in-situ testing ability, it is widely being accepted, even though it may not necessarily produce the most accurate information. A picture of semi-adiabatic calorimeter and the nature of in-field temperature evolution along with the extractable data are shown in Figure G-12.

The semi-adiabatic method primarily gathers temperature data over a period of time. The gathered data is then further processed by differentiating temperature changes over time. Using the concept of 'maxima', the peak from the first derivative offers an estimate of the initial setting time while the peak in the second derivative curve offers an estimate of the final setting time. This is called as the derivatives method. Another method called as fractions method is also used. The sample size, ambient temperature and device insulation properties are reported to have significant effect on setting time estimates. Hence, adjustments for device specific losses are important if different devices are to be used [61].

The following critique is important for proper appreciation of the results while considering the widely used penetration resistance method for conventional concretes and the newly adapted semi-adiabatic calorimetric method:

- Any method used can only provide an estimate of the setting time of concrete.
- Penetration resistance method is based on assessing the mechanical response of concrete, more specifically the punching shear. Apart from the material factors that would decide the nature of evolution of mechanical strength response, this method would not render much other information. With its current protocol, it

requires concrete derived mortar needs continuous monitoring for substantial amount of time, thus requiring personnel to conduct tests at frequent intervals.

- The principle of semi-adiabatic temperature rise is related more to the nature and kinetics of chemical reactions taking place in concrete. The temperature responses are more a result of these chemical reactions and although they may correlate well with the mechanical responses, there could be outliers to the usually accepted trend.
- While correlating the penetration resistance responses with the semi-adiabatic temperature responses, the fact that the penetration resistances are measured on mortars and the temperature responses on as-is concrete should always be taken into account. Additionally, although reported results talk about such correlations, due to different nature of measurements, no results are reproduced here.

G.3.6 Mixer selection and mixing sequence

The mixing of dry concretes like RCC acts as an influencing factor in deciding some of the properties of concern in this study. This involves mixing sequence, mixing time and the mixing energy that is provided to the concrete. The mixing sequence as such influences the rheology and cohesion of the mix. Different researchers have used different methods for mixing concrete and the significant ones are briefed in Figure G-13. This issue becomes critical especially when using air entraining admixtures and is elaborated further in the chapter on roller compacted concrete technology. Lab mixers (tilting drum) type are suitable if batch sizes are regulated properly. Pan mixers would tend not to shear the concrete and may not mix the concrete well. Lab size twin shaft horizontal mixer is highly effective in rendering a good mix. These selection criteria would be reviewed in the light of the availability of the mixer type and extent of the work.

Sec	0	30	60	90	120	150	180	210	240	270	300	330	360	390	420	450	480	510	540	570	600	630	660
Min	0		1		2		3		4		5		6		7		8		9		10		11
1	Mix cement+sand			WR + part. Water	CA + AEA + remaining water																		
2	Starting of mixer			Dry mixing of aggregates and		Addition of water and diluted water reducer and AEA and mixing																	
3	CA + Partial water with admixtures (WR + AEA)					Add cement + sand + reamaining		Mix for 3 min.						Cover the mixer and rest for 3 min						Open the cover and remix for 2min.			
4	Cement + FA + Water + AEA and mix for 2 min					Add CA and mix for 1 min.		Cover and rest for 3 min						Open and remix for 2 min									
5	Mix FA + CA for 1.5 min				Add AEA diluted in 1/2 water			Add cement/binder and mix for 2min				Add remaining 1/2 of the water and mix for 3 min											

Figure G-13 Mixing sequences used by different researchers (1:[62], 2:[63], 4:[64], 5:[65]) and as recommended by ASTM C192 [66]

G.3.7 Compacting hammer

Refer to Figure G-14. The following points are relevant:

- It is interesting to note that guides usually recommend the use of modified Proctor test for finding the optimum moisture and maximum dry density [67] and this is used in practice as well [63]. However for casting cylinders, compacting/vibrating hammer meeting the specifications is used [68]. In author's experience, this may lead to discrepancies and inconsistencies if the cylinder sizes are not correlated and specified properly. Using Proctor for casting compression test cylinder may prove to be effort intensive, uneconomical and time consuming. Increasing commensurate size of mold and using vibrating hammer seems to be more practical. However, this is just an opinion.

Figure G-14 Compacting hammer for RCC

- ASTM C1435 [68] specifies the use of 150Φ x 300H mm cylinders to compact the cylinders with a standard hammer. It is also specified that the vibrating hammer shall have a minimum mass of 10 ± 0.2 kg and capable of providing at least 2000 impacts/min. In addition to this, the tamping plate is specified to have a diameter of 140±3 mm and a mass of 3 ± 0.1 kg. These specifications are rather restrictive in nature since they limit the use of compacting hammer for only 150 mm diameter specimen. The author has come across specifications [69] which stipulate the stress/unit volume or per unit area. This offers greater flexibility and freedom to the practitioner.
- The time length of compaction is specified to be a function of mortar ring development during compaction. In addition, the time is limited to a maximum of 20s. In author's experience, this time may prove to be insufficient if the mixtures are having drier consistencies. It is appealing to notice the fact that by such specifications, the standards are indirectly limiting the use of concretes with specific consistency range. Mixes drier than these consistencies may have good compactibility and might render good quality concrete. This issue becomes more sensitive when marginal or recycled materials are used.
- The compaction energy is directly specified in terms of amount of energy per unit volume. The standard specifies formation of 300 mm height cylinders in three equal layers with a specified upper limit for the time of compaction. The specifications or recommendations for 100 mm diameter cylinders are not available.
- RCC is used for pavement structures where testing and evaluation of flexural strength is important from design verification point of view. There is no standard method or guidance on the test protocol on the formation or casting of flexural test specimens. There is some work done on this issue which states using equivalent density concept for casting flexural specimens [63, 70].

These facts are important from the point of view of revisions to the mentioned standard and practice in general.

G.4 Other considerations

G.4.1 Perspectives on aggregate grading

ACI 325 recommends combined aggregate grading for RCC concrete. With recent escalation in applications of RCC, different agencies have come up with specifications suiting specific applications while being cognizant of the locally available materials. Table G-3 offers a summary of typical gradings recommended/specified for RCC works by different agencies.

Table G-3 Comparison of recommended combined aggregate gradings

Percentage	ACI 211.3R		SCDOT		Georgia DOT		MoRTH	
Aggregate bands								
Sieve size (mm)	LL	UL	LL	UL	LL	UL	LL	UL
25.000	100	100	100	100	100	100	100	100
19.000	82	100	90	100	90	100	80	100
12.500	72	93	70	90	70	100	--	--
9.500	66	85	60	85	60	85	55	80
4.750	51	69	40	60	40	60	35	60
2.360	38	56	--	--	--	--	--	--
1.180	28	46	20	40	20	40	--	--
0.600	18	36	--	--	--	--	10	35
0.300	11	27	--	--	--	--	--	--
0.150	6	18	6	18	6	18		
0.075	2	8	2	8	2	8	0	8
FM	5	3.63	NA	NA	NA	NA	NA	NA
FA/TA (%)	51	69	40	60	40	60	35	60
Workability								
CF	54.84	34.09	40.00	15.00	40.00	15.00	60.81	40.82
WF	38.00	56.00	29.50	50.00	28.50	50.00	26.00	51.00
Grading parameters: Soil								
C_u	34.00	35.29	38.00	52.94	38.00	52.94	17.00	58.82
C_c	0.71	1.57	1.05	1.18	1.05	1.18	0.53	0.71

Notes: FM: fineness modulus; FA/TA: fine aggregate/total aggregate; CF: Coarseness factor; WF: Workability factor; C_u: Coefficient of uniformity = (D_{60}/D_{10}); C_c: Coefficient of gradation = ($D_{30}^2/(D_{10} x D_{60})$).

The following observations are relevant:

- ACI 211.3R gradations closely resemble Asphalt grading. Comparing these grading bands with typical aggregate gradings for pavements, it seems that these are quite stringent and may potentially be difficult to be controlled in practice.
- The specifications offered by local agencies (SCDOT, GADOT) are comparatively broader than ACI 211.3R. Other variations include sieve sizes of 19, 0.6 mm. The specifications by MoRTH are for base course while the others are for wearing courses in general.
- As seen before, an increase in the coefficient of uniformity (C_u) leads to an increase in the friction angle. As can be seen from the numbers above the ACI211.3R grading band may not lead to much variation with the friction angle. However, it is quite interesting to notice that the finer gradings tend to offer lesser Cu values and this could mean that the frictional resistance offered by finer gradings would be lesser than the coarser ones. In case of the MoRTH grading band the lower limit grading offers a relative lesser Cu, meaning the friction angle offered by finer grading is rather higher. This analysis is important, since as will be seen later on that the angle of friction is important from the workability point of view.
- There is a wide variation in the coarseness factor (CF) and workability factor (WF) based on the specified grading limits. Figure G-15 shows the Shilstone chart along with the above gradings, joined by straight lines. From the perspective of recommended values of CF (52-68, usual target 60) and WF (32-36, usual target 35), the following observations are pertinent:
    - The upper limit (UL) of ACI 211.3R may be considered to render very fine graded mixture, which may tend to increase the water and cement demand dramatically. While the lower limit of this grading seems to be quite acceptable when compared with the recommended numbers
    - A general comment that can be offered is when the RCC aggregate gradings are compared with this chart, this chart may offer rather misleading guidance

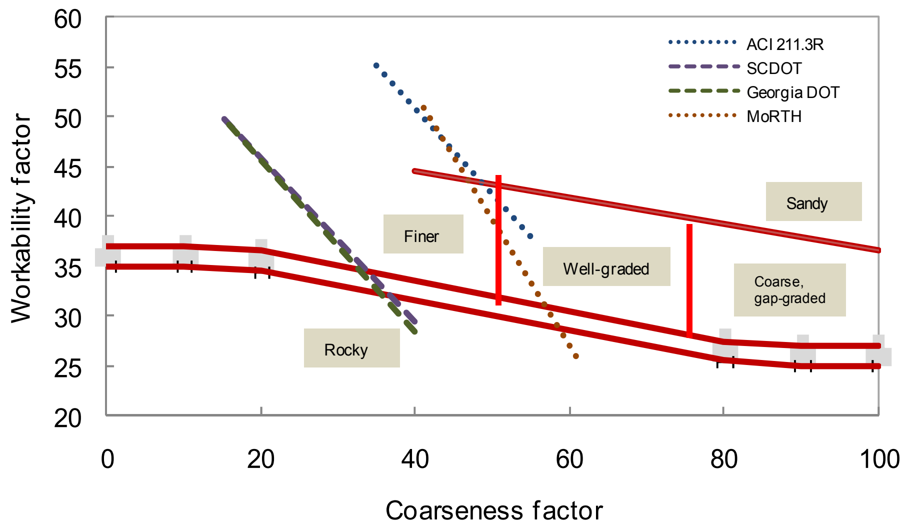


Figure G-15 Shilstone chart and the specified gradation: A comparison

- The fine aggregate selection needs special attention with increased fines. ASTM C33 may not offer the right material from finishibility perspective. However, RCC can still be manufactured with other fine aggregate gradings not recommended by ACI 211.3R. Figure G-16 shows a comparison

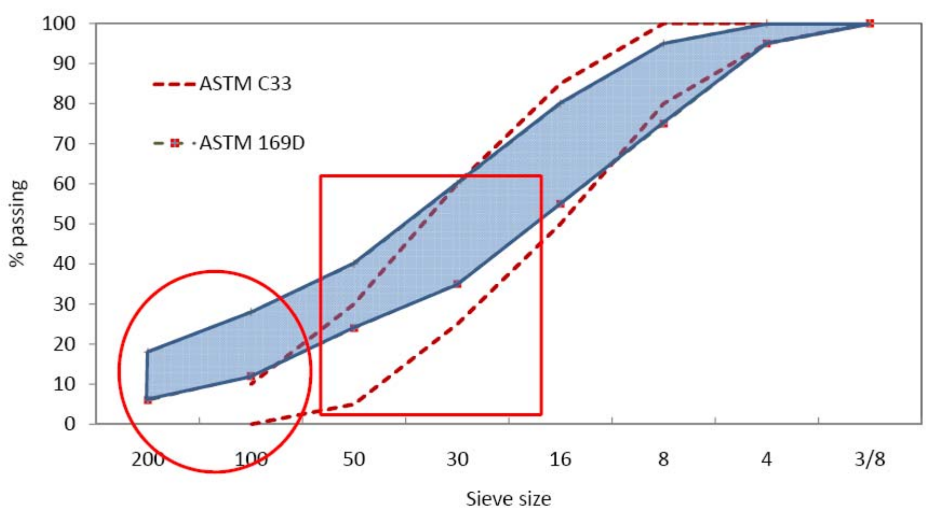


Figure G-16 Comparison of fine aggregate gradings (change figure to SI later on)

- If 0.45 Power curve is plotted for two different maximum size aggregates, it can be seen that the Power curves locate themselves closer to the lower limits of the ACI 211.3R band. This fact is shown in Figure G-17 and shall be discussed again in the results section.

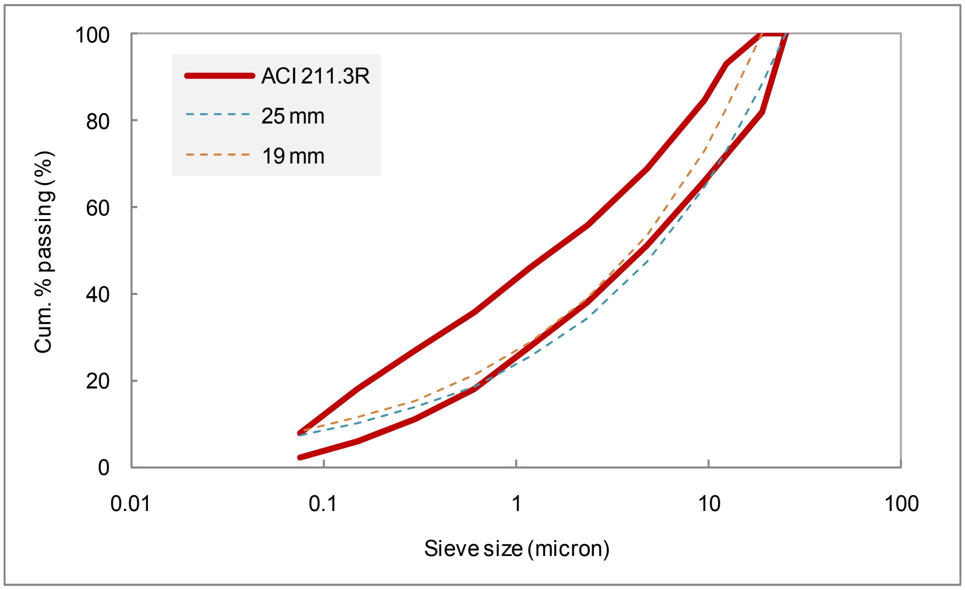


Figure G-17 Power curves and ACI 211.3R grading bands

G.4.2 Sample size

Conventionally three 150 mm diameter cylinder specimen/sample are being tested for concrete compressive strength. ACI 318-08 [71]recommends testing two 150Φ x 300H mm cylinders/sample or at least three 100Φ x 200H mm cylinders/sample at 28 days or at the test age designated for determination of characteristic strength. In the commentary to the said document, it is said that the 100 mm diameter cylinders tend to have approximately 20% higher within-test variability when compared to 150 mm diameter cylinders. This matter becomes important in case of roller compacted concrete since, it is subject to higher variability due to the very nature of the material and higher possibilities of human error in casting the specimens.

Day in the second edition [72] of his book on concrete mix design, quality control and specification argues that two specimen per sample should be okay unless there is poor testing or there is self-protection involved. While in the third edition [73] of the same book, he offers definite statistical guidance and allowable variations while leaving the choice between testing two or three specimens/sample to the user. Detwiler et.al. [74] report that although the strengths obtained from 150 mm and 100 mm diameter cylinders of same mixture are not comparable, but the statistical analysis reveals that testing two 100 mm diameter cylinders/sample does not result in greater within-test variation when compared with 150 mm cylinder. They inferred that there is little justification for future specifications to require testing of three rather than two cylinders when 100 mm diameter plastic molds are used. In an earlier study, Detwiler et.al. [75] proposed the following precision statement for 100 mm cylinder.

Table G-4 Proposed precision statement for single operator [75]

Conditions	Coefficient of variation (%)	Acceptance range (%) of	
		Two results	Three results
Single operator, field conditions	2.86	8.09	9.44

G.4.3 Mixture models

In recent years, concrete mixture proportioning is involving statistical techniques for experiment design and analysis standpoint. The statistical approach offer additional advantages in terms of offering responses that are characterized by uncertainties [76]. In this work, a specific statistical method, “mixture models” will be applied. Amongst several, the book by Cornell [77] presents the details of this method. This method will be further elaborated and explained in a later section.

Methods of mixtures have been applied to cement based materials and the following is an account of the same:

- Dehuai and Zhaoyan [78] applied simplex-centroid design for obtaining prediction equations for compressive strengths of mortars with ternary blends of cement-slag-fly ash.

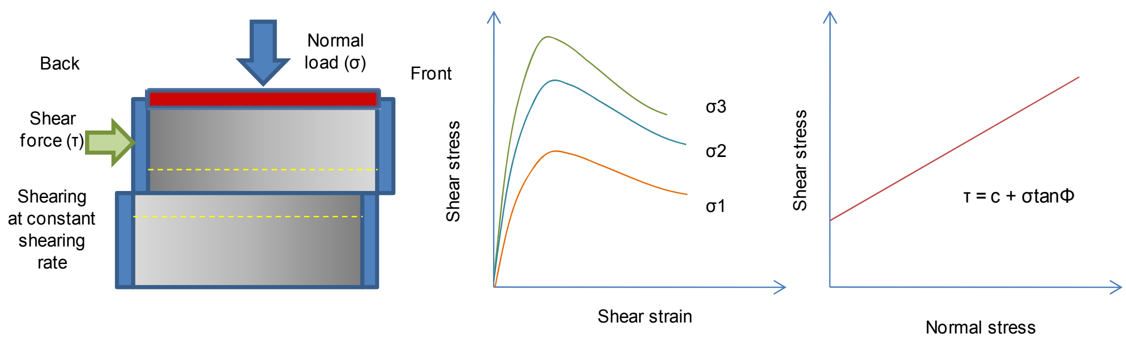
- Yeh [79] applied flattened simplex-centroid method of mixtures for optimizing concrete performance with superplasticizer, fly ash and slag in order to get the most desirable workability and strength characteristics.
- Ding, et.al. [80] used a more elaborate way of optimizing mixtures. They applied extreme vertices design to predict the 7 and 28 days strength of ternary combination of Portland cement-zeolite-fly ash. The maximum percentage error obtained using their prediction equation was 5.1%.
- Akalin, et.al. [81] applied the method of mixtures for optimizing a five component admixture system for maximizing water reduction and strength while minimizing the cost to mortars.

At this juncture, it is important to acknowledge that other statistical methods (like response surface, factorial design) have been applied for optimizing concrete performances. Published research includes testimonies by Ghezal and Khayat [82], Sonebi, et.al.[83] amongst others. The National institute of standards and technology has a concrete optimization software tool (COST) that applied response surface methodology for optimizing concrete mixtures from several different perspectives [84].

SUMMARY

Any experiment needs to take into account the strengths and possible limitations of the instrumentation used. A further complexity arises when instruments that are routinely applied in characterizing materials that are inherently different. This specificity offers several limitations in applying these instruments on other than the materials that are characterized regularly. Change of material not only necessitates adjustments and fine tuning of some of the instrumentation, but often could require scaling up or down and eventually this change leads to changes in the way the statistics of measurement is distributed.

Application of different instruments for characterizing the same property could lead to large scale variations in the measurements and hence an appreciation of such an artifact needs to be accounted for or at least acknowledged. Hence establishing the statistical information for all the instruments along with an acknowledgement of their limitations was presented in this chapter.



Various theoretical considerations are available for material selection. A closer look reveals that such widely distributed, but narrowly designed recommendations may not be possible considering the variability of the materials, thus necessitating better approach to select and evaluate local materials, while fulfilling the ultimate performance requirements.

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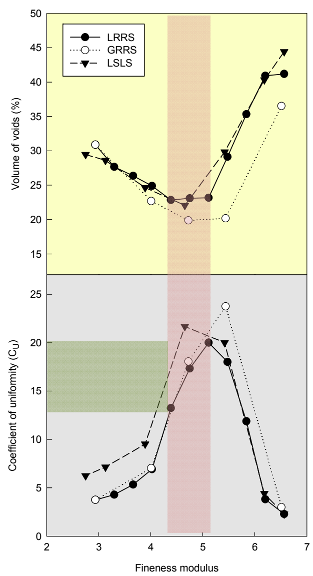
APPENDIX H PRELIMINARY STUDIES



SYNOPSIS

This chapter prepares the background for the forthcoming discussions on results. This chapter contains in three distinct sections. The first one, talks about aggregate grading evaluation in terms of compacted density, voids content, grading indices and attempts at obtain correlations between these parameters with an aim of having the least possible voids content. Ensuring this will lead to reduction in the paste volume used in the concrete. Further to these different aggregate geologies are tested along with the influences of factors such as particle shape, composition of aggregate and relative volumes and how these factors influence different parameters for evaluating aggregate gradings. The second section briefly talks about the selection of appropriate chemical admixtures for further testing. The third section reports studies on compactibility of concrete mixtures prepared with different aggregate gradings, aggregate/binder ratio and water binder ratio. The objective of this part of the study was to evaluate the influences of each of these parameters (individually and collectively) on the compactibility of concretes. Finally, the indices obtained from compactibility studies are connected to roller compactibility using the moisture-density plots.

Keywords: aggregate, grading, grading indices, voids, compactibility, density, aggregate/binder, water/binder, gyratory compaction, workability

CONTENTS

H.1 Aggregates

Aggregate grading is conventionally specified in terms of the maximum size of the aggregates. Good aggregate grading is accomplished while being cognizant of sufficient continuity of grading to render required workability, and at the same time inserting filler material in a cement paste matrix. Assessment of any negative influences on the durability and long-term performance of concrete is also routinely undertaken. Of particular relevance to the subject matter presented is the workability of concrete and how it is influenced by aggregate grading.

A vast amount of literature [1-5] is available on how to choose the most appropriate aggregate grading and how to specify. Grading specification by limit curves is very popular due to its simplicity; while other methods include percentage grading, particle interference method, fineness modulus (FM) and maximum density principles [2]. In the background, while specifying an aggregate grading band for any concrete work, adequate considerations are offered to accommodate the possible variability in the locally available material. Some aggregate grading bands are tighter (e.g. self-consolidating concrete) than the others (e.g. concrete for building foundations) depending on the nature of work and the type of concrete to be used. The specifications also take into account the relative proportions of fine and coarse aggregates and their individual and combined influences on the fresh and hardened properties of concrete.

The suite of critical properties of an aggregate system depends on its application vis-à-vis the geology in a particular geography. For example, the aggregate abrasion resistance is an important index for pavement wearing course application, but it may not be that crucial for a bridge pier. Finishibility is another such criteria. Such identification of relevant aggregate properties is important for proper selection and evaluation of different aggregates.

The matter presented henceforth approaches aggregate grading selection from compactibility perspective. Factors like geology, particle shape, relative proportions of fine and coarse aggregates, and the combined aggregate gradings are taken into account while evaluating the gradings from different perspectives.

H.1.1 Vibration responses to compaction with surcharge weight

This section reports the studies on the vibration responses of different aggregate gradings. Initially a protocol for evolving the required characterization parameters is discussed, followed by the presentation of results. ASTM C29 [6] specifies single operator precisions for bulk densities, but not for the voids content. The available information for single operator precision is presented in Table H-1.

Table H-1 Single-operator precision for bulk density measurement [6]

Aggregate type	Precision (kg/m^3)
Coarse	14
Fine	14

THE PROTOCOL AND EXPERIMENT MATRIX

The objective of this part of the study was to assess the vibration responses of different aggregate systems under a surcharge weight. For this purpose, a specially fabricated density bucket with a surcharge weight was used. The protocol for this test was based on the method explained by Sedran and de Larrard and extensively applied by de Larrard [4]. In this method a mass, M_D of dry aggregate in put in cylinder having a diameter, Ø, which is more than five times the maximum size of aggregate. A piston is introduced in the cylinder, applying a pressure of 10kPA on the surface of the specimen. Then the cylinder is fixed on a vibrating table, and submitted to a vibration for 2 min. The actual packing density, Φ, is calculated from the final height, h, of the sample:

$$\Phi = \frac{4M_D}{\pi Ø^2 h \rho_D}$$

ASTM C29 [6] specifies a minimum volume capacities of 0.0093 m^3 and 0.014 m^3 for a NMSA's of 25 and 37.5 mm and since it was intended to avoid wall effects as much as possible, a 0.01402 m^3 container was used. The surcharge weights were applied using a surcharge piston with several steel plates. The cylinder was filled twice with the oven-dried aggregates and compacted for one minute. A second layer and some excess material was added and the bucket was vibrated again for one minute. Excess material was then struck off to keep the final height constant and equal to the height of the bucket for all aggregate systems. The weights of the bucket with and without aggregate were recorded and based on the calibrated volume, the compacted bulk density (CBD) was obtained. In addition to this, the same density bucket was used for measuring the loose bulk density (LBD) of aggregates by gentle dropping the aggregate using scoop. A schematic resembling field compaction is shown in Figure H-1.

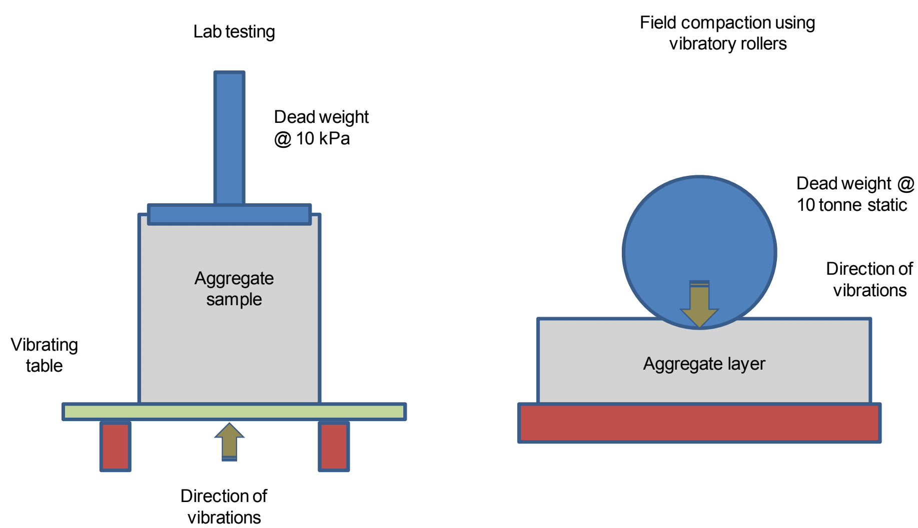


Figure H-1 Testing for vibration response of aggregate with surcharge load

Different aggregate systems were tested in order to appreciate the effects of the changes in the aggregate composition, geology and shape. Table H-2 shows a sample test matrix. The measured properties for this phase include LBD, CBD, voids ratio, compactibility (F), packing density, compaction and rate of compaction

Table H-2 Test matrix and nomenclature for testing compaction response of aggregate to density

		CA1	CA2	CA3	CA4
		Gravel	Limestone	Quartzite	Granite
FA1	River sand	GRRS	LSRS	QZRS	GNRS
FA2	Limestone	--	LSLS	--	--

H.1.2 Typical results

The results obtained are analyzed and presented as follows. At first, a typical analysis on the combination LSRS is presented, since these were the aggregates finally used for the subsequent phase of this work. This aggregate system was tested in detail with measurements at each 10% increment in the FA content of the total aggregate. Figure H-2 shows the plots of density, volume of voids and voids ratio for loose and compacted states.

Based on the figure, the trend can be explained as follows. As the fine aggregate is introduced in coarse aggregates, gradually they start filling the voids in the coarse aggregate. The system is dominated by coarse aggregate. As the fine aggregate content is increased, the system starts reaching its potentially maximum packing and reaches the least voids content. Consequently, the density also increases and reaches a peak and stays there for a narrow range of combination of fine and coarse aggregate. As the fine aggregate content is increased further, a phenomenon called "particle interference" takes place leading to decrease in packing of aggregates characterized by an increase in the volume of voids along with the drop in the density.

At this juncture, it is important to mention Weymouth's theory of particle interference, which implies that for optimum gradings there always exists optimum average clear distance between adjacent particles of the same size as they lie in the placed concrete. This optimum distance is such that each particle size has sufficient space to move into the space between the particles of the next larger size [7].

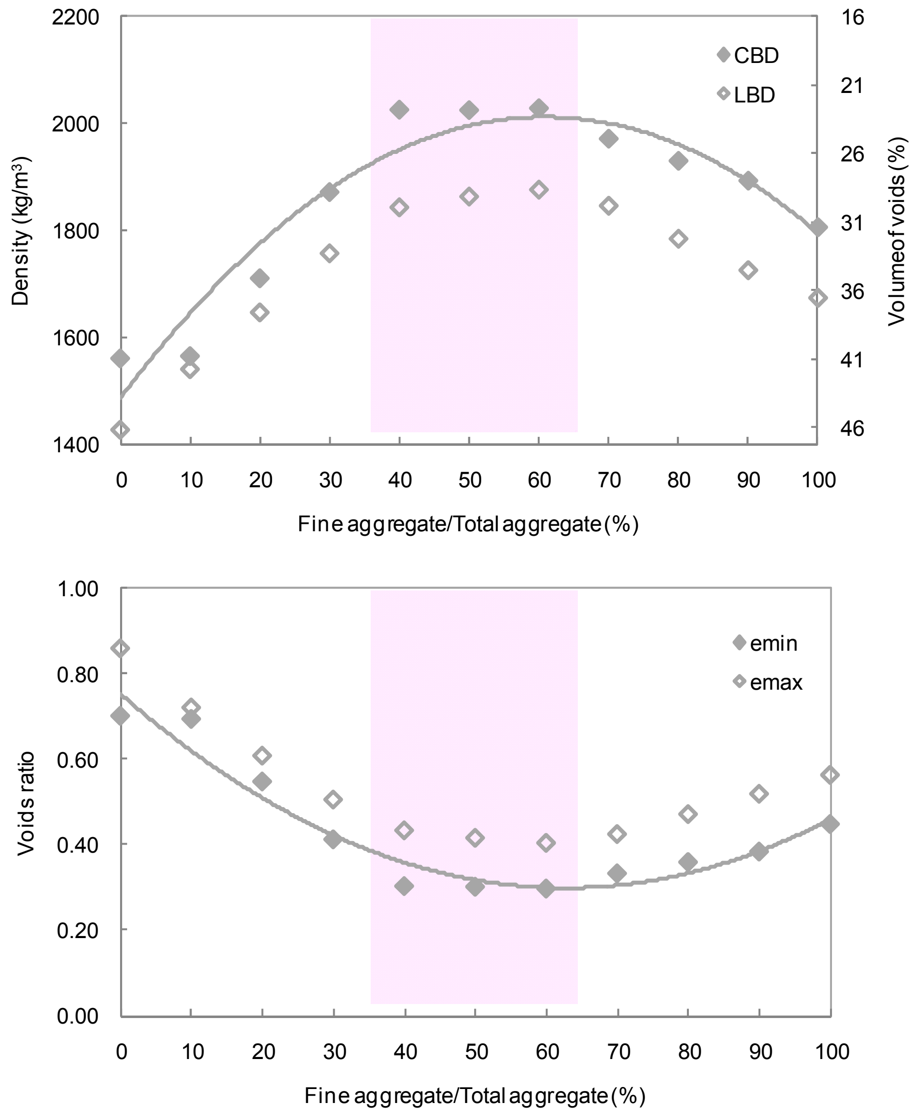


Figure H-2 Density, volume of voids and voids ratio for LSRS aggregate system

Plots shown above are important for selecting the combined aggregate gradings. Two significant observations can be made in this regard. Firstly, the top plot offers some ideas about how much a particular gradation can contribute towards the compacted density of concrete. Second, the lower part offers an estimate of the volume of the binder paste that can be anticipated to be required for filling different gradations. There will always be field variations in the aggregates and the above plot can help choose some of the most robust aggregate combinations that would safely accommodate a fixed volume of paste without causing disproportionate fluctuations in terms of measured performance of concrete in its fresh and hardened state.

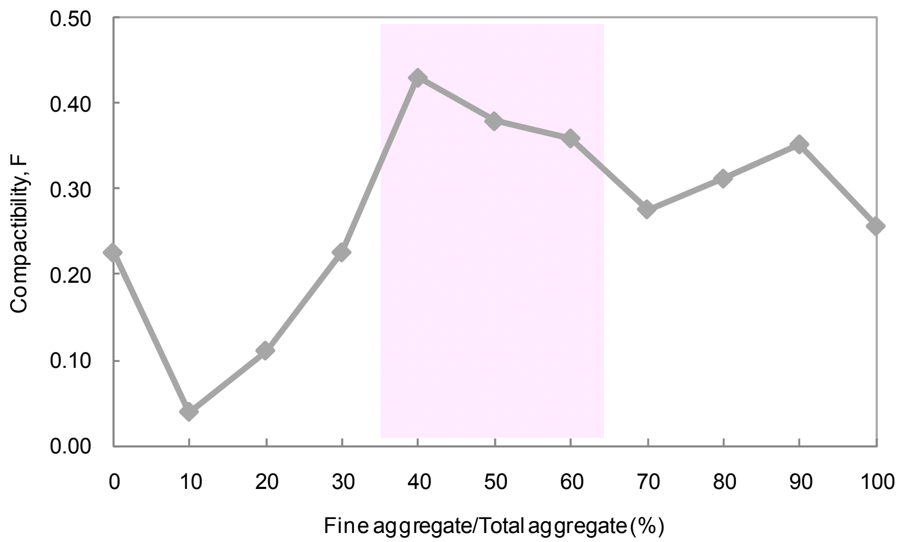


Figure H-3 Compactibility of LSRS aggregate system

Compactibility has been previously defined as the ratio of $(e_{max}-e_{min})/e_{min}$. Figure H-3 shows a plot of the compactibility as a function of the aggregate blend. It can be seen that even though the plots on density and voids content could not help us to distinguish between different gradings, a plot of compactibility has a higher ability in rendering most compactable aggregate blends. Choosing a system from compactibility perspective alone would mean selecting the most compactable aggregate blend from this plot. It should be noted that aggregates alone are neither responsible or can by themselves dictate the compactibility of concrete. Moreover, in addition to just this requirement, there would be requirements (e.g. segregation) from other perspectives that may potentially over-rule the best blend from compactibility perspective.

H.1.3 Geology-shape-combinations

The above discussion laid the foundation for further discussion as it explained the general trends and governing mechanisms. It should be noted that each pair of coarse and fine aggregate would have its own characteristic density and voids curves and compactibility profiles. In addition to the grading of aggregate, the relative shapes and surface textures of particles would have respective influences on the compactibility of aggregates. Figure H-4 shows a plot to substantiate this fact.

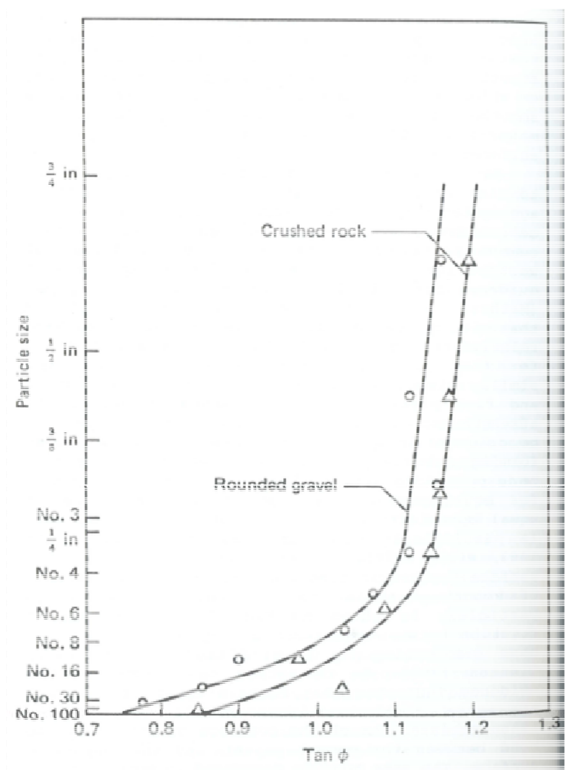


Figure H-4 Variation of coefficient of friction between aggregate particles with particle shape and size. Reproduced from [8]

Figure H-5 shows a plot of volume of voids as a function of the blend of aggregate for different geologies. The following observations are important from these plots. The rounded particles from both coarse and fine fractions of aggregates (GRRS) produce mixtures with least volume of voids and this combination is the most robust. Although not very significant; combining river sand with quartzite (combination QZRS) of available grading leads to highest volumes of voids. This would in turn mean the paste requirement for this combination of aggregates would be highest, while the GRRS blend would have the least paste demand. A combination much similar to the above one results from combining the limestone coarse and fine aggregates, as they also tend to offer higher volumes of voids. The particle shape of individual aggregate fractions and the interactions and interferences influenced by the relative friction between them result in different residual voids contents. This also means that the paste demand would also depend on these relative interactions.

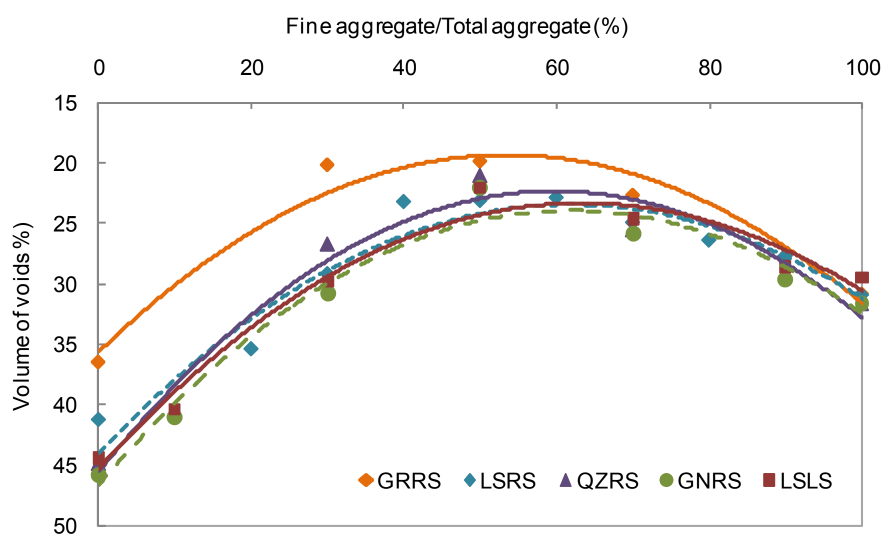


Figure H-5 Effect of aggregate blends and geologies on the volume of voids

Figure H-6 shows comparative plots of compatibilities as a function of aggregate blends for different aggregate combinations. This plot helps understand two significant attributes of aggregate combinations. The first being the robustness of compactibility to different aggregate blends. In the present case, it can be seen that the blends from combination GRRS are rendering most robust compactibility. This implies that slight changes in the composition of aggregate would not significantly influence the compactibility. The other opposite of robust is a sensitive system of aggregates. In this case, the LSLS system is the most sensitive, implying slight changes in the composition of aggregates would lead to dramatic changes in the compactibility of that aggregate system. This could be due to higher volume of finer fraction coming from fine aggregate. Moreover, using such a system would require higher level of attention to be paid to the consistency of aggregate gradings.

The second facet of such a plot is that it renders a comparison between different aggregate systems when multiple options at relatively comparable prices are available. For example, a comparison between GRRS, LSRS and LSLS seems evident. The combination LSRS could offer an intermediate solution. It may neither be the most compactable grading nor the most robust combination, but it offers a balance between robustness and compactibility, in addition to other potential advantages.

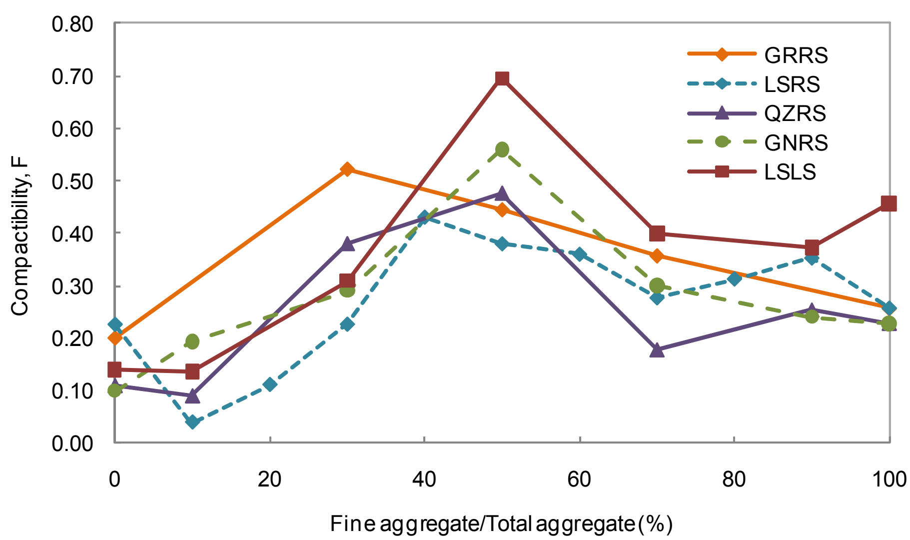


Figure H-6 Aggregate blend versus compactibility (F)

The volume of voids can offer relative estimates of the paste volumes required by different aggregate gradings. It only offers a volumetric estimate of paste requirement without taking into account two other important effects, that changes in the grading produces. The first effect is the effect on the surface area of the aggregate and second effect is due to the water absorption. With increasing fineness of aggregates in a combined aggregate grading, the surface area of the aggregate also increases, which in turn means that the surface area to be wetted by the water or paste also increases. The issue of increased surface area is addressed in terms of water demand in the standard texts.

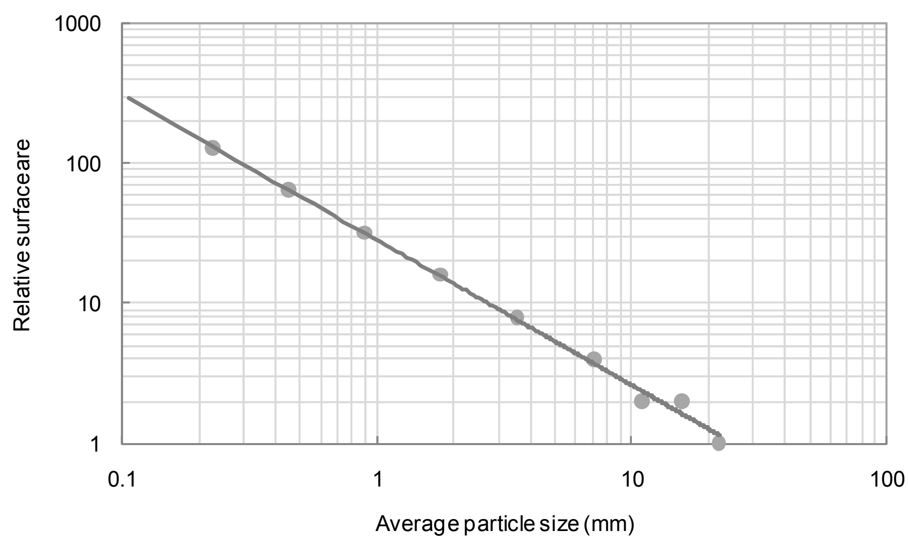


Figure H-7 Effect of particle size on the relative surface area

Estimating the surface area of aggregate, and relating it to workability and strength properties is a challenge. Neville [1] comments that no simple field test method is available for estimating the surface area of aggregates and the mathematical approach is made difficult by the variability in the shape of different aggregate particles. Moreover, the application of surface area calculations was observed to breakdown below 150 µm size aggregates. Hence empirical indices and formulae were suggested by many including Murdock [9], Edwards [10], Neville [1] and Popovics [8]. Figure H-7 shows a plot of average aggregate size versus relative surface area plot. The plot is based on the data presented by Neville [1] and is extrapolated to the range of 150 to 300 µm. In the argument below, methods readily and easily accessible are only discussed. An interesting observation in this regard is that the water demand and compressive strength of concrete mixed with aggregates of similar surface area, but with very wide aggregate gradings were found to be the same [11].

The aggregate grading is critical to the compactibility. As particle size distribution becomes increasingly well-graded, the dry density of the material will increase. Ideally, a granular material with allowed/permissible minimum voids is best for compaction. An optimum composition of coarse and fine particles consists of coarse particles with the voids just filled with fines. On this basis, the physical states can be classified into three broad categories as shown in Figure H-8.

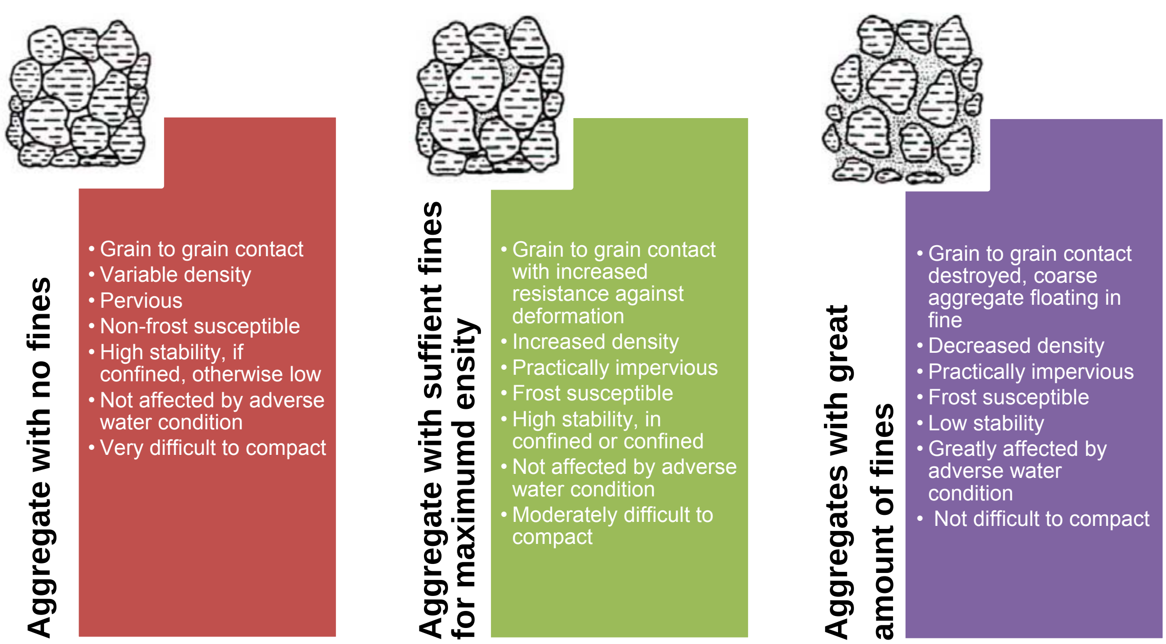


Figure H-8 Three physical states of granular mixtures [12]

H.1.4 The confluence of different methods

The following discussion is presented with the motivation of commenting on the utility of different notions of addressing aggregate gradings. Figure H-9 shows a composite plot of fineness modulus (FM), relative surface area, compactibility and aggregate blending. The FM and relative surface area are inversely and linearly related to each other. This eliminates the need for using the both and considering the wide scale acceptance of FM for fine aggregate; this index receives an upper hand in practice over the tedious computations of relative surface area.

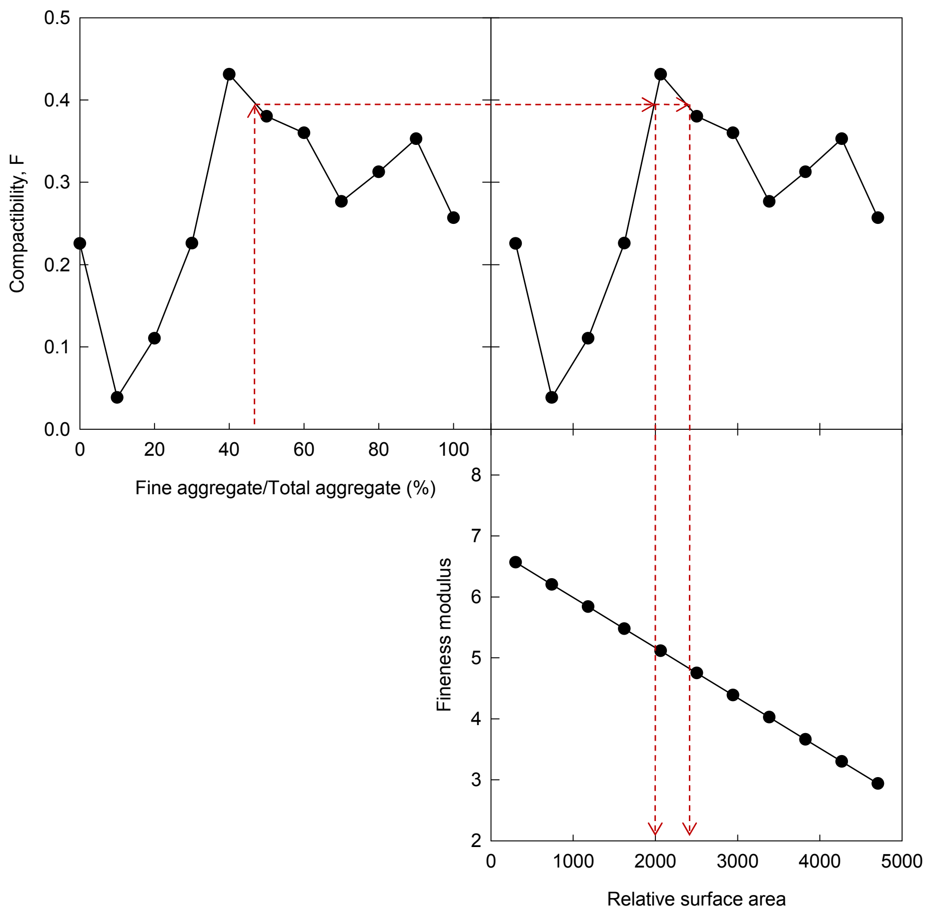


Figure H-9 Interaction plot of relative surface area, FM, compactibility and aggregate blend

The plots of compactibility versus aggregate blend and relative surface area are similar, which gives an upper hand to the former method over the latter method of plotting. Of the three methods presented here, Popovics' preference is in the order of FM > % fine aggregate > surface area method [8]. Considering this logic and blending it with what would be most needed is an essential step in mixture proportioning, Figure H-10 is constructed to illustrate this point. This interactive plot conveys two important things viz. a range of most compactable aggregate blends and a range of aggregate blends, which will offer least paste demand.

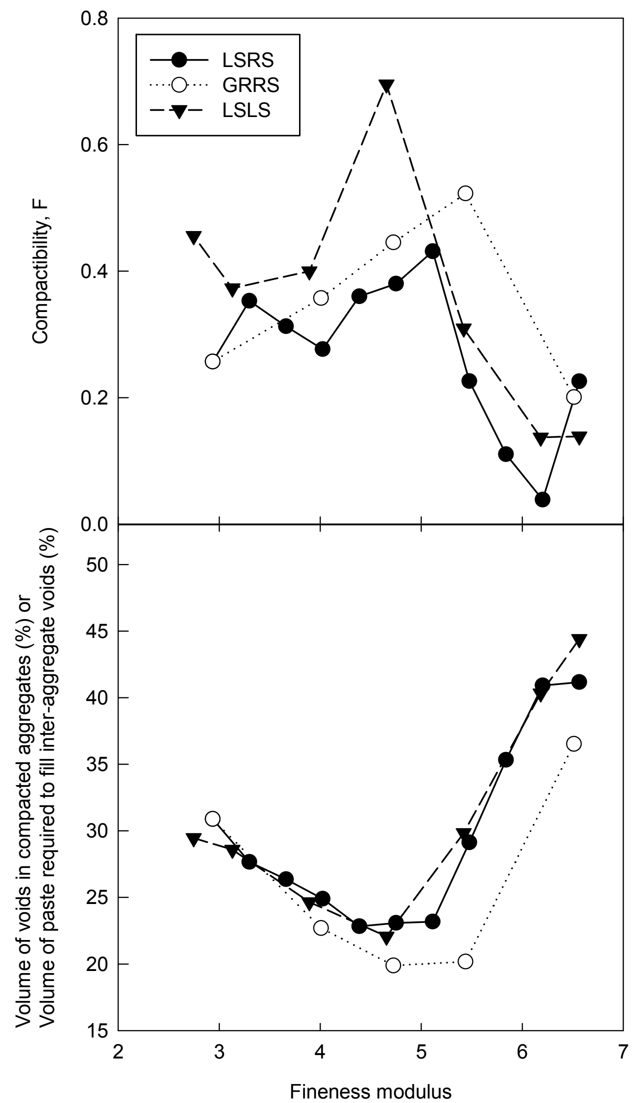


Figure H-10 interaction diagram: Fineness modulus-compactibility-volume of voids in aggregates

One of the limitations of above analyses and attempts at correlating the empirical parameters like fineness moduli or surface areas is that both of these approaches fail to take into account two important facts. These are the shape of the particle and the fines content (typically below 150 μm). This is an known limitation of this index, which further explains why concretes made with various gradings of identical fineness modulus may have significantly different water permeability or bleeding under otherwise identical conditions [2]. Fineness modulus cannot be used as a single description of the grading of an aggregate, but is a valuable measure of variations in aggregates from same source, since it offers an indication of the probable behavior of concrete [1].

A GEOTECHNICAL PERSPECTIVE

Taking into account the inherent variations of fineness modulus, an attempt to find indices to further differentiate between different aggregate gradings was made. One of the plausible set worth discussion is the coefficient of uniformity (C_U) and coefficient of curvature (C_C) as used in evaluating the particle grading in soils. The mathematical formulae are as follows:

$$C_U = \frac{D_{60}}{D_{10}}$$

and

$$C_U = \frac{(D_{30})^2}{(D_{10} \times D_{60})}$$

where,

D_{10}, D_{30} and D_{60} are the (effective) grain diameters corresponding to 10, 30 and 60% passing on a particle distribution plot. In geotechnical engineering, a soil having Cu less than 2 is considered uniform, whilst one with value greater than 10 is considered to be well graded. This also means that higher the C_U value, the broader is the range of particle size. A well-graded soil has a coefficient of curvature between 1 and 3 [13]. Compared to FM, these two indices take into account the particles finer than 150 μm.

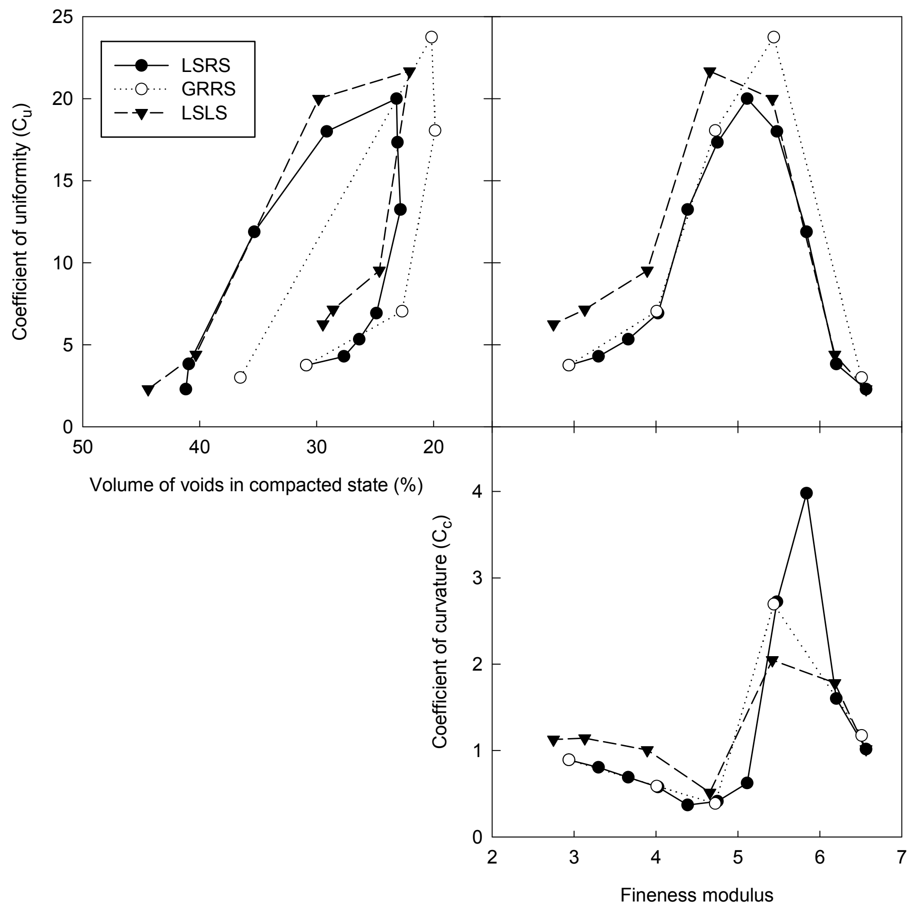


Figure H-11 C_U-C_C-FM-n_c interaction diagram

Figure H-11 is constructed based on the above discussion. It can be seen that C_U holds good relationship with the fineness modulus and the volume of voids in the compacted state, n_c. The effects of finer particles can be seen from the enhanced discriminating power this coefficient has over the fineness modulus. For a given aggregate system, the volume of voids initially decrease as the C_U increases reaching a peak at the minimum volume of voids and then due to increased fine aggregate content, the volume of voids remains more or less the same, but the C_U value drops down. The particle shape effects are more pronounced.

To further substantiate the validity of this argument, another plot with FM as a common axis was constructed. A composite plot of this kind helps understand the robustness of a grading and the susceptibility of volume of voids to changes in the grading, which the FM cannot clearly bring out. Figure H-12 shows one such composite chart.

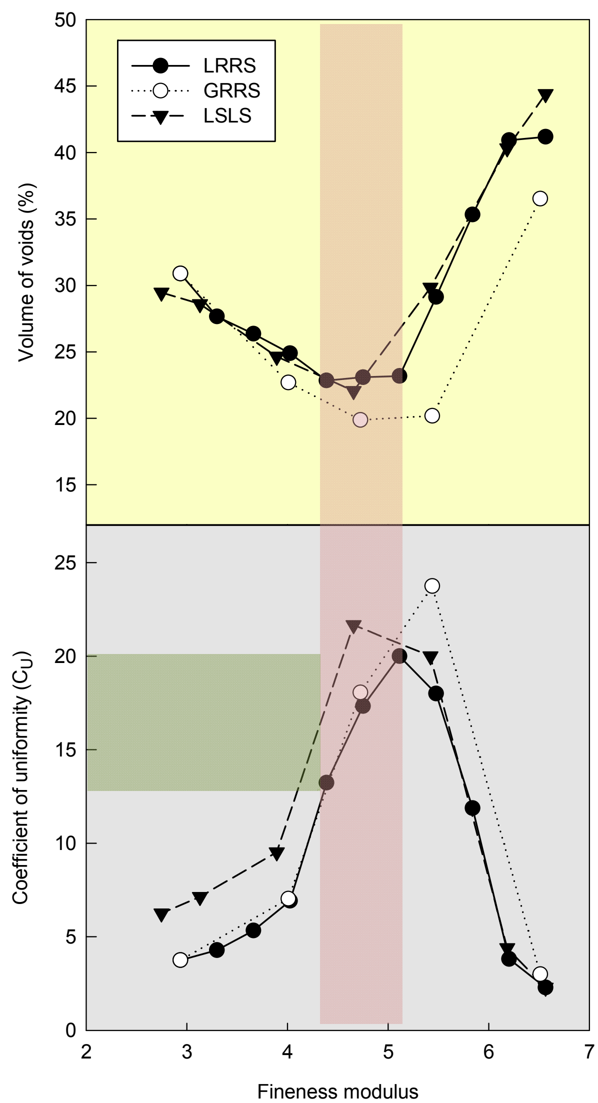


Figure H-12 FM-C_U-n_c interaction diagram

The second aspect pointed out earlier was water absorption of the aggregates. Primarily the geological characteristic decides this aspect of aggregate quality followed by crushing operations if applicable. Moreover, the water absorption of crushed aggregate is relatively higher than uncrushed aggregate. It should also be noted that the use of crushed fine aggregate could increase the early water demand of a mixture eventually increasing the cement content, from workability perspective. The increase in the water requirement is a function of the composite water absorption of the aggregate system used. Figure H-13 shows three *hypothetical examples* (Note: these are not the same aggregates as above). The LSRS offers a robust system which is insensitive to the changes in the aggregate blend, while the other two combinations show sensitivity towards changes in the grading and contradictory effects to such changes.

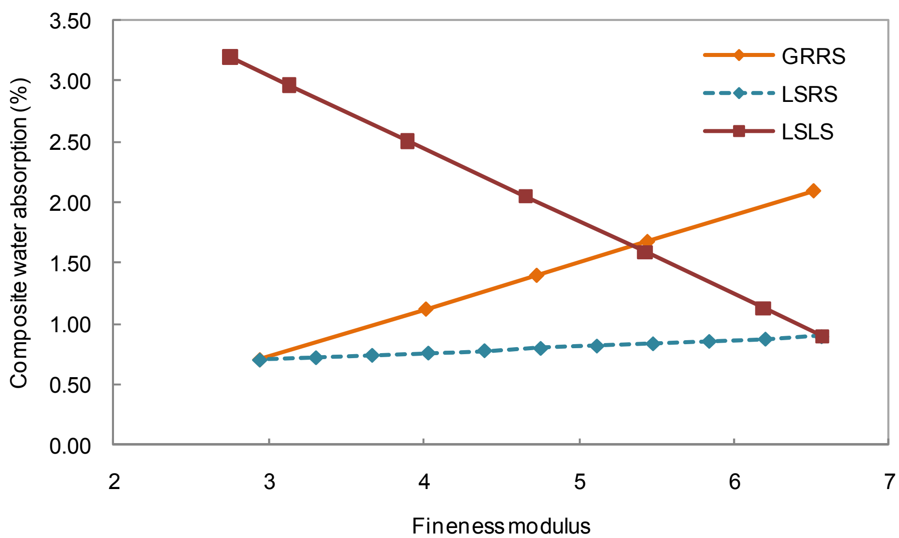


Figure H-13 24 hour water absorption as a function of different aggregate blending.

H.1.5 The interplay of moisture with granular material

Moisture density plots were evolved for different aggregate blends for different combinations of aggregates. The objective of this study was to assess the interplay of moisture on the compacted density of granular materials. The density profiles were evolved using the compacting hammer used for preparing RCC samples. Figure H-14 shows a picture taken during this lab study.

Figure H-14 Evolving moisture density profiles of aggregate systems

Figure H-15 shows a typical plot of moisture density for one of aggregate blends. It can be seen that initially the density shows a decrease due to bulking of aggregates and then reaches a peak when water acts as a lubricant after which there is again a drop in the density. This behavior is in line with the generally accepted moisture response of density in granular materials.

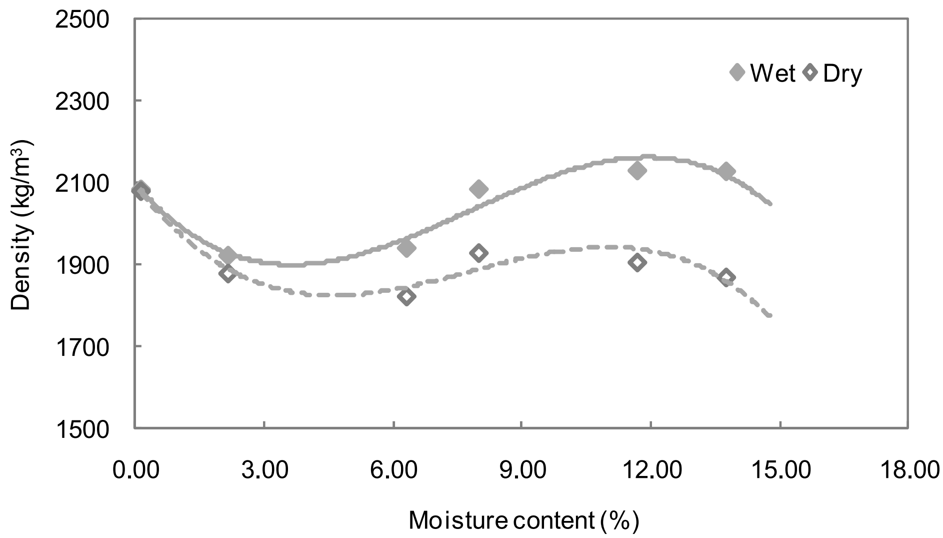
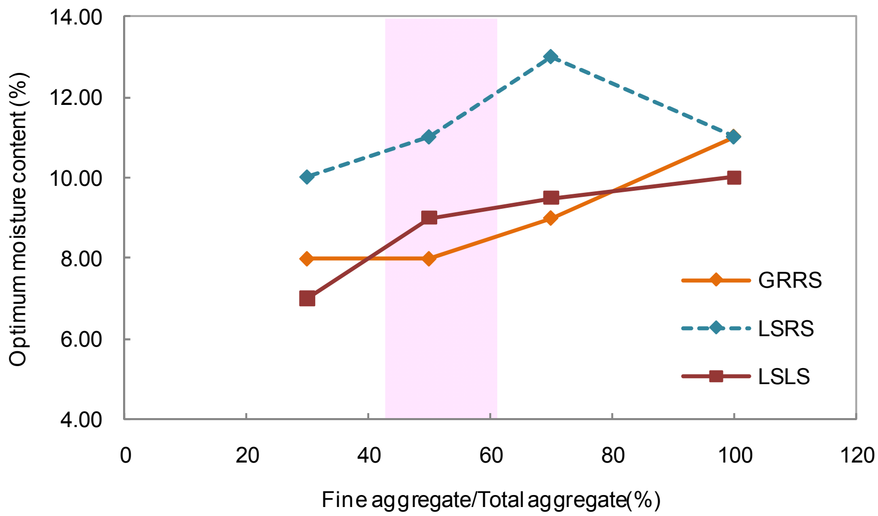


Figure H-15 Typical moisture density plot

Figure H-16 is evolved to study the effect of blending of aggregates in different proportions on the optimum moisture contents. Three distinct trends depending on the aggregate grading, relative particle shape, and their respective early water absorption values are observed. The rounded aggregate system (GRRS) shows a slow increase in the optimum moisture content as the fine aggregate content is increased. The crushed aggregate system (LSLS) on the other hand shows an initial rise in the optimum moisture content followed by a flattening effect. This could take place because of the dominating fine aggregate behavior and its effect on the early water absorption of aggregate system. The combined system (LSRS) shown follows a parabolic trend. Initially the optimum moisture content increases as the fine aggregate content is increased, reaches a peak and then decreases. Irrespective of the aggregate system used, it can be seen that the aggregate blend close to the least voids content and highest compactibility has the least water demand. This excludes the first point of each of these plots and is not a sensible aggregate blend for further work and concrete in general.



H.2 Cement paste

Five different cements were tested on 31 different chemical admixtures. These included different types of admixtures (covering the width) and for each of these types of admixtures, there were multiple chemistries. Table H-3 reports a list of most suitable admixture chemistries that was used for further testing and experiments.

Table H-3 Final list of chemical admixtures

Manufac. Code	Product Code	Primary chemical constitution	Functional classification								
			WR		Retarder			AEA	RM	DC	Misc
			ASTM C494 Type								
			A	F	B	D	G				
M-05	P-06	Triethanolamine	■								
M-04	P-11		■		■	■					
M-04	P-13				■	■					
M-03	P-05	Polycarboxylate resin	■	■							
M-02	P-10	Ca-lignosulfonate	■	■	■	■	■				
M-01	P-09	Ethylenediamine	■	■							
M-03	P-19	Sodium olefin sulfonate						■			
M-03	P-20	Na-tetradecenesulfonate						■			
M-03	P-21	Tall oil/Na salt						■			
M-03	P-24	Polysaccharide							■		
M-03	P-25	Naphthalene sulfonate/ Welan gum							■		
M-01	P-26								■		
M-04	P-28	Surfactant								■	
M-03	P-29	PC resin + Polethylene glycol								■	
M-01	P-17	Phosphonic acid			■						
M-05	P-31	New formulation									

H.3 Transcending to concrete

H.3.1 Background for the RCC aggregate gradings

Aggregate grading for RCC is more comprehensive than in other pavement concretes. Figure H-16 shows a comparative scheme of theoretical aggregate blending as prescribed by Powers and Fuller curves. The Fuller's curves is plotted for different coefficients from n = 0.2 to n = 0.6. The Powers' curve is plotted in brick red color and the thick lines represented curves recommended by ACI 211 [14].

The following observations are relevant for further discussion:

- The ACI 211.3R recommended band has a FM range of 3.63 to 5.45 for the combined aggregate grading;
- The Fuller curves are followed for the coarser fraction, however there is a deviation at the finer end of the aggregate band recommended by ACI 211;

- The Powers' curve for 25 mm maximum size of the aggregate lies outside the lower limit of the ACI band.

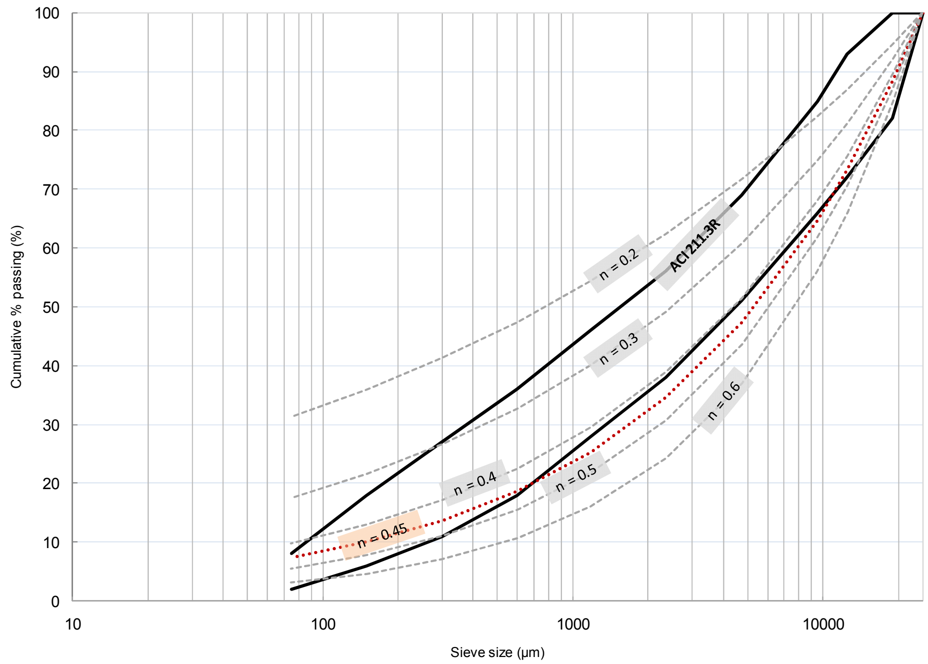


Figure H-16 Powers' and Fuller curves plotted with the ACI 211 recommended grading band

Considering these facts, a further theoretical comparison was constructed. Figure H-17 shows a comparison of Powers curve with different maximum size of the aggregates along with the ACI 211 band. It can be seen that by reducing the maximum size of the aggregate the grading becomes finer, which in turn places a higher fines demand on fine aggregates. It should be noted that the Power's curve is a good starting point for obtaining the combined aggregate grading and should not be considered as the ultimate rule.

While considering the combined aggregate grading, attention should also be paid to the availability of appropriate materials. This is especially applicable for fine aggregates, getting finer fractions in which could be a big challenge in many states. Using theoretical grading curves presents this difficulty. Figure H-18 shows a comparative sketch of fine aggregates available in four different states with the gradings as recommended in ASTM 169D [15] and specified in ASTM C33 [16]. It can be seen that wide scale availability of fine aggregate meeting, especially at the tail end of the grading as recommended in ASTM 16D is not there.

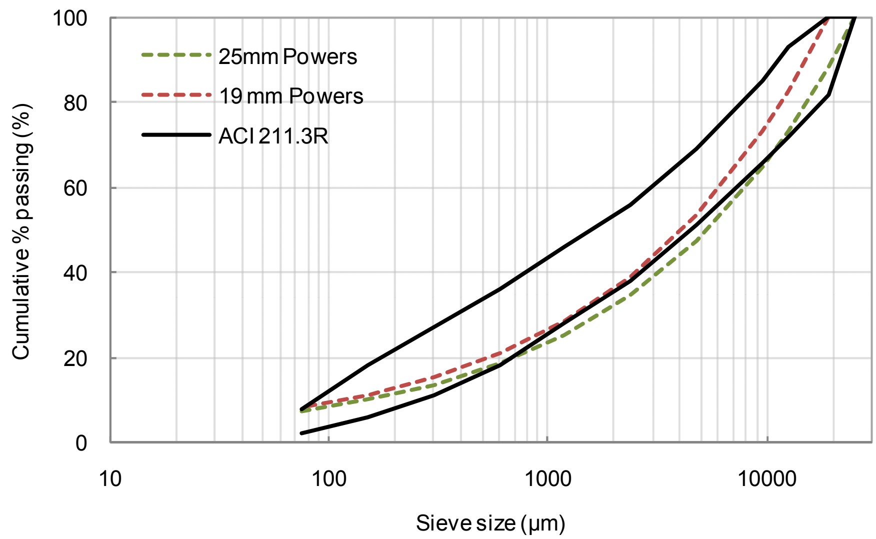


Figure H-17 Powers curve drawn with different maximum size aggregates

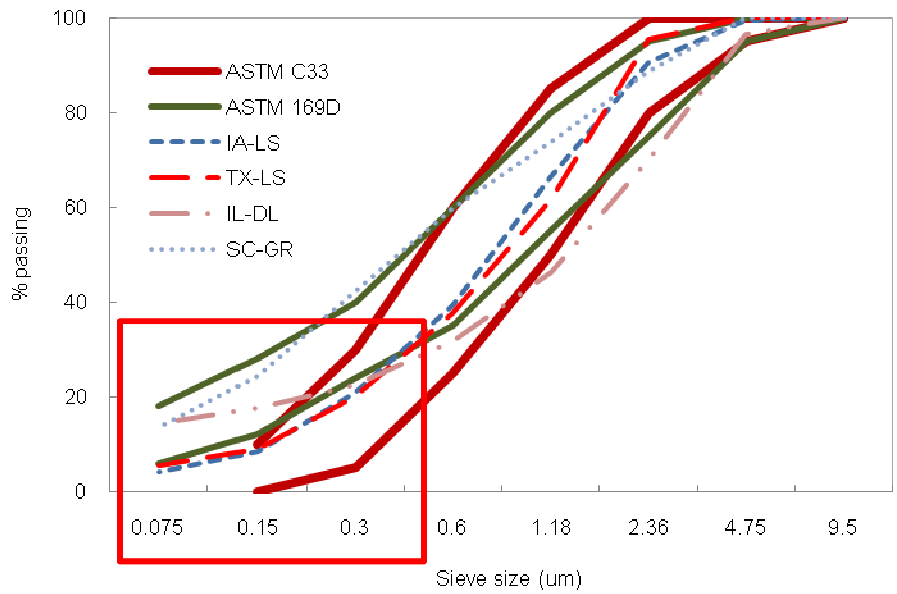


Figure H-18 Fine aggregate gradation: A comparison

H.3.2 Aggregate grading and modified Andreassen's model

A solution to this could be using combined aggregate grading based on lab tests as discussed previously or extend the blending to include the binders as well. One of such approaches, called as modified Andreassen's optimal packing approach [17] is discussed in the forthcoming section. According to this approach, the cumulative particle size distribution can be computed using the following formula:

$$CFP = \frac{(d^q - d_m^q)}{(D^q - d_m^q)} \times 100$$

where,

CFP is the cumulative volume percent finer, d is the particle size and D is the maximum particle size, d_m is the minimum particle size considered and q is the distribution modulus. Higher values of the distribution modulus (q > 0.5) lead to coarse mixtures whereas smaller values ($q < 0.25$) result in mixtures, which are rich in fine particles [18]. Kumar and Santhanam [19] noted that a q value in the range of 0.25 to 0.30 may be used for designing high performance concrete. Garas and Kurtis observed that the distribution modulus in the range of 0.26 to 0.29 is optimal for workability of ternary blend consisting of OPC, metakaolin and fly ash concretes [20].

In the present work, a distribution modulus of 0.3 was used in evolving the reference curves for different concretes. Since three aggregate/binder ratios were used, three optimized gradings were obtained and are shown in Figures 14-19 through 14-20.

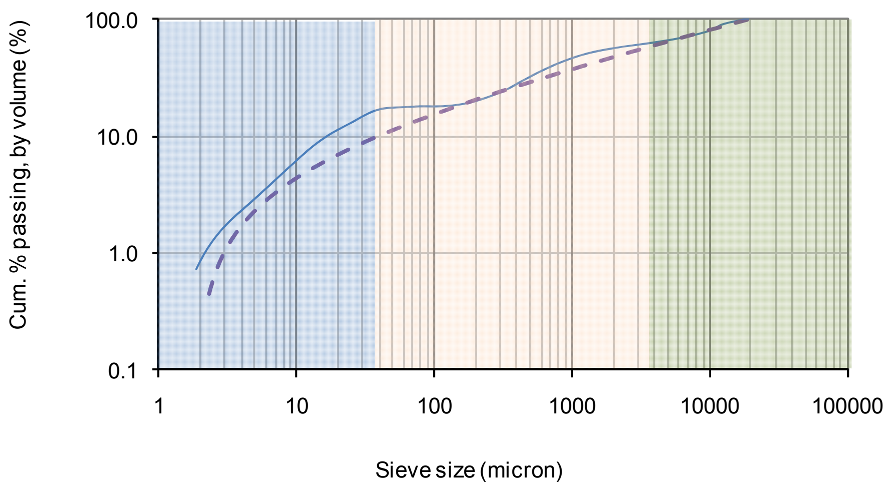


Figure H-19 Combined particle grading for Aggregate/binder = 4 compared to Modified Andreassen's grading

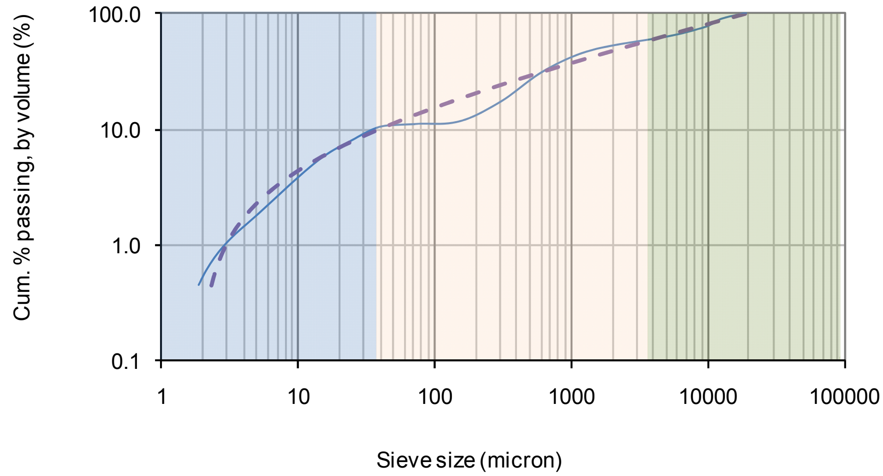


Figure H-20 Combined particle grading for Aggregate/binder = 7 compared to Modified Andreassen's grading

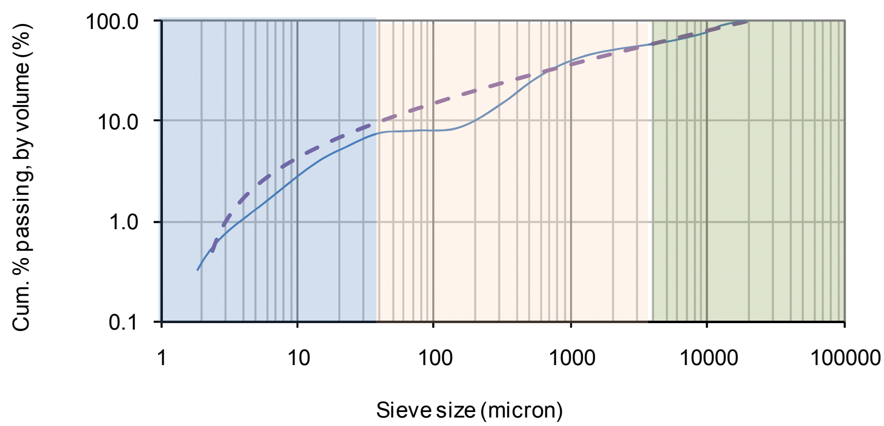


Figure H-21 Combined particle grading for Aggregate/binder = 10 compared to Modified Andreassen's grading

H.4 An argument on compaction

The ability of concrete to self-compact to one degree or another and in a limited sense invariably exits in different families of concretes. This ability can be perceptibly observed in concretes like self-consolidating concretes where at least in theory, and to a great degree in practice, highest possible level of compactness is achieved. The following argument forms the basis of the definition of compaction and compactibility.

Consider a granular material with monosize aggregate. This represents a material that will offer very high resistance to compaction and has no cohesion. The material can be compacted to a limited degree and only when it is confined. Now consider a cohesive soil having some cohesive and some granular fraction; this material is compactable, and has some cohesion and therefore has lesser requirement for being confined during compaction. Now, consider two types of concretes, one very dry concrete (shotcrete, paver blocks) and self-consolidating concrete (SCC); the former has limited cohesion, while the latter has much higher stickiness (need not be cohesion, as it is characterized). The first one needs compaction effort to reach higher densities while the latter one is proportioned to self consolidate (assuming no segregation).

Confusion arises from the fact that is the compaction retainable without confinement. The drier concrete is compactable without confinement, but SCC on the other hand requires confinement to be consolidated. If confinement is removed, SCC looses its compaction, although the material may still have similar density. Moreover, SCC, from the word go, has potentially the least air content it is designed for, but drier concretes have higher air contents, which is reduced by external effort. Now consider asphalt (a material having viscosity in the range of 100-2500 times that of cement paste); the problem of confinement is not at all crucial because the material is inherently sticky. There could still be temperature dependent volumetric instability.

Further to this, it is assumed, but clearly spelled out in only very few books is the fact that the aggregate or composite grading remains similar during compaction. This problem is typical in poor pavement base (granular) materials. It can have a big influence on the compaction and compactibility of a mixture. We have results that show this if the aggregates are subjected to larger number of gyrations. If particles are being crushed during compaction, there is simultaneous changes in the grading and with that the air content and the compactibility of the (changing) mixture.

H.4.1 Compactibility of concrete

INFLUENCING FACTORS

The objective of this part of the work was to understand compactibility as a function of concrete composition. The composition of mixtures was characterized by different aggregate grading, aggregate/binder and water/binder ratios. In the mixture proportioning of any concrete it is important to understand the limitations of a mixture in terms of different properties it could render. The objectives of this part were as follows:

- To understand and evaluate the effects of aggregate gradings on the compactibilities of concrete mixtures;
- To understand and comprehend the compactibility behavior as influenced by the aggregate/binder ratio and
- To understand and comprehend the compactibility behavior as influenced by the water/binder ratio.

Defining the gradations for realizing the framed objectives was the first step for this part of the study. Considering the available materials and conceived objectives, three distinct aggregate gradings were evolved and are shown in Figure H-22. These are the coarse grading (C) having a fineness modulus of 5.26, the medium grading (M) having a fineness modulus of 4.46 while the fine grading (F) having a FM of 3.94. These curves are plotted along with the ACI 211 recommended grading band and the 0.45 Powers curve for 19 mm maximum size of aggregate.

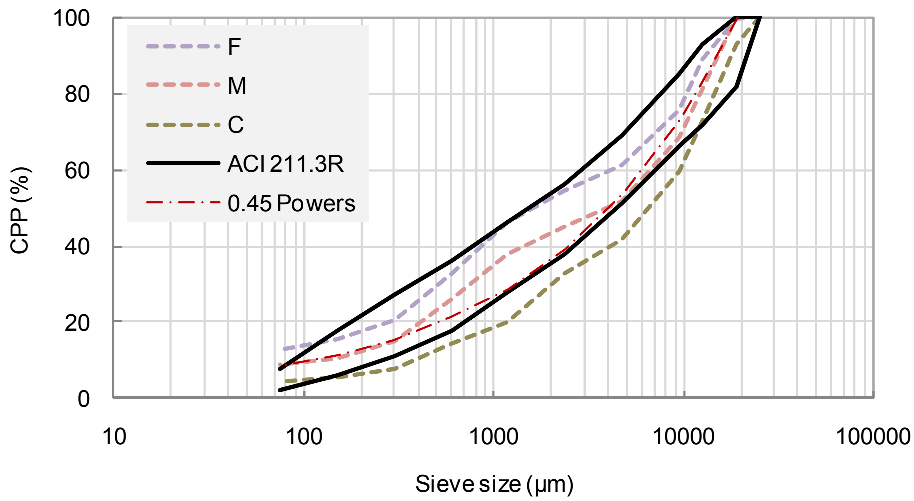


Figure H-22 Combined aggregate grading for compactibility study

Each of these gradings was tried with three different binder contents and five different water/binder ratios. Table H-4 shows a summary. A mixture's ability to accommodate and retain a volume of water is a function of the amount of reacting (cement) and non-reacting (aggregates) solids. Higher volume of finer solids will increase a mixture's ability to hold more water and vice versa. Moreover, higher fines content will also enhance a mixture's ability to resist loads. In addition to the requirement of finer fines, a concrete mixture should also have well-graded aggregate system to be able to offer volumetric stability under load and when it is fresh.

Table H-4 Concrete compactibility study matrix

Aggregate grading	Aggregate/binder	water/binder	Remarks
F	4, 7, 10	0.30 – 0.50	The water/binder ratios were adjusted further considering the aggregate grading
M	4, 7, 10	0.35 – 0.55	
C	4, 7, 10	0.45 – 0.65	

TYPICAL RESULTS

Density trends as a function the number of gyrations (hence compactive efforts) were evolved to appreciate the compactibility of different concrete mixtures. Figure H-23 through 14-25 show the density profiles as a function of the number of gyrations. These plots are shown for F grading of aggregates.

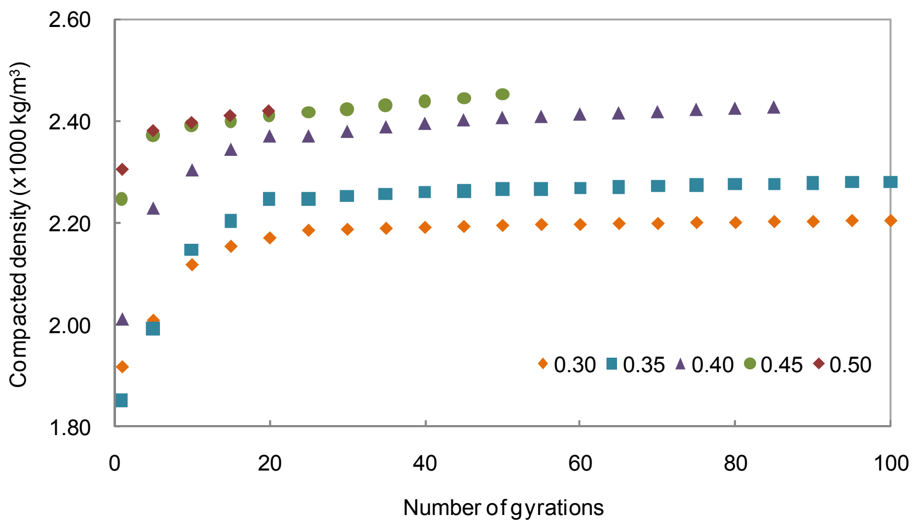


Figure H-23 Density profiles for A/B = 7 and CAG-F

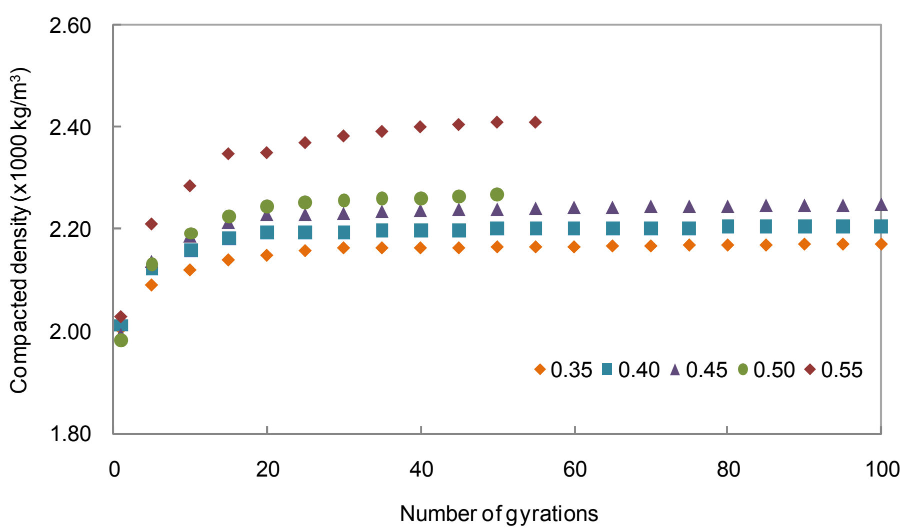


Figure H-24 Density profiles for A/B = 7 and CAG-F

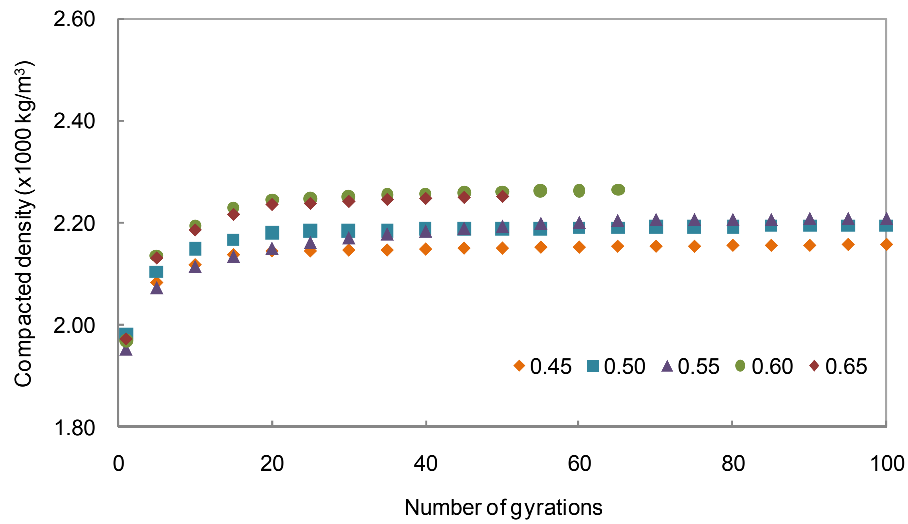


Figure H-25 Density profiles for A/B = 10 and CAG-F

The following observations are relevant for further discussions:

- The selection of the water/binder ratio is limited by the aggregate/binder ratio. The lower this ratio, the higher is the ability of the mixture to accommodate more water and vice versa. In the present study for aggregate/binder ratio of four, the water/binder ratio could be varied between 0.3 and 0.5; going beyond 0.5 lead to excessive expulsion of water. On the other hand, the water binder ratio was varied between 0.45 and 0.65 for mixtures with aggregate/binder ratio of 10. Although the ratios appear to be higher in the latter case, the fact that these mixtures were binder deficient in comparison to the earlier mixtures should be taken into account.
- The second interesting thing is the spread of density responses at a fixed number of gyrations. For richer mixtures, the change in the density is more sensitive to the change in the water/binder ratio, while it is least sensitive in case of leaner mixtures. The intermediate mixtures fall in between. This can be observed while comparing the three plots together. Rich mixtures (low aggregate/binder ratio) show wider gaps in the densities obtained at the lowest and highest water/binder ratios. This gap narrows down, as the mixtures get

leaner. This also means that rich mixtures are relatively more sensitive to the changes in the water content (less robust), while the leaner mixtures are less sensitive to the changes in the water content (more robust).

- The self-compacting ability of different mixtures is a function of their compositions. The self-compacting ability of a mixture is perceived as the ability of a mixture to reach a certain degree of compaction (characterized by density) when it is dropped in the compaction mold. In practice, this can be understood to be analogous to the compaction achieved by a pavement concrete mixture when it is dumped from the truck. From the plots under discussion, this sensitivity can be very easily seen for mixtures with aggregate/binder ratio of 4, while the clarity is reduces as the binder content of the mixtures is reduced. For a given aggregate/binder ratio, the start-up density is a function of the relative volume of water in a mixture. Physically this can be explained based on the relative volume of water to the binder present in a mixture. The riche mixtures being more sensitive to the change in the moisture content especially at lower water contents, the start-up density for these is very low as compared to mixtures with higher water/binder ratios. As discussed above, this sensitivity gradually reduces as the mixture become leaner.

Figure H-26 shows the compacted samples at the end of the respective termination cycles and after extrusion.

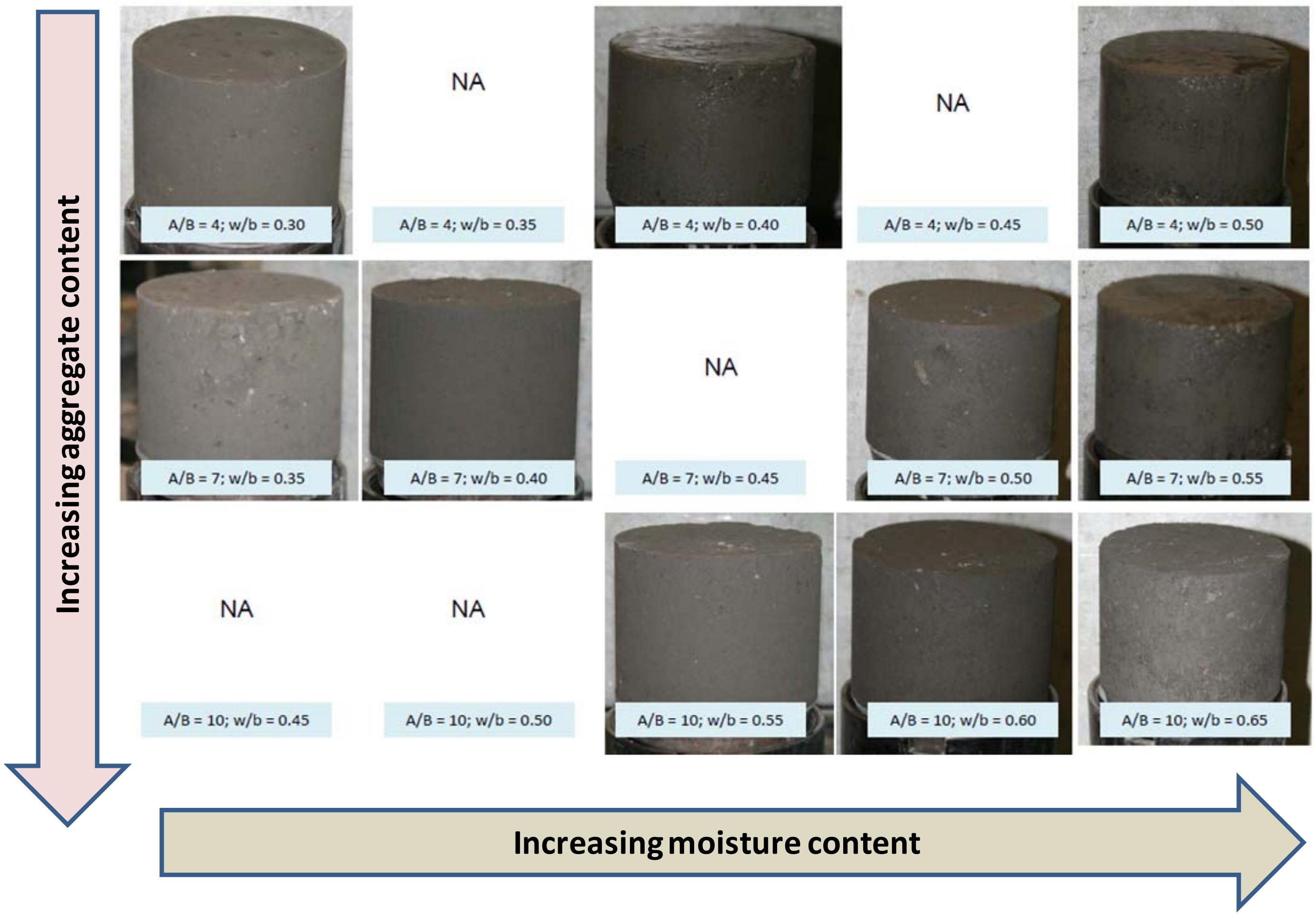


Figure H-26 Pictures of gyratory compacted samples for F grading

H.4.2 A note on density

Density is a quantification of the amount of material that is present in a unit volume of concrete, but cannot be used as a rational measure for comparing different mixture composition and their responses to compaction. Apart from depending on the specific gravity of the individual materials, the potential of a mixture to achieve a certain density depends on the composition of a mixture that is more specifically influenced by the water content in a mixture. This fact is acknowledged and used in the British (DOE) method for mixture proportioning normal concretes [21] . A figure (refer to Figure H-27) from this method is reproduced and shown below.

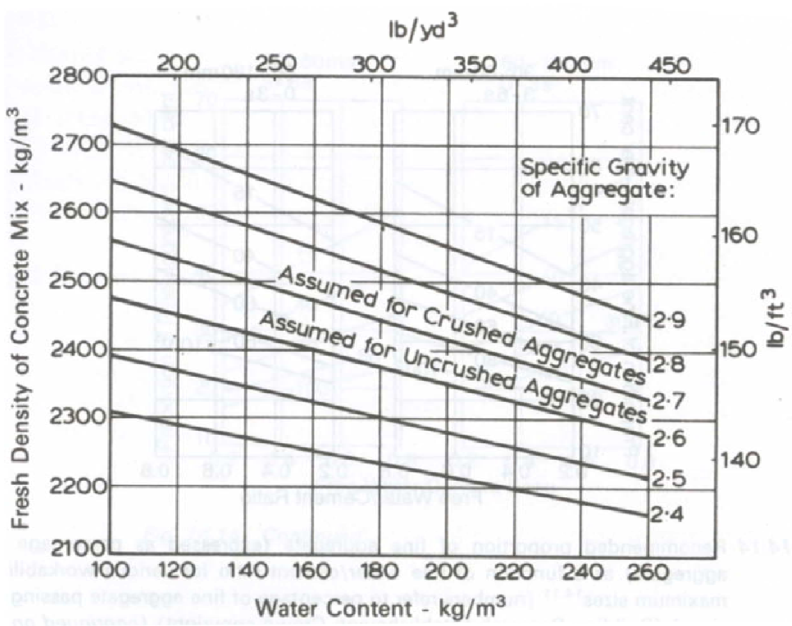


Figure H-27 Estimated wet density for fully compacted concrete [21]

H.4.3 Compactibility of various mixtures

For comparing compactibility of different concrete mixtures, a common basis for comparison is necessary. This basis has to also acknowledge the fact that not all the material compositions will be able to acquire or reach similar density in quantified terms. However the materials could be benchmarked with reference to the maximum potential density it could achieve with a given composition. The benchmarking has to exclude the variable factor (e.g. air content in a fresh concrete mixture) density, which leaves us with a theoretical basis of comparison. This work makes use of a term called as relative compaction and is formulated as follows:

$$(Relative\ compaction)_N = \frac{(Compacted\ density)_N}{Air - free\ theoretical\ maximum\ bulk\ density\ (TMBD)}$$

The relative compaction is measured at a fixed number of gyrations (N) and from the density compacted at that level of compactive effort. The computation of the air-free theoretical maximum density is based on the following formula analogous to that given by Atkins [22]:

$$TMBD = \frac{\sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} \frac{P_i}{G_i}}$$

where, P_i is the percentage by weight of the i^{th} material and G_i is the specific gravity or relative density of that material. Note that the air content is not considered in this formula. A similar approach was adopted by Nader et.al. [23]

Figure H-28 is developed or prepared to appreciate the aforementioned fact for the mixtures under consideration. This figure was developed with % moisture content to have a common basis of comparison. Two things can be clearly observed from this set of plots. The first being the definition of the self-compacting index (SCI). This is defined as the relative compaction at beginning of first gyration and reflects the each with which a mixture can be compacted without the application of compactive effort. It can be seen that different mixtures have different SCI indicating their ability to be get self-compacted as a function, primarily of relative moisture and binder contents. The second being the slope of the equations of the lines of fit indicates the responsiveness of an aggregate-binder system to changes in the moisture content. For the mixes shown in this figure, it can be seen that the slope of mixtures with aggregate/binder ratio of 4 is 0.0604, which is four and six times that for mixture with aggregate/binder ratios 7 and 10, thus indicating very high sensitivity of rich mixture.

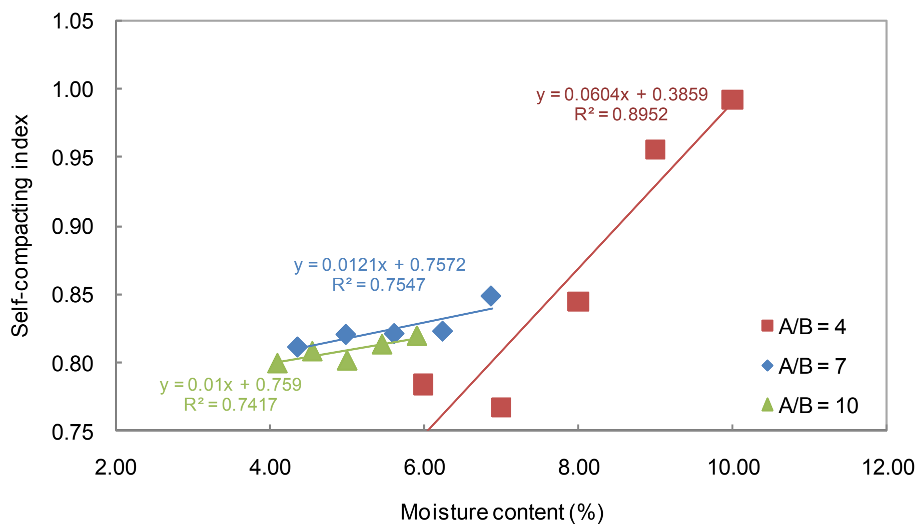


Figure H-28 Responsiveness of mixtures (F grading) to moisture content

Further to this, the relative compaction is used in analyzing the data generated out of the density profiles. Figure H-29 shows such relative compaction profiles for A/B ratio of 4. Apart from the above discussion on this mixture, it can be seen that the relative compaction is a very useful tool in appreciating the workability of mixtures under consideration. These plot help answer the critical question of what composition is compactable and what factors act in favor and/or against good compactibility.

It can be seen from this set of plots that not all mixtures would be able to achieve their maximum potential density as computed from theoretical considerations. When a mixture is not inherently potent of rendering higher densities, expending efforts in compacting it would not be meaningful. Moreover, mixtures of this kind will not lead to a good internal concrete structure, since proximity of a mixture to its theoretical maximum density reflects on the volume of air as well. The farther a mixture is from its theoretical maximum density, the more entrapped air voids it has.

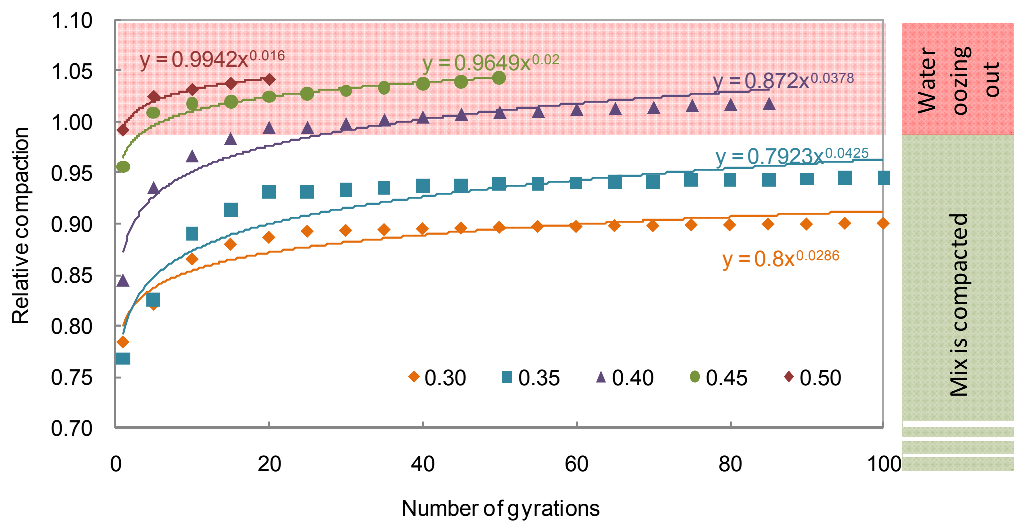


Figure H-29 Relative compaction in A/B = 4 mixtures w/ CAG-F

Another important aspect of these plots is a reflection of the ability of a mixture to hold a certain quantity of water under sustained loading conditions (similar to a roller compacting concrete in field). As can be seen from the above figure, the mixtures with w/b ratio of 0.40 and above are reaching relative compaction beyond 0.98. A pink band is drawn on this figure to show that the compaction above a 0.98 may mean something other than compaction. Assuming that all these mixtures would have a total air content of no more than 2% (NMSA being 19 mm), it could be said that the maximum possible compaction would be 98% of the theoretical maximum density. Density above this number could either mean that the concrete is squeezing out water due to the lack of capacity of that mixture to hold water under a sustained compacting pressure or the applied pressure is more and is leading to changes in the aggregate grading (hence the maximum possible density is changing due to grading effects). In the present scenario, the first reason seems to be plausible, since the gyratory compactor mold has a circular, ring like gap at the bottom, since the puck is held loose to allow for gyratory compaction. This is shown in Figure H-30.

Figure H-30 Paste oozing out from the gyratory compacted sample

The relative compaction plots were modeled using simple power relationships and the equations are shown in the above figure. The general form of this equation can be written as follows:

$$RC = C_1 N^{C_2}$$

Where,

RC is the relative compaction, N is the number of gyrations, C_1 and C_2 are compactibility coefficients depending on the mixture composition. It is anticipated that these would also depend on the consolidation pressure and other gyratory compaction parameters, but it is not possible to offer further elucidations on this fact based on the available data.

Figure H-31 shows the relative compaction plots for mixtures with A/B ratio of 7. It can be seen that this mix has better compaction responses. Only one mixture (w/b = 0.55) showed the tendency to give out water. It is also interesting to note the limiting w/b ratios for different mixtures. In this case, it appears to be close to 0.55. Mixtures with lesser w/b ratios (viz. 0.35, 0.40 and 0.45) cannot be compacted even with extended compactive effort.

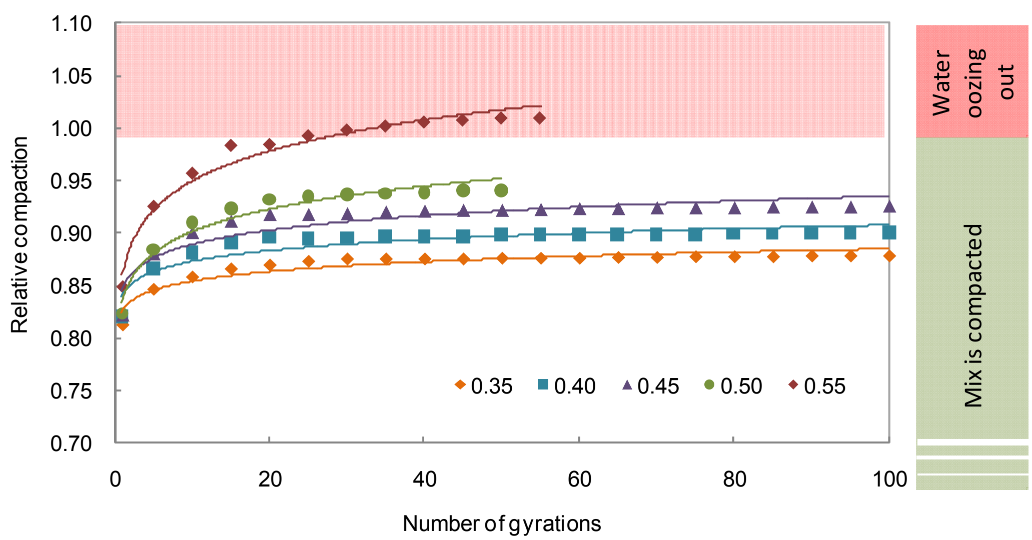


Figure H-31 Relative compaction in A/B = 7 mixtures w/ CAG-F

Figure H-32 shows the relative compaction plots for A/B ratio of 10 with various w/b ratios. It can be seen that the relative compaction achieved by the tested mixtures is well within the compactable boundaries and the mixtures are composed such that the water oozing out phenomenon is not occurring even at higher w/b ratios.

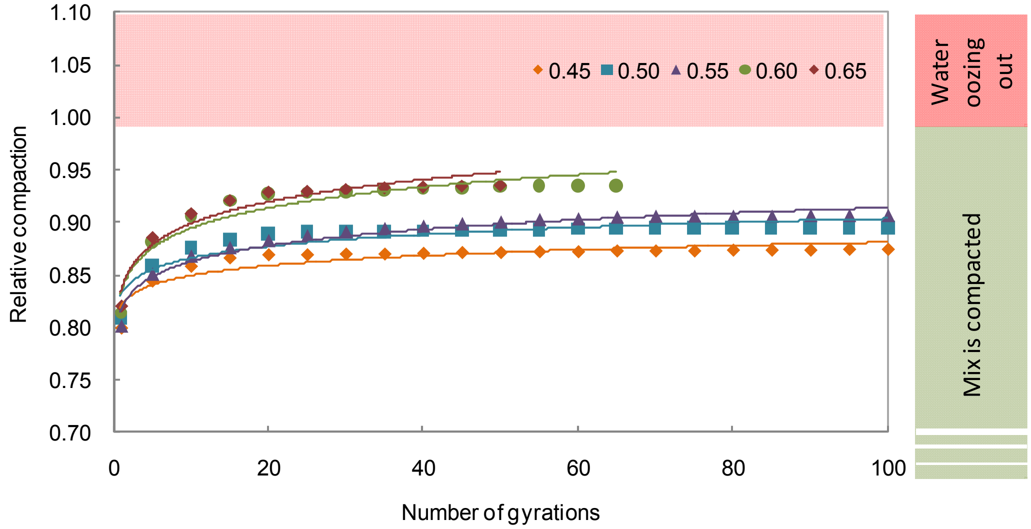


Figure H-32 Relative compaction in A/B = 10 mixtures w/ CAG-F

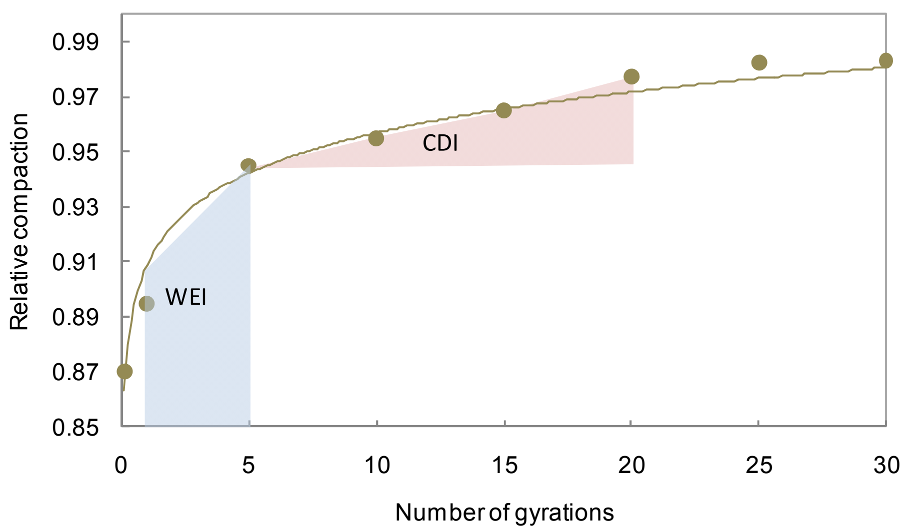


Figure H-33 Definitions of WEI and CDI

Further comparison of this data was done in terms of the workability energy index (WEI) and compaction densification index (CDI) as defined in the literature review section. A simplification for obtaining the indices was as applied as follows. The WEI is defined as the area between the first and fifth gyratory compaction and is obtained by approximating the area under the relative compaction curve by the trapezoidal rule. The CDI on the other hand is shown considered to be the area above the relative compaction at N_5 and confined by N_5 and N_{20} and the relative compaction plot. These definitions are pictorially represented in Figure H-33.

Based on above definitions the values of WEI were computed and are shown in Figure H-34. It can be seen that the WEI varies linearly with the w/b ratio, the trend being a function of the A/B as well. Quite similar to the trends for the self-compacting indices, the WEI for A/B = 4 shows high sensitivity towards any changes in the moisture content. The sensitivity reduces as the A/B ratio increases. For comparable w/b ratios, as the mixtures become richer in the binder content, the WEI increases indicating that it is easier to compact richer mixtures than the leaner mixtures. A preliminary inference that could be deducted based on these observations is that mixes with WEI greater than eight seem to have higher than required compactibility or tendency to give out water under sustained load or pressure. This also means that the mixture is not capable of holding the respective volume of water. In turn, this implies that there is a limit to w/b ratio, below which a mixture can be compacted with a fixed amount of compaction pressure and beyond this w/b ratio, the mixture will either give off water or render a non-pressure compactable surface.

The CDI on the other hand can be considered to be supplementary to WEI. Figure H-35 shows trend obtained from this grading and A/B ratios. Interestingly, for rich mixture, since the work done in the first five gyrations is good enough to achieve highest possible compaction, therefore the CDI values are showing a decreasing trend. This implies that not much work is done in increasing the density further for these mixtures. On the other hand, the mixtures with A/B ratios of 7 and 10 show an increasing trend with increasing w/b ratio. This indicates that some work is done in further increasing the density of concrete mixtures after the initial compaction is achieved. A classification scheme cannot be proposed at this stage.

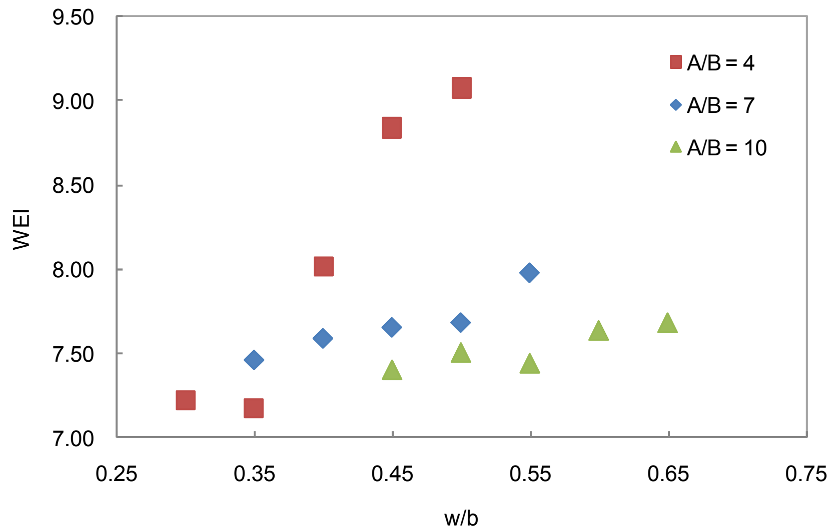


Figure H-34 WEI for F-grading and different A/B ratios

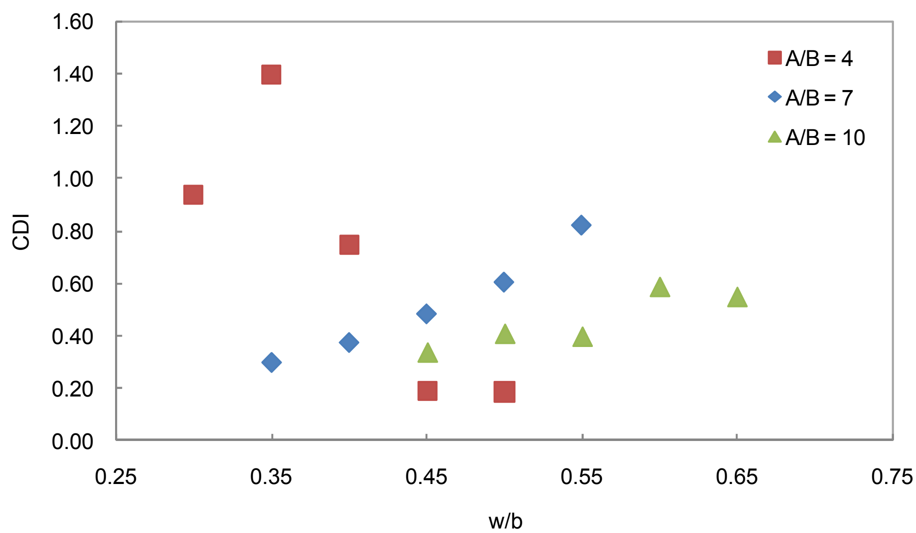


Figure H-35 CDI for F-grading and different A/B ratios

H.4.4 Interaction effects

A/B-W/B-WEI

Figure H-36 shows the interaction effects of A/B and w/b ratios on the WEI. It can be seen that both of these ratios have a meaningful influence on how compactable a concrete could be.

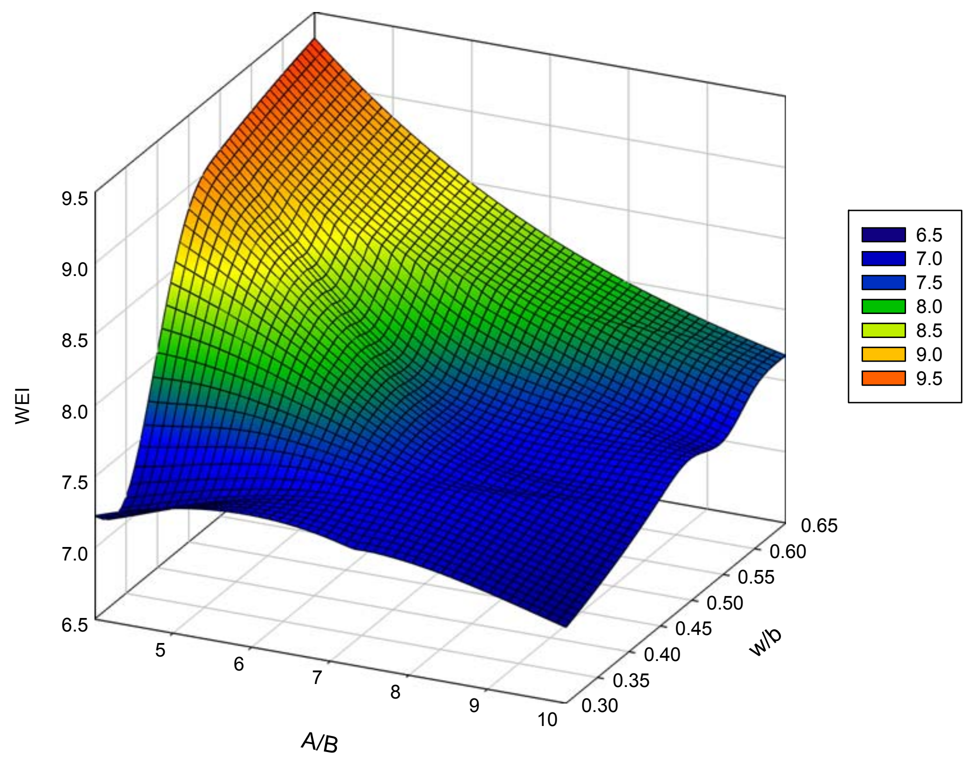


Figure H-36 Interaction effects of A/B, w/b ratios on WEI for F-grading

The following observations are relevant:

- With the increase in the w/b ratio, a mixture becomes more compactable; however, the relative proportions of aggregate and binders influence the rate of change of compactibility. This means that for a given A/B ratio, as the w/b ratio increases the trends take different profiles. At lower A/B ratio, the compactibility is highly sensitive to the changes in the moisture content, while the sensitivity reduces as the A/B ratio is increased.

- With the increase in the A/B ratio, the mixture looses its compactibility, while being a function of the relative proportions of water and binder. It is interesting to note that there are three different trends followed as a function of w/b ratio. At lower w/b ratio, parabolic trends are followed, implying with the increase in the A/B ratio the compactibility increases initially, reaches a peak and then starts dropping down. At intermediate w/b ratios, initially with an increase in the A/B ratio, there is a sharper drop in the compactibility followed by a flattening effect with further increase. At higher w/b ratios there is however a continuous decrease in the compactibility with increasing A/B ratio.
- It can be said that w/b and A/B ratios play a very influential role in shaping the nature of workability. A mixture at a fixed A/B ratio and with a specifically narrow range of w/b ratio will only produce potentially highest compactibility.
- It should also be noted that aggregate shapes would also influence the compactibility; the results of those studies are not produced here.

A/B-W/B-SCI

The interaction trends followed by SCI are quite similar to the WEI and are shown in Figure H-37. The trends are however a little more clearer than the WEI. The self-compactibility of a mixture is again a composite function of A/B and w/b ratio, however the effects produced by w/b are more pronounced than the A/B ratio, considering other gradings viz. M and C

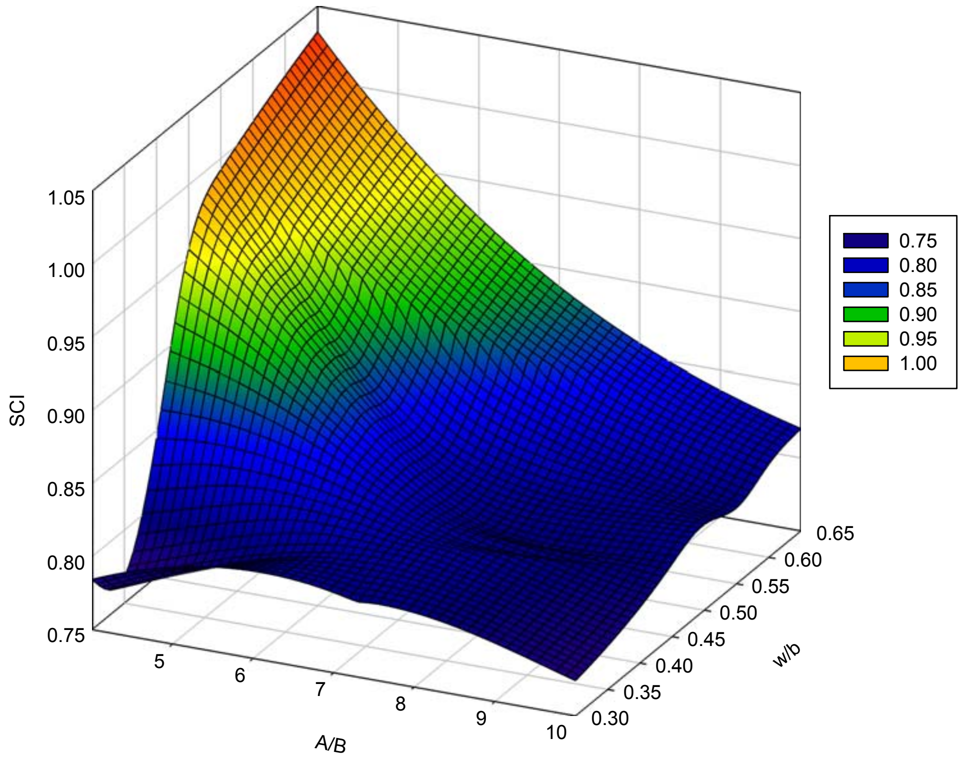


Figure H-37 Interaction effects of A/B, w/b ratios on SCI for F-grading

A/B-W/B-CDI

The CDI however follows a complicated trend as shown in Figure H-38. Based on the available data, it is difficult to offer any comprehensive inference and hence this plot is not discussed in detail.

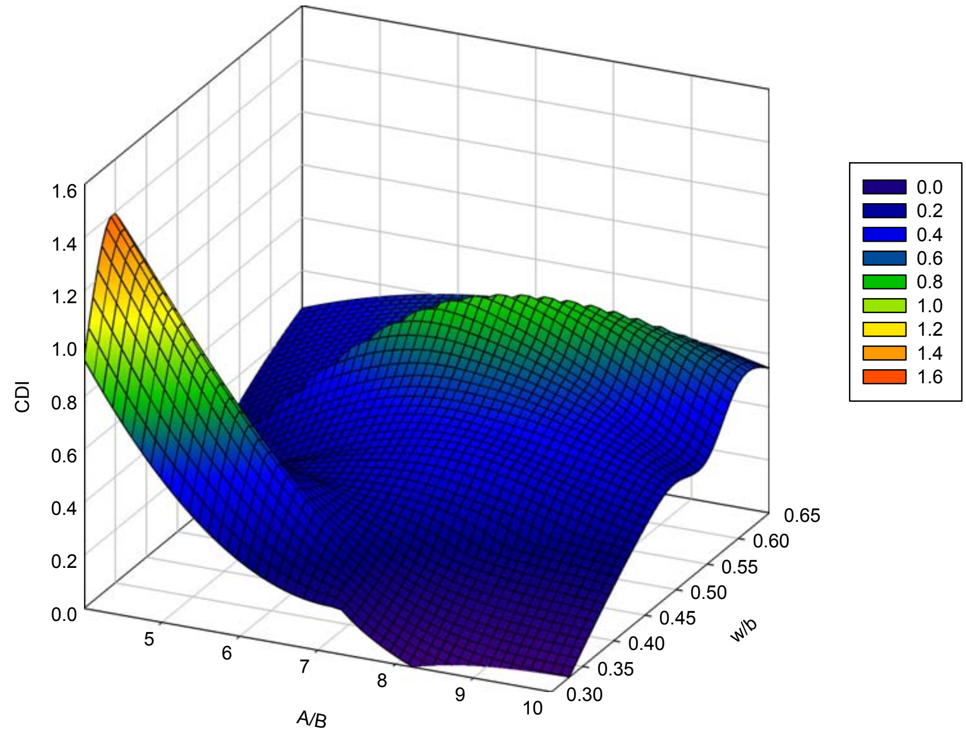


Figure H-38 Interaction effects of A/B, w/b ratios on CDI for F-grading

INFLUENCE OF COMBINED AGGREGATE GRADING ON COMPACTIBILITY

As discussed before the three different combined aggregate gradings were used in this study to test and evaluate the influence of the grading on compactibility. The coefficient of uniformity for these three gradings were 200 (F), 56 (M) and 25 (C). Mixtures were gyratory compacted at 200 kPa pressure and the compaction was terminated depending on the composition and behavior of the mixture. Figures 14-39 through 14-41 show the relative influences of fineness of gradings, A/B and w/b ratios on gyratory compacted samples.

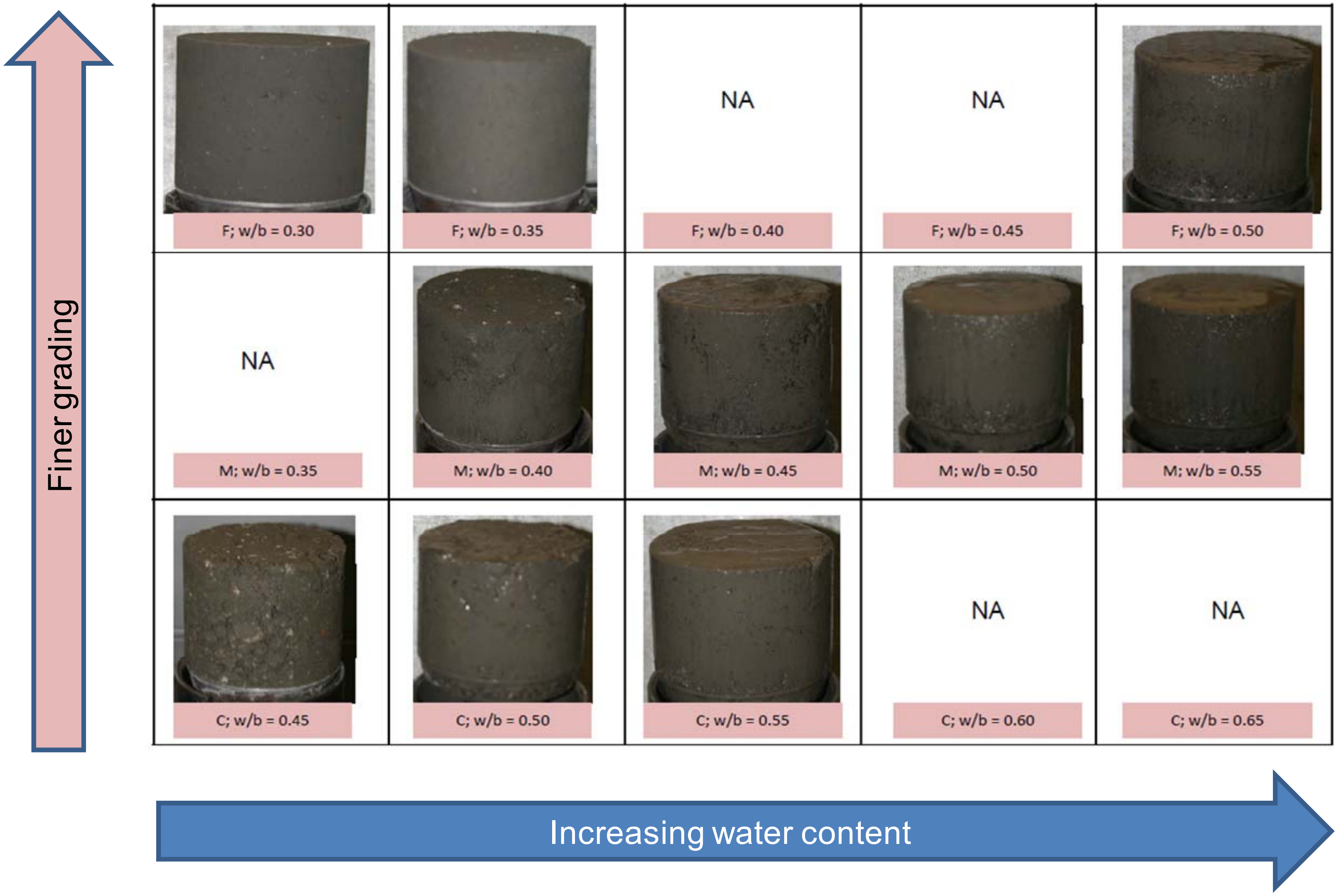


Figure H-39 Effect of aggregate grading and w/b ratio for A/B = 4 mixtures

Figure H-40 Effect of aggregate grading and w/b ratio for A/B = 7 mixtures

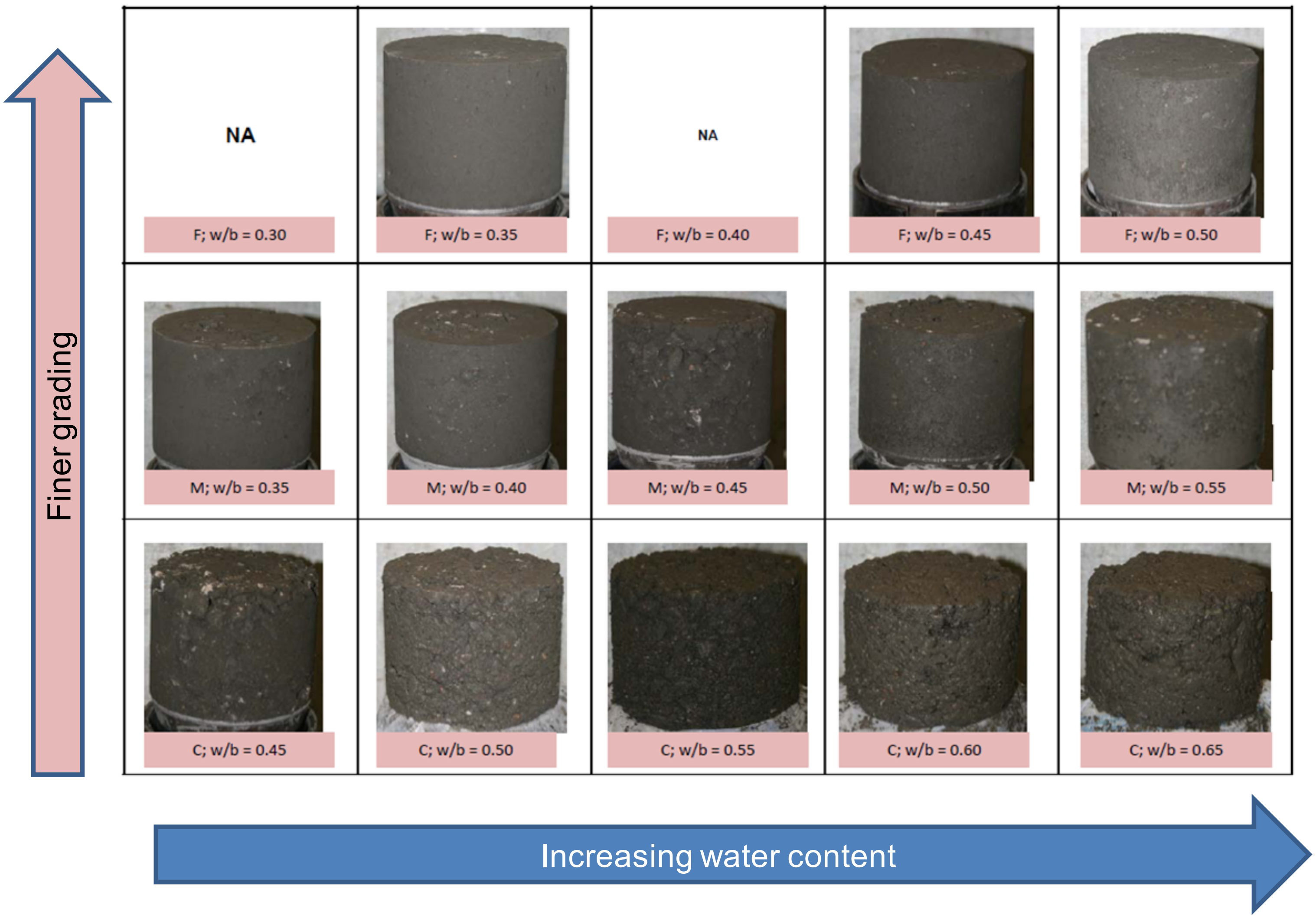


Figure H-41 Effect of aggregate grading and w/b ratio for A/B = 10 mixtures

Figure H-42 shows the general trend of the influences of w/b ratio and the coefficient of uniformity for different mixtures. A caveat to this and plots of similar kind is that these are indicative of the trends the materials are following and need not be able to explain the intricate details and specifics. From the said figure, it can be seen that w/b ratio has a significant influence on the WEI. The F-grading used in this study has a C_u of 200, indicating the presence of high volumes of fine material in the aggregate grading. The Cu values for the other two gradings are much lesser, indicating relative coarseness of these gradings. Considering these two facts, it could be said that the central zone may not render much information.

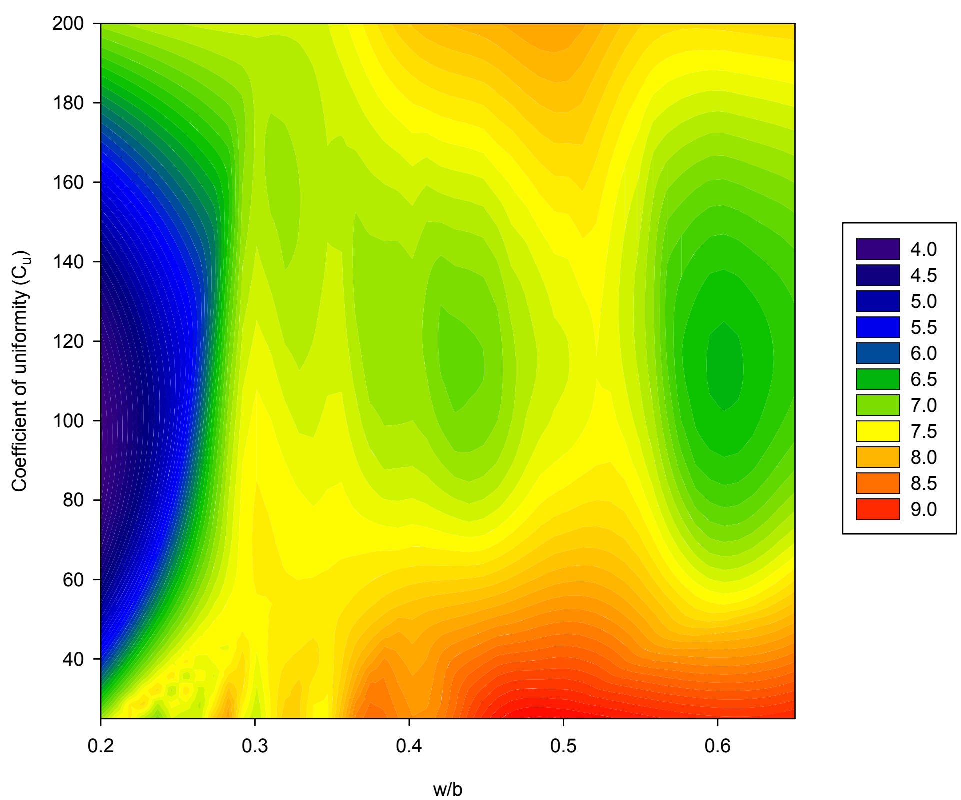


Figure H-42 WEI as influenced by C_u and w/b: A composite picture

Similarly, a plot for SCI is constructed and is shown in Figure H-43. This plot shows the range and combinations of w/b ratios and aggregate gradings that would render higher initial compactibilities.

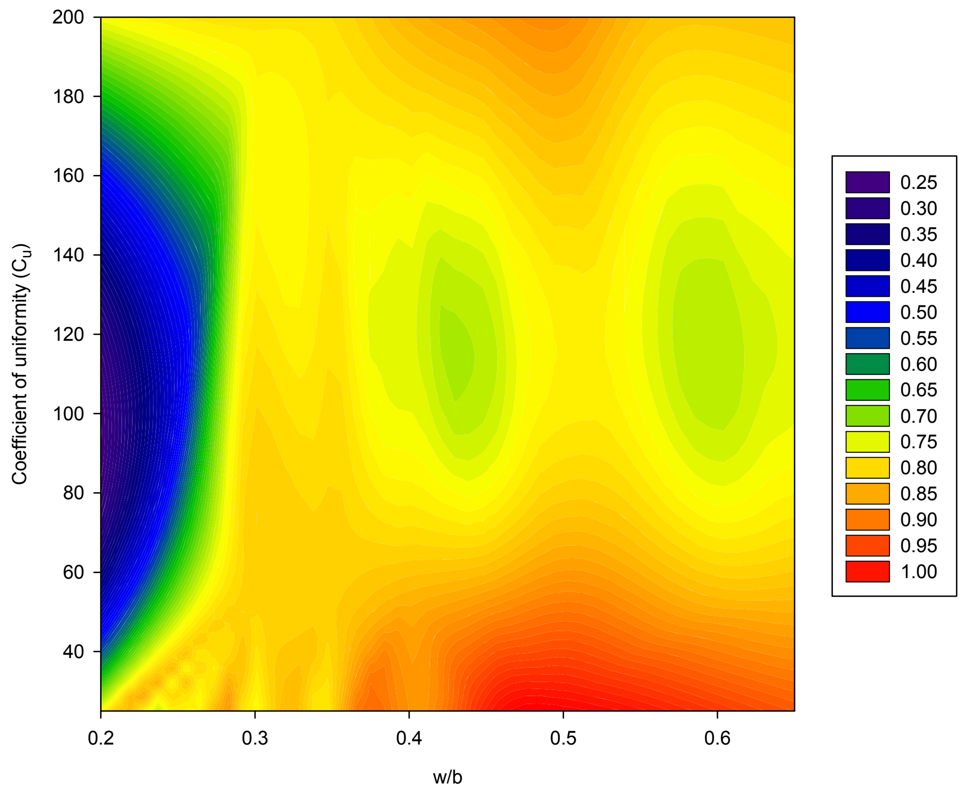


Figure H-43 SCI as influenced by Cu and w/b: A composite picture

Thirdly, a contour plot for different mixtures is constructed and is shown in Figure H-44. It can be seen from this plot that certain mixtures would required higher compaction effort, after the initial compaction is completed. For instance, mixtures with lower w/b ratios would require extended compaction effort to achieve higher densities and would still not be able to render the required compaction economically. Mixtures with higher w/b ratios and intermediate C_u, due to the presence of more water would require extended amounts of compaction efforts to reach higher degree of compaction.

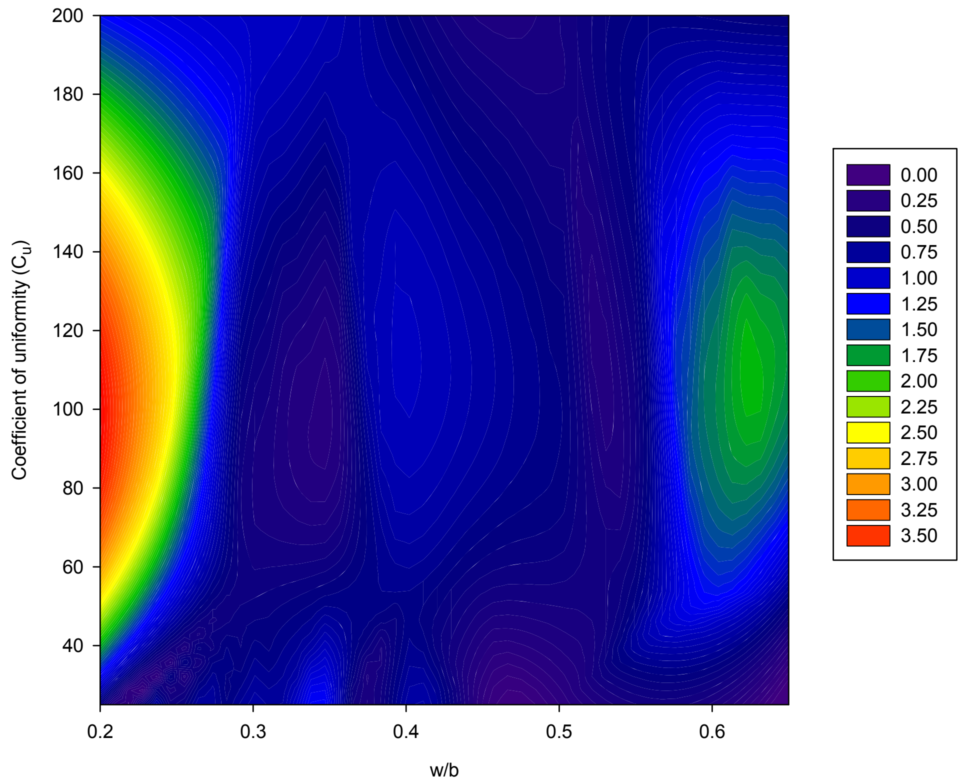


Figure H-44 CDI as influenced by Cu and w/b: A composite picture

INTERACTION EFFECTS, A FURTHER ANALYSIS

A model was fitted to further appreciate the effects of aggregate grading and A/B ratio. JMP was used for conducting this analysis, considering the WEI, A/B, w/b and C_u. Figure H-45 shows the plot of the WEI from the prediction model versus the actually measured numbers. Although there is a spread in the data, but there is a good predictability obtained from the prediction model. The R^2 value is 0.822. this model helps us appreciate the relative importance of each of these factors on the compactibility of different concrete mixtures. The residual plot shows a wider spread.

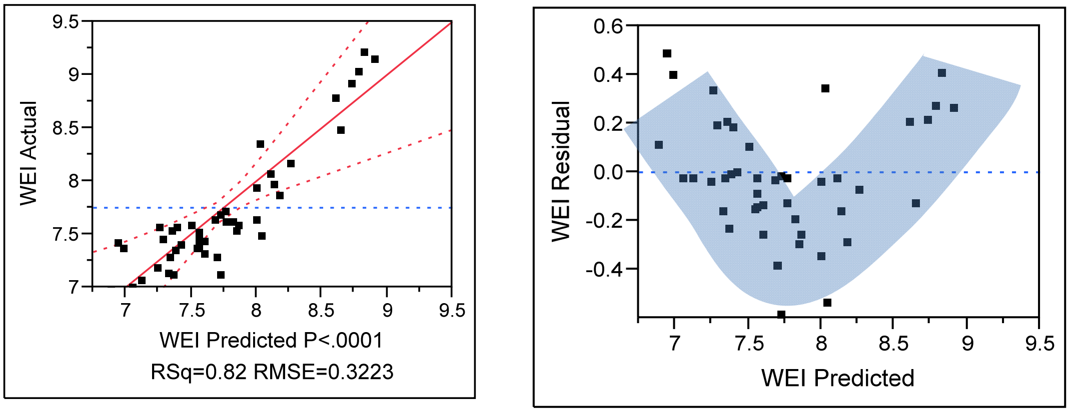


Figure H-45 WEI as predicted versus as measured and the residual plot

Figure H-46 shows the respective least square means plots showing the influences of each of the factors considered in the modeling. Due to lack of repeatability, a further construction of a comprehensive model is not offered here.

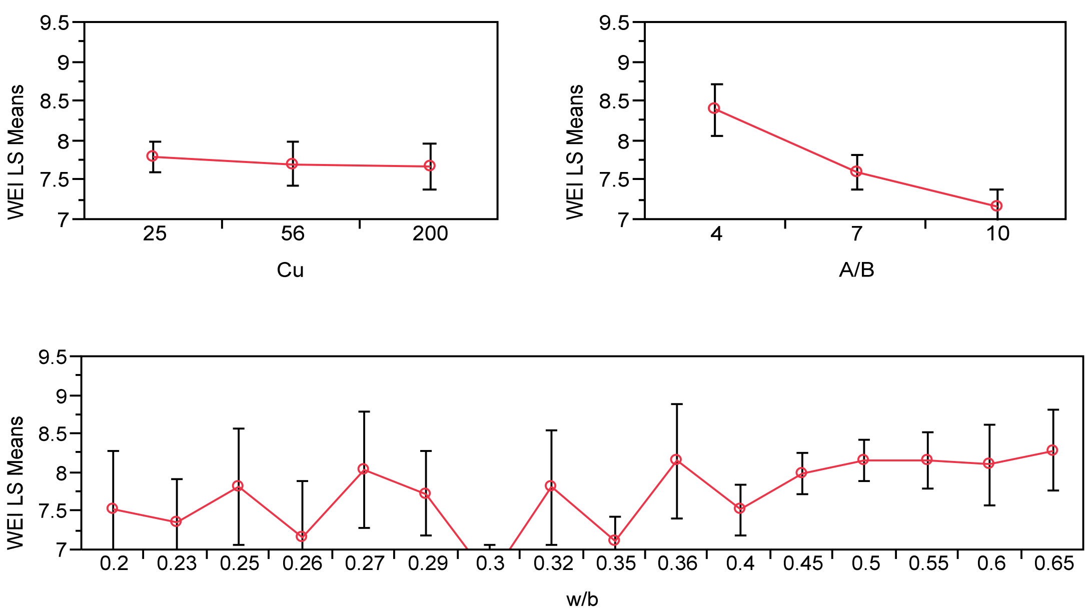


Figure H-46 Least square means plots

Further to this, desirability and prediction profiles are presented in Figure H-47 below. From these plots, it can be seen that lower A/B ratio and intermediate coefficient of uniformity is desirable for better compactibility. w/b ratios can be selected based on these two ratios individually.

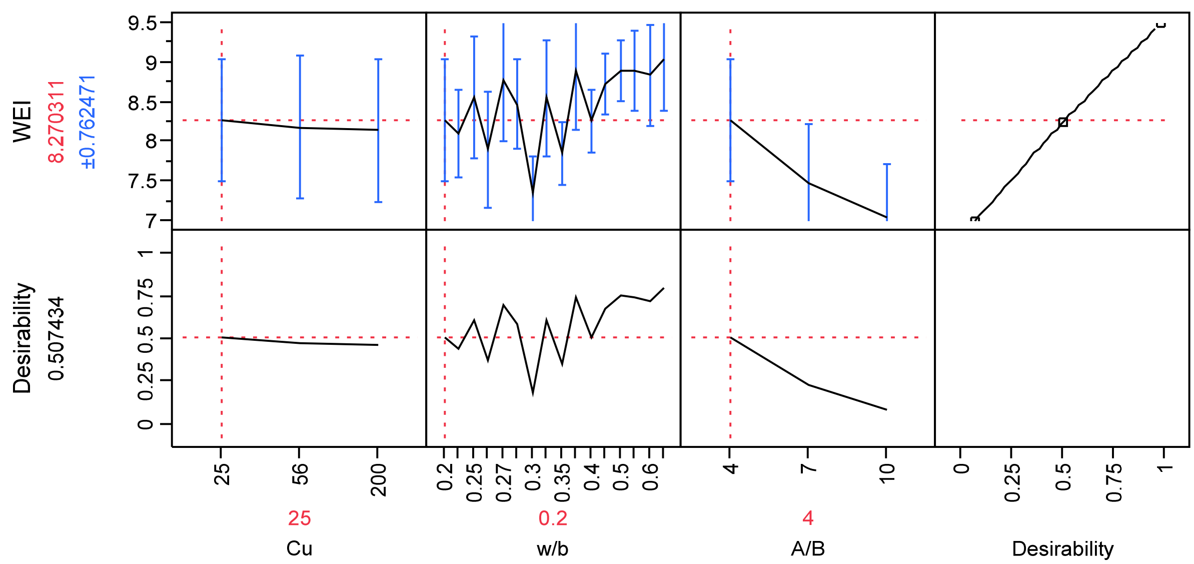


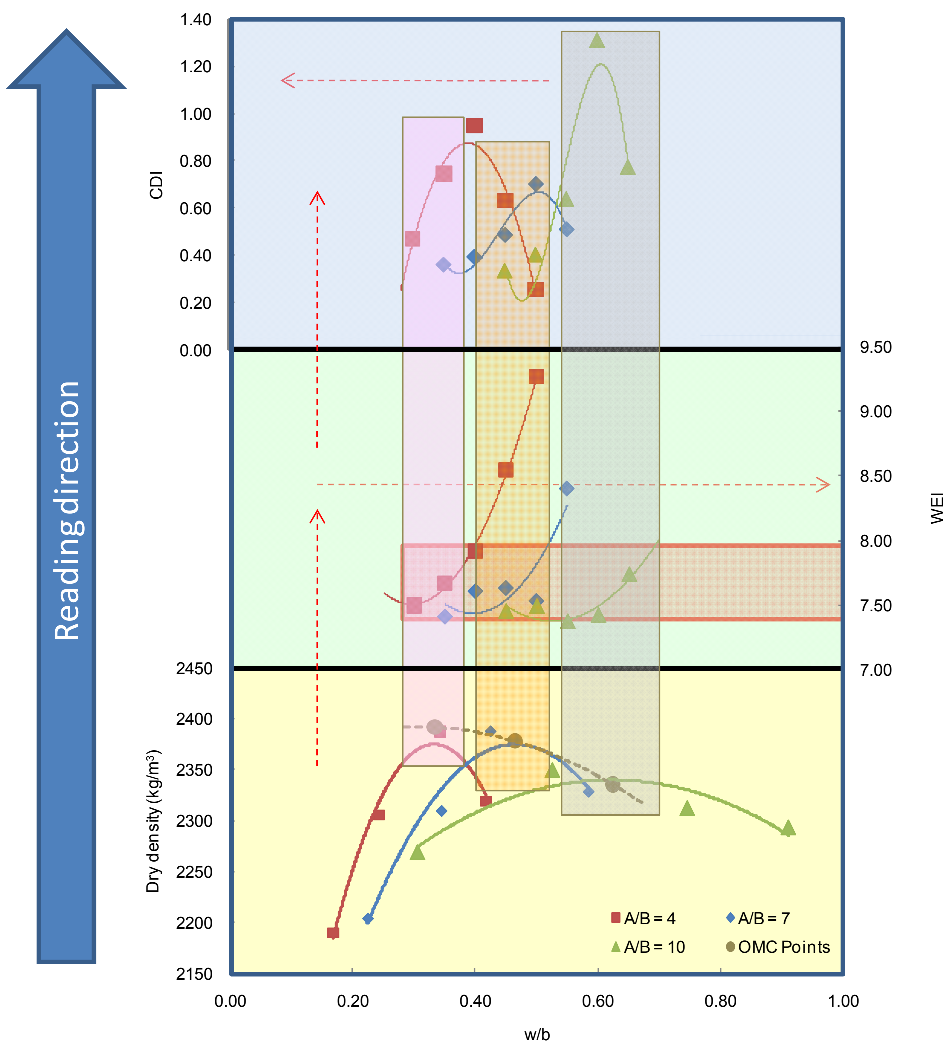
Figure H-47 Prediction and desirability profiler

H.5 Connecting with roller compactibility

After doing this analysis, it is necessary to connect it with what will be roller compactable. For this, an intermediate aggregate grading was selected, moisture density plots were constructed, and an interaction plot was constructed to link roller compactibility to the indices obtained from gyratory compaction. It should be noted that this type of interaction diagram will differ under field conditions, but is a good starting point. Figure H-48 shows an example proof of this concept. The step-wise procedure is as follows:

- First a moisture density plot for different A/B ratio is constructed;

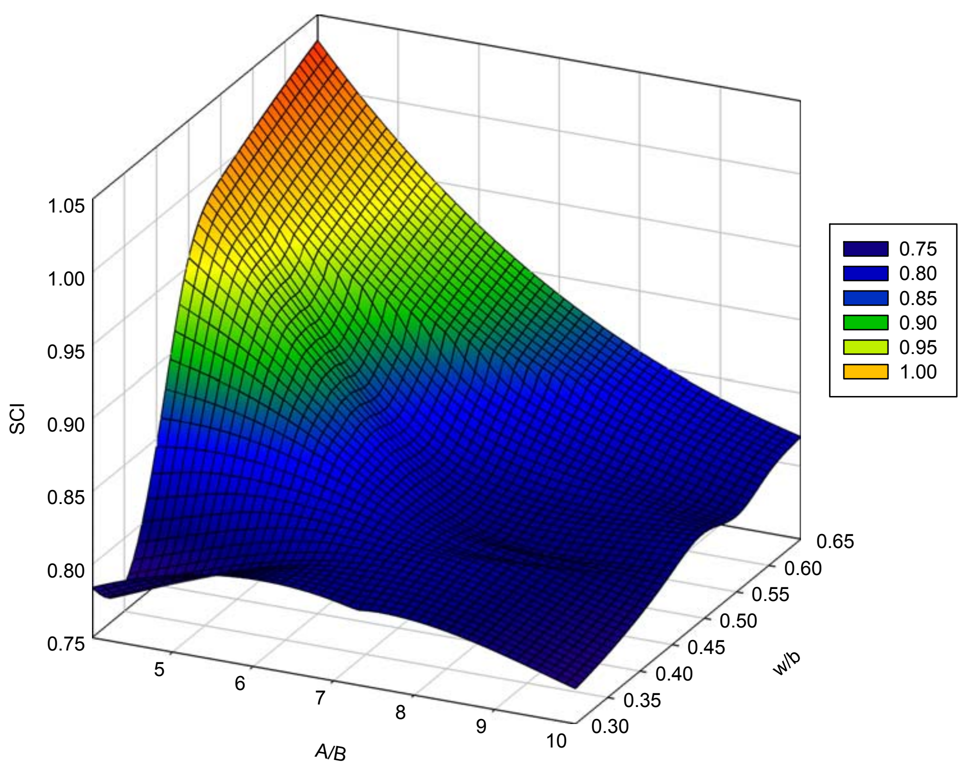
- Gyratory compaction plots and the corresponding indices are obtained for these mixtures;
- A connection between these plots is made for similar w/b ratios;
- The w/b ratio in proximity of the w/b ratio would render roller compactable points and hence WEI indices.



H-48 Deriving indices for roller compactable mixtures

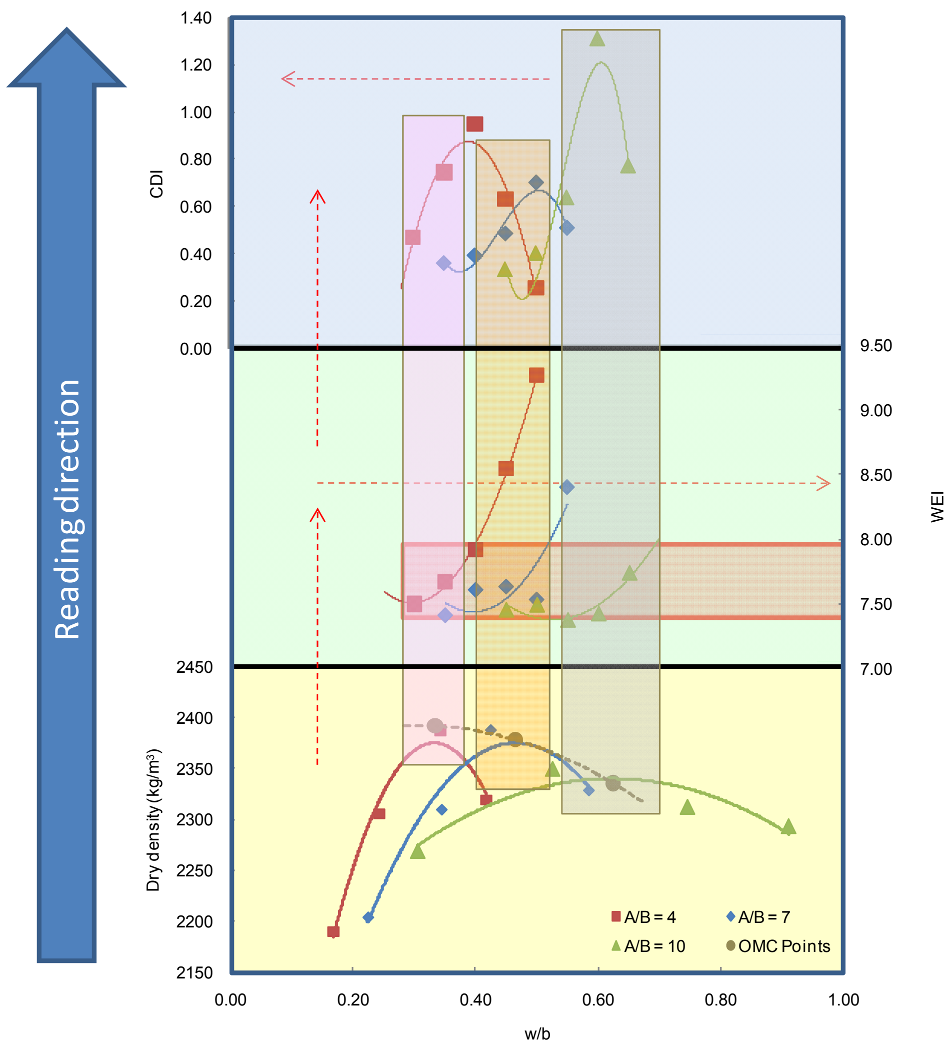
SUMMARY

Compaction responses to vibration for various aggregate systems and combinations were tested and evaluated. Compactibility of different aggregate geologies were also quantified to evaluate the effects of particle shape and aggregate grading. Different aggregate systems were differently sensitive to the changes in the aggregate gradings. The compactibility indices were then correlated to fineness, aggregate surface areas and comparative arguments were offered. Appreciating the limitation of fineness modulus as a grading index that excludes the finer fraction, two new indices were applied in quantifying the aggregate grading. Of which the coefficient of uniformity was found to be useful.



Various theoretical aggregate grading methodologies were applied and evaluated for their usefulness in RCC. Finally the modified Andreassen's method was used for combining aggregate used in this study. The effects of factors like aggregate gradings, water/binder ratio and binder contents were studied on compactibility of several concrete mixtures. It was observed that the compactibility is highly dependent on the volumetric composition of concrete and is differently sensitive to different binder contents. Two new indices for compaction were introduced and applied successfully.

Other reported studies include the admixture screening and correlations of the compactibility indices with the moisture density profiles to extract meaningful correlations and range of parameters.



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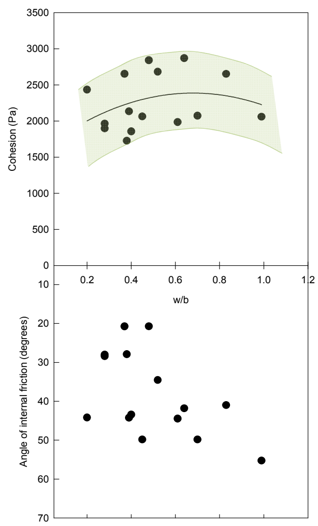
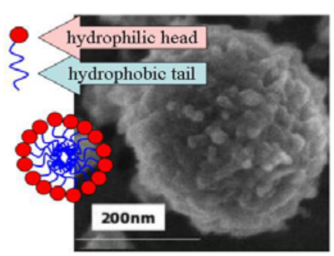
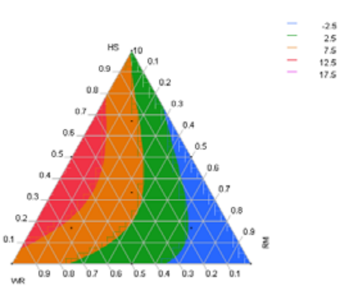
APPENDIX I PROSPECTIVE VIEW AT THE COMPONENTS OF WORKABILITY







SYNOPSIS

This chapter presents a summary of the significant findings from the work done on fresh properties of different concrete mixtures. Initially a brief review on the factors affecting workability is followed by various properties of control mixtures. This includes the moisture density plots, consistency, air content, and their interrelations. Subsequent to this a detailed accounts of the effects of various water reducing, air entraining, rheology modifying admixtures on the water reduction, air content, consistency, etc, are offered. Binary and ternary combinations are discussed as well. A synoptic section presents the methodology for data manipulation of shear force-shear displacement plots. A comparative picture of trends in various control concrete mixtures in terms of cohesion and angle of internal friction is presented. Following this various composite plots are developed to appreciate the relative influences of different kinds of chemical admixtures on concrete cohesion and angle of internal friction. Finally a section is dedicated to how these admixtures can assist in reducing the roller compaction costs. Thus this chapter isolates various components of concrete workability.

Keywords: workability, water reduction, air content, Cabrera slump value, shearing stress, work done, cohesion, friction angle, roller compactibility

CONTENTS

I.1 Aspects of workability, a review

For a properly workable concrete, the following properties are to be simultaneously exhibited:

- The concrete becomes a well-mixed, homogeneous material during reasonable mixing time.
- Segregation or bleeding does not take place during the transportation of concrete.
- Little or no segregation or bleeding occurs during the handling and placing.
- The concrete can be easily and adequately compacted throughout its whole mass with the available equipment while the uniformity of the mixture is preserved. In addition, the compacted concrete fills the form completely and encompasses fully the reinforcement embedded in it.
- No imperfection, such as honeycombs or channels caused by bleeding, occur in the concrete, even if these can be covered by later repair [1].

Powers [2] defined workability as the combined effect of those properties of fresh concrete that determine the amount of internal work required for placement and compaction and that determine the resistance to segregation.

I.2 The landscape of control (non-admixed) mixtures

I.2.1 Evolution of moisture-density plots

Table I-1 shows the mixture proportions used in evolving the moisture-density plots. While keeping the Aggregate/Binder ratio constant, the moisture content was varied and the changes in compacted density and other properties of fresh concretes were observed and are reported in this chapter.

Table I-1 Mixture proportions for non-admixed concretes: Moisture density plots

A/B	Materials, kg/m^3				w/b
	Cement	F Fly ash	Aggregates	Water	
4	322	106	1731	72	0.1681
4	334	110	1795	108	0.2432
4	334	110	1796	153	0.3434
4	320	106	1721	178	0.4185
4	336	111	1803	149	0.3341
7	210	69	1974	63	0.2242
7	218	72	2047	100	0.3444
7	215	71	2021	121	0.4245
7	203	67	1906	158	0.5848
7	212	70	1998	131	0.4653
10	144	48	1938	59	0.3052
10	149	49	2005	104	0.5257
10	151	50	2024	149	0.7461
10	143	47	1925	174	0.9115
10	154	51	2068	128	0.6244

Figure I-1 shows the moisture density plot for A/B = 7. As explained in the literature review section, the density response of concrete mixtures to changes in moisture contents follows an optimizing (parabolic) trend. Initially with increasing moisture content the concrete density is mobilized gradually to reach the maximum possible density and later on the density shows a decreasing trend.

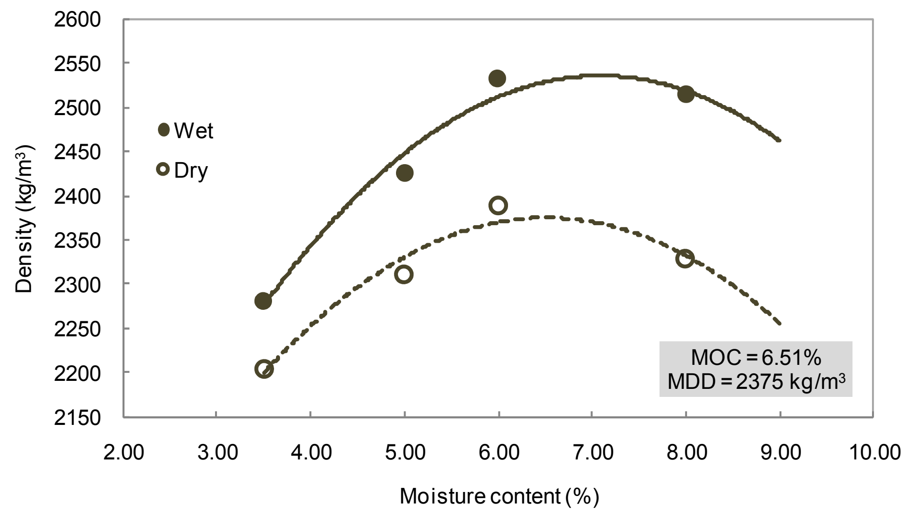


Figure I-1 Moisture-density plot for A/B = 7

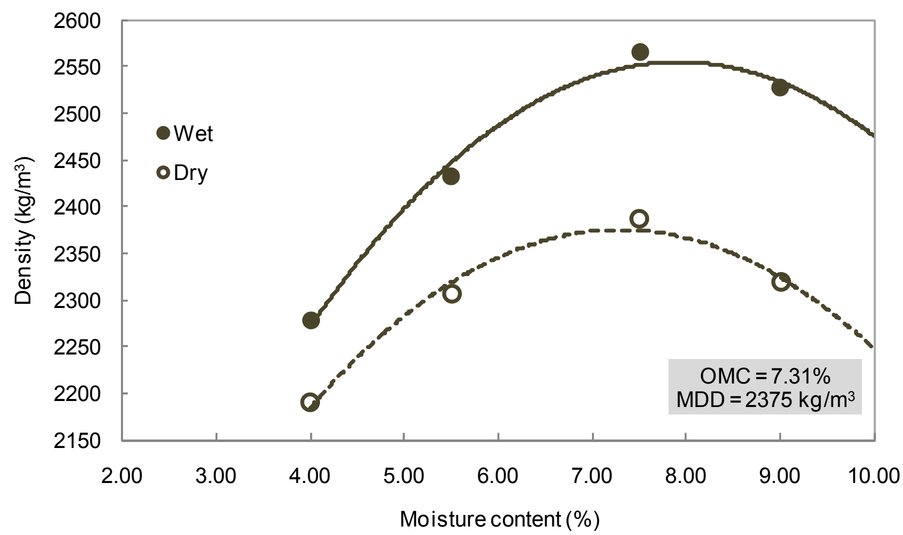


Figure I-2 Moisture-density plot for A/B = 4

Similarly, a moisture density plot was constructed for A/B = 4 (refer to Figure I-2), implying the richest mixture in this set of experiments. Comparing this curve with the curves for A/B ratios of 7 and 10 indicates that the density of these mixtures is relatively more sensitive to changes to moisture content. Also due to higher cement content (hence surface area) of these mixtures, the water demand from plasticizing perspective is highest.

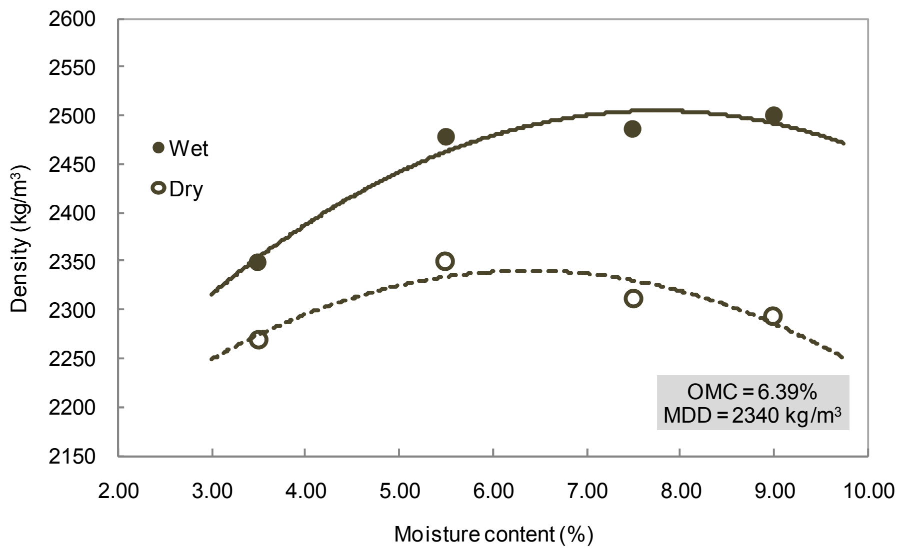


Figure I-3 Moisture-density plot for A/B = 10

Finally the moisture density plot for A/B = 10 is shown in Figure I-3. It can be seen that the density is least sensitive to the changes in the moisture content. This could be due to the following reasons. With increasing aggregate content, the water demand of a mixture is dominated by the aggregate water content. Furthermore, due to lower binder content, the surface area of cement to be wetted for offering the required plasticizing effect is reduced and a dominating portion of the water is consumed by wetting the aggregates.

Figure I-4 is constructed to present the variation of density in a conventional X-axis of w/b ratio format. It can be seen that as the binder content of the mixtures increases, the water sensitivity of the mixture increases, i.e. even a small change in the w/b ratio would make a significant difference in the dry density of concrete. On the other hand, lean mixtures are least sensitive to changes in the w/b ratio. Richer mixtures are quite significantly affected by lower w/b ratio (or water content), while the leaner mixtures are less affected.

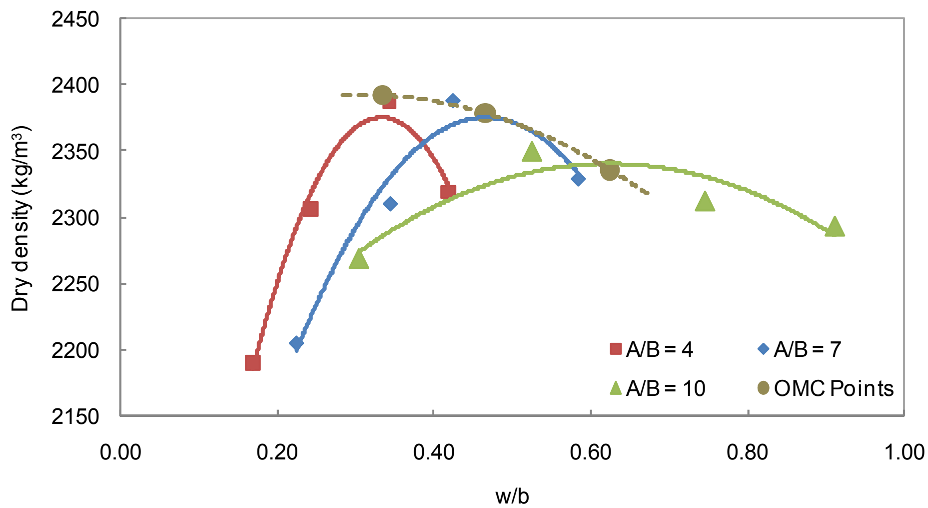


Figure I-4 w/b ratio versus dry density: effect of binder content

The plot of maximum dry density at the respective optimum moisture contents indicates that the dry density decreases as the mixtures become leaner. Although the quantity of water required to reach the maximum possible density reduces as the mixture becomes leaner, the w/b ratio increases due to a simultaneous reduction in the binder content.

I.2.2 A retrospect at the "assumption of independence"

Popovics [3-5] in his different accounts on workability of concrete propose the "assumption of independence" which states that the relative amount of change in consistency, which is due solely to the relative change in the water content of the mixture, is independent of the composition of the mixture. A caveat to this is though the change in consistency of a fresh mixture, such as cement pastes, mortars, concretes, and soil-water mixtures, seems to follow a complicated pattern even when the change is due only to a change of the water content. Figure I-5 conceptual sketch and an example showing the application.

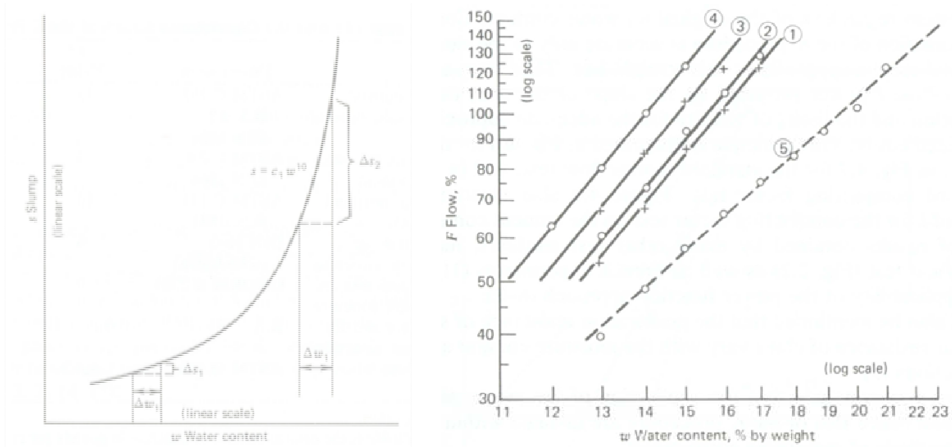


Figure I-5 Assumption of independence and its application [6]

Popovics [6-7] on the basis of above assumption further proposes the following relations between consistency and water content of fresh concrete:

$$w_2 = Kw_1$$
$$y = c_1 w^i$$
$$K = \left(\frac{y_2}{y_1}\right)^{1/i}$$

where,

w_1 and w_2 are the water contents of fresh mixtures for the initial consistency (y_1) and the changed consistency (y_2) respectively
K is the thinning factor, which is independent of the composition of mixture
c_1 parameter that depends on the composition of the mixture and the method of measuring consistency
i is the test method constant that is independent of the composition of the mixture but depends on the method of measuring consistency

Powers [8] presents the above equation in a differential form implying that a fractional change in consistency (S) in consistency is proportional to the fractional change in water content (w). The equation is as follows:

$$\frac{dS}{S} = n\left(\frac{dw}{w}\right)$$

Drawing inspiration from the above logic and applying the concept to the fresh density of concrete the fresh density is differentiated with respect to moisture content. Figure I-6 represents a family of lines obtained by differentiating the fresh density with respect to the moisture content for different binder contents.

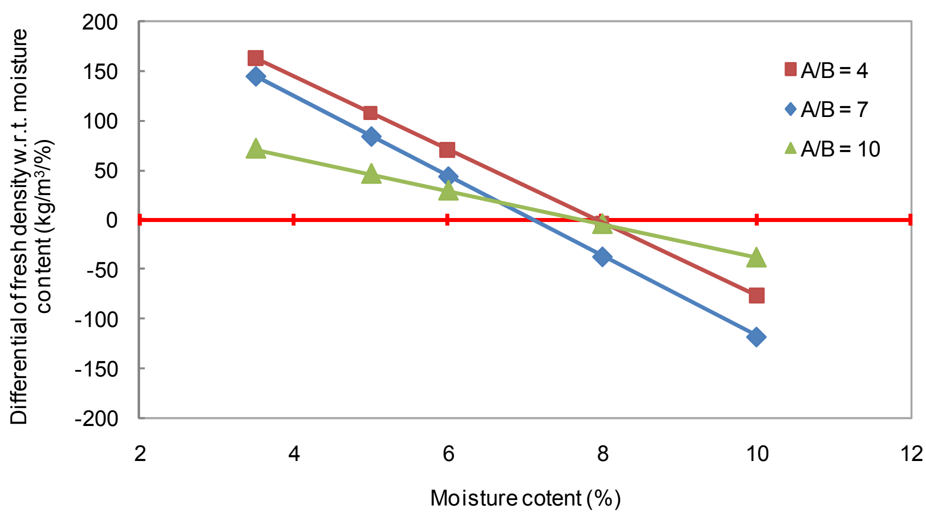


Figure I-6 Assumption of independence applied to RCC mixtures

A numerical quantification of this nature helps appreciate the qualitative differences in mixtures. Quantitatively, differentiating the density numbers for different mixtures is not possible, neither is it hoped that they would render any meaningful information. However, a quantification like the above mentioned one helps make a differentiation. Since the variation of the fresh density with moisture follows a parabolic (quadratic) trend, the differential of density, ρ, with respect to moisture content, m, (dρ/dm) is a straight line. Therefore, the relationship can be proposed as follows:

$$\frac{d\rho}{dm} = \kappa_r m + k_d$$

where,

κ_r is a sensitivity constant and k_d is the intercept on the differential axis (Y-axis) indicating the theoretical value of differential at zero moisture content. The sensitivity coefficient κ_r is a good indicator of the responsiveness of a mixture composition to the changes in the moisture content.

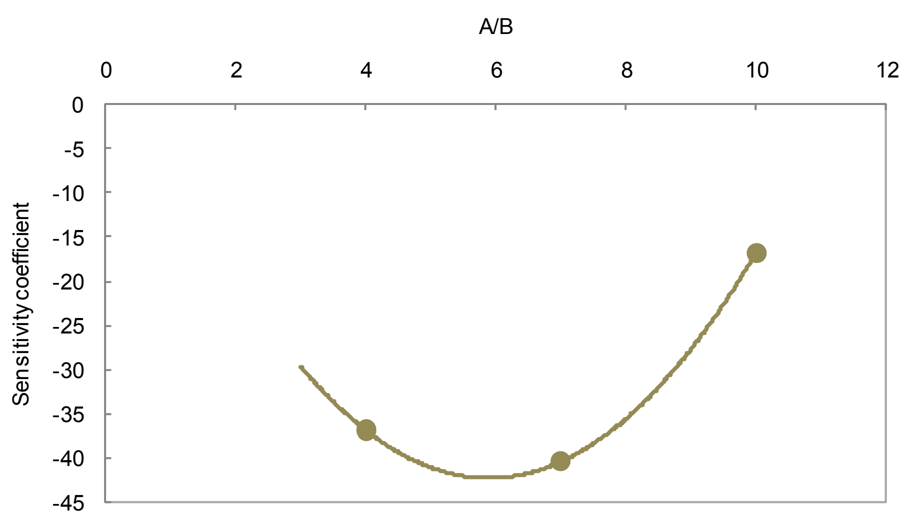


Figure I-7 A/B versus sensitivity coefficient

Figure I-7 represents the sensitivity coefficient as a function of the A/B ratio. This curve is helpful in assessing the moisture sensitivity and vulnerability of mixtures with different binder contents. In this case for example, the inverted parabolic indicates that there is an the sensitivity of RCC mixtures goes through a transition, reaching a minimum value (indicating highest moisture sensitivity) and then as the A/B ratio increases the sensitivity reduces significantly. From practical perspective, a plot like this helps appreciate the vulnerability of mixtures to moisture variations. A slightly change in moisture (dm) content for a lean mixture (higher A/B ratio) will not affect the density significantly, however a similar change in moisture content could lead to a dramatic change in an intermediate mixture. It can be hypothesized that the water sensitivity of a particular send of materials is closely associated with the granular packing. For higher A/B ratios due to insufficiently filled voids and at lower A/B ratios due to particle interference, the mixtures are relatively less packed than at an intermediate A/B ratio, where they are most densely packing and are highly sensitive to alterations in the moisture contents.

I.2.3 The interactions

Figure I-8 shows the variation of dry density as a composite function of binder and moisture contents. Here the interaction effects produced by these two components of the mixtures are evident more clearly. This graph has a very high utility in mixture proportioning. Knowing the aggregate composition, and a start-up binder content, this plot can let one estimate the water content of the mixture and also the dry density of concrete.

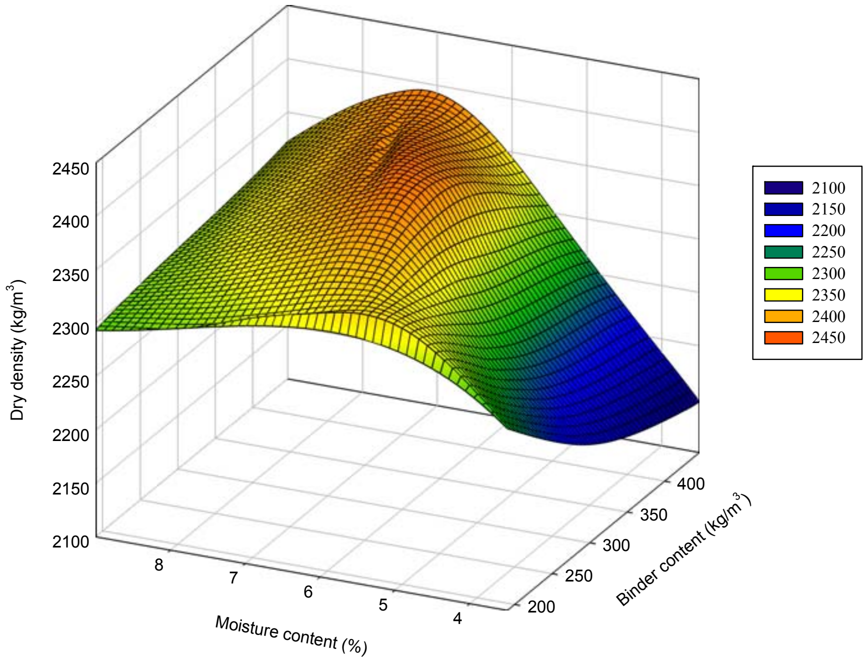


Figure I-8 Interaction effects of binder and moisture contents on the dry density

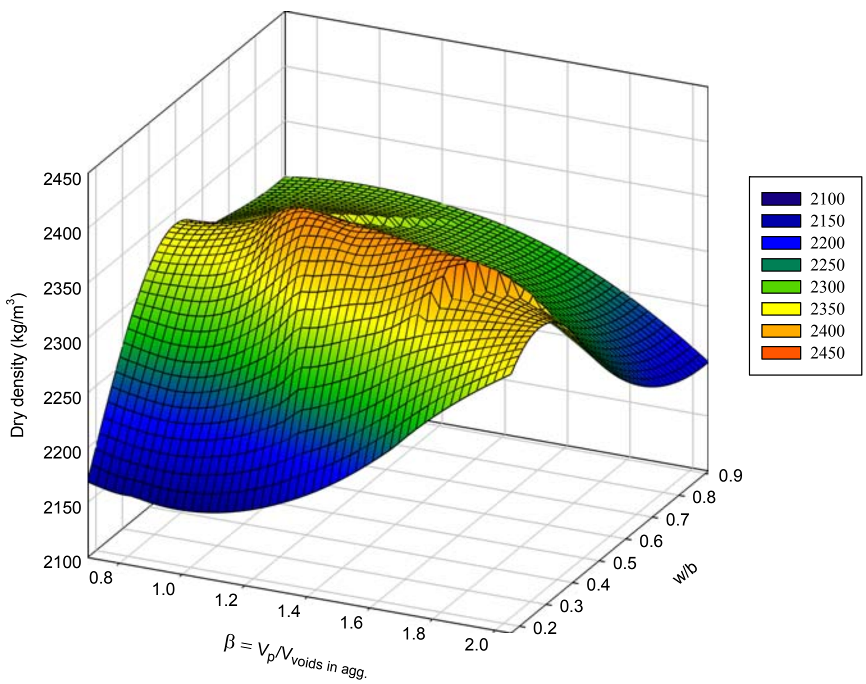


Figure I-9 Interaction effects of β and w/b on the dry density

Figure I-9 shows the variation of the dry density as a composite function of the relative volume of the paste and the voids in the aggregate and water/binder ratio. It can be seen that the w/b ratio alone is not responsible for producing a specific density. The following observations are relevant:

- There is a requirement of sufficient paste content in combination with the right quantity of water in a mixture to impart the maximum possible density. The filling of aggregate voids by paste is crucial and for a given compaction effort, there is a need for the right quantity of water to sufficiently plasticize the paste for it to enter into maximum possible volume of voids.
- Richer mixtures, having lower w/b ratio need more paste to reach the maximum dry density. As the mixtures become leaner (while transitioning from intermediate binder content), the paste requirement reduces.
- For a given β, the sensitivity of density reduces as the w/b ratio increases and especially beyond optimum moisture contents.
- As β increases, the sensitivity of density to changes in moisture content increases. In this regard, it is important to recognize a fact that the paste is composed of binders and water. For a fixed β, assuming that the volumes of binder and that of voids in aggregates is held constant, the moisture content changes comes out the single-most dominating factor that is responsible for changes in the density. The effect is produced through changes in the plasticizing effect of water on binders.
- Quite interestingly, at lower w/b ratio, increasing β leads to increases in the dry density. This follows a transitional path as w/b ratio is increased. Contradictory to the first effect, at higher w/b ratios, increasing β leads to decreasing of dry density.

Figure I-10 offers another perspective on the compactibility of these mixtures.

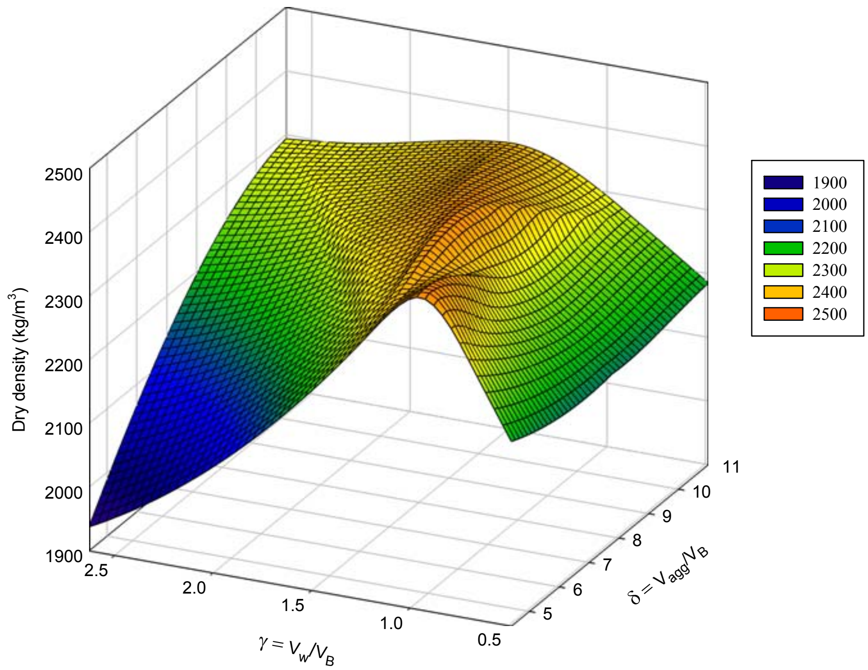


Figure I-10 Interactions effects of the relative volumes of water, binder and aggregates on the density

I.2.4 Cabrera slump value (CSV) and compactibility

Figure xx shows the variation of the Cabrera slump value (CSV) [9-10] as function of moisture content for various A/B ratios. Using these plots the optimum moisture content offering most compactable mixture can be obtained for a fixed A/B ratio. The values obtained for each A/B ratio are given in the Figure I-11. These values are comparable to the values obtained by the actual moisture-density plots. It should however be noted that the responses of the mixtures to compaction by vibrating table and compacting hammer is slightly different. In case of vibrating table, the vibrations are applied from bottom in upward direction and without any surcharge weight. While in case of compacting hammer, the vibrations are applied for a relatively longer time, in vertically downward direction and with a specific surcharge weight. The differences in the optimum moisture contents could partially be accounted to be due to these reasons.

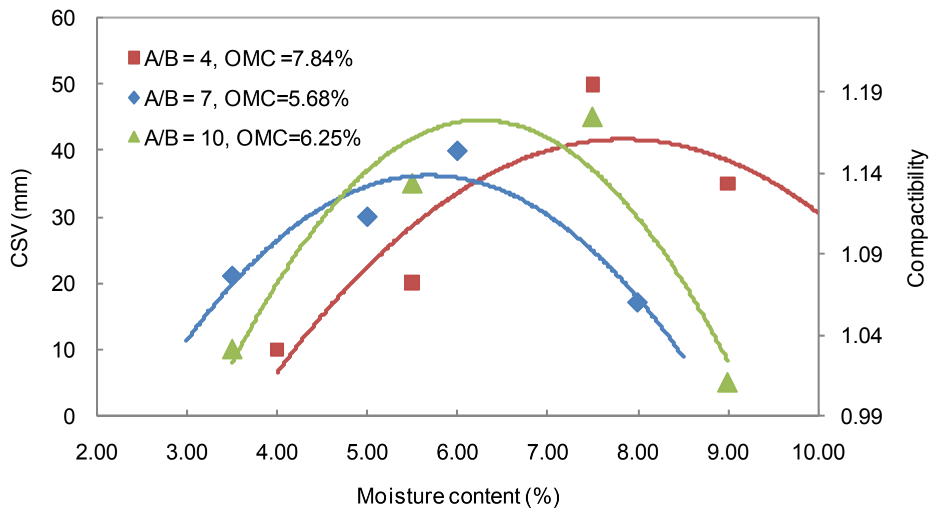


Figure I-11 Moisture content versus CSV

Another term, compactibility, similar to that defined in [11] is defined as follows and is used in quantifying the relative compactibilities of different mixtures:

$$Compactibility = \frac{300\ mm}{(300 - CSV)mm}$$

Like moisture-density plots, these curves also show parabolic optimization trends. For a set of CSV values, there are pairs of moisture contents that can produce the same CSV. As has been explained previously the difference in these two cases is of the presence of higher air content on the drier side, while filling up of the aggregate voids in the latter (higher) moisture content. It is easier to appreciate one density at two different moisture contents; however it is a bit difficult to appreciate the variation in the CSV.

To resolve the above confusion, Figure I-12 is constructed with the relative water (RW) as the X-axis. RW is defined as follows:

$$RW = \frac{Moisture\ content\ of\ a\ mixture\ for\ a\ fixed\ A/B}{Optimum\ moisture\ content\ for\ the\ same\ A/B}$$

The below figure illustrates the use of RW in interpreting the CSV. Mixtures above the OMC will have RW > 1. CSV for these mixtures will be a consequence of filling up of aggregate voids by presence of water in excess of the optimum moisture content. While on the other hand, mixtures below RW < 1 will have similar CSV values, but because of presence of air voids and lower potential of the mixture to achieve higher compactibility.

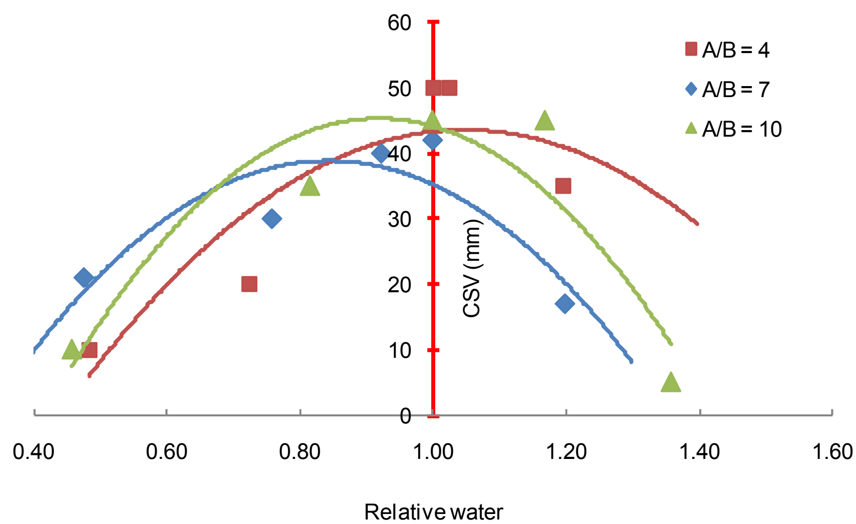
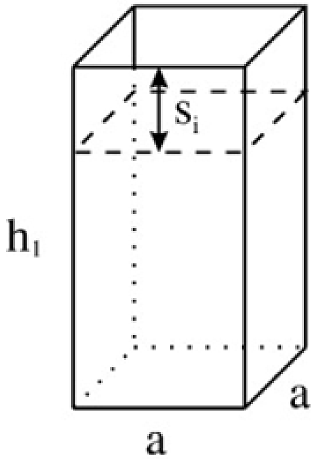


Figure I-12 Relative water versus CSV

One of the critics of this test method is the very narrow range of slumping due to the presence of the slump cone during the compaction and slumping process. This test is quite similar to the compactibility test prescribed by the German standards [11] and is reported to be used for characterizing the consistency of fresh concretes, earth-moist concrete [12]. Figure I-13 shows a schematic sketch along with the equation used in computing the compactibility.



$$c_{DIN} = \frac{h_1}{h_1 - \bar{s}} = \frac{h_1/\bar{s}}{h_1/\bar{s} - 1}; \quad \bar{s} = \frac{1}{4}\sum_{i=1}^{4} s_i.$$

Figure I-13 Sizes of the square container described in DIN-EN 12350-4. The size is 200 · 200 · 400 mm^3 and the slump is measured at four edges [12]

To appreciate the variation of compactibility (as measured by CSV) with the variation in relative volumes of the paste volume and the voids in the aggregates, β and the role of water, a 3D plot is constructed (Figure I-14). The resulting plot has a saddle like appearance and has a very good potential of being used as a tool for estimating the compactibility of a wide range of mixtures when the relative volumes of materials are known. Similar plots for different β were constructed by Khunthongkeaw and Tangtermsirikul [13] in 2D with an objective of estimating the vibration consistency of RCC mixtures used in dam construction.

It can be seen that the paste composition is vital in deciding the compactibility of a mixture. For a given β, the compactibility increases as the moisture content increases, then reaches a peak (at optimum moisture content) and then reduces. Thus, the richness of a mixture in terms of its binder content alone is not a good condition to render best of the compatibilities. At this point, it is pertinent to appreciate two things here. The first is the granular packing ability of a mixture in its dry state and second, its ability to deform under pressure (sustained, static or dynamic).

The first ability is decided by the optimization of the granular packing, the relative friction between different particles and response of the composite granular system to respond to pressure (static or dynamic). Use of higher than required binder for a given aggregate system could lead to particle interference causing the density to drop rather than progressively increase. On the other hand use of less than required binder content in an aggregate system, the voids will not be filled progressively with smaller and smaller particles leaving behind less than potentially least voids content. This also implies that for a given aggregate system there would be a narrow range (within engineering tolerances) of binder content that could be accommodated in the aggregate voids and that would render potentially the maximum density, economically with the available compaction effort.

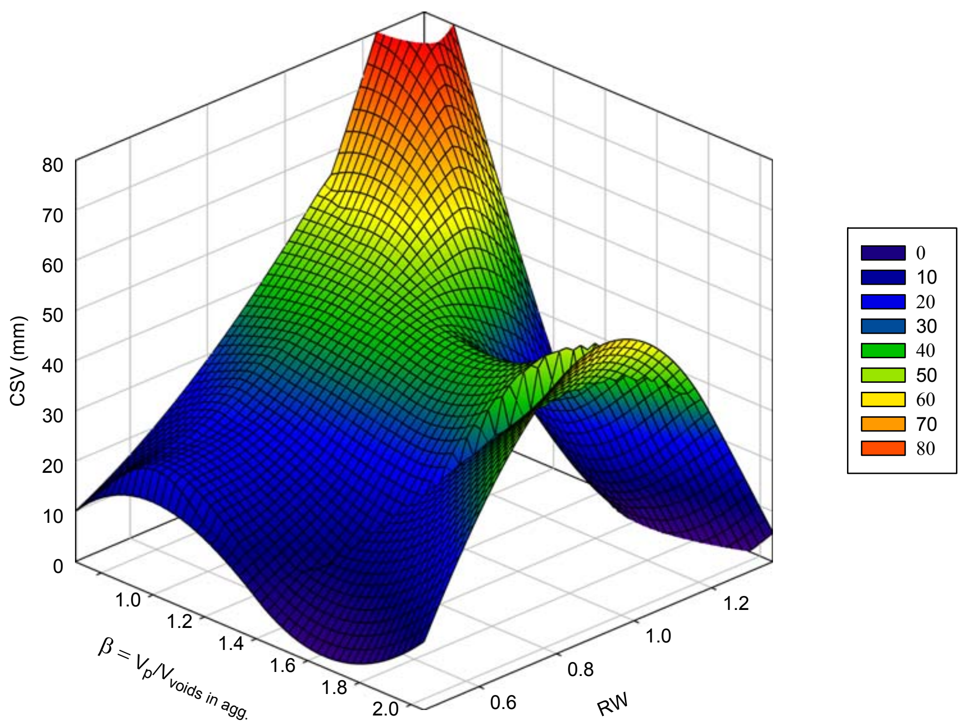


Figure I-14 Interaction of relative water (RW) and β

The second ability of deforming under applied pressure is mobilized in the presence of water. This does not mean that the dry material cannot be deformed under pressure; it simply means that the material will not assemble sufficient cohesion under normal working pressures in construction industry to stand when the form is removed. Water is the ingredient that imparts the required cohesion. In the presence of water above a certain limit, the binder is plasticized enough to initiate the process of imparting cohesion to a mixture. As the water is progressively increased, the cohesion improves leading to improvements in the compacted densities. It can be hypothesized that there must be a balance between the cohesion and friction forces that must be rendering highest possible deformation for a given compaction effort. A pre-qualification to the fulfillment of this condition from practical perspective is the self-standing ability of concrete without any forms. Thus, in summary, the forces should be so balanced and the material is so composed as to offer the highest potential to render maximum density while being able to self-stand.

The following critique on the CSV tests is important:

- The discriminative power of the test appears to be reliable within the scope of present work. However, this test method needs further testing for statistically establishing and validating it as an accepted test method by standards.
- The robustness of the test was not verified in this program. From the variation of CSV in response to the changes in the moisture contents, it appears that the test method is sensitive enough to be used in the future.
- One of the potential shortcomings of CSV test could be differential compaction responses of mixtures with varying moisture contents. The initial compaction effort in filling a slump cone is kept constant (25 strokes/layer; three layers) and so is the later vibration table compaction. The hand-compaction responses of the drier mixtures, which are very stiff, are considerably different than the corresponding responses of wetter mixtures, which are less stiff and penetrable with the rod.

I.2.5 Air content

The variations of air content as measured by pressure-meter for different mixtures are shown in Figure I-15. In general, the air content reduces as the moisture content is increased, reaches minima and then shows a slightly increasing trend. This behavior is quite typical and is discussed previously. Figure I-16 shows the variations of air contents as a function of w/b ratio for various binder contents

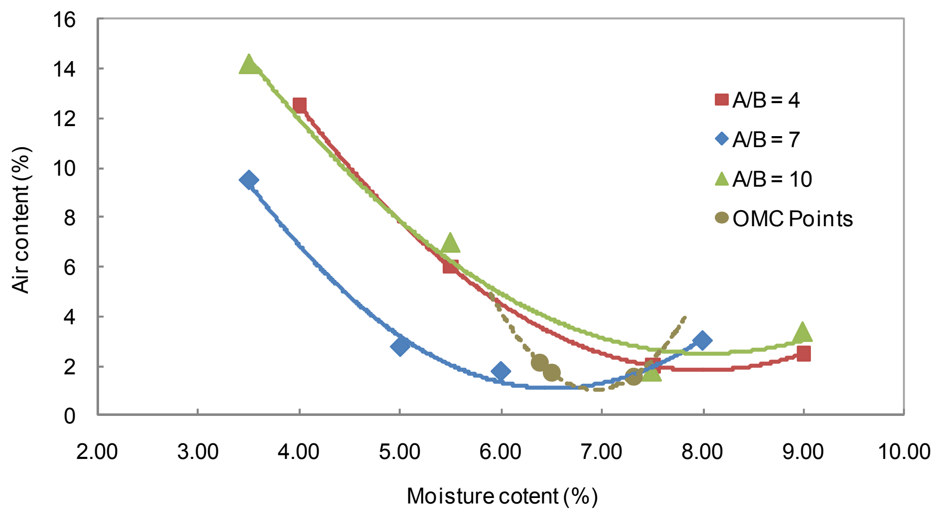


Figure I-15 Variation of air content: effects of binder moisture contents

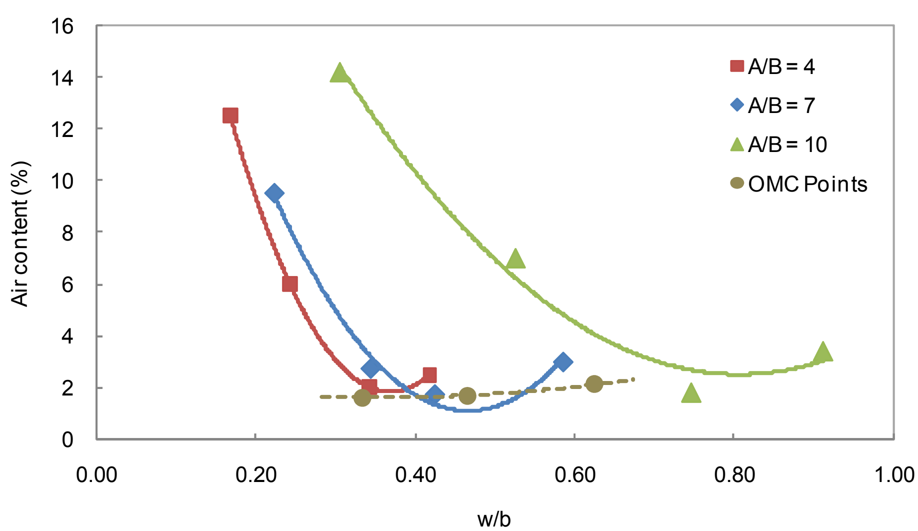


Figure I-16 Variation of air content: effects of binder contents and w/b ratio

Figure I-17 was constructed to appreciate the change of rate of air content in a mixture as a function of moisture content. The curves were obtained by differentiating the plots of moisture content versus the air content. The slopes resulting straight lines indicate that the air content responses of different mixtures to changes in the moisture contents is more or less similar. The slopes for A/B 4, 7 and 10 are 1.33, 1.81 and 1.15 respectively. The mixtures with A/B ratio of 7 are the most sensitive to the changes in moisture content in their responses in terms of air content, while mixtures with A/B ratio of 10 are least sensitive to the changes in the moisture contents.

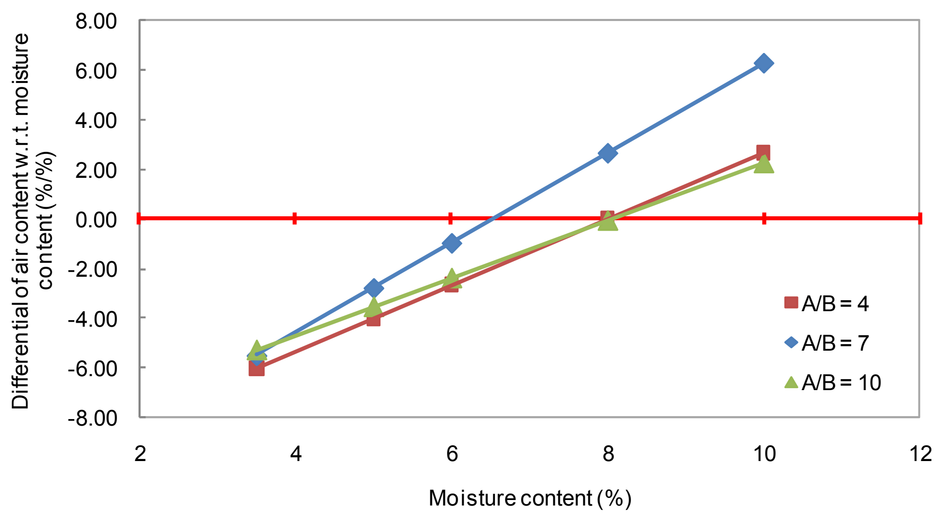


Figure I-17 Rate of change of air content as a function of moisture and binder contents

Figure I-18 is constructed to appreciate the effect of relative water on the measured air content.

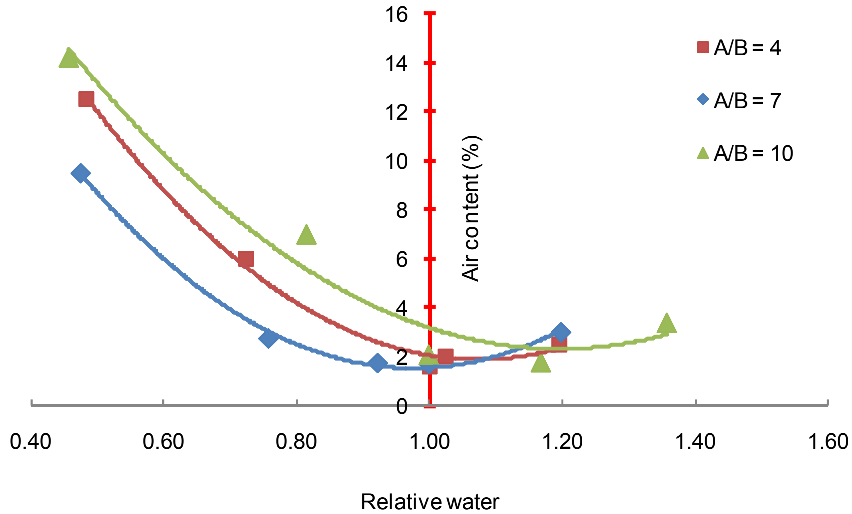


Figure I-18 Air content as a function of relative water (RW)

Figure I-19 is developed with an objective of appreciating the interaction effects of relative volumes of water, binder and aggregates on the measured air content. The effect of relative volumes of water and binder (analogous to w/b ratio) can be clearly seen in the form of a diagonal valley formed at the bottom. Again it can be seen that the paste composition is so vital that it could change the air contents dramatically. For example, for a fixed relative volume γ the changes in the relative volumes of aggregate and binder δ can make significant changes in the air contents. At lower water contents, there are significantly higher air contents present in the mixture and can be seen as a half-ridge on the right hand side of the plot. These high air contents take a very steep slope and decrease as the relative water quantity is increased. After the optimum moisture contents the increase in the water content of the mixtures does not offer significant changes in the air contents, but this is again contingent to the volumetric composition of the mixtures.

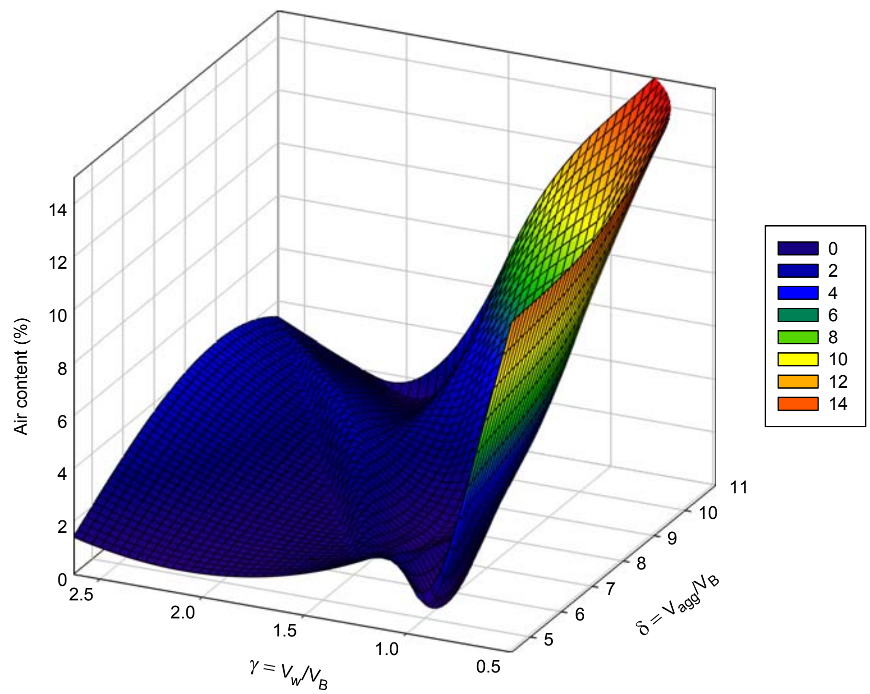


Figure I-19 Interaction effects of relative volumes of binder, water and aggregates on the air content

Figure I-20 is constructed to appreciate the importance of right quantity of water in a paste to reach the minimal air content in a mixture. It is quite interesting to note that there is a significant interaction between the relative volumes of water and paste. It needs to be stated again that the paste is composed of binder and water. Having less water than the required will lead to compaction voids or voids resulting due to lack of sufficiently plastic paste to enter into all possible voids with a given compaction effort in a stipulated time frame. On the wetter side however there could be a slight creation of excess air volume primarily due to compaction process.

An interesting aspect of this plot is that at lower paste volume, there could a deficiency of enough paste to fill all the voids at all water contents tested. Increasing water alone is not the solution, since it will only add the water part, and not necessarily the "much needed" suspension to penetrate the voids and effectively reduce the air content. Nevertheless, with increasing water content at lower paste volumes, the air content reduces. A similar behavior is observed at the higher paste volumes as well; however the air content is highly sensitive to the changes in the water content. For the intermediate paste volumes there is a gradual transition that takes place.

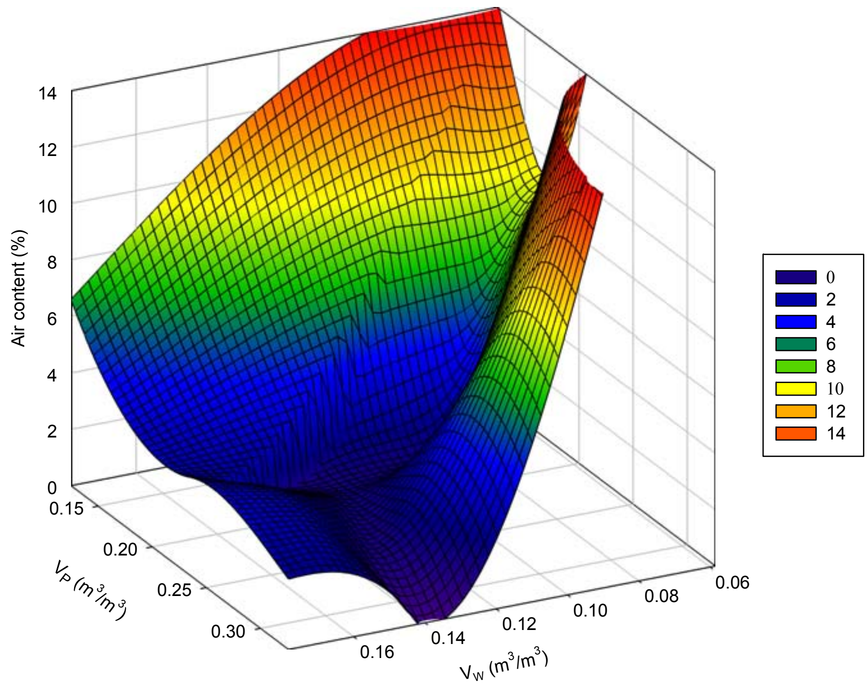


Figure I-20 Effect of water content in paste on the air content

The most interesting point of this presentation is that interaction of the paste volume and the volume of the water which is responsible for the creation of a valley-like trough in the center. If this region is observed from both sides, it appears that this is the region where there is the right quantity of water present in the paste that renders least air content. However, slight changes in the composition of the binder-water suspension can cause significant changes in the air content indicating high sensitivity. Taking another perspective also indicates that the air content shows relatively higher sensitivity to changes in the water content than the changes in the paste volume. Since the paste is only composed of binder and water, it can be concluded further that the air content is relatively more sensitive to the water content than to the binder content.

Figure I-21 shows a ternary plot of the variations of air content as a function of the composite volumes of binder, aggregate and water. The pink area is an artifact resulting from the software and may not offer physically compatible information. A caution should be exercised in interpreting this ternary plot. A construction of this kind would need more data points for improved robustness.

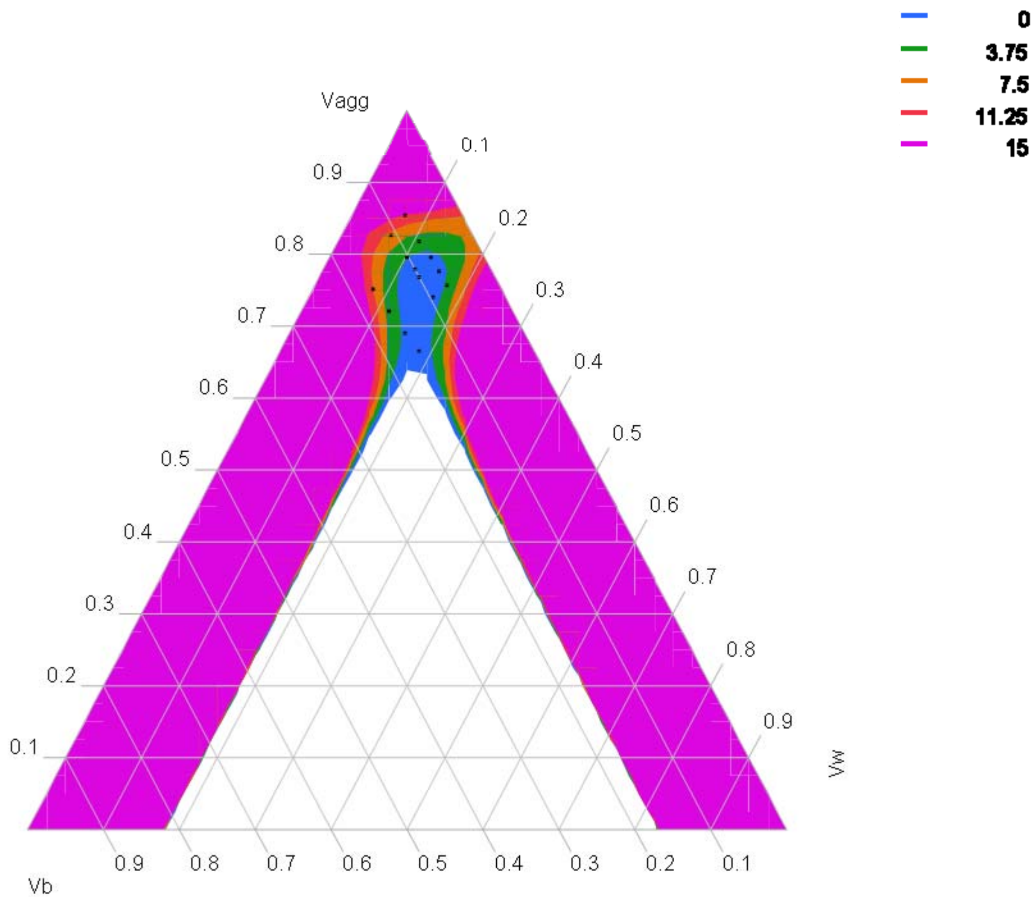


Figure I-21 Ternary diagram showing variation of air content as a function of volumetric composition of mixture.

I.2.6 Air content versus dry density

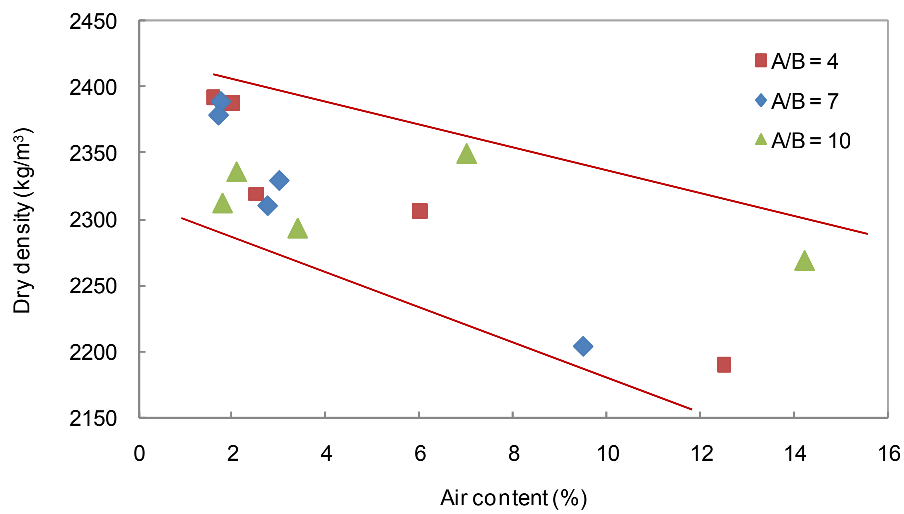


Figure I-22 Air content versus dry density: a composite picture

I.2.7 The composite picture

Figure I-23 represents the influences of the interactions of various parameters and ratios with w/b ratio as a primary parameter on the dry density. Several interactions and optimizations can be observed. Within the scope of present work, the influences of A/B, w/b, Vp, Vair are represented in these contour plots, which represent iso-density lines.. Note that the paste volume is air-free paste volume and consists of only binder and water.

It can be seen that not all and any combinations of cement-aggregate-water-air would produce just and economical concretes. In the foregoing commentary, it should be noted that the word optimization is categorically used. This means that optimization is relative, when a factor is kept constant. A caveat to this presentation is that some of the areas observed in these figures may not necessarily make physical sense; however, broad trends can be seen.

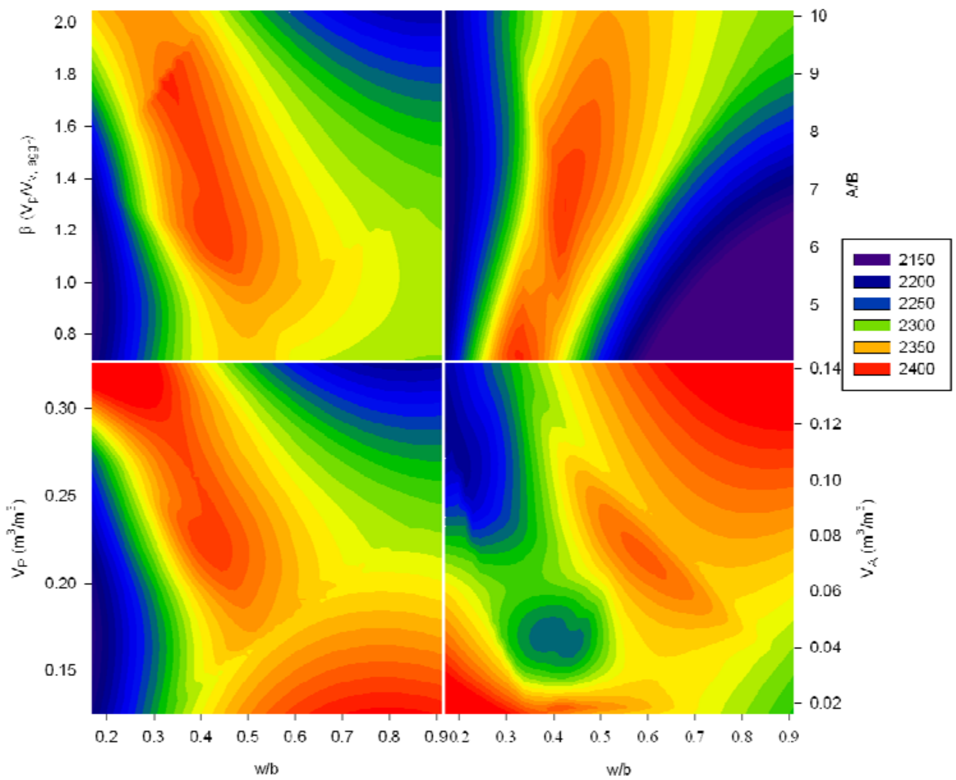


Figure I-23 Dry density (kg/m^3): Interactions of volumetrics as function of w/b, by mass

The following observations are relevant from the above figure:

- First quadrant (RHS-Top): For a given A/B, there are ranges that would produce compactable mixtures. Only a narrow range of w/b will produce optimum compaction characteristics. Similarly, for a given w/b, only typical ranges of A/B will produce good concrete. From the current study it can be seen that the dry density is optimized once at w/b close to 0.3 for A/B = 4, 0.45 for A/B = 7 and 0.6 for A/B = 0.6. This implies that as A/B ratio increases the optimal w/b ratio from maximum dry density perspective also increases. Although the water demand of aggregates systems does not change significantly, the amount of binder changes; thus reflecting in terms of higher w/b ratio with increasing A/B ratio. The smudged blue areas can be ignored.
- Second quadrant (LHS-Top): Again, there is a two-way optimization going on. There is an inverse trend observed; higher A/B ratio mixtures have lower volume

of paste/volume of aggregate voids ratio (β) and vice versa. It can be seen that the filling up of aggregate voids by binder paste plays a crucial role in optimizing the dry density behavior. It is not required to have the highest β value for an A/B ratio to achieve its potentially highest dry density. From the obtained numbers, it can be seen that having paste volumes beyond a certain limit is actually leading to dropping down of dry density, thus offering a testimony to the nuisance it creates. This can partially be explained based on the composition of paste. In the present study, the binder contents were kept constant for a given A/B ratio, while the water content was increased. This means that increasing paste volume implicitly means increase in the volume of water (and hence w/b). On the other hand, having lesser paste volume leads to incomplete filling up of aggregate voids and insufficient mobility (not close to optimal) required for full compaction thus restricting the realizing of maximum dry density, the existing binder quantity is capable of offering.

- Third quadrant (LHS-Bottom): The objective of this plot is clarify the role that the relative amounts of water and binder plays in deciding the quality of paste and their composite effect on the dry density. It can be seen that for every paste volume, there is one or more ranges of w/b ratios that would offer optimized dry densities. There would certainly be interplay of other factors that would be considered in the subsequent sections. Analyzing this from another angle reveals that having a certain quantity of water in a mixture is not sufficient for achieving certain compactibility. There has to be commensurate amount of binder that leads to a compactable mixture that could potentially achieve the highest dry density.
- Fourth quadrant (RHS-Bottom): The objective of this plot is to explain the role of air content in RCC mixtures and the sensitivity of dry density to air content vis-à-vis the w/b ratio. As a response to compaction effort a mixture can be compacted to various air contents, but individually, depending on the binder content and w/b ratio, the mixtures' responses to dry density will differ.

Figure I-24 represents the influences of the interactions of various parameters and ratios with A/B ratio as a primary parameter on the dry density. These plots are constructed to appreciate the influences and interactions caused due to the alterations in the aggregate contents of the mixtures.

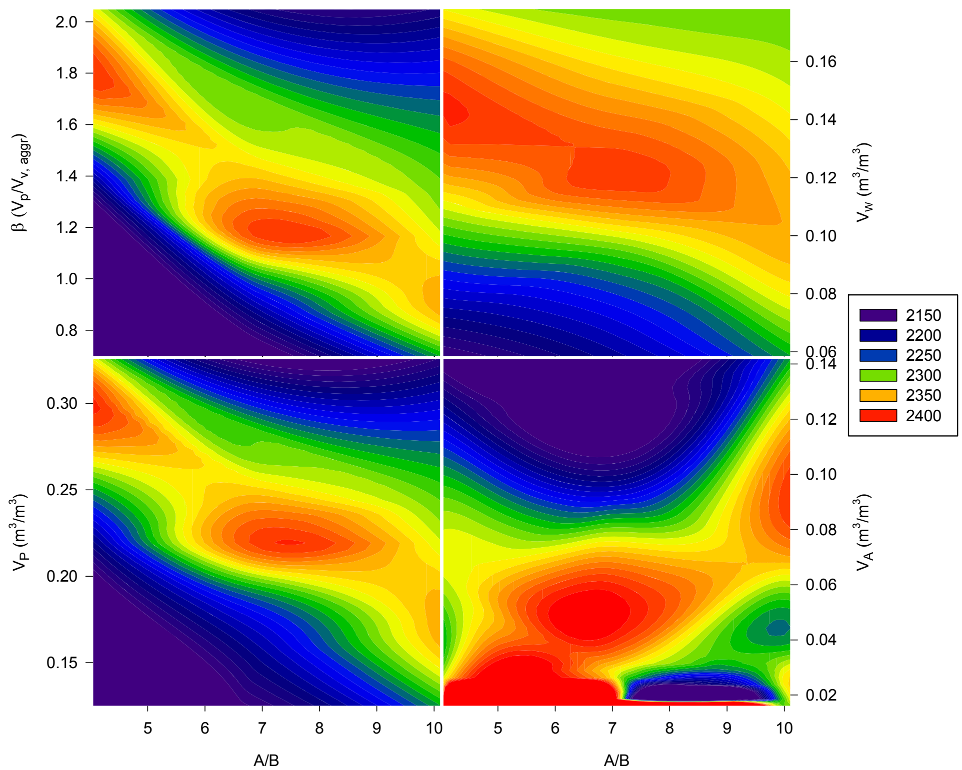


Figure I-24 Dry density (kg/m^3): Interactions of volumetrics as function of A/B, by mass

The following commentary is relevant:

- First quadrant (RHS-Top): This plot shows the interplay of A/B and volume of water. The remarkable fact that comes out of this plot is the water volume requirement for making compactable concrete that would in turn render dry density commensurate to the amount of binder used in making a concrete mixture. As A/B ratio increases the water required for reaching higher densities reduces. Having higher water is associated with corresponding nuisance value both in fresh state and from dry density perspective. It can also be noticed that a fixed A/B ratio has its own robustness and tolerance band within which the dry density is not much affected. This robustness seems to be a function of A/B ratio with higher robustness observed at higher A/B ration than at the lower end.

- Second quadrant (LHS-Top): The objective of this plot was to capture the influences of paste volume relative to voids in aggregates on the measured dry densities. With an increase in the aggregate content, the volume of voids in aggregates also increases. The ratio, β should be carefully interpreted, since, like w/b ratio it has two-fold meaning and can be altered by changing one parameter at a time or both. The effects however would be different for different changes. Nonetheless, with increasing A/B ratio the β for obtaining potentially maximum dry density decreases and vice versa. Three distinct nebulae (one partially seen) can be observed, each showing its central core of maximized dry density. An interesting thing that this plot reinstates is that not all combinations of binder-water-aggregate can make compactable concretes. There are definite demarcations and limits to the amount an individual material can be added and in turn can meaningfully and effectively contribute to a concrete property, in this case UUCS.
- Third quadrant (LHS-Bottom): This plot was evolved to simple have a feeling of the quantities of the paste volumes. It shows similar trends as the second quadrant and hence is not discussed further.
- Fourth quadrant (RHS-Bottom): The objective of this plot is to explain the role of air content in RCC mixtures and the sensitivity of dry density to air content vis-à-vis the w/b ratio. As expected, higher dry densities are obtained at the bottom of the air content axis. Another perspective on this is that every A/B ratio has a range of *tolerable air content* for which the mixture dry density will not be affected substantially; once this range is crossed, there will a dramatic drop in the dry density. Richer mixtures are quite sensitive to dry density changes in response to changes in the air contents, while leaner mixes do not show such sharp responses. Due to the combined effect of the amount of paste and higher A/B ratio, higher air is caught up in these mixtures for a given compaction effort. An important note about the large red bulb seen at the LHS bottom corner is that it would need further magnification to interpret the trends.

Figure I-25 presents the data on the volumetric basis. All the trends have been discussed in the previous two sections; hence, no further elaboration is presented here.

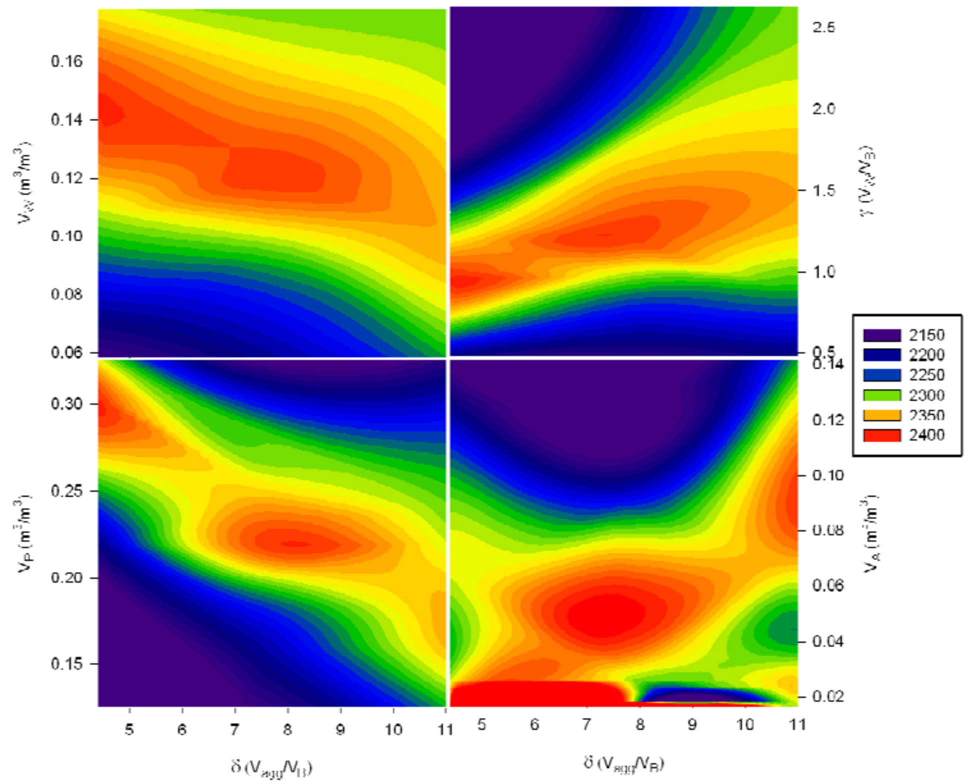


Figure I-25 Dry density: Volumetric relations and interactions influencing strength

I.3 Primarily water reducing admixtures

15.1.1 Water reducer: type A for normal concrete

Type A admixture (P-06) was used in assessing the effectiveness of this admixture in different RCC mixtures. The manufacturer of this product claims more complete hydration of Portland cement with no effect on concrete air entrainment and a typical water reduction of 3-10%. The recommended dosage is in the range of 0.130 to 0.455 lit/100kg of cement for normal concretes. Table15-2 presents the experimental plan.

Table I-2 Experimental plan for a Type A water reducer

Binder content (kg/m^3)	A/B	Dosages (%, w/w of binder)					Remarks
		1	2	3	4	5	
205	4	0.00	0.50	1.50	3.00	--	
282	7	0.00	0.19	0.75	1.50	3.00	Detailed investigation
446	10	0.00	0.50	1.50	3.00	--	

Figure I-26 shows the water reduction of this admixture as a function of the dosage for various binder contents. The water reduction for rich mixtures (A/B = 4) ranged between 0 and 17%, intermediate mixtures (A/B = 7) between 2 to 19% and lean (A/B = 10) between 11 and 30%. It can be seen that for a given dosage of admixture the water reduction increases as the binder content decreases. Initially for rich mixtures, higher dosages are required for mobilizing the water reducing and plasticizing ability. As the binder content reduces, the admixture volume required to mobilize the manifestation of the anticipated water reducing effect is reduced. As such even with smaller dosage of admixture measureable water reduction is produced. A caveat to this s the fact that for leaner mixtures the initial dosage was 0.50%.

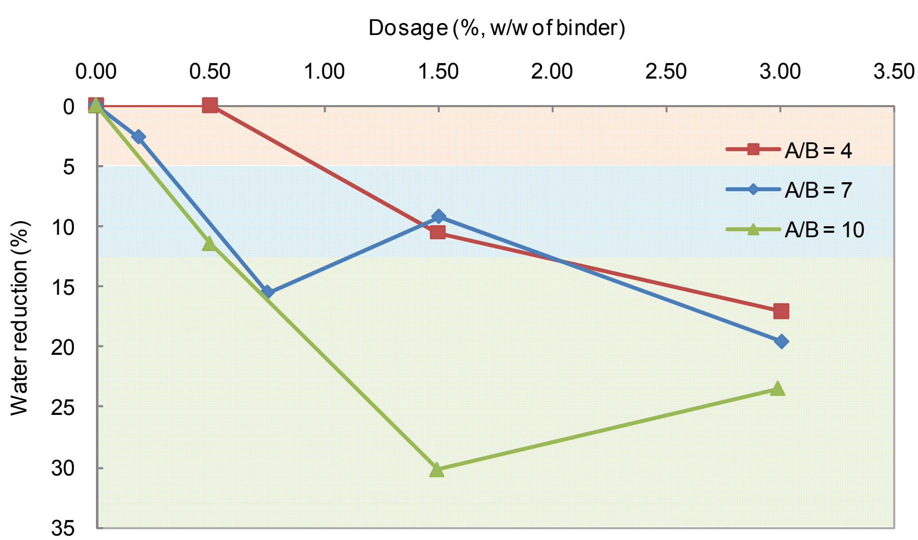


Figure I-26 Effect of admixture dosage and binder content on water reduction: P-06

I.3.1 Water reducer: type A, B, D for normal concretes

Admixture meeting the ASTM C494 requirements for Type A, B, D admixture (P-11) was used in assessing the effectiveness of this admixture in different RCC mixtures. The manufacturer recommended dosage is in the range of 0.130 to 0.399 lit/100kg of cement for normal concretes. Table I-3 presents the experimental plan. The dosages were fixed at 0.25, 1.00 and 2.00% w/w of binder for all the binder contents. The corresponding water reduction, fresh properties and strength development were evaluated.

Table I-3 Experimental plan for a water-reducing cum retarding admixture: Type A, B, D (P-11)

Binder content (kg/m^3)	A/B	Dosage (%, w/w of binder)		
		1	2	3
205	4	0.25	1.00	2.00
282	7	0.25	1.00	2.00
446	10	0.25	1.00	2.00

Figure I-27 shows the water reduction of this admixture as a function of the dosage for various binder contents. The water reduction for rich mixtures (A/B = 4) ranged between 7 and 23%, intermediate mixtures (A/B = 7) between 0 to 13% and lean (A/B = 10) between 0 and 22%. For this admixture at a given dosage, the water reduction increases as the binder content increases. Initially for rich mixtures, higher dosages are required for mobilizing the water reducing and plasticizing ability. The effect produced by this admixture is complementary to the effect produced by the above admixture in terms of the binder content effects. In terms of the water reducing capability, both the admixtures produced similar results.

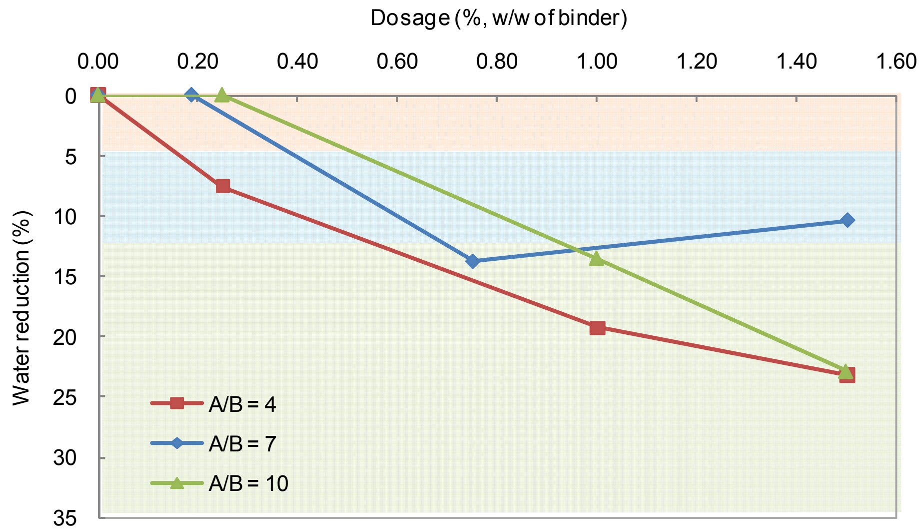


Figure I-27 Effect of admixture dosage and binder content on water reduction: P-11

I.3.2 Water reducer: type B and D for normal concretes

Admixture meeting the ASTM C494 requirements for Type B (retarding) admixture (P-13) was used in assessing its effectiveness in different RCC mixtures. The manufacturer recommended dosage is in the range of 0.130 to 0.266 lit/100kg of cement for normal and mass concretes. This admixture is a strong retarder and is expected to delay the setting times, reduce w/b ratio and improve the density of the mixtures. Table I-4 presents the experimental plan. The dosages were fixed at 0.20, 0.60 and 1.20% w/w of binder for all the binder contents. The corresponding water reduction, fresh properties and strength development were evaluated.

Table I-4 Experimental plan for a retarding admixture: Type B (P-13)

Binder content (kg/m^3)	A/B	Dosage (%, w/w of binder)		
		1	2	3
205	4	0.20	0.60	1.20
282	7	0.20	0.60	1.20
446	10	0.20	0.60	1.20

Figure I-28 shows the water reduction of this admixture (P-13) as a function of the dosage for various binder contents. The water reduction for rich mixtures (A/B = 4) ranged between 0 and 10%, intermediate mixtures (A/B = 7) between 0 to 18% and lean (A/B = 10) between 0 and 26%. For this admixture at a given dosage, the water reduction increases as the binder content increases. Irrespective of the binder content, dosages higher than 0.2% are required for mobilizing the water reducing and plasticizing ability. This being primarily a retarder does not have a comparable water reduction as the other water reducers do and can be classified as a mid-range water reducer.

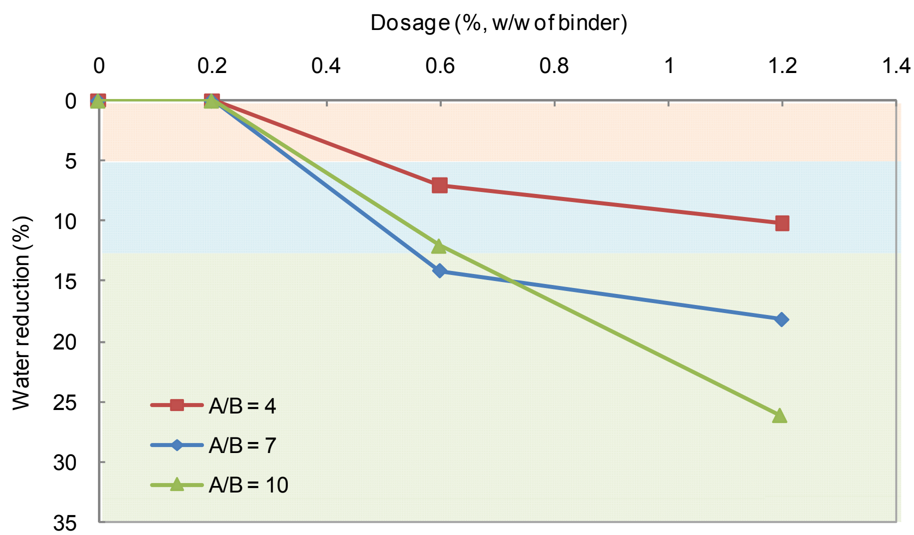


Figure I-28 Effect of admixture dosage and binder content on water reduction: P-13

Since this admixture is primarily a retarder, there could be a competitive adsorption between the water reducing and retarding components of the admixture. these effects could mutually compete with each other depending on the ionic charge density leading to one component dominating the other [14].

I.3.3 PC-based water reducer

A polycarboxylate based admixture meeting the ASTM C494 requirements for Type A and F admixture (P-05) was used in assessing its effectiveness of this admixture in different RCC mixtures. The manufacturer recommended dosage is in the range of 0.341 to 0.650 lit/100kg of cement for normal concretes. Table I-5 presents the experimental plan. The dosages ranged between 0.19 and 3.00% w/w of binder for all the binder contents. A thorough investigation at various dosages was conducted for the intermediate binder content, while the A/B contents of 4 and 10 were tested at lesser frequency of dosages.

Table I-5 Experimental plan for PC-based water reducer

Binder content (kg/m^3)	A/B	Dosages (%, w/w of binder)							Remarks
		1	2	3	4	5	6	7	
205	4	0.00	0.25	1.50	3.00	--	--	--	
282	7	0.00	0.19	0.56	1.13	1.69	2.25	3.00	Detailed investigation
446	10	0.00	0.25	1.50	3.00	--	--	--	

Figure I-29 shows the water reduction of this admixture (P-05) as a function of the dosage for various binder contents. The water reduction for rich mixtures (A/B = 4) ranged between 0 and 22%, intermediate mixtures (A/B = 7) between 0 to 29% and lean (A/B = 10) between 0 and 31%. This admixture was a broad range water reducer implying it could be used for low-, mid- and high range water reduction. The intermediate binder content is reaching close to its saturation dosage where its effectiveness in reducing the water further is tending to reduce.

Similar data is represented in Figure I-30 in 3D. It can be seen that the water reduction is binder content specific. Irrespective of the binder content the water reduction increases as the admixture dosage is increased. For the intermediate binder content the admixture shows higher responsiveness. This could possibly be due to the optimal effectiveness of this admixture for this binder content range. A premise that could be offered to this behavior is as follows. A composition of binder has a specific surface area and the admixture has a specific effectiveness over that surface area.

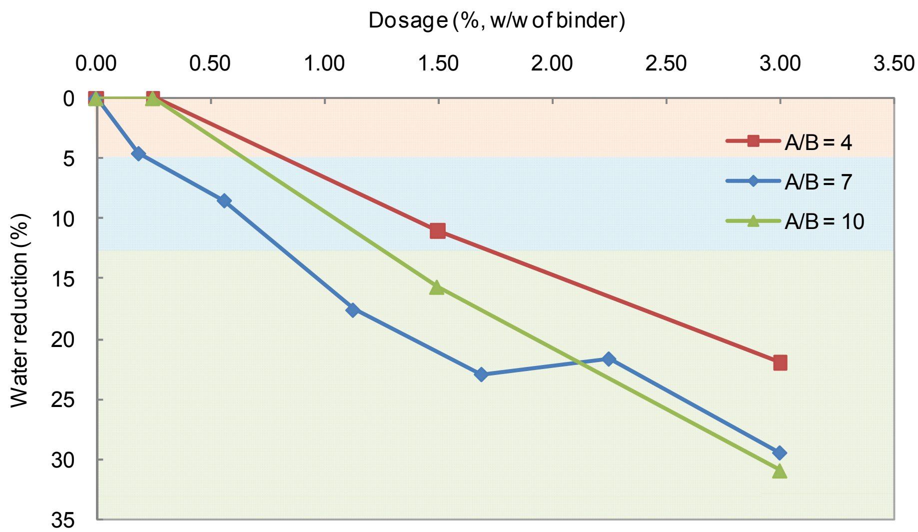


Figure I-29 Effect of admixture dosage and binder content on water reduction: P-05

In a similar research investigating the effect of specific surface area of cement on the effectiveness of PNS admixture dosage, the following conclusions were made:

- The effect of the fineness of cement on cement-superplasticizer interaction seems to be largely dependent on the chemical composition of cement
- The effectiveness of a particular admixture is dosage and specific surface area dependent. The rheological properties may not show a sizeable difference with either lower or higher specific surface are of cement, but could have a possible range of effectiveness [15]

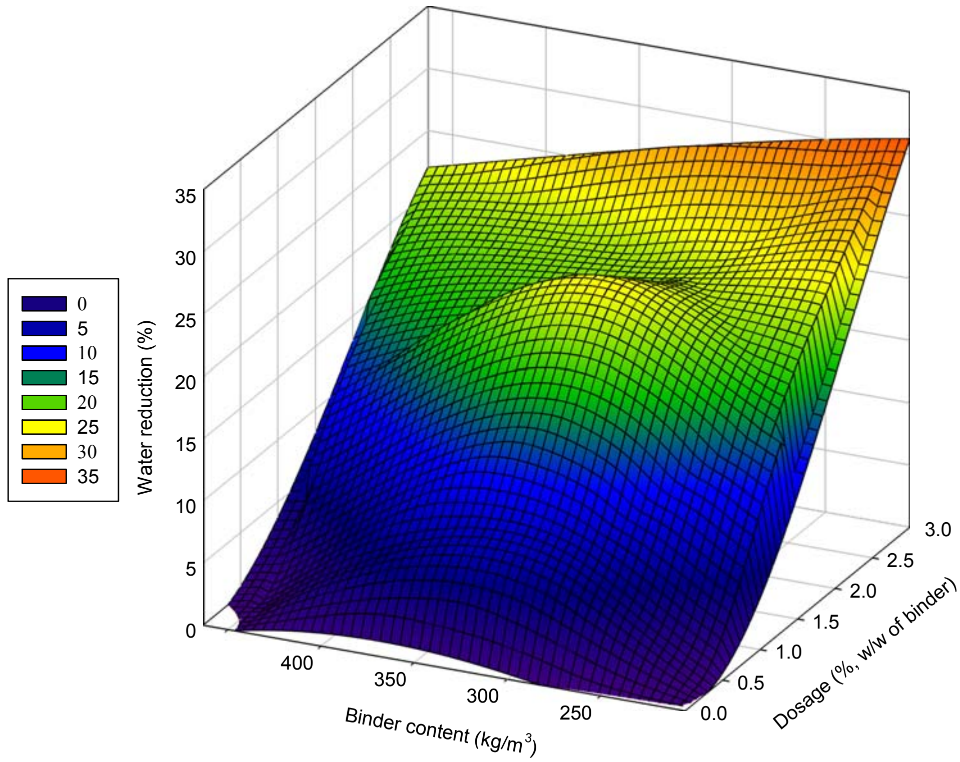
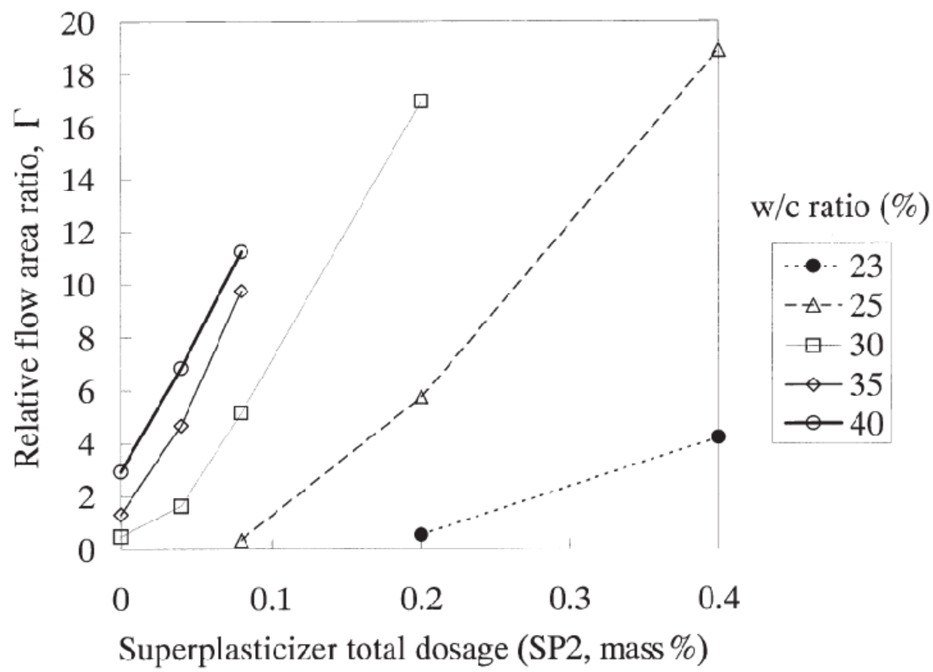


Figure I-30 Interaction effects of binder content and admixture dosage on water reduction: P-05

Yamada, et.al. [16] in their studies on polycarboxylate-type superplasticizers with polyoxyethylene side chains observed that effectiveness of a SP is dependent on the w/c ratio of the mixture. In a region of higher w/c ratio, the effects of w/c ratio on the fluidity were not very significant, while the effects were more significant at lower w/c ratio. This is shown in Figure I-31. The fluidity was more sensitive to admixture dosage in higher w/c than in lower w/c. at lower w/c ratio; a slight fluctuation of water content in concrete can cause large variations of the fluidity. At higher w/c ratio, a small fluctuation of water content can be negligible but a small fluctuation of the amount of SP can cause significant variations in the fluidity.



I-31 Superplasticizer dosage versus flow area ratio [16]

The point that is relevant to this research is the consideration from the perspective of w/b ratio. For richer mixtures, the w/b ratios were very low ranging between 0.25 to 0.33, while for the lean mixtures, the w/b ranged between 0.40 to 0.62. Since the w/b ratio for lean mixtures were quite high including the control mixture (w/b = 0.62). The higher w/b ratios make these mixtures highly sensitive to the changes in the SP dosages. With richer and hence lower w/b ratio mixtures, the sensitivity of the SP is reduced and can be seen by the reduced slope of the line.

Quite interestingly, the intermediate binder content mixtures showed highest sensitivity to the variation in the admixture dosage. One of the hypothesis that can be proposed for this is the possibility of most optimum particle packing (from cement particles to aggregate) occurring near the intermediate binder content. This combination of aggregate and binder may be highly optimized and sensitive to the changes in the water content and also SP dosage. A combination of these two effects could be resulting into the highest water reduction amongst the tested binder contents. Another thing that could influence would be as follows. Any admixture has a certain efficiency to wet the binder particles. The relative volumes of the admixture and the surface area of the binder to be wetted could play a decisive role in the process of fluidification.

I.3.4 Ligno-based water reducer

A detailed investigation was undertaken to compare the PC-based with a ligno-based water reducer. The selected ligno-based water reducer was claimed by the manufacturer to behave as type A, B, D and F and for extended applications as type G admixture. Table I-6 revisits the dosage comparison.

Table I-6 PC-, Ligno-based admixture dosage comparison

Product chem.	A/B	Dosages in %, w/w of binder														
		4				7							10			
	Prod.	1	2	3	4	1	2	3	4	5	6	7	1	2	3	4
PC-	P-05	0.00	0.25	1.50	3.00	0.00	0.19	0.56	1.13	1.69	2.25	3.00	0.00	0.25	1.50	3.00
Ligno-	P-10	0.00	0.25	1.50	3.00	0.00	0.25	0.75	--	1.50	2.25	3.00	0.00	0.25	1.50	3.00
Remarks						Detailed investigations										

Figure I-32 shows the water reduction of this admixture (P-10) as a function of the dosage for various binder contents. The water reduction for rich mixtures (A/B = 4) ranged between 0 and 17%, intermediate mixtures (A/B = 7) between 0 to 20% and lean (A/B = 10) between 0 and 33%. This admixture was a broad range water reducer implying it could be used for low-, mid- and high range water reduction. Clear trends were seen with changes in both the admixture dosage the binder content. The effectiveness of water reducing admixture increased with the increase in the dosage irrespective of the binder content. As the binder content increased, for a given a dosage, the water reduction increased as the binder content reduced. It is interesting to note that the total volume of the admixture also increases as the mixture becomes richer, although the normal values (in terms of %, w/w of binder) may appear to be similar. The water reduction may appear to be similar but the percussions of high dosing vis-à-vis the binder content could manifest in terms of other properties of fresh, transitional and hardened concrete properties.

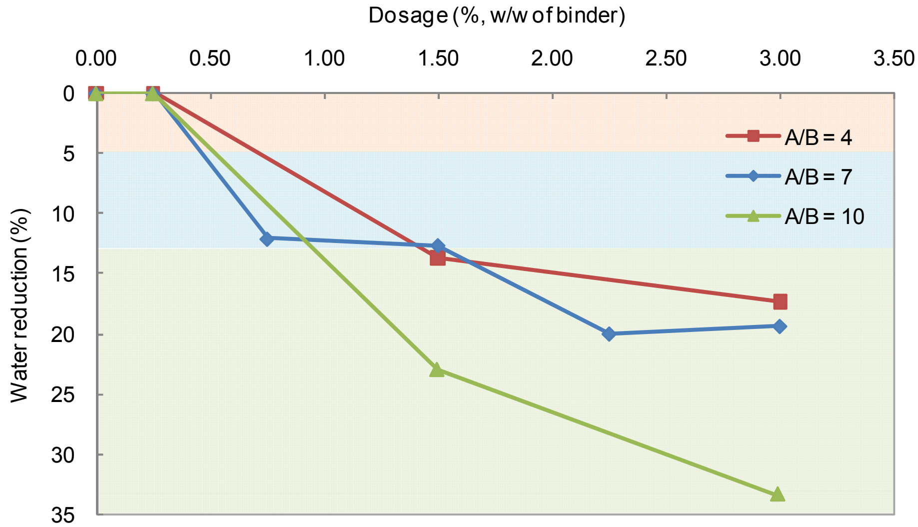


Figure I-32 Effect of admixture dosage and binder content on water reduction: P-10

Figure I-33 shows the interaction effects of the admixture dosage and binder content on the admixed concrete mixtures' water reductions. The intermediate and rich mixtures are showing a saturation effect, meaning the incremental advantage obtained in terms of water reduction with the increasing admixture dosage is reducing. Unlike the PC-based admixture the test matrix for this admixture is not able to capture the most effective range of binder vis-à-vis the admixture dosage.

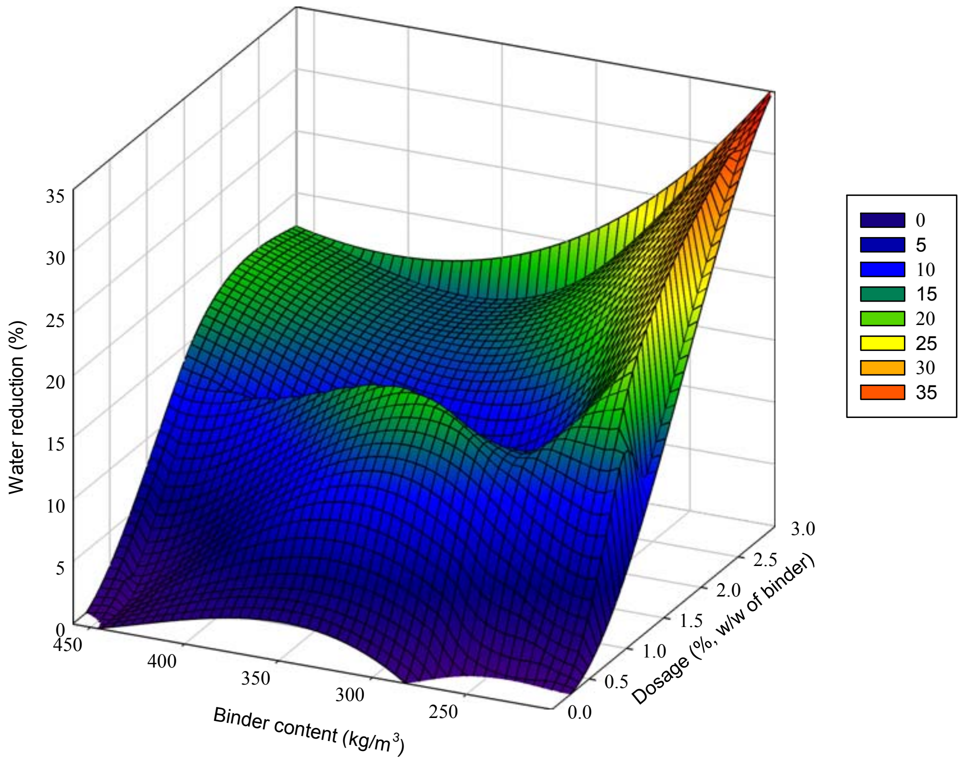


Figure I-33 Interaction effects of binder content and admixture dosage on water reduction: P-10

I.3.5 Comparison between PC-based (P-05) and Ligno-based (P-10) water reducers

Figure I-34 shows a binder content specific comparison for these two water reducers as a function of their dosage. From the comparison it can be seen that the Ligno-based water reducer is more effective in water reduction for lean mixtures, while the PC-based admixture is relatively more effective in reducing water for intermediate and rich mixtures. Amongst the later two binder contents, as the mixture becomes richer the relative effectiveness of Ligno-based water reducer reduces when compared to the PC-based water reducer

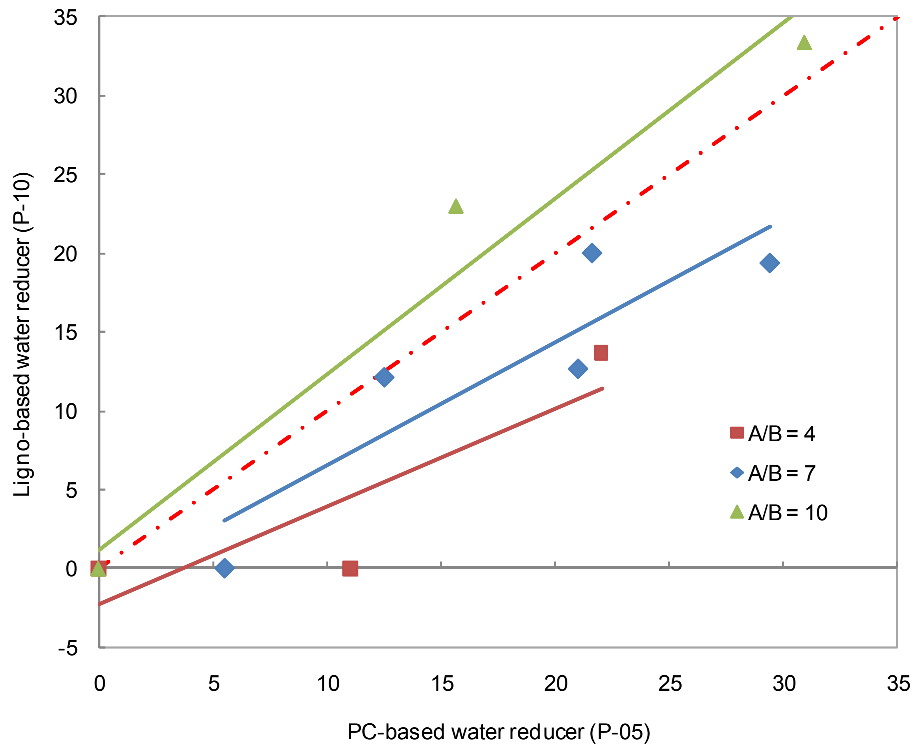


Figure I-34 Comparison of water reduction by Ligno-based and PC-based water reducers

A further analysis for comparing the performances of these two water reducers was performed using JMP. Figures 15-35 indicate the results of the correlation and the paired t-test. The correlation diagram was constructed using the water reductions at similar admixture dosages and shows that there is a good correlation between the water reductions of these two admixtures. The R2 value is 0.78 and the correlation equation is as follows:

$$(WR)_{P\text{-}10} = 0.8736(WR)_{P\text{-}05} + 0.2803$$

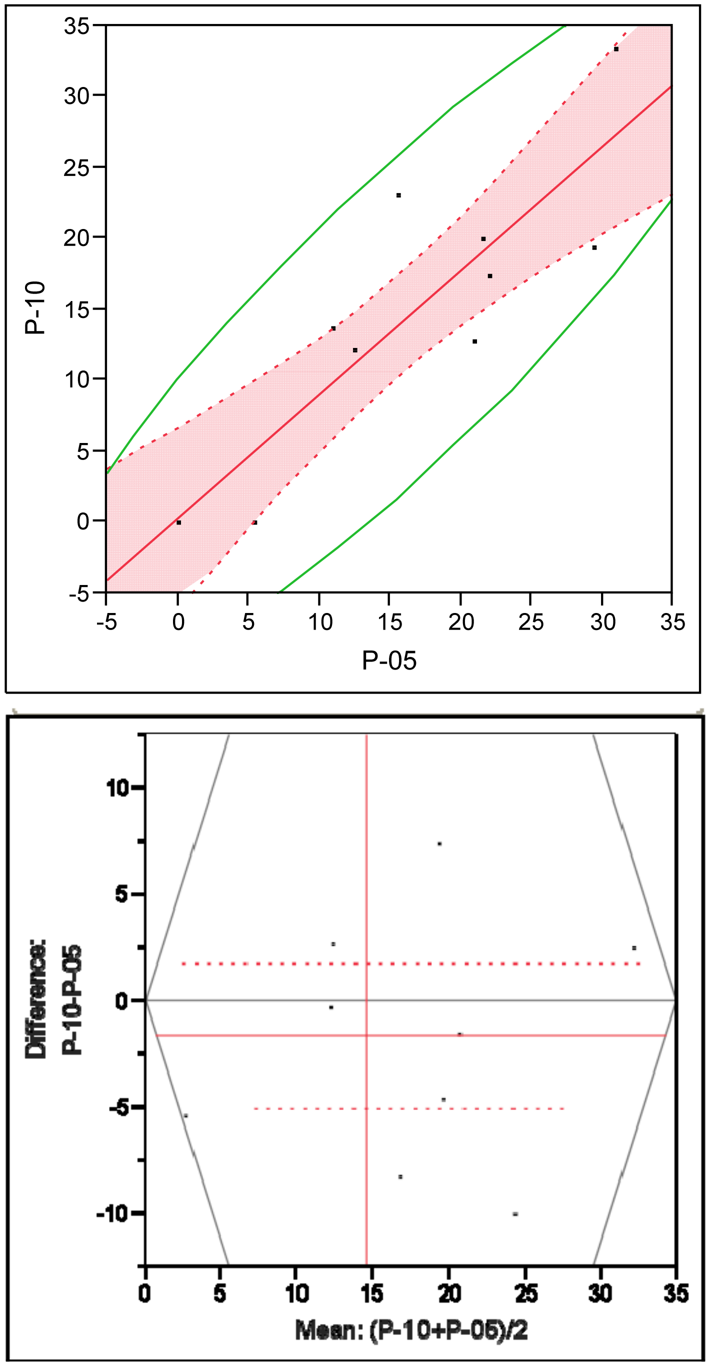


Figure I-35 JMP analysis showing the correlation between the water reduction of PC-based versus Ligno-based water reducer. Lower figure shows the two-paired t-test plot.

The paired t-test indicates an average difference of 1.66% in water reduction between this pair of water reducers.

I.4 Primarily air entraining admixtures

The objective of this part of the work was twofold (Table I-7):

- To find the best admixture chemistry from workability perspective and
- On the selected chemistry, the effect of binder content was to be studied

Table I-7 Experiments on AEA's

A/B	SD (P-19)				WH (P-20)			MR (P-21)		
	1	2	3	4	1	2	3	1	2	3
4	0.10	0.35	0.70	--	--	--	--	--	--	--
7	0.076	0.188	0.376	0.700	0.150	0.300	0.750	0.076	0.188	0.376
10	0.10	0.35	0.70	--	--	--	--	--	--	--

15.1.1 Effect of chemistry

Although the AEA's are not used as a water reducing admixtures, they can potentially reduce the water content of the mixture, primarily due to the ball-bearing effect [17] caused by the entrainment of millions of air bubbles. The bubbles plasticize paste in concrete and besides increasing the consistency or reducing the water demand for a given consistency, these also improve the workability. However, it should be noted that practice requires more than just water reduction, it requires retention of workability. And being primarily surfactants, the AEA's do not interfere with the proceedings of hydration leading to conventional drop in consistency, as if the mixture is not having any retarding aid.

Figure I-36 shows the relative water reduction for the three chemistries used in this work. A saturation dosage is reached for the SD- and MR-based water reducer, while the WH-based AEA still shows an increasing trend although the slope is reduced. For all the AEA's there is a minimum dosage required before these can manifest a water reducing effect. This start-up dosage is chemistry dependent and the effect is captured for one of the AEA's. This may perhaps be due to the fact that the mixtures dealt in this work are drier mixtures. At lower dosages the plasticizing effect of AEA's is utilized in overcoming the initial barrier due to the dryness of the mixture or lack of water. Once this barrier is overcome, then the resulting fluidification can be utilized in the form of water reduction. In case of surfactant based AEA's, at low dosages, the surface tension of the solution of water-AEA is not reduced.

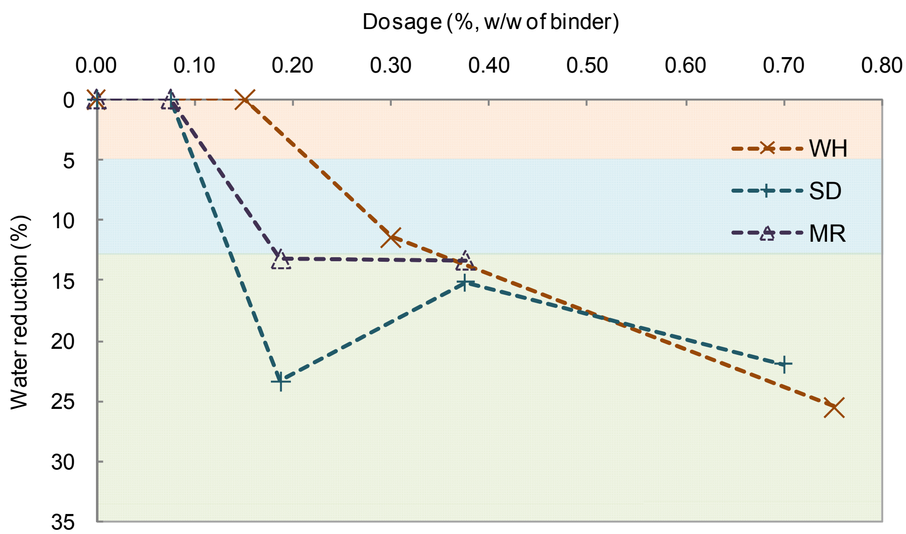


Figure I-36 Effect of AEA chemistry, dosage and binder content on water reduction: P-19, 20, 21

Typically, AEAs are composed of a mixture of surfactants with different molecular weights and the adsorption. AEA's primarily tend to reduce the surface tension of water (= 76 mN/m in pure state). The surface tension of a liquid decreases as the concentration of the (monomer) surfactant in solution increases (assuming positive adsorption) up to the point of surface saturation. In addition to this, there is a finite time requirement during which the surfactant in the solution must diffuse to the interface in order to lower the surface tension. These two surface tension effects are usually complementary [18]. The foaming capacity of a surfactant depends primarily on its effectiveness to reduce the surface tension of the solution, its diffusion characteristics, its properties with regard to disjoining pressure in thin films, and the elastic properties it imparts to interfaces [19]. Different kinds of surfactants have different adsorptive behaviors on hydrating cement [20]. The addition of surfactants to water may significantly reduce the surface tension at water and air/vapor interface. At very low dosages, the surface tension of the solution is not reduced, implying that a minimum dosage of AEA is required in concrete for the surfactant to produce air bubbles. The surfactants in the liquid phase, beyond the amount adsorbed on solid (hydrating) surface, are responsible for foaming behavior. For high dosages, there is a phenomenon called micelle formation that accounts for the limit of surface tension reduction. A micelle (refer to Figure I-37) is the aggregation of surfactant molecules and may be viewed simplistically as structurally similar to solid crystal or crystalline hydrate. Above a certain surfactant concentration [critical micelle concentration (cmc)] the monomer concentration is almost constant and the micelle concentration increases with surfactant concentration. The micelles do not contribute to the reduction of surface tension. This likely accounts (partly) for the observation that there is a maximum amount of any admixture dosage beyond which there is no more increase in entrained air.

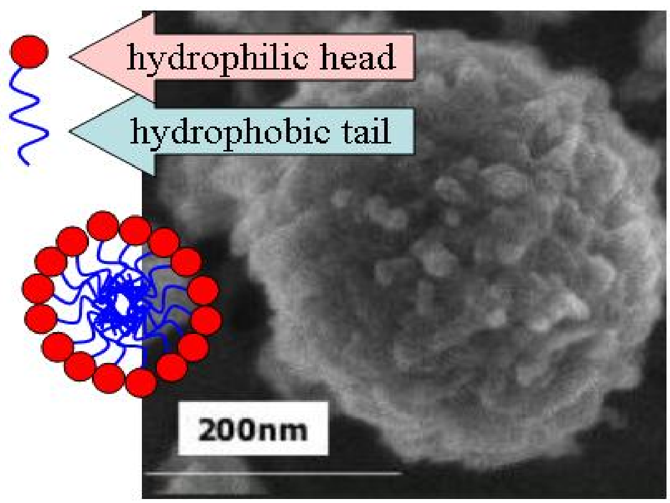


Figure I-37 A Casein micelle [21]

Another perspective was obtained by plotting the water reduction versus measured air content. A caution needs to be exercised in interpreting Figure I-38 is that the air content is measured using pressure-meter method. This air is inclusive of the entrapped and entrained air content and no differentiation between the entrained and entrapped air content can be made on the basis of the obtained results. The following discussion is relevant. It is known that up to a certain point, as the slump of a mixture increases the air content increases [17, 22]. It is noted before that the air could get entrapped if there is a lack of water and it is quite (at least in a specific region) possible to have similar air contents for two different water contents, one on the drier side and one on the wetter side.

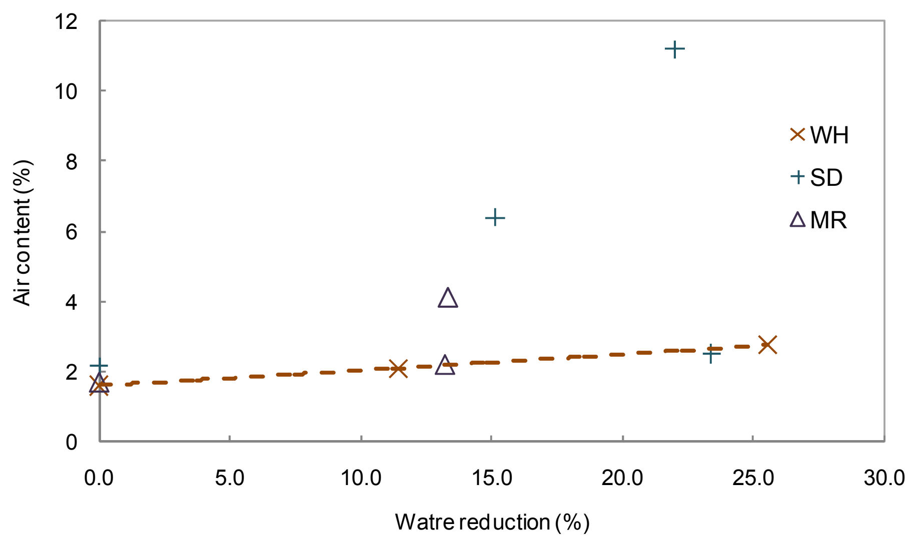


Figure I-38 Water reduction versus air content: effect of admixture chemistry

Taking into account the above two points and considering Figure I-38, it can be seen that the air content varies linearly with water reduction for the WH-based AEA, while constructing such relations on the basis of available test results is difficult. In case of SD-based AEA, the lower air content with higher water reduction could not be fully explained. However higher water reduction accompanied by higher air content can perhaps be explained. For all these tests, the air contents were measured between 10-20 min after mixing. This time frame may not account for the stabilization of air contents in the concrete, which could possibly have entrapped air as well. In case of the MR-based AEA, the doubling of dosage from 0.18 to 0.37 % did not change the water demand significantly. The air content however showed a slight increase from 2.2 to 4.1 %, which may perhaps be not statistically significant.

I.4.1 Detailed study on SD based

Figure I-39 shows the water reduction of this admixture (P-19) as a function of the dosage for various binder contents. The water reduction for rich mixtures (A/B = 4) ranged between 0 and 12%, intermediate mixtures (A/B = 7) between 0 to 23% and lean (A/B = 10) between 0 and 27%. In general as the binder content increased, the water reduction for a given admixture dosage reduced. Moreover, as the dosage of the AEA increased the water reduction also increased, however the ability of the AEA to reduce water decreases with the increasing binder content. This could be explained on the basis of the fact that lower binder content also mean lower surface area of the charged sites where the surfactants have to act. With lower volume of adsorbed admixture, more volume is available for entraining air and this fluidizing the paste. With all the binder contents and tested dosage ranges, the saturation dosage in terms of water reduction seems to have approached. This is evident from the flattening of the dosage versus water reduction plots.

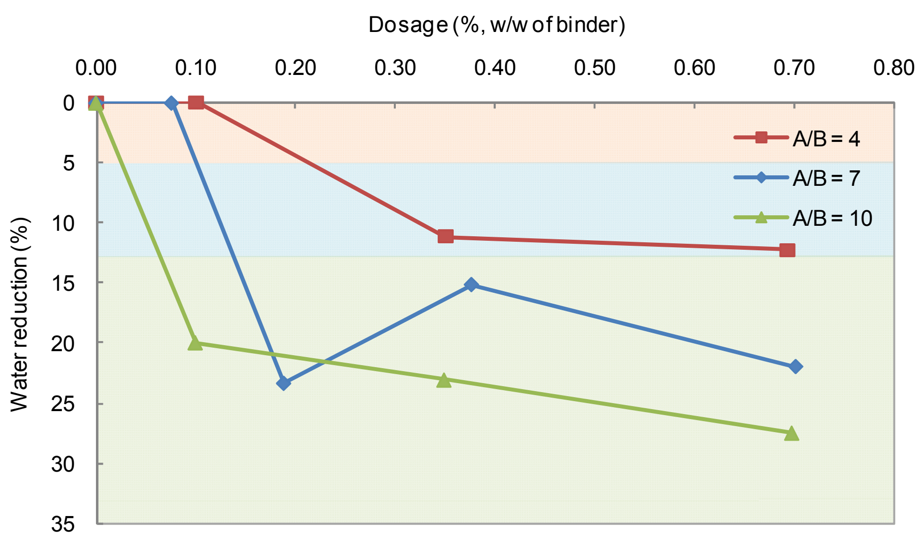


Figure I-39 Effect of admixture dosage and binder content on water reduction: P-19

The quantity of the air content vis-à-vis water reduction can be appreciated from Figure I-40. In general, it can be seen that the air content increases with increasing water reduction at a fixed initial consistency. This can partially be explained on the basis of the fact that AEA's, although can act to improve the paste fluidity, they cannot maintain that fluidity if the air bubble system is not stable. Moreover, the AEA's do not intermingle with hydration, neither encouraging nor discouraging it. In addition to this, if the water reducing potential of AEA is exploited without a harmony with its air entraining potential, then the possibility of rendering a relatively drier mixture cannot be denied. A mixture of this type would initially show very good appearance and pleasing Finishibility, but the life of this appearance is very short-lived. As such for a fixed compaction effort, the mixture could have higher air content possibly due to entrapped air rather than entrained air. Although the later part of the argument cannot be substantiated with physical evidence in the form of measured air void parameters, the rate of loss of consistency can offer some explanation of the drying out of mixture in the presence of diminishing surfactant effect.

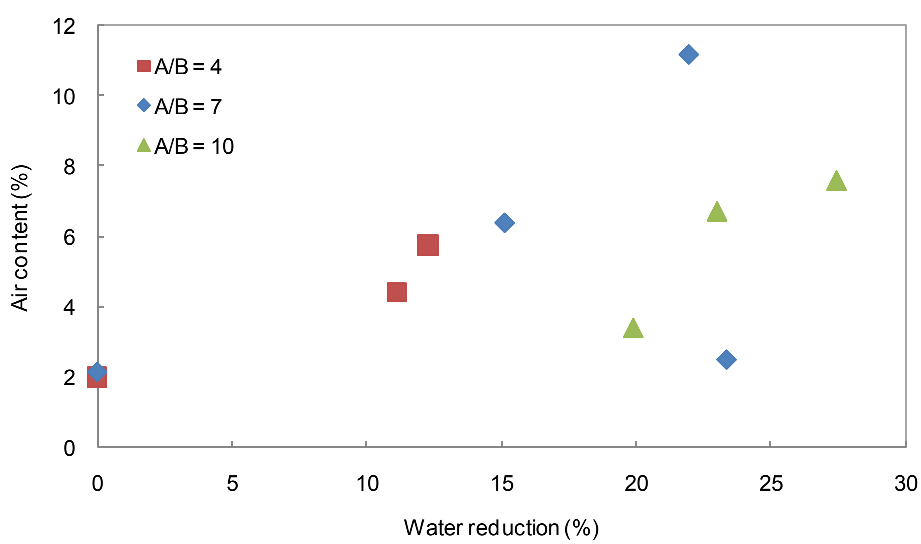


Figure I-40 Water reduction versus air content: effect of binder content, P-19

I.5 The rheology modifiers

Two rheology modifiers were tested in detail for the modifications in the fresh properties of concrete. These were the starch based rheology modifier (P-24) that was claimed to primarily affect the yield value of concrete and the welan-gum based rheology modifier (P-25), which was claimed to primarily affect the viscosity of the concrete. The manufacturer recommended dosages for P-24 and P-25 are 0.5 to 2.3 lit/100kg and 0.039 to 0.46 lit/100kg of cement. Table I-8 summarizes the test matrix.

Table I-8 Test matrix for rheology modifiers

A/B	Starch based (P-24)			Welan gum based (P-25)		
	1	2	3	1	2	3
4	0.25	1.00	--	0.4	1.2	--
7	0.19	0.38	0.75	0.3	0.6	0.9
10	0.25	1.00	--	0.4	1.2	--

No water reduction was observed for the rheology modifiers. In fact the water demand of the mixtures incorporating the rheology modifiers increased and was subjectively observed in the fresh concrete mixtures by their increasing tendency of segregating as the dosage increased. This tendency was higher in the starch based product than in the welan-gum based product. This may perhaps be due to better enhancement of viscosity of paste with one rheology modifier than the other.

I.6 Dry cast products

One surfactant based (P-28) and one PC-Glycol based (P-29) dry cast products were used in this study. The recommended dosage both of these products is 0.130 to 0.390 lit/100kg.

Figure I-41 shows the water reduction of this admixture (P-XX) as a function of the dosage for various binder contents. The water reduction for rich mixtures (A/B = 4) ranged between 0 and 26%, intermediate mixtures (A/B = 7) between 0 to 21% and lean (A/B = 10) between 0 and 25%. Quite interestingly, this surfactant based shows comparable water reductions for all binder contents at similar dosages. This implies that this admixture is not sensitive to the binder content of a mixture. As far as its water reducing potential is concerned, it shows the ability to act as a low-, mid- and high-range water reduction.

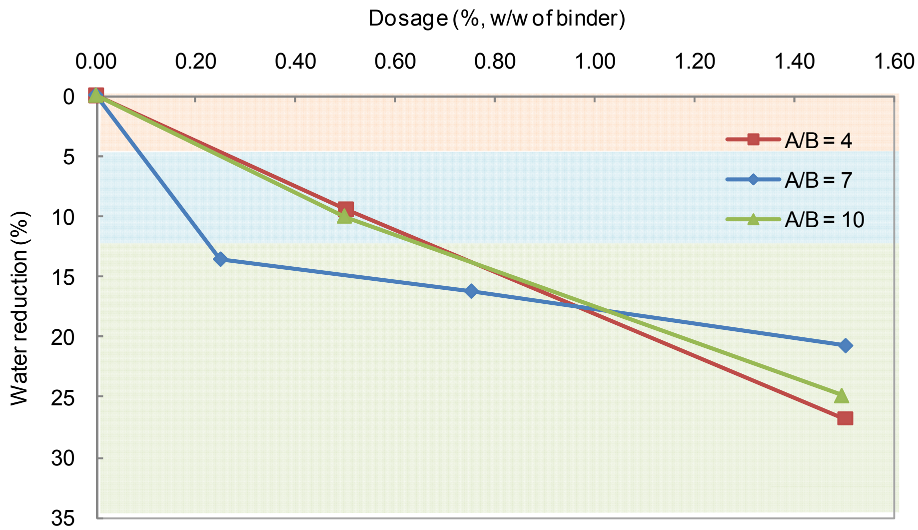


Figure I-41 Effect of admixture dosage and binder content on water reduction: P-28

I.7 A composite picture…effects of different admixtures

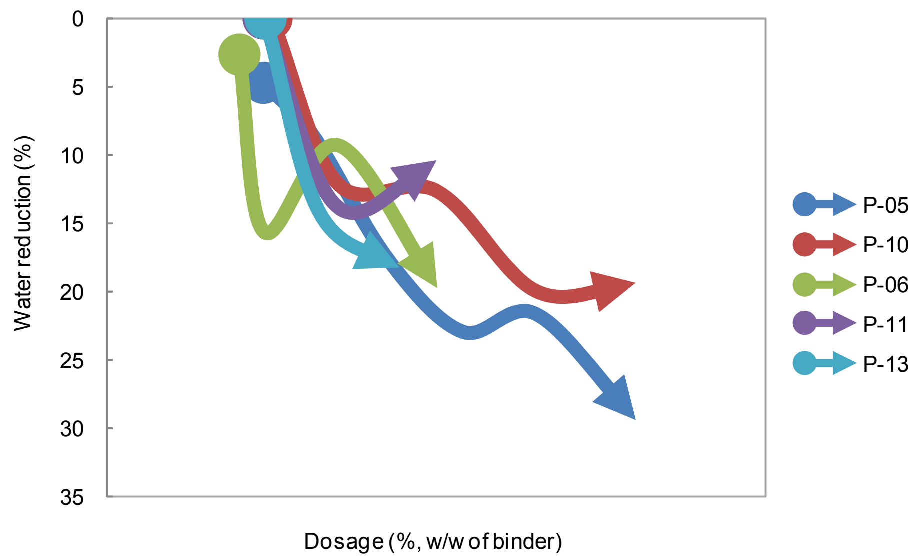


Figure I-42 Water reductions for different water reducing admixtures

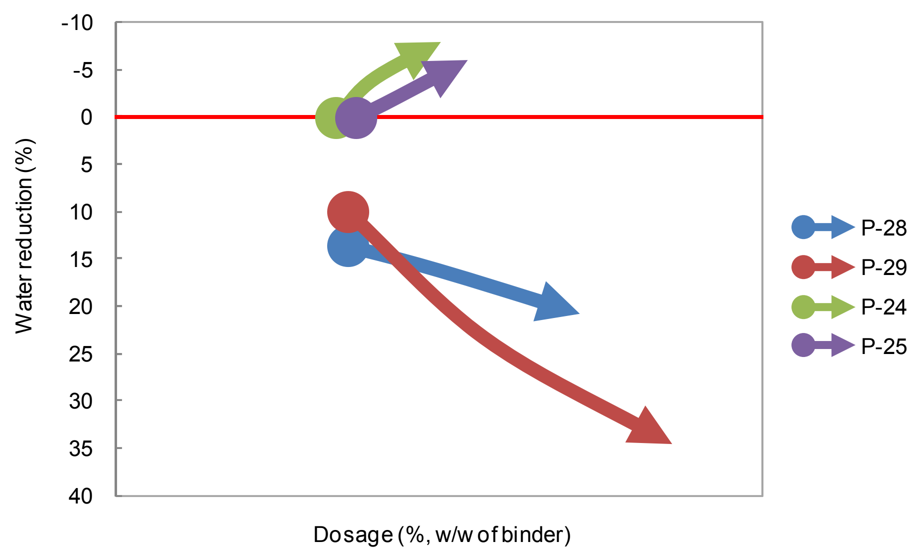


Figure I-43 Water reductions for DC products and RMs

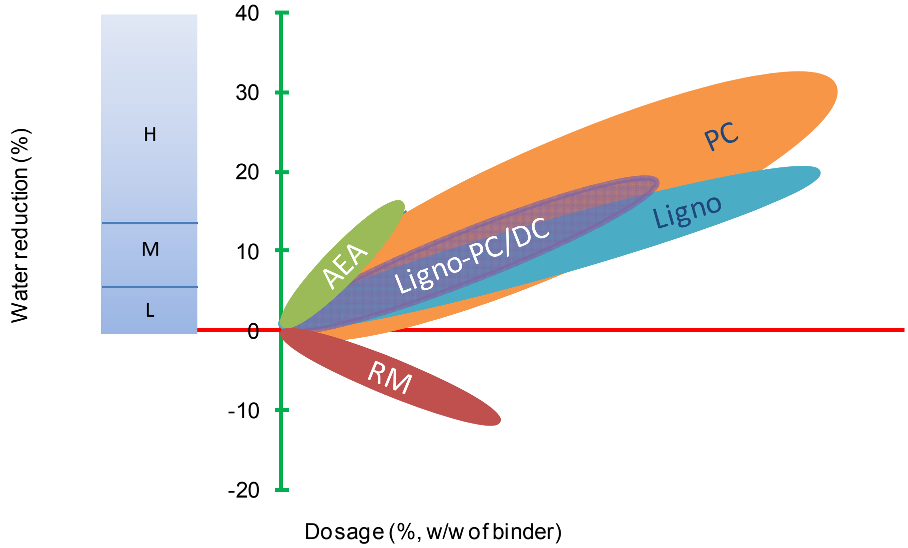


Figure I-44 A schematic comparison of different admixtures for their water reducing potential. L: low-range, M: mid-range and H: high-range water reducer

I.8 Binary combinations

Admixture duets were primarily formulated with an objective of using two admixtures in a complementary way. This means the strength of one admixture is used to overcome the weakness of the other. For example a surfactant based product leads to a better *swipe* or finish with decent water reduction as required in dry cast products. At the same time, and per the on-site requirements, the consistency retention of this admixture is relatively poor. This can be overcome by using a retarder to hold the consistency constant when using the earlier product to overcome the workability loss problem and at the same time improvising the finishibility of the later admixture, when used in combination.

All the admixture duets (five total) were tested on mixtures with A/B = 7 i.e. the intermediate binder content, since this binder content is the closest to the typical pavement mixtures. Since the admixtures could act in different ways at different binder levels, any generalizations or extrapolations of the results to both ends (i.e. A/B of 4 and 10) are not possible.

15.1.1 Ligno-based water reducer and SD based AEA

This admixture combination was used with two objectives as follows:

- To overcome the lack of good finishibility obtained by using the Ligno-based water reducer by extracting the benefit from the SD-based AEA and
- To overcome the lack of consistence retention by using the SD-based AEA alone by extracting the benefit of hydration retardation from the Ligno-based product.

A caution that can be anticipated with the use of such a combination is the air entrainment. Ligno-based products are known for entraining air in concrete and when added with a strong AEA could lead to enhanced air entrainment. Although this may perhaps work in favor of the fresh RCC, but could potential influence the strength in a negative way. The % admixture and their % in total compositions are reported in Table I-9.

Table I-9 Admixture compositions for Ligno-based water reducer and SD based AEA duet.

Total dosage		Dosage-1: @ 0.75%, w/w of binder					Dosage-2: @ 2.00%, w/w of binder			
Composition		1	2	3	4	5	1	2	3	4
WR (%)	P-05	0.750	0.562	0.375	0.188	0.000	2.000	1.750	1.000	0.000
AEA (%)	P-19	0.000	0.188	0.375	0.562	0.750	0.000	0.250	1.000	2.000
WR (%)	P-05	100.0	75.0	50.0	25.0	0.0	100.0	87.5	50.0	0.0
AEA (%)	P-19	0.0	25.0	50.0	75.0	100.0	0.0	12.5	50.0	100.0

Note: The last two rows are the % compositions in the total admixtures

Figure I-45 shows the water reductions by various admixture compositions and at two different dosage levels. It can be seen that the water reduction is highest with the SD-AEA is used alone at a both the combined dosage levels. As the contribution from the AEA increases, the water reducing capacity of the newer compositions increases gradually, pretty much following similar slope at both the dosage levels. At intermediate and combined dosages, the blend produces water reductions between those produced by the WR and AEA.

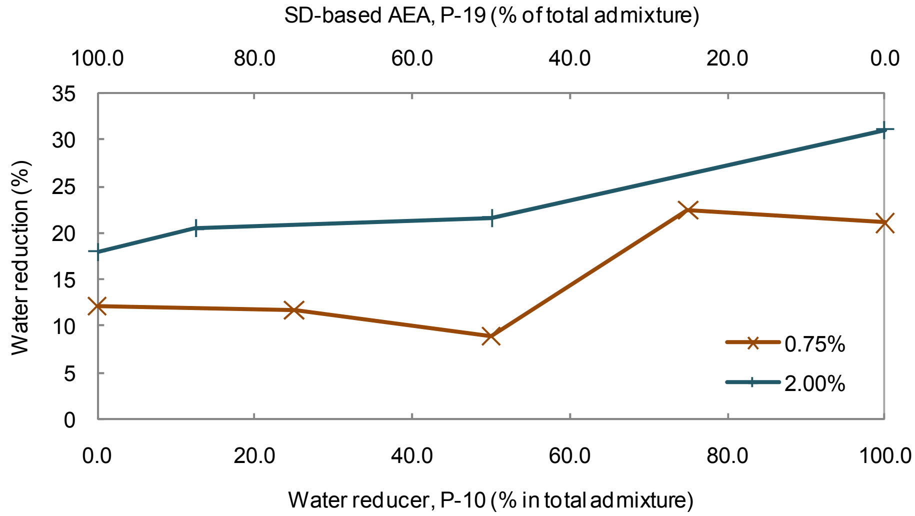


Figure I-45 Water reduction of the admixture duet: Ligno-based water reducer and SD-based AEA. Total admixture dosage is in percentage, w/w of binder

I.8.1 Surfactant based dry cast product and retarding water reducer

Table I-10 shows the admixture compositions used with this blend. Two dosage levels were fixed at 0.50% and 1.00% w/w of binder. This admixture combination was used with two objectives as follows:

- To overcome the lack of consistence retention by using the surfactant based DC product alone by extracting the benefit of hydration retardation from the retarding water reducer (R-WR).
- To extract the benefit of improved finishibility with the use of a surfactant based DC product.

Table I-10 Admixture compositions for surfactant based dry cast product and retarding water reducer

Total dosage		Dosage-1: @ 0.50%, w/w of binder				Dosage-2: @ 1.00%, w/w of binder			
Composition		1	2	3	4	1	2	3	4
R-WR	P-13	0.00	0.17	0.33	0.50	0.00	0.33	0.67	1.00
DC	P-28	0.50	0.33	0.17	0.00	1.00	0.67	0.33	0.00
R-WR	P-13	0	33.3	66.7	100.0	0.0	33.3	66.7	100.0
DC	P-28	100	66.7	33.3	0.0	100.0	66.7	33.3	0.0

Note: The last two rows are the % compositions in the total admixtures

Figure I-46 shows the water reductions by various admixture compositions and at two different dosage levels. It can be seen that the water reduction is highest with the R-WR is used alone at a lower combined dosage of 0.50% and as the contribution from the surfactant increases the water reducing capacity of the newer compositions reduces and reaches a plateau where it remains more or less the same. At higher combined dosage of 2.00% however, the uses of individual admixtures leads to almost similar water reduction. At intermediate and combined dosages the blend produces almost similar water demand to the formation of a saucer shaped profile.

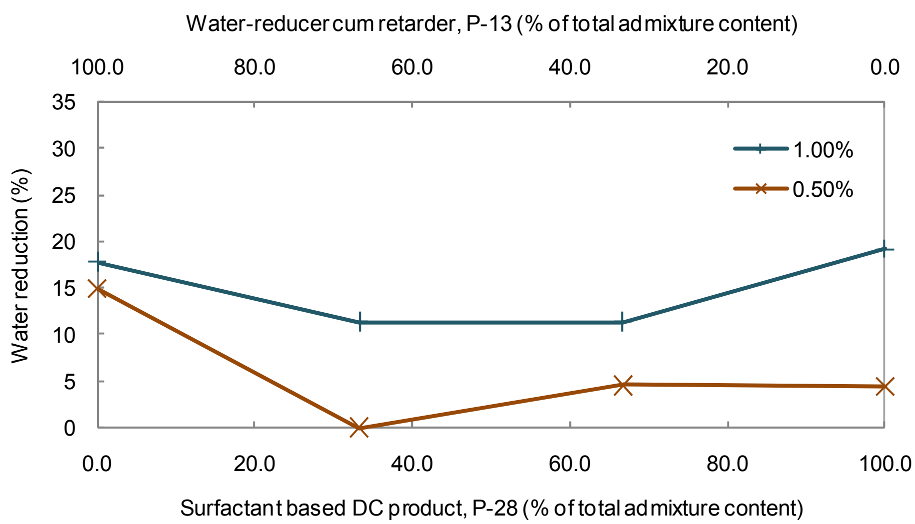


Figure I-46 Water reduction of the admixture duet: Surfactant based dry cast product and retarding water reducer. Total admixture dosage is in percentage, w/w of binder

I.9 Ternary combinations

Admixture triplets were primarily formulated to assess if there are any incremental advantages in using rheology modifiers in RCC mixtures. The benefits would primarily be seen in the terms of fresh properties and it was anticipated that the compressive strength will not be much affected by using the triple blends.

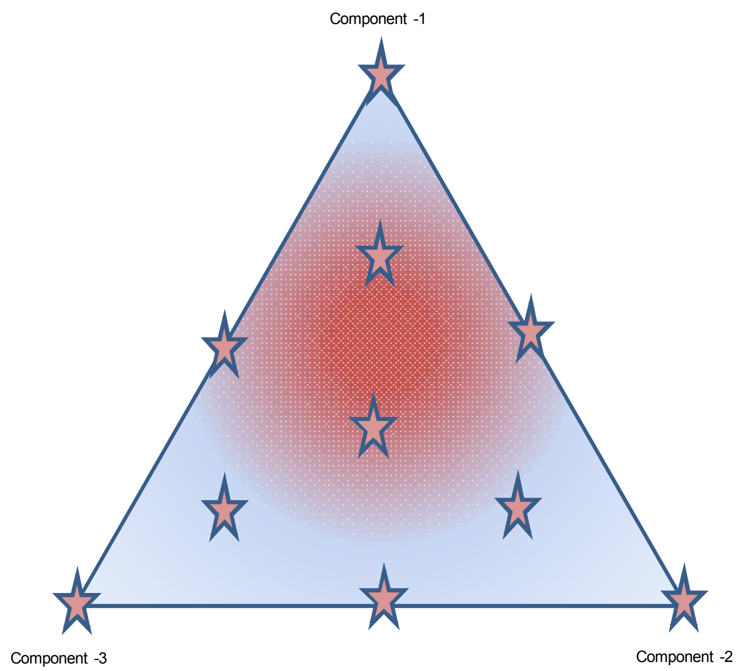


Figure I-47 Response surface generated by simplex-centroid design augmented by three interior points. Stars represented the point at which the composition is tested for the required property

The *method of mixtures* was used for generating the experimental matrix. The model used was ABCD, generated by JMP; this makes use of ten points on the ternary plot. This design is called as a simplex-centroid design augmented with three interior points. Refer to Figure I-47. It is said that a good design of mixture experiment should be able to

- generate a satisfactory distribution of information throughout the experimental region (the triangle);

- ensure that the fitted model predicts a value as a function of given combination at all points in the experimental region that is as close as possible to the true value of the response;
- give good detectability of model lack of fit; and
- provide an internal estimate of the error variance [23].

I.9.1 Combination 1: PC-based water reducer-hydration stabilizer-rheology modifier (WR-HS-RM)

This combination is typically recommended for pervious concrete and is used at a fixed combined dosage of 1.5%. This combination consists of a PC-based water reducer (P-09) that is comparable to the product P-05, a hydration stabilizer (P-17) that can retain slump for normal concretes for different time durations depending on the dosing and a viscosity modifying rheology modifier (P-26). Table I-11 presents the individual mixture compositions for this blend.

Table I-11 Triplet combination-1: Compositions

Mixture ID		A	B	C	D	E	F	G	H	I	J
WR (P-09)	(%, w/w)	1.50	0.00	0.00	0.75	0.00	0.75	1.00	0.25	0.25	0.50
HS (P-17)	(%, w/w)	0.00	1.50	0.00	0.75	0.75	0.00	0.25	1.00	0.25	0.50
RM (P-26)	(%, w/w)	0.00	0.00	1.50	0.00	0.75	0.75	0.25	0.25	1.00	0.50
WR (P-09)	(%)	100.00	0.00	0.00	50.00	0.00	50.00	66.67	16.66	16.66	33.33
HS (P-17)	(%)	0.00	100.00	0.00	50.00	50.00	0.00	16.66	66.67	16.66	33.33
RM (P-26)	(%)	0.00	0.00	100.00	0.00	50.00	50.00	16.66	16.66	66.67	33.33

Note: The last three rows are the % compositions in the total admixtures

The following ternary diagram shows the water reduction contours for this combination of admixtures. It can be seen the sole use of water reducing admixture does not lead to maximal water reduction. A combination of hydration stabilizer and rheology modifier leads to the maximal water reduction. Quite interestingly the use of rheology modifier increases water demand and can be clearly seen by the negative water reduction. Intermediate compositions lead to water reduction to different degrees.

Further to design a model was run to appreciate the effects of different components on the water reduction of this combination of admixtures. The resulting prediction equation having a R^2 = 0.9482 is as follows:

$$WR\ (\%) = 11.05(WR) + 7.10(HS) + 0.81\ (RM) + 26.73\ (WR{\cdot}HS) - 12.92(HS{\cdot}RM) - 4.08(RM{\cdot}WR) + 50.17\ (WR{\cdot}HS{\cdot}RM)$$

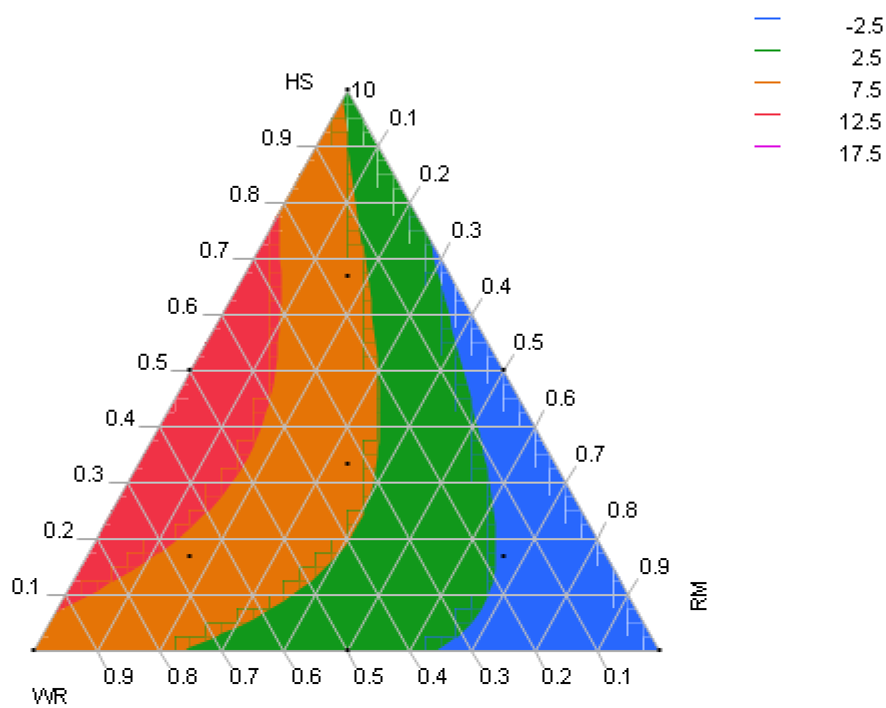


Figure I-48 Water reduction by ternary combination-1

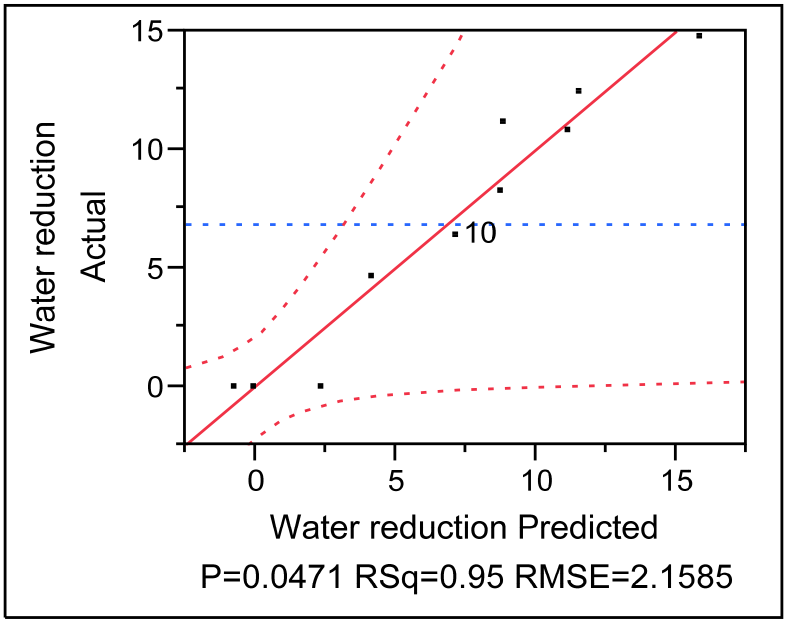


Figure I-49 Actual by predicted plot of the model for ternary combination-1

The equation shows a strong influence of water reducing admixture on the water reduction. Table I-12 tabulates the parameter estimates. Figures 15-48 through 15-50 show the prediction and desirability profiles.

Table I-12 Table of parameter estimates for ternary combination-1

Term	Estimate	Std Error	t Ratio	Prob>|t|
WR	11.05482	2.086555	5.30	0.0131*
HS	7.0884559	2.086555	3.40	0.0425*
RM	-0.807908	2.086555	-0.39	0.7244
WR*HS	26.730551	10.50328	2.54	0.0843
HS*RM	-12.9229	10.50328	-1.23	0.3062
WR*RM	-4.082176	10.50328	-0.39	0.7235
WR*HS*RM	50.167059	69.24477	0.72	0.5212

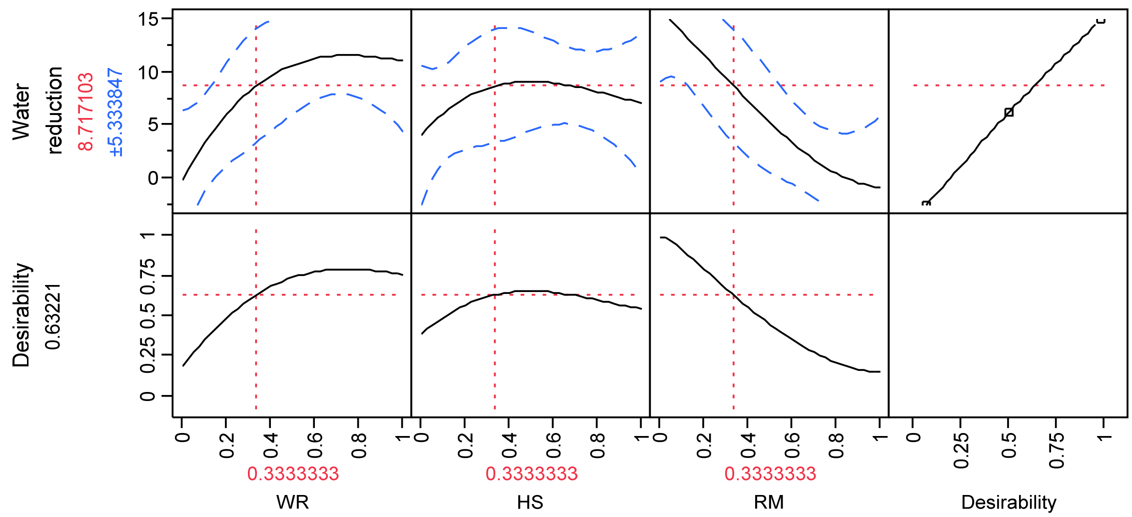


Figure I-50 Prediction and desirability profiles for ternary combination-1

I.9.2 Combination 2: Ligno-based water reducer-SD based AEA-Starch based rheology modifier (WR-HS-RM)

This combination is formulated and tested with an objective of improving the compaction properties of Ligno-based water reducer and SD-AEA combination. The dosage used was fixed at a combined dosage of 1.5%. This combination consists of a Ligno-based water reducer (P-10), a SD-AEA (P-19) and a yield modifying rheology modifier (P-24). Table mixture compositions for this blend were similar to those listed in Table I-11.

The resulting water reduction trends are plotted in the iso-lines in the ternary diagram (refer to Figure 51-51). The model for the is as follows with a R^2 = 0.82:

$$WR\ (\%) = 16.52(WR) + 17.19(AEA) + .8354\ (RM) + 7.86(WR{\cdot}AEA) - 43.95(AEA{\cdot}RM) - 25.29(RM{\cdot}WR) - 40.69(WR{\cdot}AEA{\cdot}RM)$$

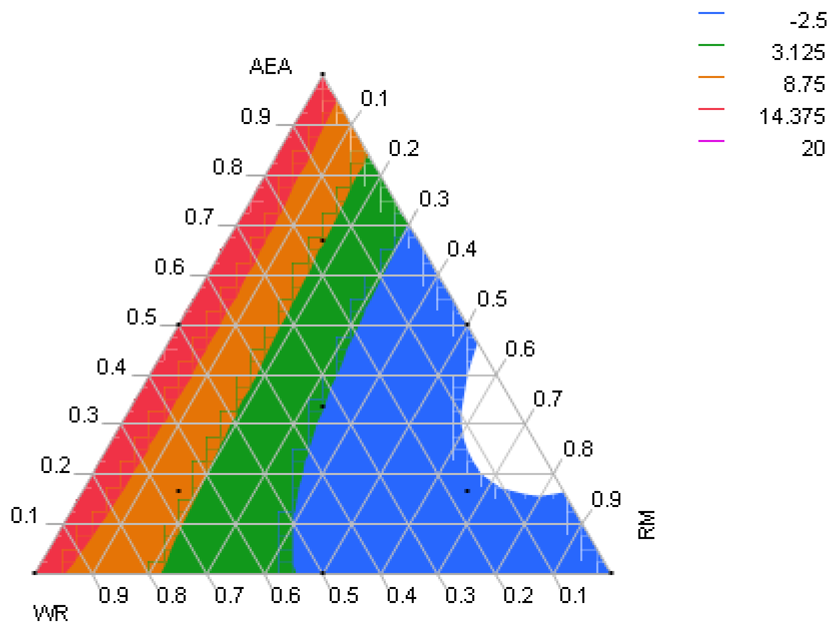


Figure I-51 Water reduction by ternary combination-2

The predicted versus actual water reduction values are shown in Figure I-52. Figure I-53 shows the prediction and desirability profiles. Table I-13 shows the parameter estimates.

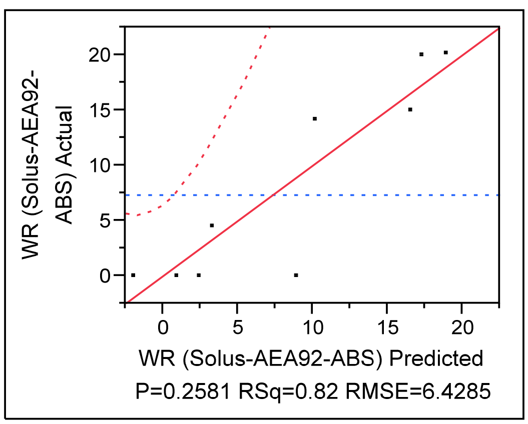


Figure I-52 Actual by predicted plot of the model for ternary combination-2

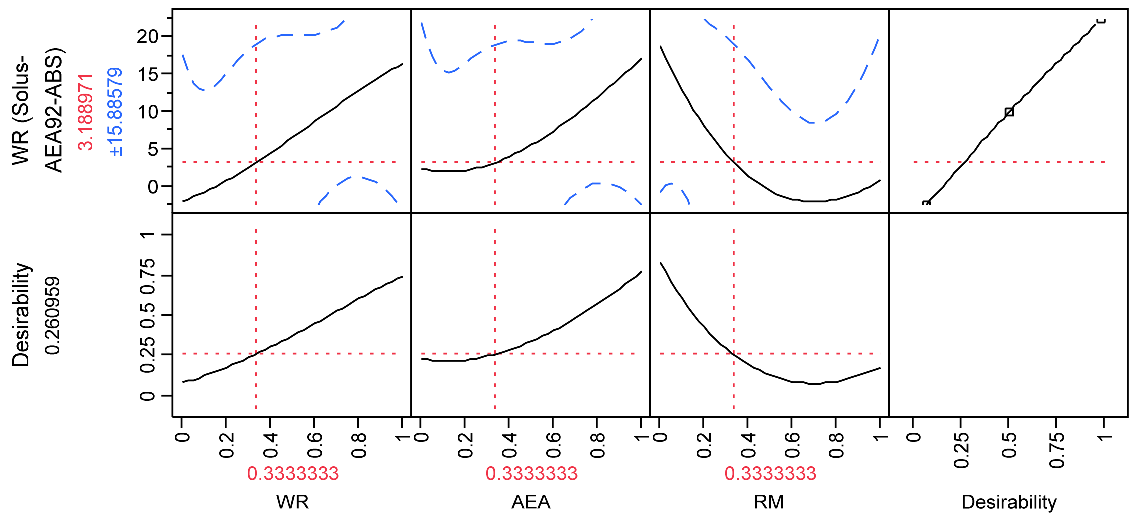


Figure I-53 Prediction and desirability profiles for ternary combination-2

Table I-13 Table of parameter estimates for ternary combination-2

Term	Estimate	Std Error	t Ratio	Prob>|t|
WR	16.521805	6.214382	2.66	0.0764
HS	17.189078	6.214382	2.77	0.0698
RM	0.8354412	6.214382	0.13	0.9016
WR*HS	7.8617647	31.2819	0.25	0.8178
HS*RM	-25.28551	31.2819	-0.81	0.4781
WR*RM	-43.95096	31.2819	-1.40	0.2547
WR*HS*RM	-40.69059	206.2315	-0.20	0.8562

I.9.3 Combination 3: Ligno-based water reducer-SD based AEA-Welan gum based rheology modifier (WR-HS-RM)

This combination is formulated and tested with an objective of improving the compaction properties of Ligno-based water reducer and SD-AEA combination. The combined dosage used was fixed 1.5%. This combination consists of a Ligno-based water reducer (P-10), a SD-AEA (P-19) and a yield modifying rheology modifier (P-25). Table mixture compositions for this blend were similar to those listed in Table I-11.

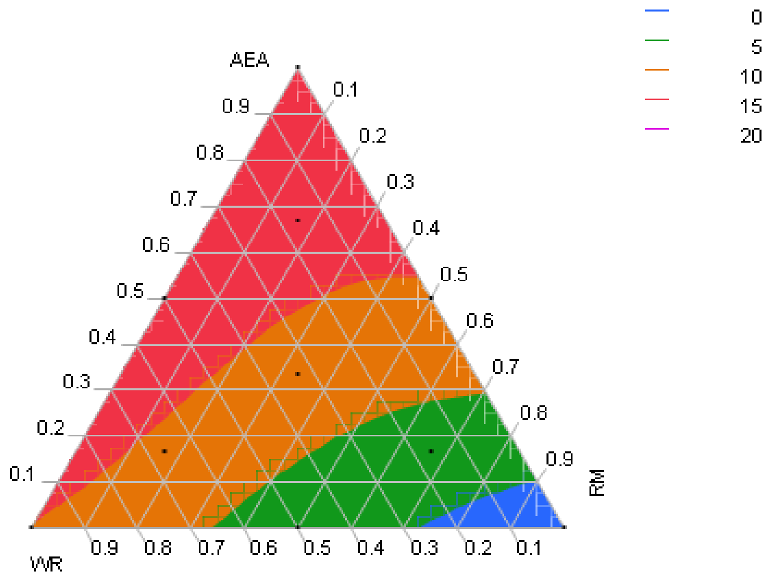


Figure I-54 Water reduction by ternary combination-3

The resulting water reduction trends are plotted in the iso-lines in the ternary diagram (refer to Figure I-54). The model for the is as follows with a R^2 = 0.82:

$$WR\,(\%) = 14.85(WR) + 19.14(AEA) + 1.86\,(RM) + 8.42(WR{\cdot}AEA) - 2.02(AEA{\cdot}RM) - 14.80(RM{\cdot}WR) - 37.95\,(WR{\cdot}AEA{\cdot}RM)$$

The predicted versus actual water reduction values are shown in Figure 55. Figure I-56 shows the prediction and desirability profiles. Table I-15 shows the parameter estimates.

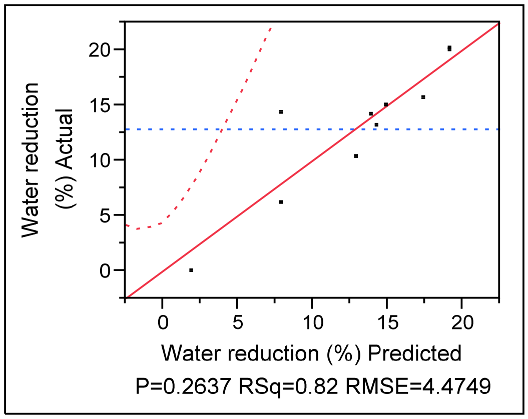


Figure I-55 Actual by predicted plot of the model for ternary combination-3

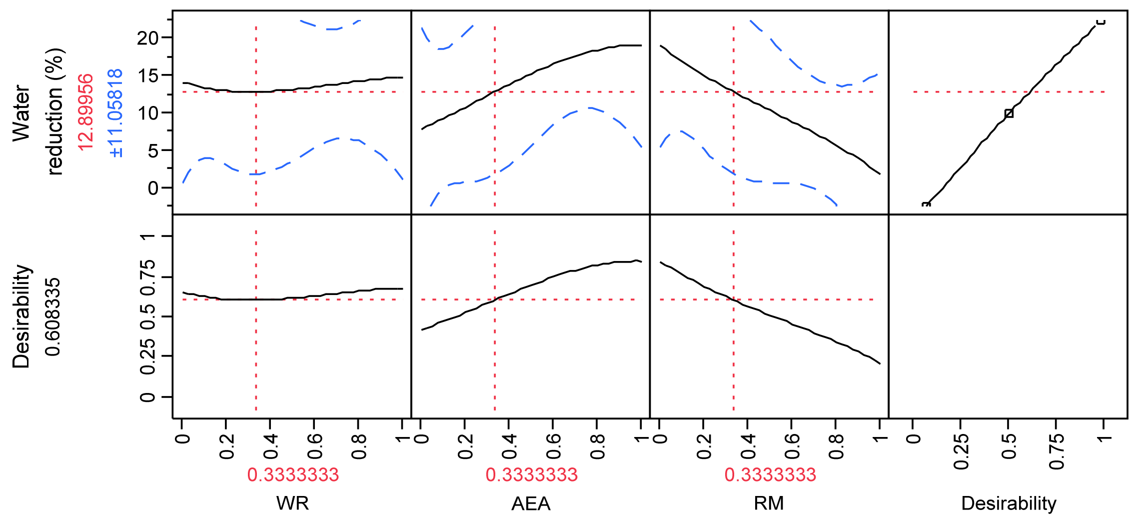


Figure I-56 Prediction and desirability profiles for ternary combination-3

Table I-14 Table of parameter estimates for ternary combination-3

Term	Estimate	Std Error	t Ratio	Prob>|t|
WR	14.850254	4.325863	3.43	0.0415*
AEA	19.141163	4.325863	4.42	0.0214*
RM	1.8584358	4.325863	0.43	0.6965
WR*AEA	8.4228342	21.77549	0.39	0.7247
WR*RM	-2.02262	21.77549	-0.09	0.9319
AEA*RM	14.799198	21.77549	0.68	0.5455
WR*AEA*RM	-37.95882	143.5588	-0.26	0.8086

- The compaction properties of pharmaceutical powders are for clarity separated in two distinct terms, i.e. the compressibility as the ability of the powder to deform under pressure and the compactibility as the ability of a powder to form coherent compacts [24]. Compactibility is the process of volume reduction and bond formation in a powder bed during compression, which produces compacts of a certain mechanical strength. When pressure is applied to a powder bed, particle rearrangement occurs first, followed by particle fragmentation and deformation (plastic and elastic deformation), and bond formation on the contact surfaces [25]. Plastic deformation is an irreversible process of particle shape changing that contributes to stronger tablets, while elastic deformation is reversible and leads to elastic recovery of compacts in the decompression phase and the breakage of some previously formed bonds, which results in lower tablet strength and capping problems [26].
- Comparative research on modified lignosulfonate (LS), polycarboxylate (PCE) and polynaphthalene (PNS) based superplasticizers indicated that the degree of retardation varied with the type and dosage of the admixtures. The LS showed much stronger retarding effect compared with the PCE and PNS admixtures. The initial setting times of the pastes with the PCE and PNS admixtures determined by the penetration depth method were much shorter than that with the PLS admixture. Although the pastes with PLS admixture had longer workable time, the longer setting time has to be taken into consideration in practice whenever early strength development is essential [27].
- This is also a function of the water/cement ratio of a mixture. The water/cement ratio controls the concentration in the pore solution. At a low water/cement ratio, the surface of interstitial phases especially of C_2A and C_4AF is covered by the adsorbed superplasticizer, thus very little SP is left in the pore solution. With an increase in the water/cement ratio, more Alite hydrates and thereby more Ca^{2+} ions are produced. Lime saturation in the pore solution increases poisoning the hydration process. Subsequently, the fluidity increases [28].
- Slump loss is related to the degree of hydration and involves physical and chemical processes, which varies with different SP's and their dosage. The loss of consistency in the cement paste during the dormant stage is mainly attributed to

the physical coagulation of cement particles rather than to chemical processes. The hydration of the interstitial phases occurs mainly during the first hour just after mixing water. This hydration is affected by the concentration of $Ca2+$, $OH-$, and SO3 in the mixing water. The concentration of these ions depends upon the hydration reaction of Alite. The hydration of the interstitial phase is affected in particular by the lime saturation ratio, which varies with time. In a study, it was shown that the variation over time of the lime saturation ratio when using lignine sulfonic acid-based admixture is smaller than in the case using melamine or naphthalene sulfonic acid-based admixtures. The reason is that lignine sulfonic acid-based admixture takes up Ca2+ from the mixing water [29]. This is in agreement with the experimental results reported here, i.e., slump loss is lower for mortars with LS than for those with SMF or SNF, since more LS remains in the solution. Carboxylic acid-based admixture (CE) produces high fluidity and maintains this fluidity for some time, i.e., slump loss is very low. The mechanism of interaction for CE is different than for sulfonic acid-based admixtures. The sulfonic acid-based admixtures are anionic surface active admixtures. Accordingly, these are adsorbed on the cement particles, which are then provided with a negative surface potential in water. Cement particles with negative potential are electrostatically repelled by each other. Polycarboxylic acid-based admixtures are nonionic surface active compounds. The side chains of polyethylene oxide extending on the surface of cement particles migrate in water and the cement particles are dispersed by the stearic hindrance of the side chains [28, 30].

- Polycarboxylate based water reducers generally reduce the yield stress significantly. They also reduce the plastic viscosity significantly at higher water/cement ration, but much less at lower water/cement ratio [16].

I.10 Shearing stress-cohesion-angle in internal friction

As discussed previously, the shear resistances of different concrete mixtures were characterized by the direct shear test conventionally used in geotechnical engineering. The scaled up test box was used at a nominal shear displacement (s) time rate of 6.55 mm/min. It should be noted that the shear stresses and displacements developed in the direct shear box are non-uniformly distributed within the specimen. Consequently, an appropriate height cannot be defined for calculating the shear strains. Therefore, true stress-strain plots and associated shear modulus cannot be obtained based on the results from this test [31]. Considering this, the strains and stresses developed in the samples shall be considered as nominal.

15.1.1 Data manipulation

For each sample, three tests at increasing normal loads were run. The method of analysis used in this work is a bit different from that conventionally used. These are not discussed in detail here. The data obtained from the tests was plotted in three different ways as follows:

- Nominal shear displacement versus nominal shear load;
- Nominal Shear displacement versus friction ratio and
- Normal stress versus nominal shear stress

While appreciating the results, the inherent heterogeneous nature of concrete as a material should always be borne in mind. It also implies that there could be more than conventionally observed variations. Another phenomenon of interest is the slip between the concrete and the shear boxes. Different concrete mixtures at differing water contents were tested; potentially some of the drier mixtures could not have been in complete contact with the walls of shear boxes during shearing.

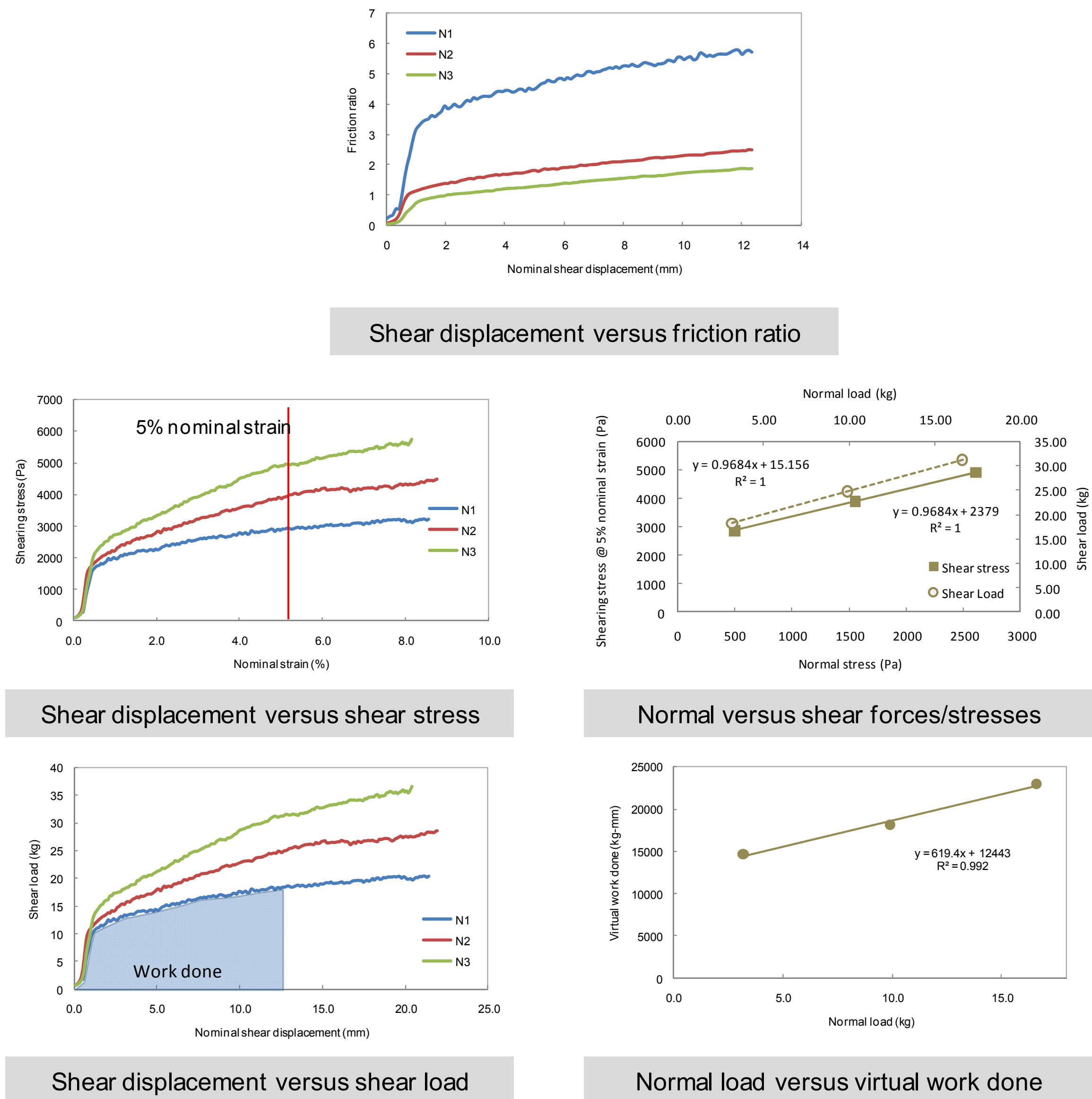


Figure I-57 Typical plots from direct shear test. Note: $N_1 < N_2 < N_3$

Typical plots are shown in Figure I-57. The displacement versus load plots was used for computing the work done. The work done is considered to be equal to the area under the curve. The following is the general formula:

$$W = \int_0^{12.5} S ds$$

The area was computed using the trapezoidal rule. The area so computed from each of these plots was used in developing the normal load versus work done plot. This plot offers a relative idea about the roller compactibility of a concrete mixture with different static weight rollers. This in simulation is shown in Figure I-58. The slope of the line indicates the relative easy with which deformation can be achieved with increasing roller weights. A flatter line will indicate that there is not much advantage in increasing the static weight of a roller, while a steeper line will indicate that the concrete is relatively less workable with lesser roller weights and need to be improved in composition to achieve better compactibility and economically. This plot also gives an idea about the roller weight selection. While comparing two mixtures, a mixture that has a lower intercept on work-axis would mean the mix is readily compactable, while a higher intercept will mean that the mixture has lower compactibility and would require longer compaction times.

The nominal shearing strain versus stress plots were constructed to obtain the cohesion and angle of internal friction. Considering the strain hardening nature of the curves, selecting a distinct and consistent point of failure was difficult, hence a nominal strain of 5% was used to determine the stress. This stress at this point was used in composing the normal stress versus nominal shear strain plot. The intercept of this plot gave cohesion (C′), while the slope of the line represented the angle of internal friction (Φ′).

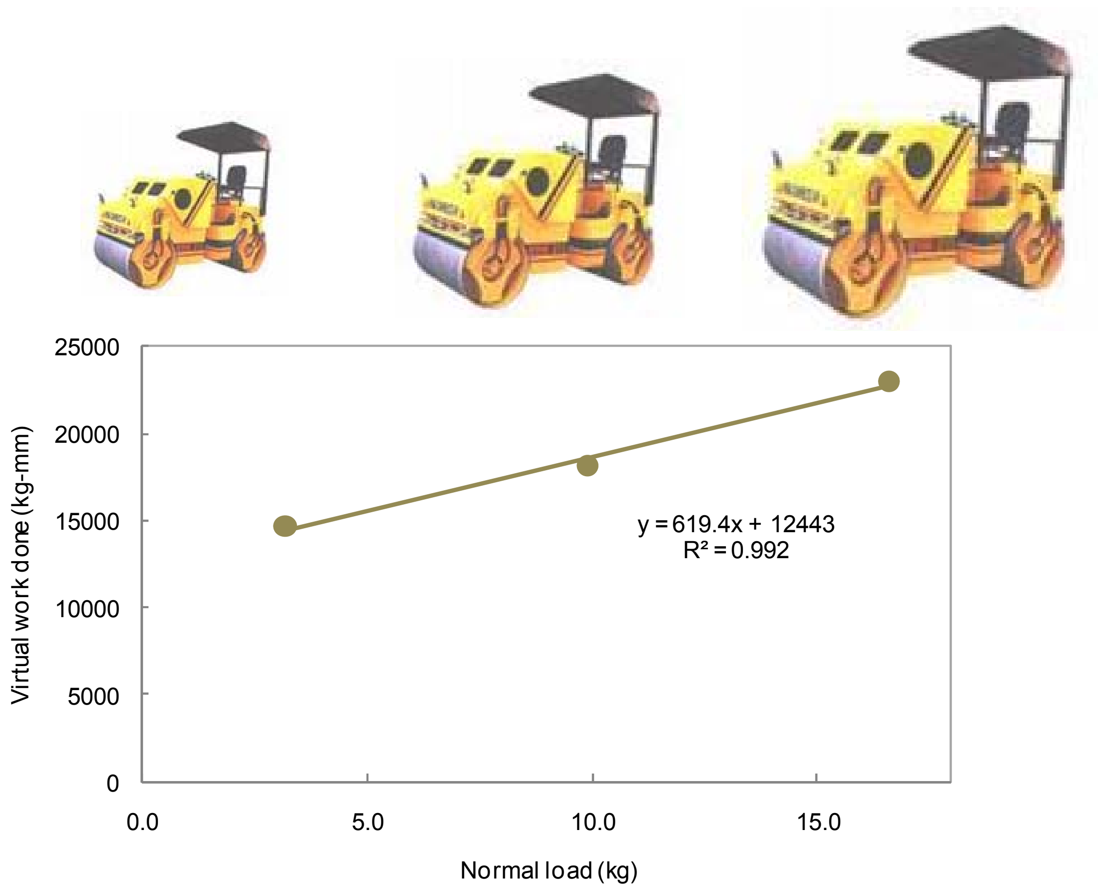


Figure I-58 Analogy with roller weight selection

I.10.1 Control mixtures

This section offers trends observed in the control mixtures. Instead of presenting separate pictures for different aggregate/binder ratios, a composite picture as a function of water/binder ratio is presented here.

Figure I-59 shows the trends in the cohesion and angle of internal friction. The data is scattered over a wider range and this could be possibly due to the noise in the measurements. The cohesion shows a trend with water/binder ration, but the angle of internal friction is scattered over a wider range. to infer with greater confidence repeat trial runs will be required. Less cohesion is mobilized at lower water/binder ratio, with an increase in the water/binder ratio, the cohesion increases reaches a peak and then with further increase in the water content, the cohesion drops down. The angle of friction is however showing a higher variability with the vales spanning between 20 and 55˚.

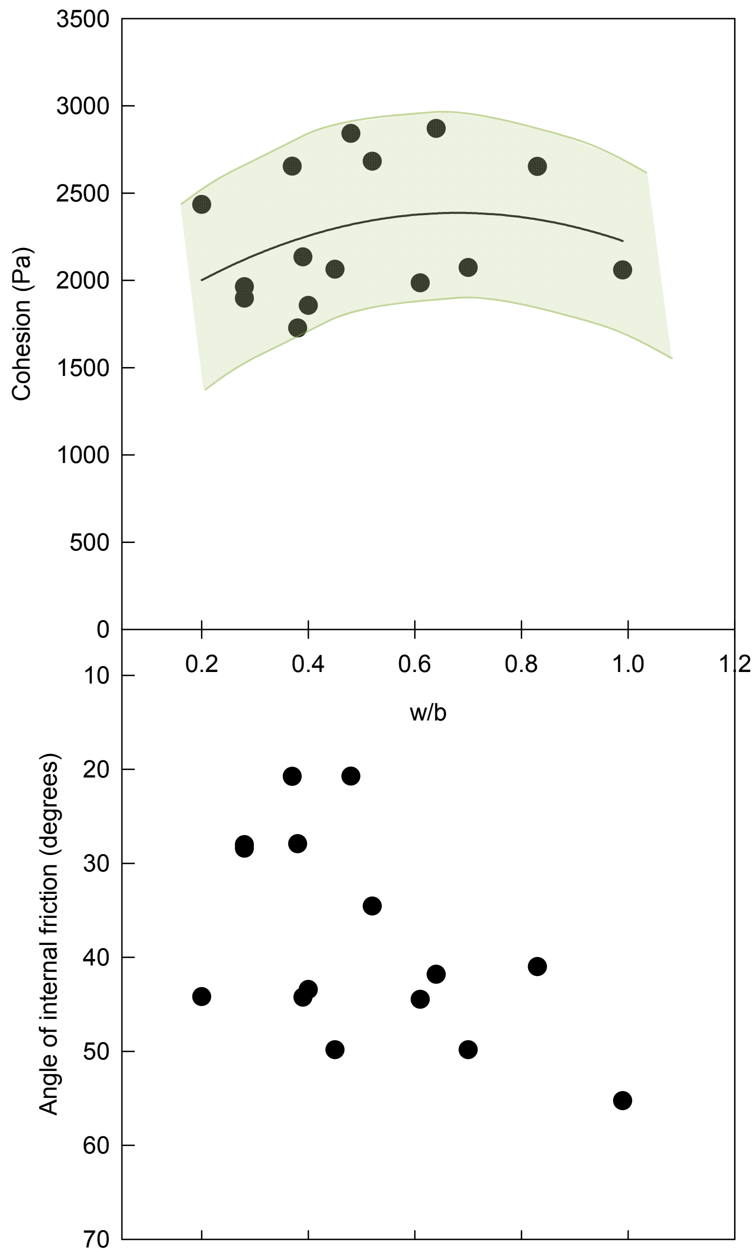


Figure I-59 Cohesion and friction angle for control mixtures

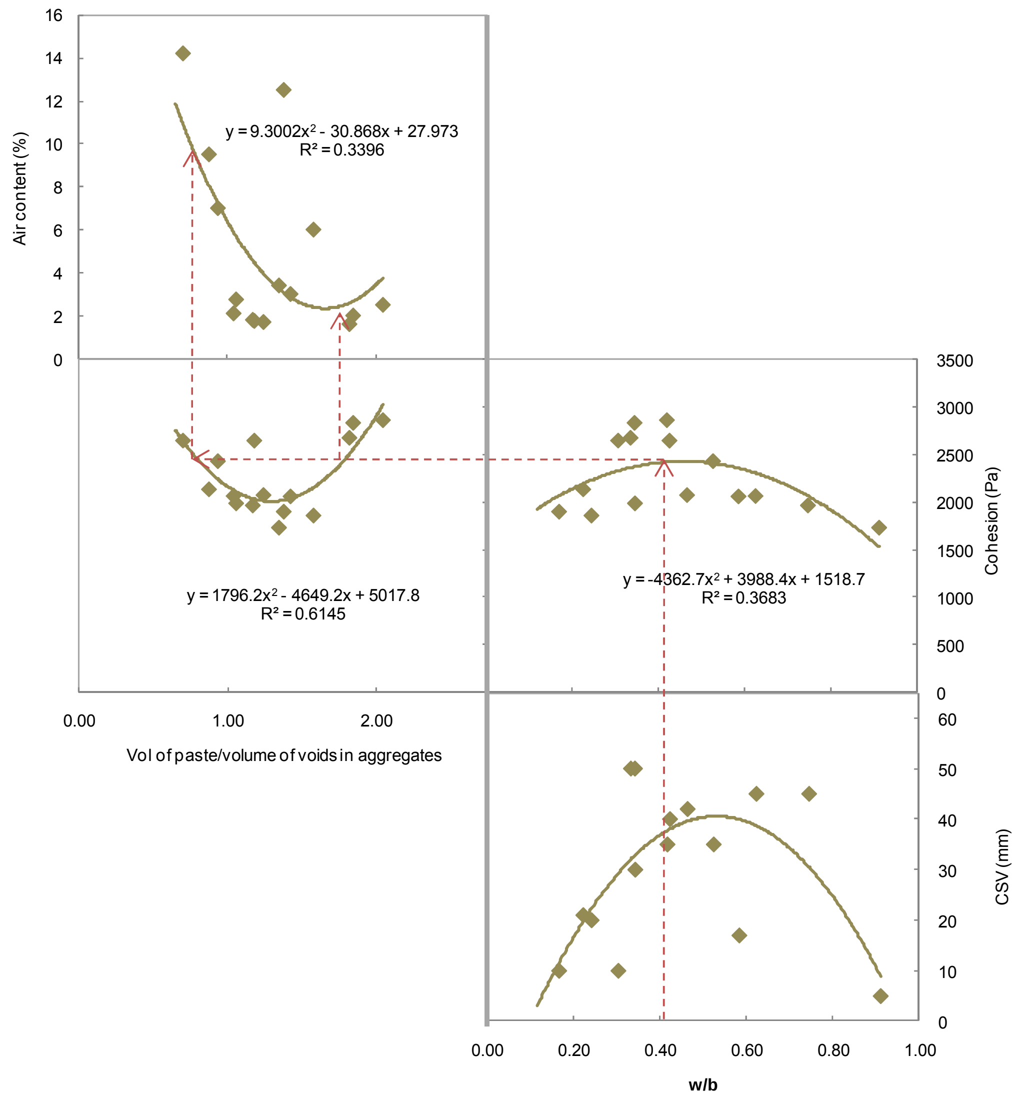


Figure I-60 w/b ratio-CSV-Cohesion-γ -Air content

Figure I-60 shows a composite figure that helps select multiple parameters at the same time, all a function of water/binder ratio. The following are salient inferences:

- The CSV shows a parabolic variation, lower w/b ratio representing less compactibility because of presence of higher air volumes and higher w/b ratio representing lower compactibility because of presence of higher water or voids flooded with water;

- Each of this cohesion value will correspond to a pair of ratio of volume of paste/volume of voids in aggregates. Not all pairs can be used for making roller compactable concrete. for example in the case highlighted in the figure, at the lower end of this ratio, due to higher air content, the concrete will not be economically roller compactable, while at the higher end there is a possibility of making good concrete. Care should be exercised in selecting this ratio properly, since the economics of material selection shall be influenced by proper paste selection.

I.10.2 Use of different chemical admixtures: Two case studies

The cohesion and angle of internal friction were measured for all the concrete mixtures incorporating different chemical admixtures. The angle of internal friction was fluctuating in the above mentioned range and no hence no detailed discussions are presented here. Similarly, instead of offering elaborate discussions a synoptic picture of how admixtures influence the cohesion is presented here.

Figure I-61 shows the cohesion for two water reducers viz. PC-based (P-05) and ligno-based (P-10). A relative comparison of two admixtures can be made when the corresponding water reductions are taken in to consideration. Since changes in the water content of a mixture leads to changes in the cohesion, therefore the cohesion in admixed concretes should be seen from this perspective in mind. It can be seen that the PC based admixtures even after significant water reduction are capable of maintaining similar value of cohesion, while the ligno-based water reducer is comparatively showing poorer performance. One of the points of PC-based admixture is showing a very high cohesion value. This is happening in higher binder content mixture with higher dosage, where the plasticity imparted by the admixture is very high, making the mixture like a rubbery mass. The composite picture becomes clearer in the third plot of w/b ratio versus cohesion.

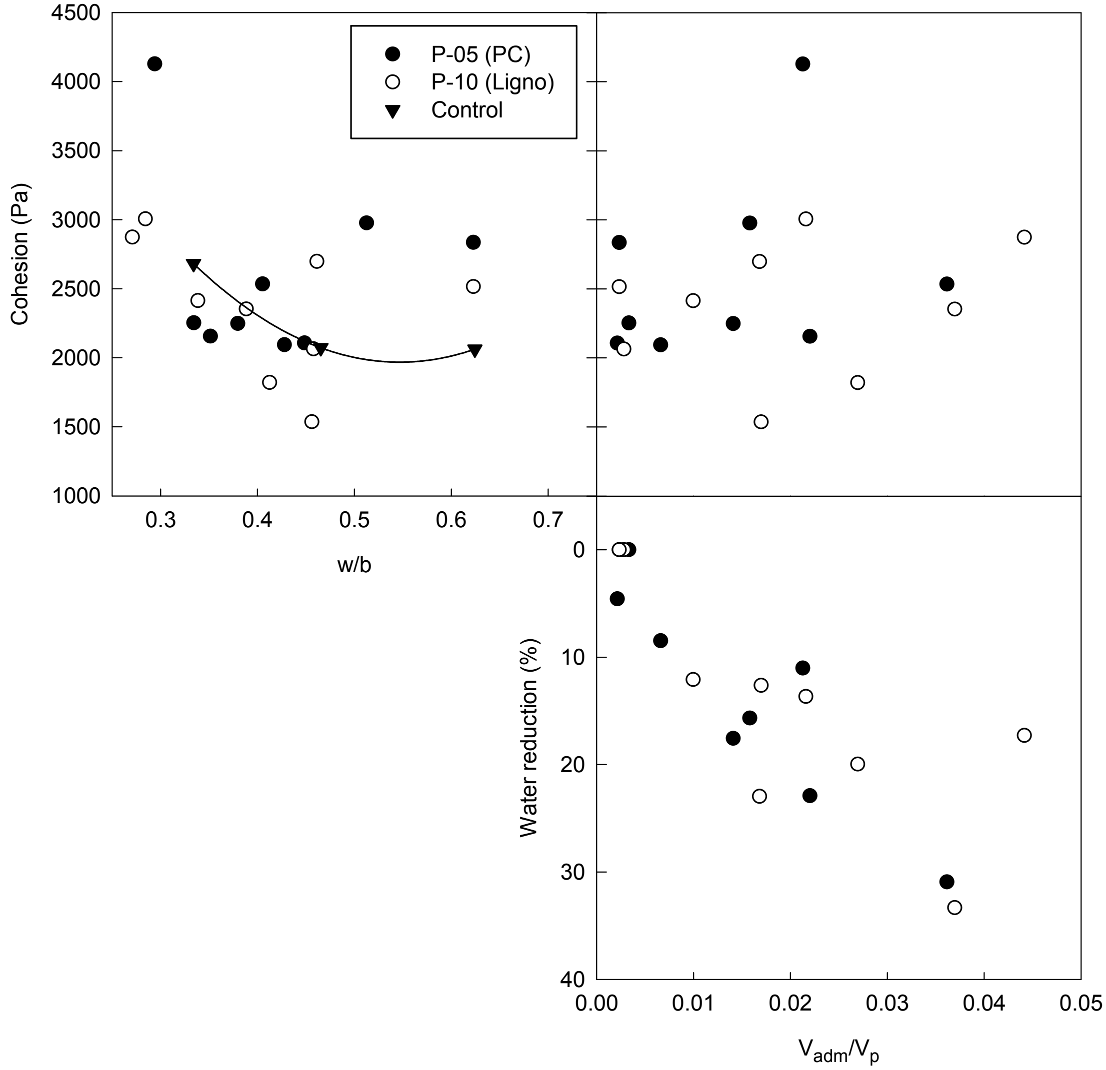


Figure I-61 Cohesion as obtained with Pc- and Ligno-based water reducers

Figure I-62 shows a composite diagram of w/b, air content, water reduction, admixture dosage and cohesion. The cohesion of air entraining admixture mixed mixtures is a function of AEA chemistry and corresponding water reduction. Although the initial consistency as characterized by CSV is similar, but the nature of cohesion and hence its quantified value is different vis-à-vis the chemistry, the entrained air volume and the water reduction. The SD-based AEA entrains relative larger amounts of air in concrete mixtures leading to more or less similar cohesion values, although there is significant water reduction observed in the mixtures. The cohesion of mixtures containing other two AEA's drops down as the dosage of admixture increases. Another interesting facet of AEA concrete is that the cohesion values are all less than the control concrete, indicating AEA reduces the cohesion in concrete, at similar initial consistency.

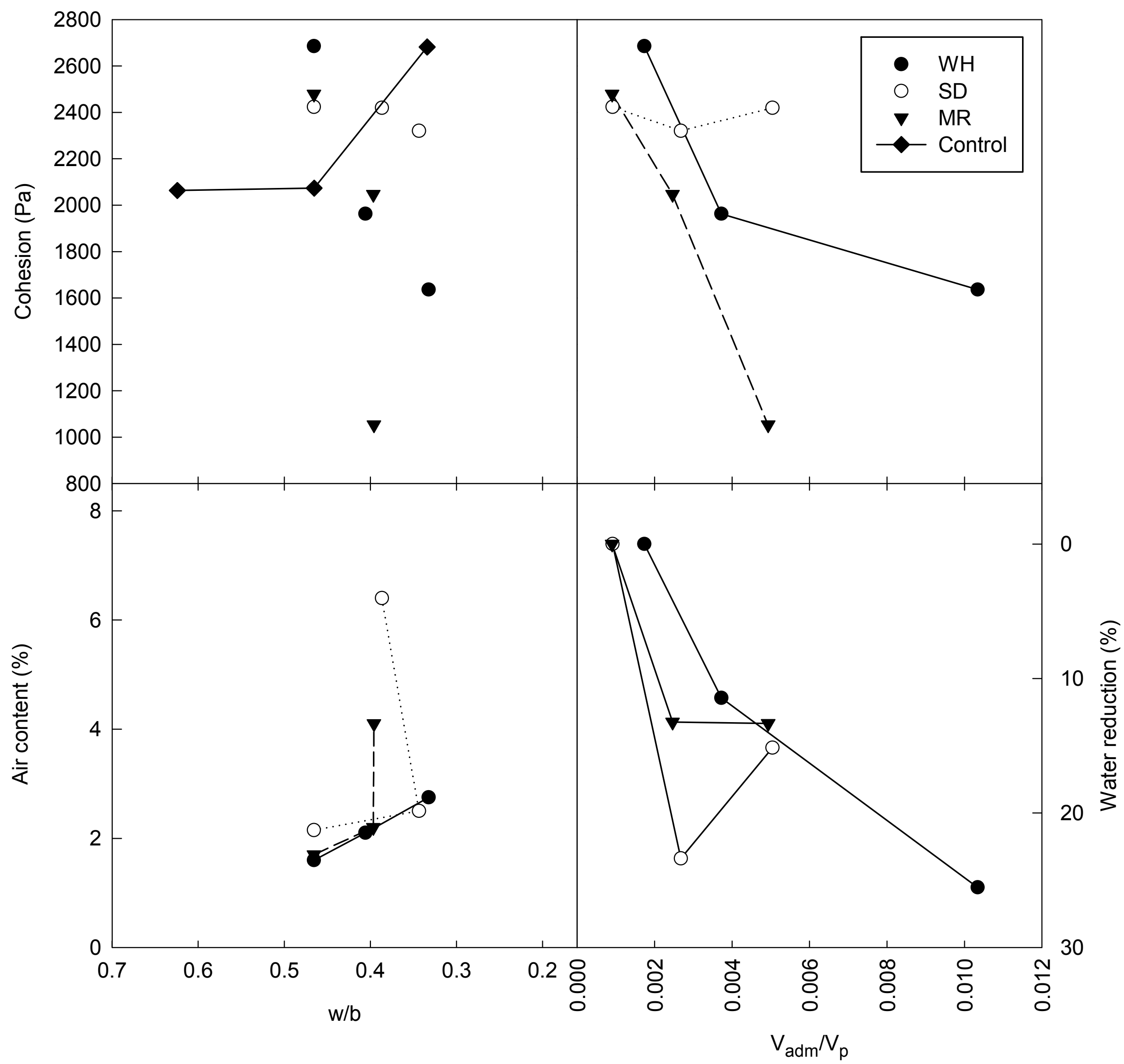


Figure I-62 Effects of AEA type on cohesion of concrete: A composite picture

I.11 Composite picture

15.1.1 Cohesion

Composite plots were constructed to evaluate the relative performances of different admixture families in terms of the cohesion they produce at increasing dosages. For this purpose relative cohesion is defined as the ratio of cohesion in admixed concrete mixture to the cohesion in control mixture. Figure I-63 shows the trends for water reducing admixtures.

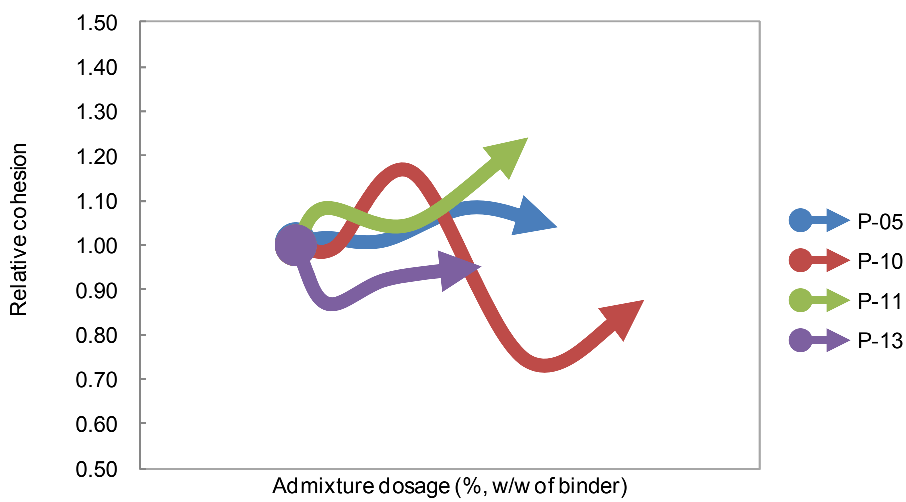


Figure I-63 Relative cohesion offered by different water reducing admixtures at increasing dosages

It can be seen that the PC based admixture is able to maintain similar cohesion at increasing dosages, while ligno-based product shows a drop at higher dosages. Other admixtures show relative performance as shown. It should be noted that these changes in cohesion are associated with corresponding water reduction and these plots are constructed for similar initial consistency as measured by CSV.

Figure I-64 shows the relative cohesion offered by different air entraining admixtures and DC products. It can be seen that AEA's tend to reduce the cohesion after a certain dosage. This can be seen in conjunction with their water reducing ability. The DC products on the other hand showed improved cohesion, although the PC based product showed a decreasing trend after certain dosage.

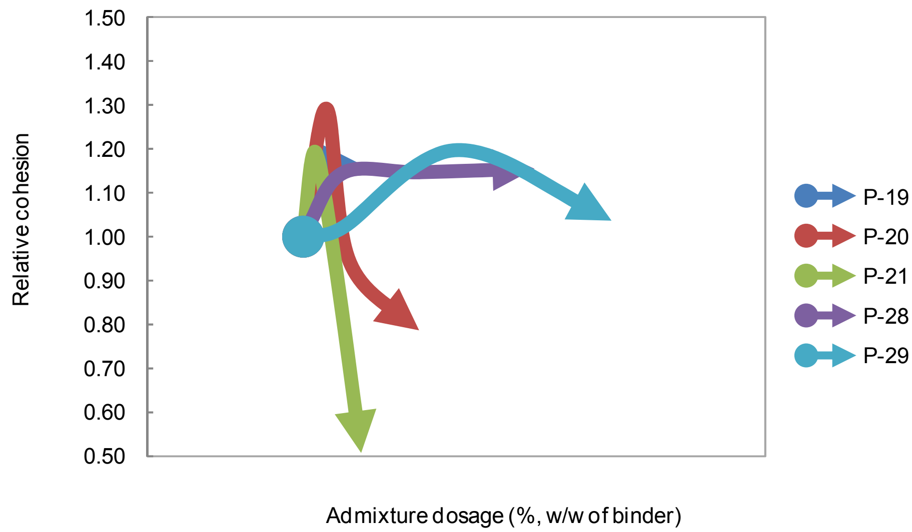


Figure I-64 Relative cohesion for different AEA and DC products

Figure I-65 shows the relative cohesion for the two rheology modifiers. Quite contradictory to their anticipated behaviors in self-consolidating concrete, these admixtures lead to reduces cohesion in RCC. This is partly a consequence of the increase in the water demand of the concretes and partly due to the chemistry of these admixtures.

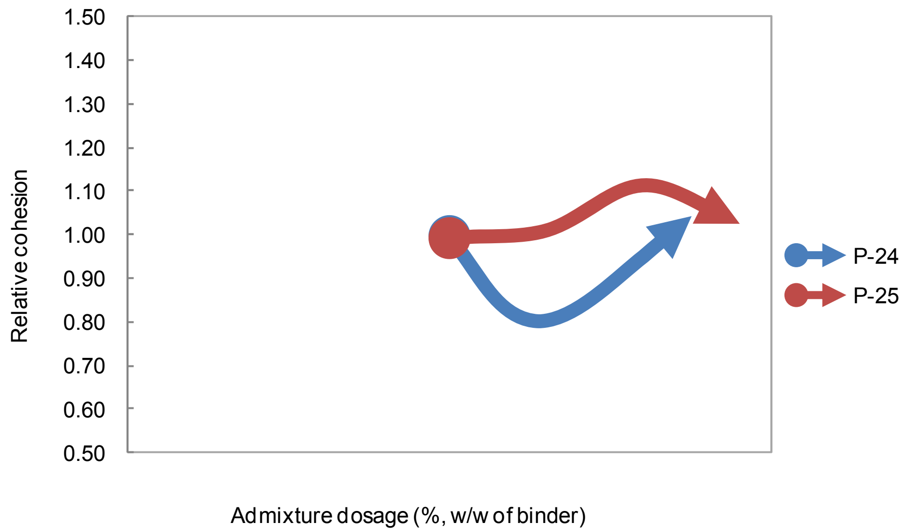


Figure I-65 Relative cohesion in mixtures admixed with rheology modifiers

I.11.1 Work indices

As discussed earlier work indices were obtained to compare the work required for obtaining similar deformations with different normal loads. It indicates how susceptible a concrete system is to varying normal load and whether or not savings could be made by applying lighter or no roller with the use of different admixtures.

Figure I-66 represents a plot of relative workability indices for different water reducing admixtures. It can be seen that the PC based admixture system (vis-à-vis their corresponding water reductions) render a more sensitive system. Lignos and their blends with PC's offer less sensitive systems. Slight changes in the weights of rollers could cause high deformations in case of PC's, while others would render lesser sensitive systems. In practice however, changes in roller weights is not that common and the industry follows its own norms according to what is most practicable. This fact can be used in a reverse way as follows. Paver compacted concrete technology will overtake the roller compacted concrete technology in near future. The advantage of using these chemical admixtures in the concretes for the (paver compacted) technology is that they would render uniform compactable mixtures due to the high sensitivity and thus help eliminate the rolling costs. While using water reducing admixtures, care must be exercised in evaluating the no-slumping of vertical edges as well.

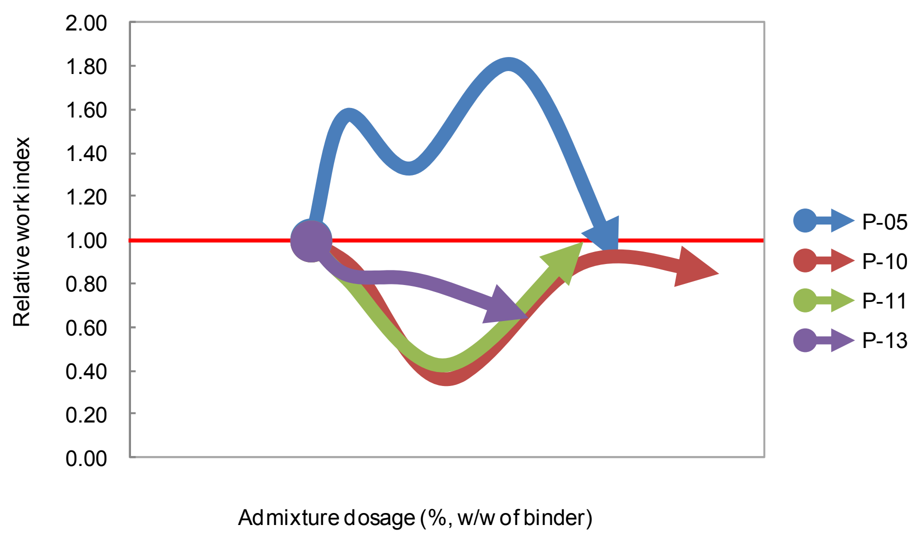


Figure I-66 Relative work indices for water reducing admixtures

Figure I-67 shows the relative work index for different AEA's and DC products. It can be seen that the AEA admixed systems are poor in offering robust systems and could lead to chaos, if their dosing is not carefully regulated monitored. An important aspect of this appreciation is that AEA's do not have the capability of retaining the workability or delaying the process of hydration. Hence the AEA admixed systems could potentially leave a mixture unworkable after sometime, if their water reducing potential is evaluated using the initial consistency test. Hence it should be appreciated that although AEA's or DC products could reduce the water demand of a mixture, they need a boost in terms of sufficient retardation to continue their effects over a practical time range.

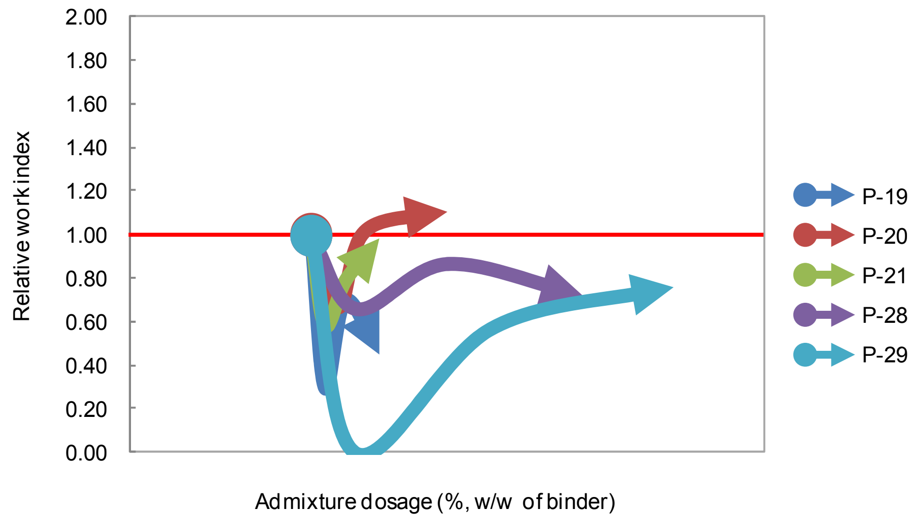


Figure I-67 Relative work indices for AEA's and DC products

Rheology modifiers on the other hand reduce the sensitivity of concrete mixtures substantially as a consequence of their water reduction and the nature of action. Figure I-68 shows the trends. Although they make the system relatively more robust to changes in the roller weights, they are complementary admixtures and need to be used in conjunction with other admixtures that offer primarily required benefits.

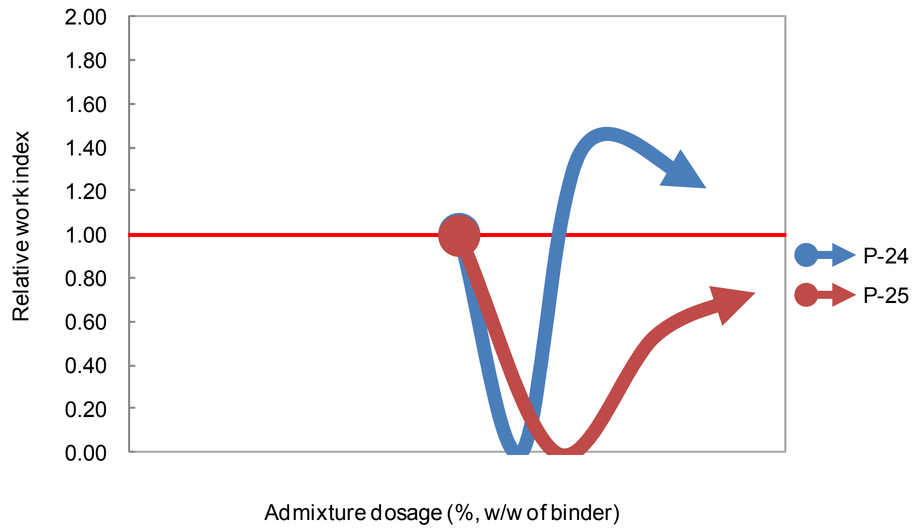
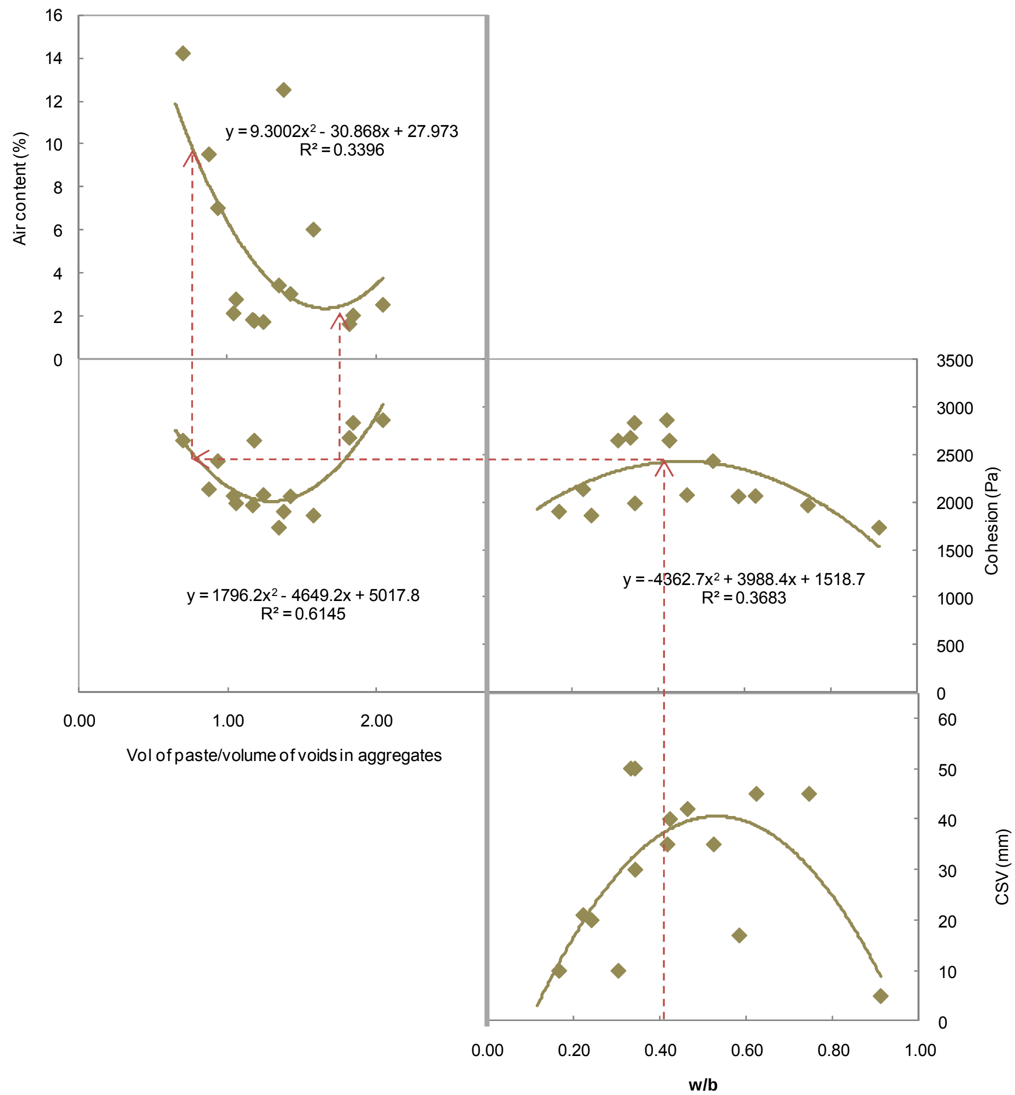


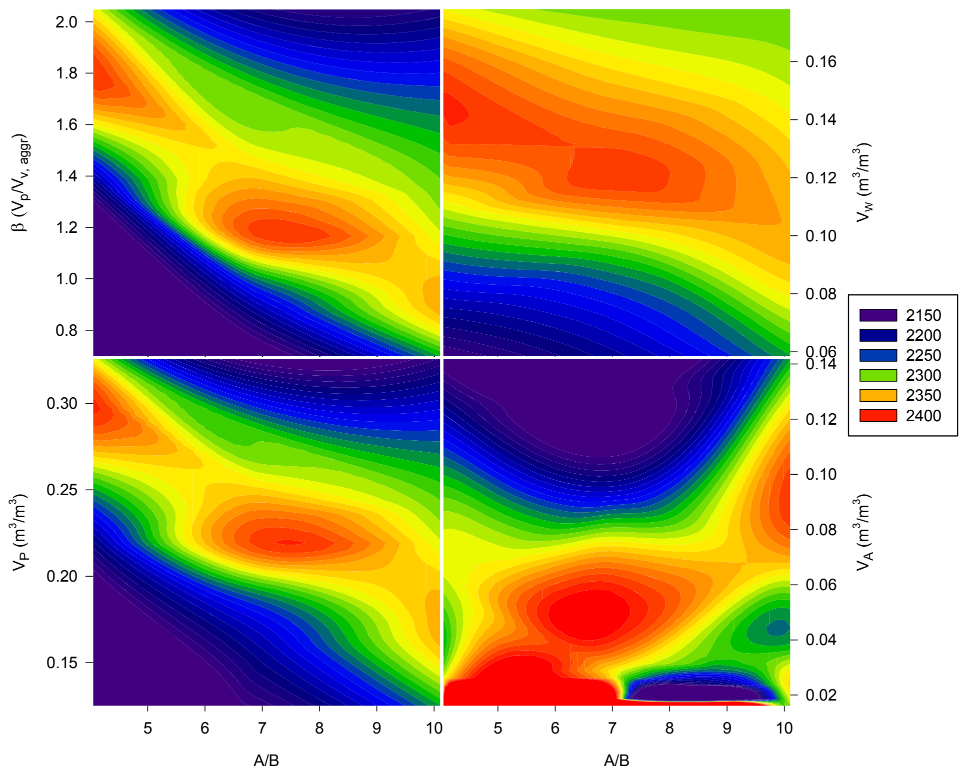
Figure I-68 Relative work indices for rheology modifiers

SUMMARY

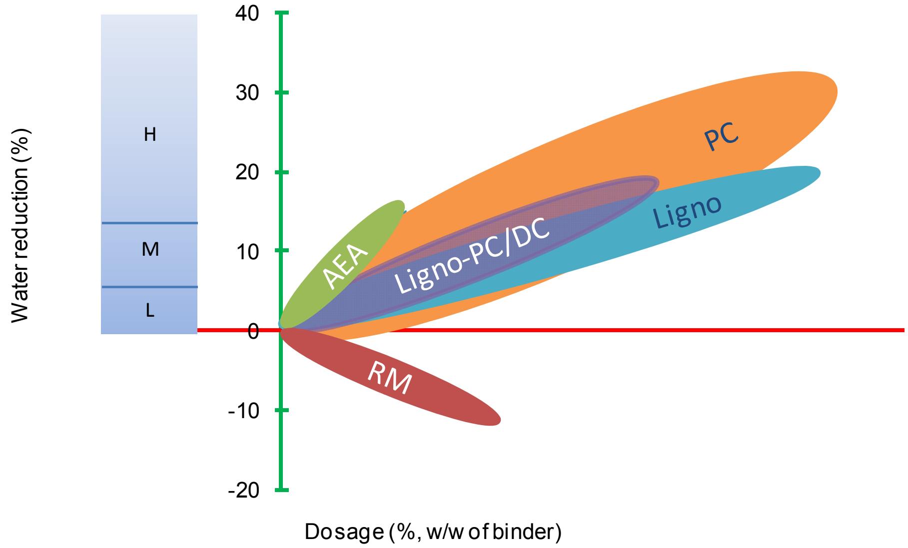
This chapter presented data on workability aspects from multiple perspectives. Fresh behavior of RCC was analyzed and quantified in terms of cohesion, angle of internal friction, compactibility, consistency, air content among others. New indices to define the ease with a mixture can be worked with were defined and used successfully. It was shown how the data obtained from shear test can be manipulated and used in analyzing and comparing different concrete systems.



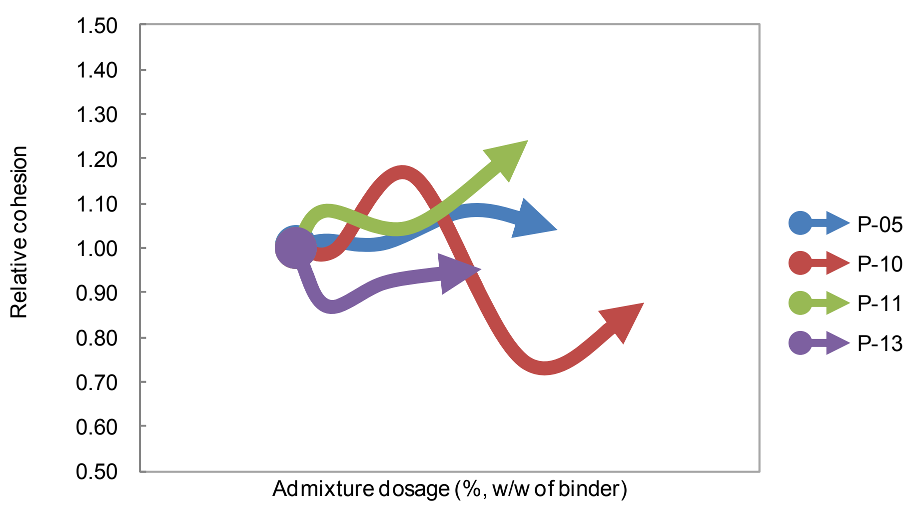
One of the interesting aspects of this work has been the description of concrete systems in terms of its paste quantity and quality. The composition of paste plays a decisive role in influencing the properties of fresh concrete and good correlations with most of properties can be established.



Different chemical admixtures were used to evolve comparative plots to help select the most appropriate admixtures and their dosages. The effectiveness of many chemical admixtures was found to be dependent on the binder content. For each of the admixture tested, there was a specific range of binder content over which the admixture showed optimal performance.



Multiple plots were developed to better appreciate the relative effectiveness of different admixtures and many concepts were evolved and applied to the tested materials to offer the proof of concept.



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APPENDIX J PERSEPCTIVES ON THE STRENGTH ASPECTS OF ADMIXED CONCRETES

SYNOPSIS

This chapter offers the analysis of strength results obtained from various phases of the project. Initially a pertinent review of the factors affecting strength development is discussed. This lays the foundation for the following discussions. Subsequently, a summary of statistics of data from the tests performed for current work is presented. Before starting on the strength analysis of the admixed concrete an analysis of the non-admixed concrete mixtures is presented. Subsequently, admixture-wise details are presented.

The compressive strength results for admixed concretes are presented taking one admixture at a time. These include water reducers, retarders, air entraining admixtures, rheology modifiers, dry cast product and the combinations of admixtures (pairs and triplets thereof). Each of the strength analyses covers studies on the binder efficiencies, rate of strength development, effects of binder contents and admixture dosages, relation of strength to admixture dosages and comparison with the ASTM specifications for different types of admixtures. The analysis also makes use of some concepts like the omega index factor (O.I.F.), which is discussed and applied in the chapter. Finally, a comparative summary of relative strength with various admixtures vis-à-vis their cement saving ability is offered.

Keywords: compressive strength, curing age, binder efficiency, water reducers, air entraining admixtures, rheology modifiers, dry cast product, omega index factor

CONTENTS

J.1 Some notes on strength of concrete

Before appreciating the strength relationships with admixed concrete mixtures, their interactions with different binder contents and the consequent effects on the strength evolution, it is important to have an idea about the nature of relationships strength has with each of the compositional variables. The objective of this section is to offer a preamble to the following presentation and discussion on strength results. The changes in the water contents resulting in the changes in the water/cement (w/c) or water/binder (w/b) ratios also result in changes in the microstructure, hydration kinetics, thermodynamics, and resulting pore structure. The following notes offer some of the salient and relevant aspects of strength of concrete.

J.1.1 Hardening cement paste and its interface with aggregate

There are three main components of the hardened paste, viz. hydrated material, non-hydrated residual cement and pores. The strength of the cement paste is affected by qualitative factors such as a the type of hydrates produced, the adhesive force between hydrates or between hydrates and anhydrous material, and the size and shape of pores as well as the quantitative factors such as pore volume and volume of hydrates [1]. Hydrated material is mainly responsible for achieved strength achieved at a particular age; unhydrated material acts as filler and cannot resist external tensile stresses. At a constant porosity, the strength increases with increasing amount of hydrates being formed and a declining amount of non-hydrated material [2-3]. Pores of different sizes affect the strength unequally. Pores with greater radii are more detrimental than very fine gel pores. More specifically, the total volume of pores primarily affects compressive strength and elasticity of cement paste and concrete. However, these properties can also be influenced by the size and the spatial distribution of pores, maximum pore size, pore shape and connectivity. It is also important to bear in mind that the pore system in hardened cement paste and concrete is highly tortuous, complex and spatially non-homogeneous [4]. Figure J-1 shows a summary of concrete porosity versus in-situ strength. Contextually, in drier mixtures like RCC if the much-needed water is supplied by one means or the other (using water reducers for example), the process of hydration, the resulting microstructure and the porosity or pore structure of RCC mixtures can be improved. This in turn would be reflected in changes in the strengths. Due to the dry nature of the material and the resulting stiffness of the concrete, the internal structure of RCC is inherently different from conventional and newer generation concretes.

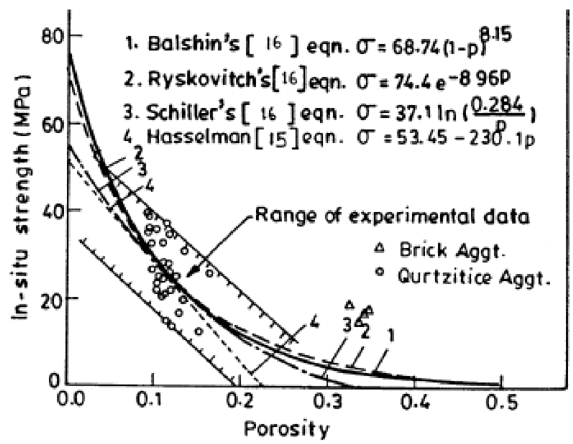


Figure J-1 Strength-porosity relationships [5]

It is important to keep in mind that when the amount of water is decreased i.e., when water/cement ratio is smaller than 0.40, not enough water is available for all cement to hydrate, therefore the cores of the cement grains do not react. At the same time, no water remains in the paste structure, and the total porosity decreases substantially. The combined volume of water and cement together is more than the volume of hydration products, and as such, there is already an increase in the porosity. As stated earlier, the pore-size distribution is directly dependent on the water/cement ratio used. Refer to Figure J-2. The total porosity increases with increasing water/cement ratio and the increase is limited mainly to an increase of the amount of smaller pores [6].

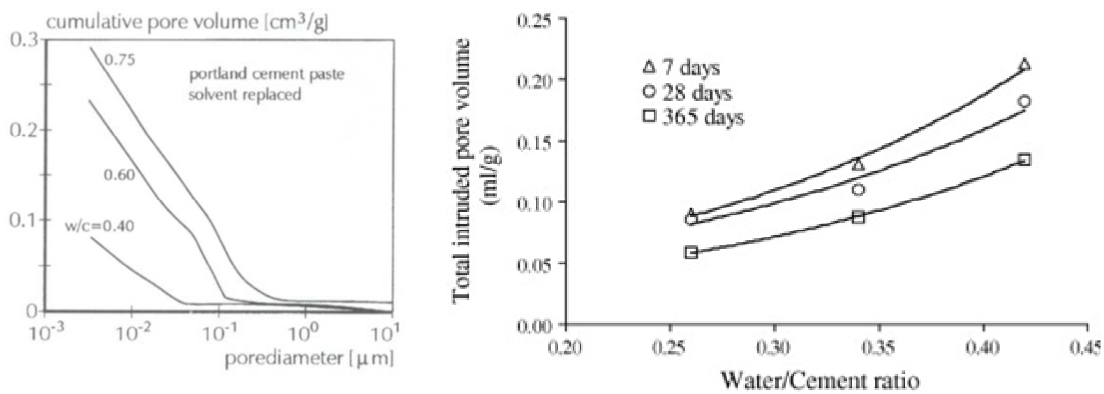


Figure J-2 Effect of water/cement ratio on the pore-size distribution and pore volume of hardened cement paste [6]. Effect of age on the pore volume [7].

Water/cement ratio governs the capillary porosity of cement paste and also the transition zone porosity in concrete [8]. The degree of compaction on the other hand controls the pores of higher magnitudes like entrapped air voids. The degree of compaction itself is dependent on the energy imparted to the system compared to the the compaction energy applied to the system. It is interesting to note that the pore system present in mortar is markedly different from the pores of well-compacted mortar prepared independently using identical proportions of relevant ingredients. The difference in the two pore systems is due to the transition zone present at mortar-aggregate interface [9]. In addition to this, the interfacial transition zone (equivalent to a zone of higher w/c ratio) is heterogeneous, relatively more porous [10], with higher connectivity [11] than the bulk phase. A typical image and results are shown in Figure J-3.

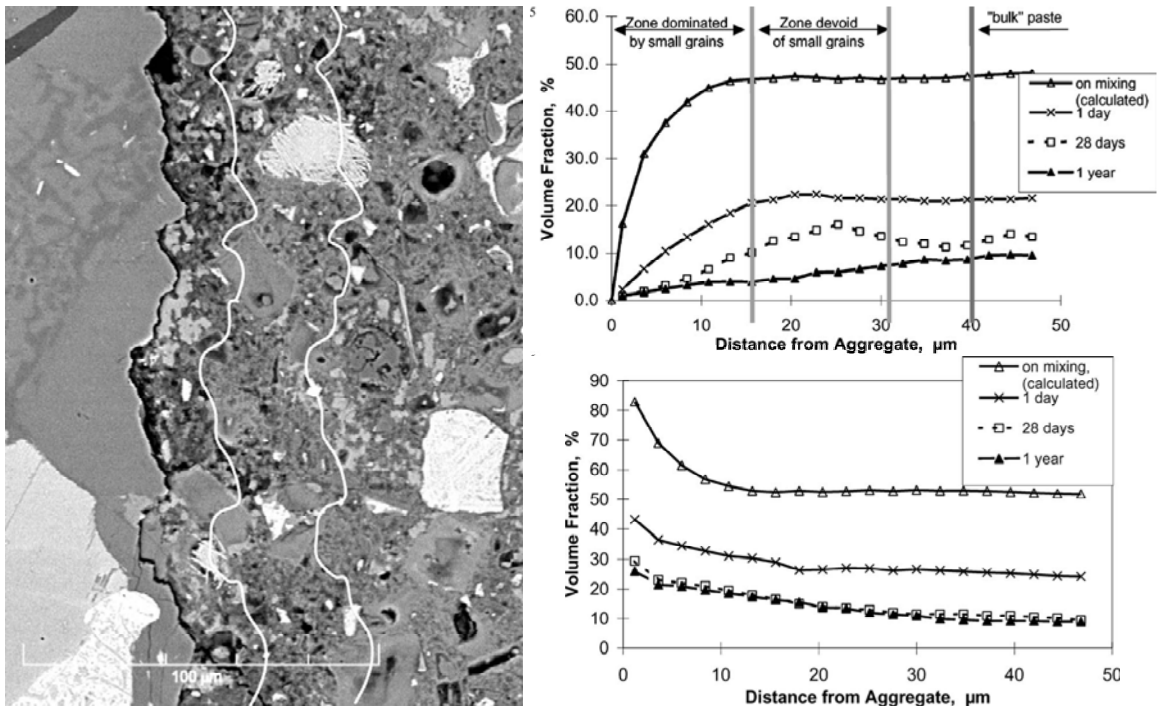


Figure J-3 Backscattered image illustrating typical in homogeneities with an aggregate; white lines are sketched at distances of 20 and 50 μm. Upper plot on right side is the distribution of unhydrated cement in concrete (w/c = 0.4) lower plot represents the average porosity in ITZ at various ages [10]

Marchand, et.al. [12] studied the microstructure of dry concrete products including RCC in comparison with a normal concrete mixture (80 mm slump, similar w/c ratio). Using mercury intrusion porosimetry (MIP), they observed that the drier concretes are intrinsically heterogeneous; tend to have inconsistent and relatively higher porosity (volume) and coarser pore size distribution. Based on their studies, they inferred that MIP is inappropriate for measuring the air void size distribution and compaction voids. Refer to Figure XX. They also made observations on the microstructure using fluorescent thin sections and inferred that the paste fraction of most dry concrete appears to be much more heterogeneous than the normal concrete. The dispersion of water was much more inconsistent and uneven and the variations were observed in the bulk paste in addition to those in the vicinity of the aggregates. Furthermore, SEM observations also indicated that the RCC samples were heterogeneous with large zones of very porous C-S-H, surrounded by more compact C-S-H or coarse aggregates. Irregular shaped air voids were also observed. The interfaces were less dense than the bulk microstructure and were generally cracked, which were speculated to be due to stiffness of the mixture restricting the easy movement of the paste around the aggregates.

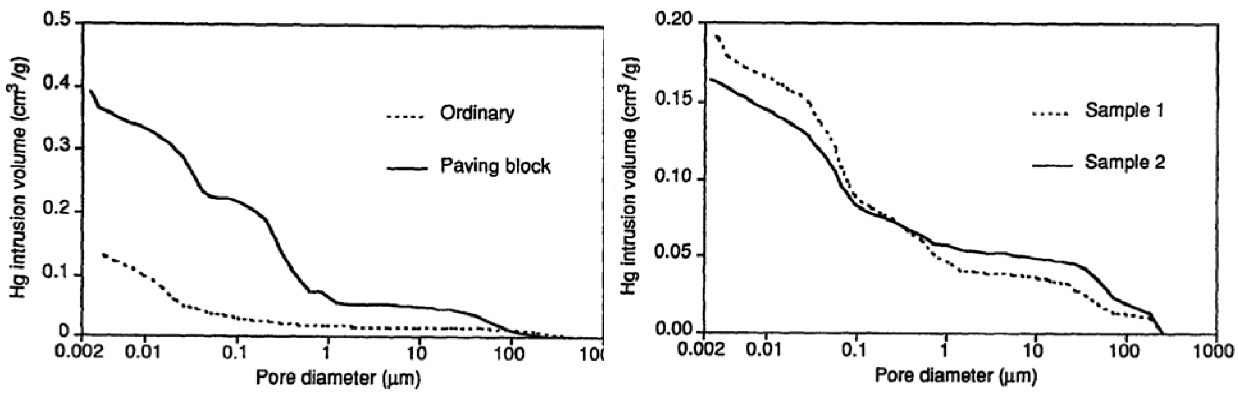


Figure J-4 L: Pore size distribution of ordinary concrete and pre-cast paving block sample. R: Variations in two RCC samples [12].

The microstructure of hydrated portland cement pastes varies considerably with factors such as the chemistry and fineness of the cement used, the water/cement ratio, the use of chemical admixtures, variations in mixing procedures, difference in early curing temperatures, and variations in the hydration conditions. Diamond [13-14] calls the cement paste in concrete of normal water/cement ratios as 'patchy' when observing in backscattered mode in a scanning electron microscope and at low magnification. It is often possible to distinguish zones or patches of relatively dense paste containing little observable porosity, which are distinct from zones, or patches of obviously much higher local porosity. Based on the scope of his work, he infers that the porous zones tend to be irregular in shape and variable in size, of the order of several hundred micron or more. One of the typical images from his work is shown in Figure J-5. Other studies using different techniques including energy-dispersive electron probe microanalysis (EPMA) [15-18], analytical electron microscopy (AEM) [19-23] have identified uneven distributions of elements within the paste and substantiate Diamond's observations. These heterogeneities are considered to be a normal feature of well formulated concrete [10]. One of the pertinent remark is about the effect of the water/cement ratio; hydration of paste with w/c = 0.30 exhibits a very dense structure, while, quite contrastingly paste made with w/c = 1.00

exhibits a much less compact structure with easily detectable pores [24]. This is the range of water/binder ratio quite close to that used in this work.

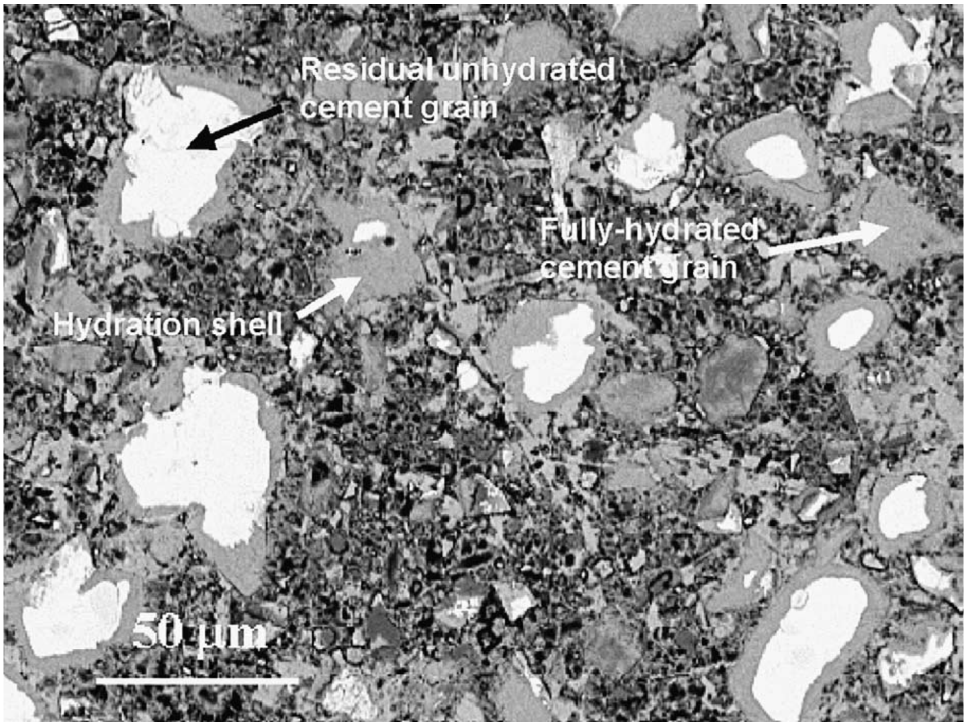


Figure J-5 View of cement paste microstructure of a 100-day old , w/c = 0.3, cured at room temperature

As stated previously, one of the necessary conditions for Abrams' strength-w/c ratio 'law' to be followed is full compaction of concrete. With lower w/c ratios, in the absence of admixtures, reduction of water/binder ratio beyond a certain limit leads to dropping of the density. Density reflects the degree of compaction; but does not necessarily indicate how compact the internal structure of the paste is. In RCC, specifically, the compacted density plays an important role. Strength varies directly and linearly with the density (refer to Figure J-6).

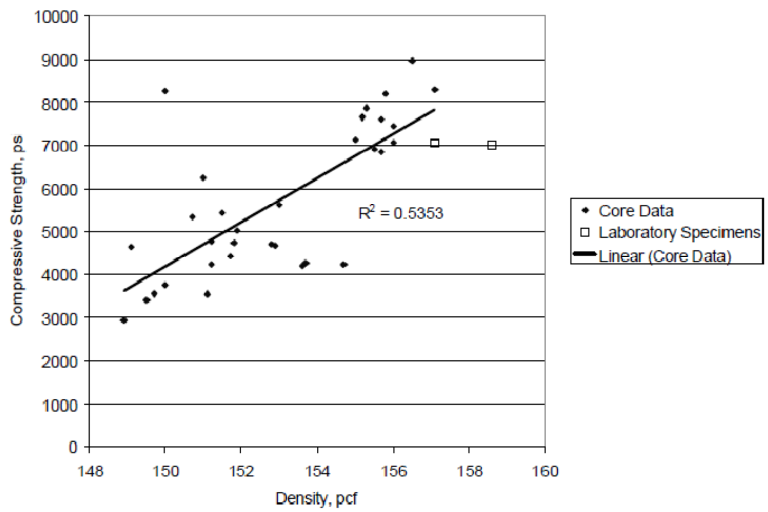


Figure J-6 Variation of compressive strength with density [25]

The relationship between strength and w/c ratio will not always fit the mathematical form prescribed by Abrams. The relationship may differ depending on several factors, but in general, the strength reduces with increasing w/b ratio. Odler [24] states that at a given degree of hydration the attained strength increases with declining water/cement ratio. For all practical purposes, the strength of ordinary concrete is governed by the porosity that is in turn controlled by the water/cement ratio, age and the degree of compaction achieved. Thus concrete mix design can still *generally* be based on Abram's w/c ratio law. However, as is the case with hardened cement paste, the strength versus porosity (or strength versus w/c ratio) relationships are only ***approximations*** in that they do not take into account all the factors involved. Indeed, the w/c ratio 'law' itself is really *a family of relationships for different mixtures*. Quite pertinent is the fact that the w/c ratio law ignores the effect of the cement-aggregate bond, even though this is considered the weakest part of the concrete. The mechanical properties of cementitious systems are controlled largely by the hardened cement paste, its microstructure, pore geometry and, indirectly, chemical composition. The effect of the aggregate in concrete is to modify deformations of the paste under load or under conditions of wetting and drying [26].

The short-term or early strength of neat cement paste and concrete is determined mainly by the fineness of cement and increases with increasing amount of fine particles and increasing specific surface area (at constant water/cement ratio). The long-term strength is only slightly dependent on the fineness of the binder and for a given water/cement ratio is determined mainly by the composition of the cement. Mixtures with low water/cement ratio gain strength, expressed as a percentage of the long-term strength, more rapidly than mixtures with higher water/cement ratios. This is because in the former case the cement grains are closer to one another and a continuous system of gel is established more rapidly. This is true under similar curing conditions [27].

J.1.2 Aggregates

The following is a summary of relevant points on the influences of aggregates on the compressive strength of concretes extracted from [28]:

- The coarse aggregate size exerts an influence on concrete strength independently of water/cement ratio, with strength decreasing as the maximum size of the coarse aggregate increases. This effect could be offset in leaner mixtures of lower strength by the reduction in mixing water requirement, which accompanies an increase in aggregate size.
- Different aggregates are unique in their influence on concrete properties.
- A careful selection of aggregates, without changing the mixture proportions can increase the strength of concrete, depending on the target design strength.
- Surface texture, shape and grading have a direct effect on strength by influencing stress concentrations, degree of micro-cracking, crack branching, tortuosity of crack paths, macro- and micro-roughness effects at interfaces and amount of binder surface area of the aggregates. A relationship for estimating the 28-day cube compressive strength (u), psi was offered as follows

$$\log_{10}(u) = 3.896-1.293w+0.0296E+0.00547i+0.0168n+0.0225a$$

  where, w/c is water/cement ratio, E is the static elastic modulus of coarse aggregate (106 psi), i is the aggregate impact value (%), n is the angularity number (%) and a is coarse aggregate/cement ratio.

- Strengthening of the paste-aggregate bond may result in improved strengths of the order of 20-40%. The aggregate-paste bond strength directly influences the concrete strength. The general form of relation is reproduced in Figure J-7.
- Aggregate packing plays an important role in determining strength but the potential of aggregate to contribute directly to concrete strength is realized only on concretes in which microstructure of the paste and in particular of the transition zone has been modified.
- Concrete shrinkage differs with different aggregate types that may amount to a maximum of about 20-25%. Similar differences in specific creep are reported.

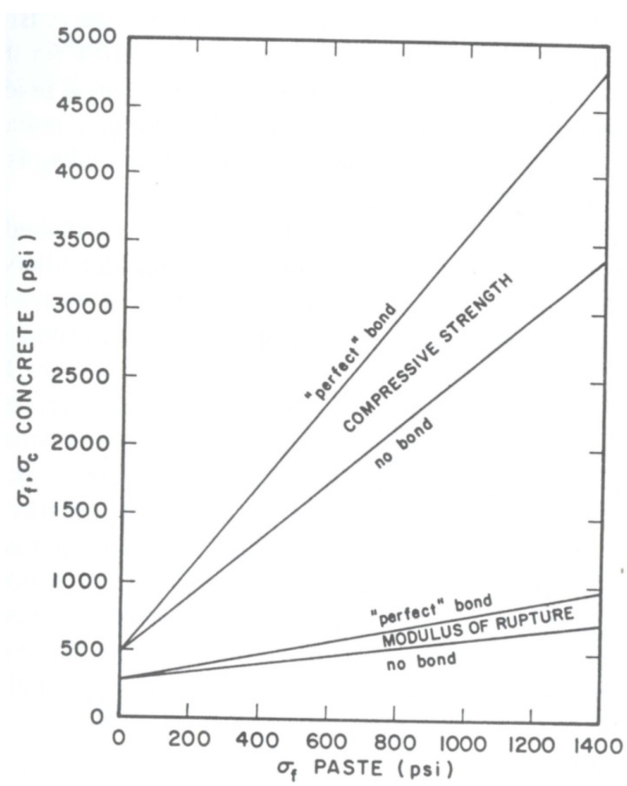


Figure J-7 Effect of cement-aggregate bond strength on the compressive strength and modulus of rupture of concrete

The use of different chemical admixtures has manifold effects on each of the aforementioned components of the hydrating cement paste, and hence concrete. The following is a sampling from the literature on water reducers and retarders.

- Depending on the chemistry, water reducers lower the water demand and hence the water/cement ratio of a mixture and increase the surface area for early hydration [29]. Due to increased surface area, the early age strength gain may increase. If retarder is used, the early strength gain will be reduced. The ability of an admixture to increase the strength is related to its ability to stabilize the structure in the hardening cement paste; higher water reduction may not necessarily yield higher strength [30].

- The influence of normal water reducers on the porosity of cement paste or mortar depends upon the degree of hydration and water/cement ratio. At a given water/cement ratio, normal water reducers affect the porosity and pore size distribution to a less marked extent. With increasing age, when the effect of water reduction on degree of hydration is reduced, the admixed concretes might have a total porosity and pore size distribution quite similar to the control concrete [31]. In case of superplasticizers, within normal dosage ranges, the effects on pore volume, and pore size distribution depends on the chemistry, dosage, degree of hydration and water/cement ratio. The pore volume may increase, decrease or remain unaffected. The pore structure can either get coarsened or refined or can show selective effects (coarsening for a specific size range and refinement for another) [32-38]. Highly purified lignosulfonates may offer comparable results to sulfonated naphthalene formaldehyde and polycarboxylates [39]. Similarly, the hydration rates can be variable.
- Water reducer can increase the amount of entrained and entrapped air in concrete, whether an air-entraining agent is present or absent. This is again chemistry dependent. Lignosulfonate-based and PC- based water reducers are both known to entrain some air in concrete. Due to the plasticizing effect, the water reducers are potentially capable of increasing the density of concrete as well.
- The presence of water reducers (low range to high range) does not affect the preservation of Abram's law. Normally, depending on the nature and chemistry of the water reducer, and mixture composition, higher or comparable strengths can be obtained [40]. This is true provided no excessive air is entrained due to overdosing or as a side effect.

- Dodson [29] proposes a factor, omega index factor (O.I.F.) for evaluating the effectiveness of cement in a concrete mixture and can be used further in evaluating the effectiveness of the admixtures as well. This factor relates the compressive strength, cement content (C.F.) and water/cement ratio by the following relationship:

$$\text{Compressive strength at any age} \approx \frac{\text{C. F.}}{\text{w/c}}$$

The factor CF/ (w/c) is O.I.F. The strength varies directly as the O.I.F.

J.2 Statistics of testing

J.2.1 Test ages

All the concretes were tested at 1, 3, 7 and 28 days with the aim of understanding the rate of strength gain, comparing mixture performance for control and admixed concretes. The concrete mixing and testing times were recorded, thus allowing the computation of concrete age in hours and minutes. These concrete ages were then used in developing the chronological history and mathematical models of concrete strengths.

J.2.2 Loading rate

The loading rate for concrete tests was recorded for most of the tests. For some of the concretes, at early ages, the loading rate was kept below the range recommended by ASTM C39 [41]. The data from the measured test samples was compiled and analyzed for statistical information. Figure J-8 shows the histogram, normal distribution curve and normal quantile plot for the loading rate. The loading rates spanned between 0.05 to 0.32 MPa/s with the mean loading rate centered at 0.196 MPa/s with a corresponding standard deviation of 0.0357 MPa/s.

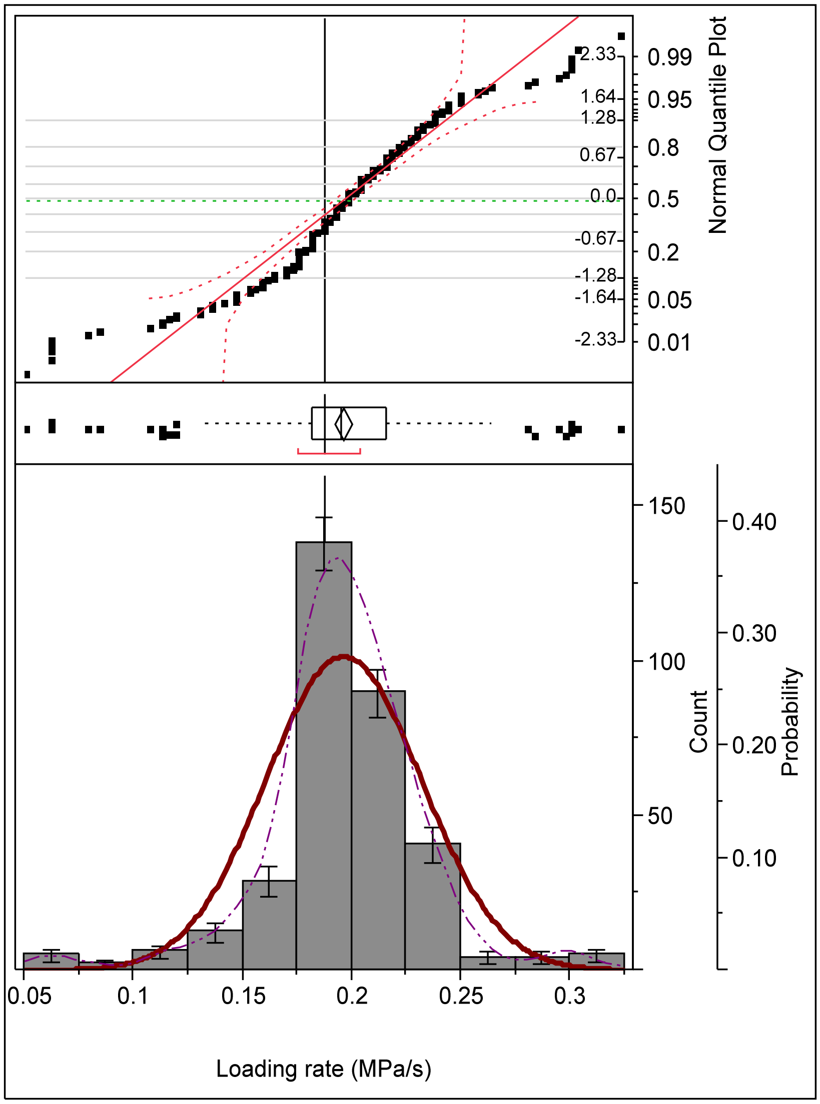


Figure J-8 Statistical descriptions of the loading rates used in this research. Histogram, noramal distribution, smoothed curve and normal quantile plot.

J.2.3 Standard deviation and CoV

This section offers a statistical description of the overall compressive strength, UUCS testing. Test data from control and admixed mixtures was used for developing this description. Mean, standard deviation and coefficient of variation (CoV) are used and analyzed. Data from all ages was used. Figure J-9 shows the variation of standard deviation with the measured UUCS. It should be pointed out that three outliers were discarded from this analysis and no further description of it is offered here. As expected, in general the standard deviation shows an increase with the increasing UUCS.

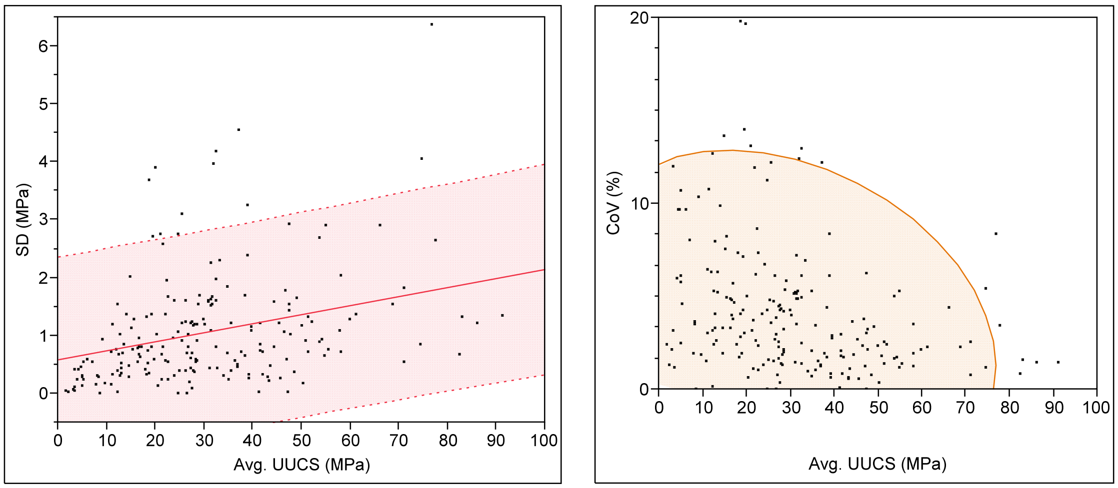


Figure J-9 Variations of standard deviation and CoV with UUCS (JMP analysis)

Similarly, to appreciate the variability in testing, the CoV was plotted against UUCS for different ages and strength ranges. Figure J-10 shows the scatter. It is interesting to note that the coefficient of variation actually shows a decreasing trend with increasing strength. Further analysis on this data was considered to be beyond the scope of this work. To further appreciate the data, a histogram and normal quantile plots were constructed and are shown in Figure J-1. The data shows a right skewed normal distribution.

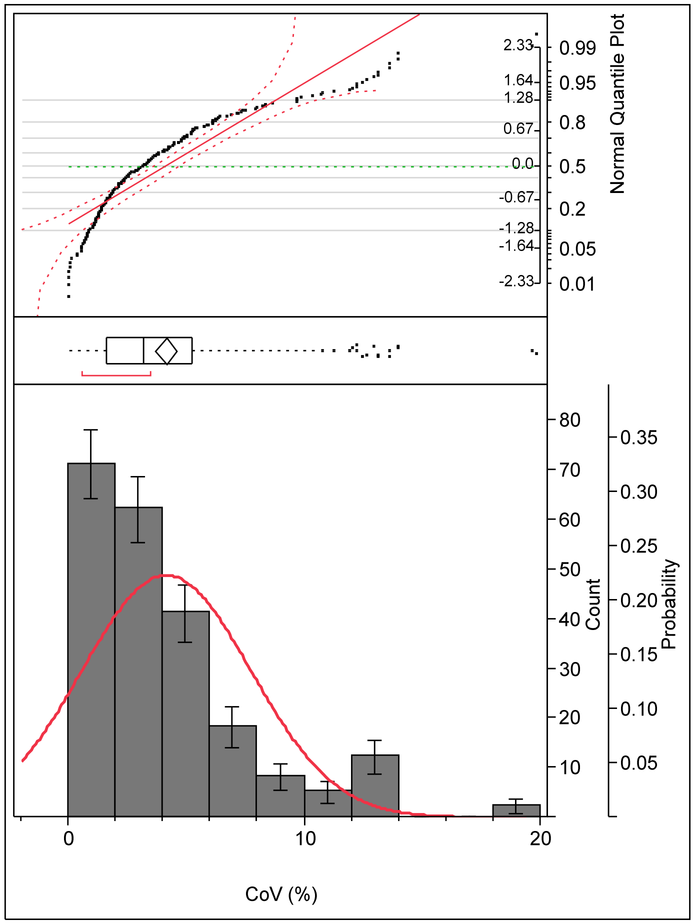


Figure J-10 Distribution of coefficient of variation from strength test data

J.3 Another audit on control mixtures

This section offers additional perspectives on the mixture compositions and their implications on the forthcoming analysis. As discussed previously, water/binder ratio alone is insufficient to describe a cementitious system under consideration; hence, it is important to appreciate other factors, ratios and parameters that could influence the strength of concrete.

It is important to acknowledge the fact that due to incomplete experimentation or otherwise, more often than not, rather narrow and incomplete inferences are drawn and presented. At the fundamental level, the following discussion offers a presentation based on the premise that concrete is primarily composed of binder, water, air and aggregates. Additionally there could be additives that influence the strength behavior of concrete. Furthermore, these materials could potentially interfere with each other's performance. They could also have interaction effects that an objective-specific planned experiment may not be able to capture. It seems safe to have a preliminary understanding that strength cannot be seen as affected by only one of these factors but is a synergistic representation.

J.3.1 Mixture compositions

In this section, the mixture compositions for non-admixed concretes is reproduced and discussed. All the mixtures used for developing the moisture-density profiles are considered control/neat or virgin mixtures. Table 17-1 offers a summary of mixture proportions along with the uniaxial-unconfined compressive strength (UUCS) at various ages. These will be used for further discussion.

Table J-1 Mixture proportions for non-admixed concretes

A/B	Materials, kg/m^3				w/b	UUCS, MPa			
	Cement	F Fly ash	Aggregates	Water		1-day	3-day	7-day	28-day
4	322	106	1731	72	0.1681	1.66	3.03	4.74	5.07
4	334	110	1795	108	0.2432	16.55	23.72	28.11	32.39
4	334	110	1796	153	0.3434	13.44	28.49	34.71	47.26
4	320	106	1721	178	0.4185	8.23	21.50	30.95	38.72
4	336	111	1803	149	0.3341	19.07	31.28	41.87	54.00
7	210	69	1974	63	0.2242	4.24	6.52	6.89	10.82
7	218	72	2047	100	0.3444	8.12	15.01	17.76	21.22
7	215	71	2021	121	0.4245	11.14	20.41	30.11	32.49
7	203	67	1906	158	0.5848	4.89	10.70	17.00	23.52
7	212	70	1998	131	0.4653	12.09	14.45	20.98	34.65
10	144	48	1938	59	0.3052	3.43	5.44	9.67	12.79
10	149	49	2005	104	0.5257	5.13	12.84	15.44	21.61
10	151	50	2024	149	0.7461	3.29	4.98	7.69	10.98
10	143	47	1925	174	0.9115	2.20	3.31	3.99	6.07
10	154	51	2068	128	0.6244	4.99	9.12	12.19	18.57

Notes: The material weights are rounded off. Green shaded rows indicate optimum moisture content mixtures. UUCS: uniaxial, unconfined compressive strength

J.3.2 Compressive strength

TYPICAL ANALYSIS

Figure J-11 shows a typical strength variation plot as a function of added moisture content. This trend follows the moisture density plot. Initially due to low water content and hence drier consistency, the mixture is not fully compactable. Increasing binder in a mixture does not guarantee commensurate strength development, unless there is adequate water to lubricate the paste and hence pack all the solids (chemically active and inert) into a composite and dense material. Under well-cured conditions, and for a given Aggregate/Binder ratio, this composite material is characterized by its proximity to its potentially maximum density and minimum air content. A simple trend is represented in the plot. Since no further discussions on the mathematical relations were planned, therefore these are categorically not mentioned in any discussions henceforth.

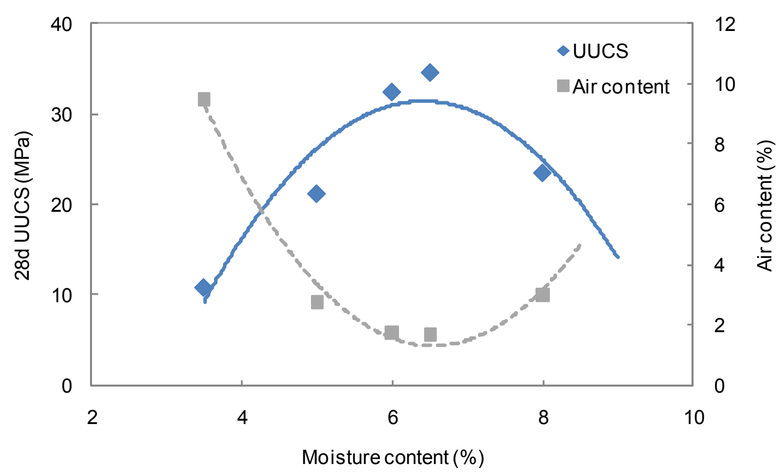


Figure J-11 Typical trends in UUCS and Air content: A/B =7.

The role of air is clearly visible in the above figure. Two regions show quite different influences. On the drier side of the curve, due to less mobile paste, air is entrapped during compaction. The mixture cannot actually be compacted beyond a certain density with routine compaction effort. While on the wetter side, presence of more water facilitates more air entrainment. Moreover, due to higher w/b ratio when compared to the corresponding counterpart on the drier side, the strength is already following a dropping trend, following Abrams's law.

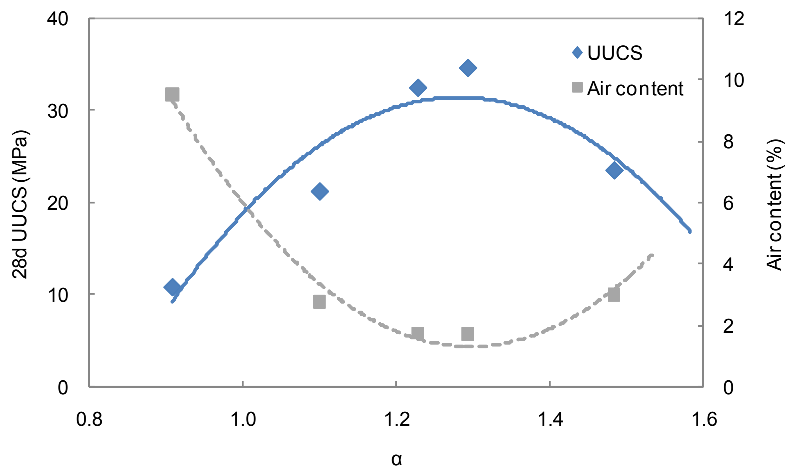


Figure J-12 Typical trends in UUCS and air content as a function of relative paste and fine aggregate volume. A/B = 7.

Similar to above, Figure J-12 represents a plot of strength and air content versus the ratio of paste content to volume of voids in fine aggregates (α). Again, the role of water in influencing a paste and resulting air content and strength is marked. Moreover, the filling of fine aggregate voids with adequate paste is crucial. This will be discussed further in later sections.

The role of compacted density is very important in drier mixtures like RCC. Figure J-13 shows simple trends between strength and dry density of different mixtures. These trends indicate that the farther the mixtures are from the potentially maximum densities, the greater the drop they will show in strength. The effect of water content is not clear from this figure, however it can be seen that the two corresponding points (on drier and wetter sides of optimum) are located fairly close to each other in these plots. Juxtaposing the last two figures together, it could be seen that the strength development is not following the conventionally accepted Abrams' law. This can be explained based on the compacted density. For the stated law to be valid, the concrete has to be compacted to its maximum (or at least proximally) density. Another way of appreciating this law could be in terms of air content. It can be hypothesized that for fixed air content, drier mixtures would in general obey a trend of decreasing strength with increasing water content, albeit the mathematical form might differ.

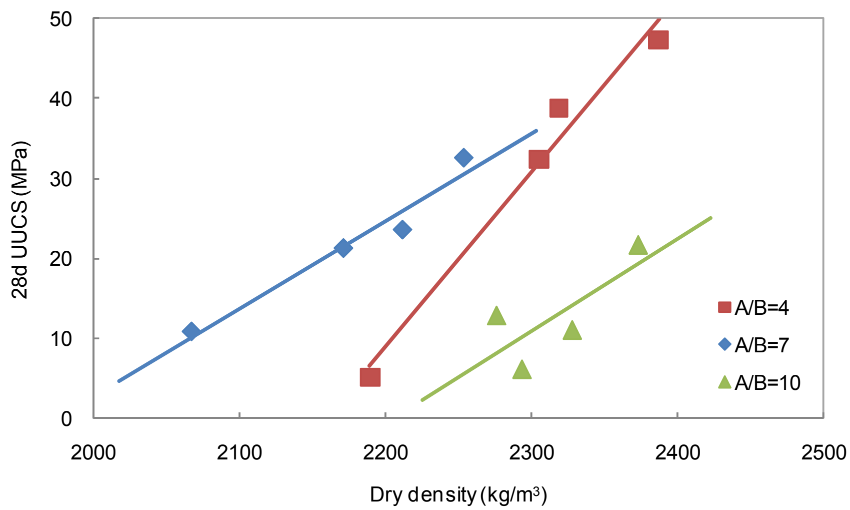


Figure J-13 Effect of compactibility on strength

In general, the temporal evolution of UUCS follows the trend followed by conventional concretes. Under normal curing conditions, this is more or less governed by the hydration and pozzolanic reactions of the binders. The limiting role of water (and hence resulting structure of concrete) is clearly visible. Irrespective of age, UUCS cannot be harnessed from a mixture if there is insufficient of water for hydration and compaction. However, at a given age, the strength optimization as a function of the moisture content is preserved. This is shown in Figure J-14. For clarity, two forms of presentation are used.

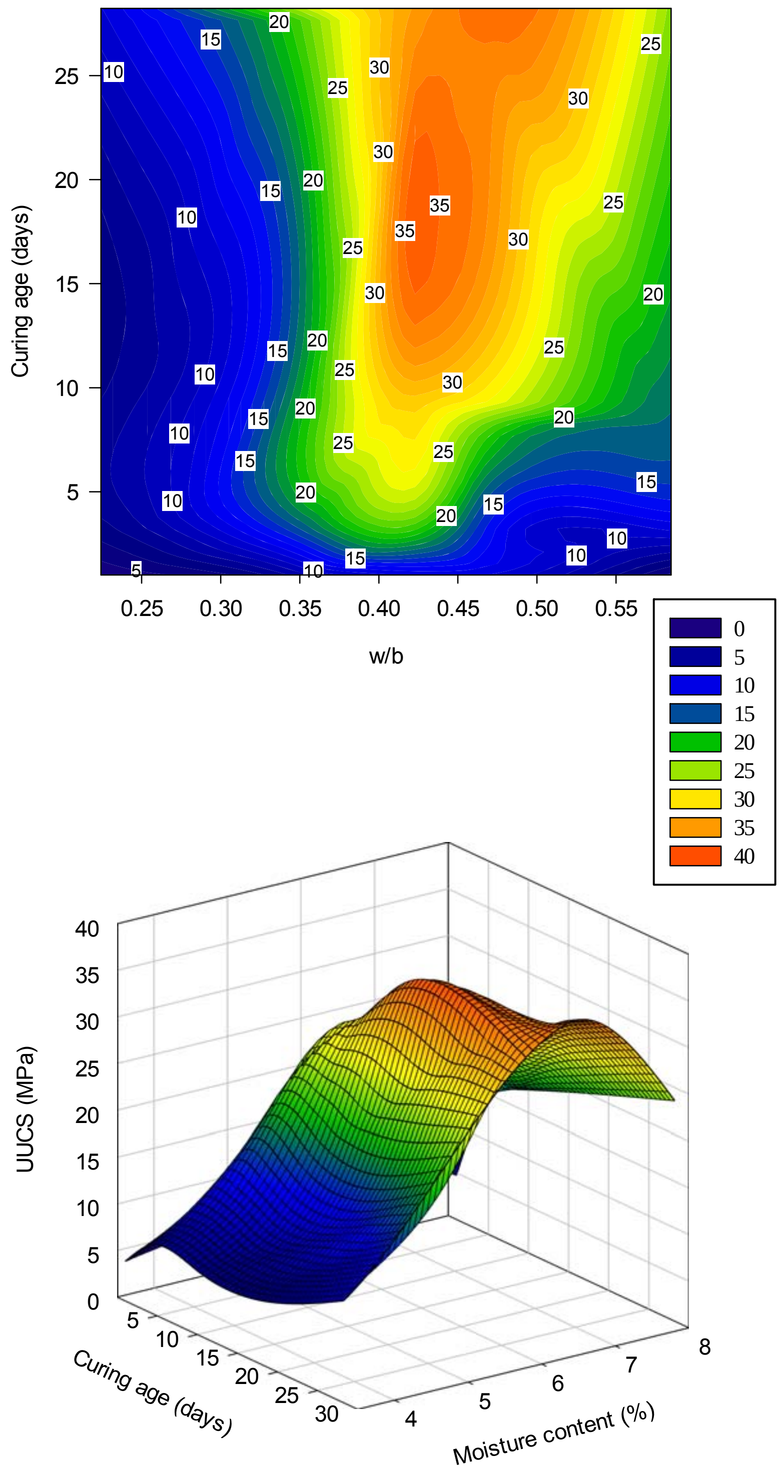


Figure J-14 Temporal evolution of UUCS as a function of moisture content

The temporal evolution of UUCS was modeled using a simple exponential model of the form

$$S = a(1 - \exp(-bt))$$

This relation was observed to follow the hydration process trend and captures the development in two parameters. The term b should be carefully interpreted, since it carries a negative sign meaning the higher this number is, the slower is the rate of strength development at greater ages. Figure J-15 represents the typical strength development trends for A/B = 7.

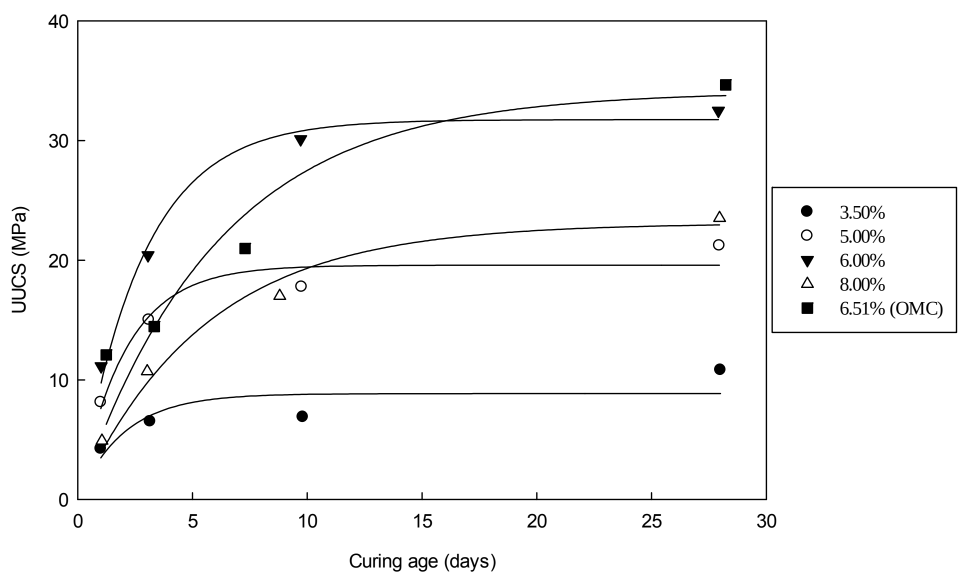


Figure J-15 Modeling temporal evolution of strength development for various moisture contents and A/B = 7

Taking a time derivative of the above equation offers estimates of the rate of strength development. Here the life of concrete is considered to sufficiently long for a day to be small. The following equation results:

$$\frac{dS}{dt} = abexp(-bt)$$

This rate of strength development can be obtained for various ages. Figure J-16 shows typical curves for A/B =7. It can be seen that the initially the rate curve is asymptotic to rate-axis while it later becomes asymptotic to the time-axis. This means that the rate of strength development approximates zero at longer ages. Based on this dataset, it is rather restricting to draw inferences about the relations between the rate of strength development and the w/b ratio or moisture content. A further analysis is offered in a later section.

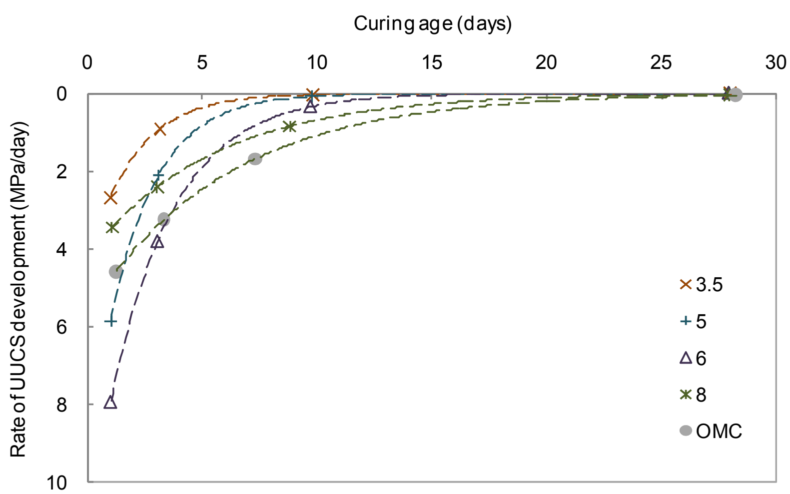


Figure J-16 Time rate of strength development for different moisture contents

These curves are significant from a practical perspective. Knowing the rate of strength development would assist in estimating strength at first day. At later ages, if the area between these curves and the axes is integrated it would provide an estimate of the strength of concrete at any age starting at one day along with an idea of *how fast* would the remaining (*how much*) strength would be achieved.

Cementing efficiency factors are often used in RCC dam construction to characterize the efficacy of cement or binder in providing strength. In this thesis, a similar term called binder efficiency [42] is used. At a given age, the following formula is used for computing the binder efficiency:

$$Binder\ efficiency\ (\eta) = \frac{UUCS\ (MPa)}{Binder\ content\ (\frac{kg}{m^3})}$$

Figure J-17 represents the binder efficiency at different ages as a function of moisture content at a fixed A/B ratio. It can be seen that the binder efficiency increases with age, however its time rate with curing age decreases. This follows the trend shown by the hydration reactions, quite fast initially gradually transitioning to minimal at later ages. This will be discussed in detail in a later section, when analysis for all the control mixtures will be presented.

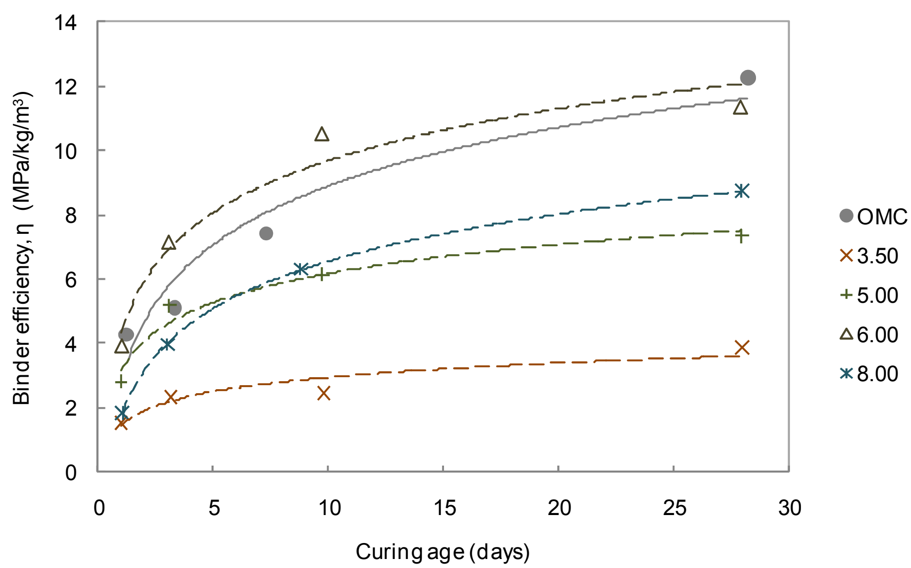


Figure J-17 Effect of moisture content and curing age on binder efficiency

COMPOSITE PICTURE

AN ACCOUNT OF DEVIANT BEHAVIOR

Figure J-18 shows the strength trends as function of w/b. This data is for 28d UUCS. The following observations are relevant:

- In general, there are deviations from the conventionally accepted Abrams law for each A/B ratio. The deviations originate at different w/b ratios, however it is interesting to see that the water content of these mixtures are quite comparable at optimum moisture contents.
- The optimum moisture content and w/b ratios beyond it follow the Abrams' law, however the points on the drier side of optimum show significant deviations.

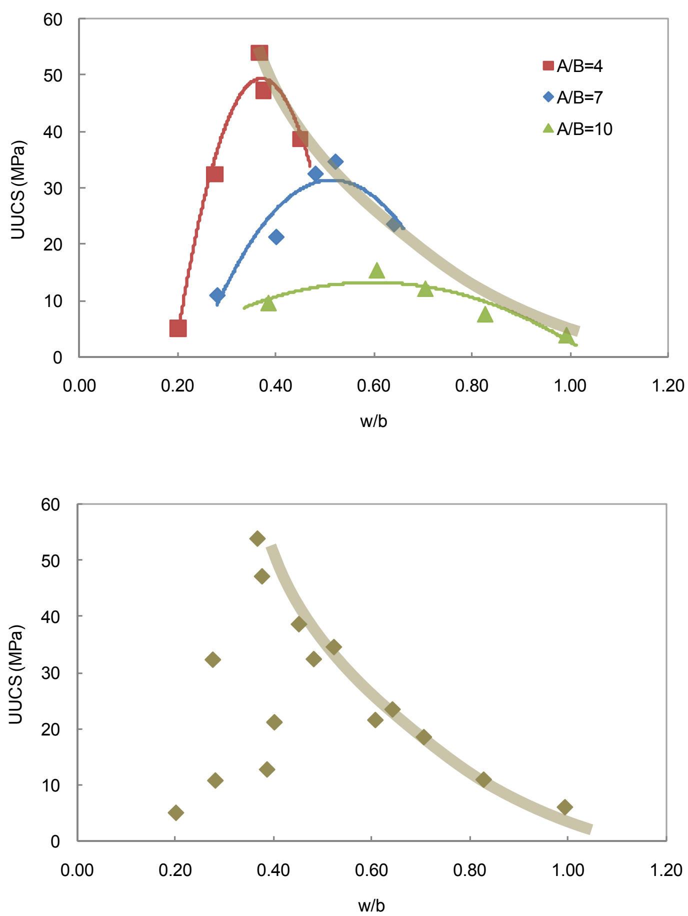


Figure J-18 Deviations from conventionally accepted Abrams law: Individual A/B and composite curves

- The drop in the strength depends on the binder and aggregate content of the mixtures. Richer mixtures (A/B = 4) show a dramatic drop with reduction in water content and this is characterized by a steep slope. While intermediate binder content mixture follows a transitory behavior, it is quite interesting to note that leaner mixtures are far less sensitive to the alterations in the moisture content. This is shown by a flat curve and very gentle slope. A possible explanation is presented. Higher cement contents would need a higher volume of water to achieve a similar amount of hydration. Moisture additions to these mixtures were done based on percentage moisture content on the dry solids basis. As the mixtures become leaner, the volume of cement and hence the water requirement for hydration reduces. Moreover, the aggregates make higher contribution to strength than in the richer mixtures.
- The composite picture shows that the deviation from Abrams law is observed in general. Here, the effects produced by aggregate quantity are not accounted for and the strength is considered only a function of the w/b ratio. Only mixtures that can be compacted to potentially maximum density followed Abrams' law.
- Another interpretation of the available data is presented in Figure J-19. It is believed and proved that the strength-w/c relation follows logarithmic relationship that can be represented by straight lines on a semi-log plot. In the present study, there are strong deviations observed from the conventionally accepted linear relationships.

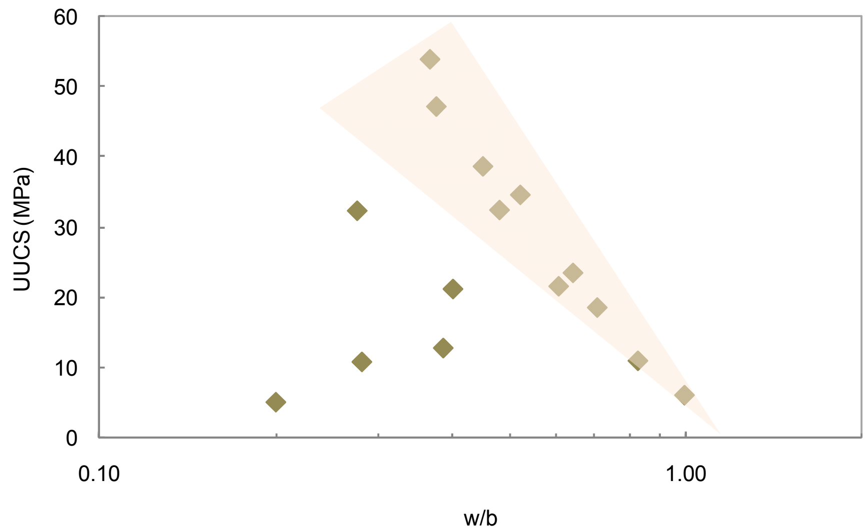


Figure J-19 Another representation of deviation from conventionally accepted concrete behavior

- An important note is all the w/b ratios ranged between 0.17 to 0.91 and were below 1.2.

THE TEMPORAL EVOLUTION

Figure J-20 shows a composite diagram of the temporal evolution of UUCS as a function of w/b. The objective of presenting the data in this form is to comprehend the various strength levels at different ages. No clear trends can be derived from this plot.

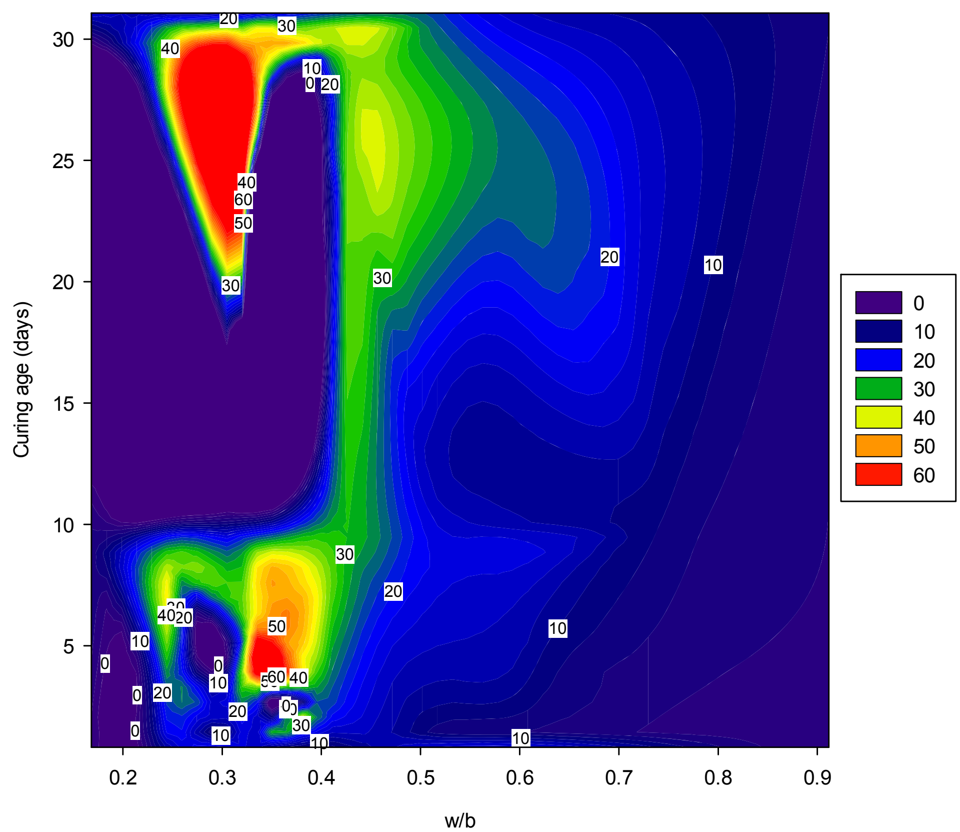


Figure J-20 Composite Age-strength diagram

VOLUMETRICS AND IMPORTANT RATIOS

Figure J-21 represents the interactions of various parameters and ratios with w/b ratio as a primary parameter on the 28d UUCS. Several interactions and optimizations can be observed. Within the scope of present work, the influences of A/B, w/b, Vp, Vair are represented in these contour plots, which represent iso-strength lines. Similar plots can be obtained at all ages. Note that the paste volume is *air-free paste volume* and consists of only binder and water.

It can be seen that not all combinations of cement-aggregate-water-air would produce economical concretes. The following observations are relevant from Figure J-21:

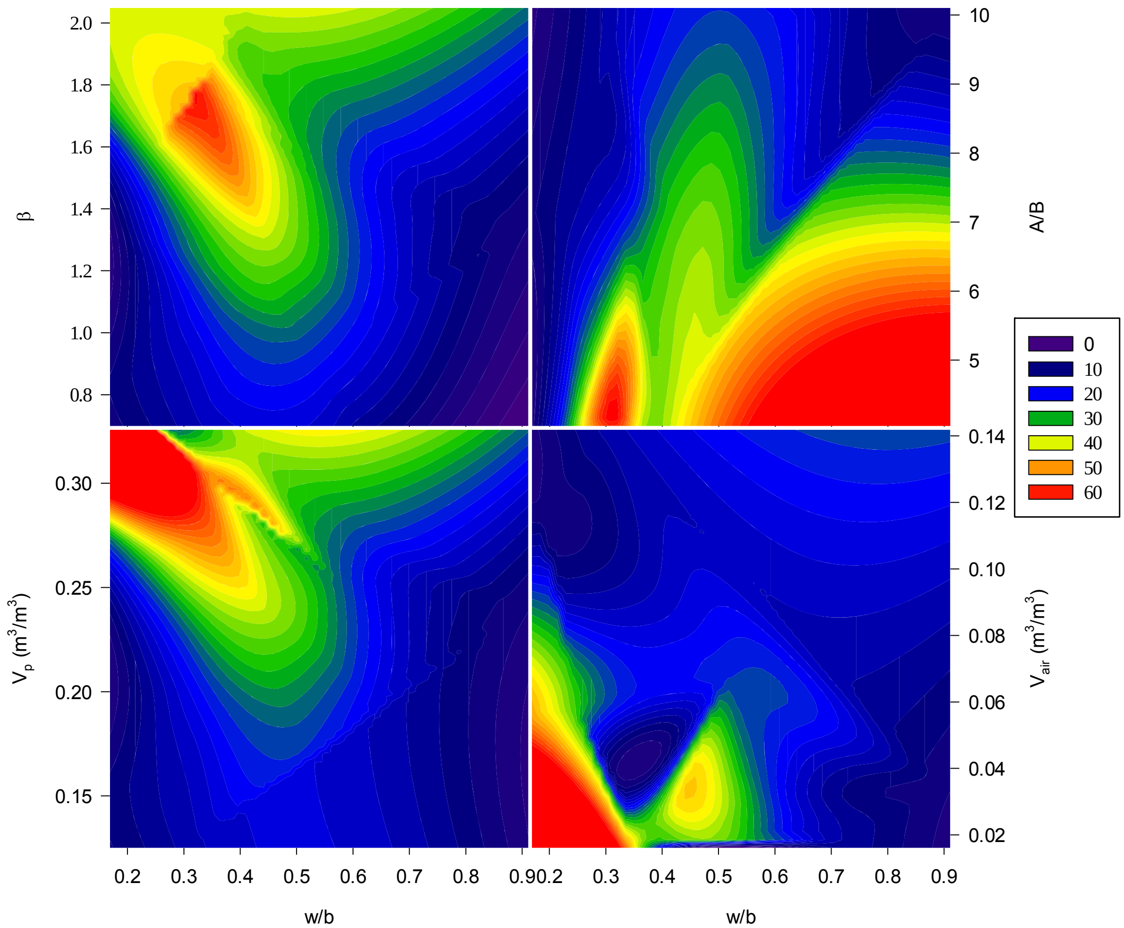


Figure J-21 UUCS: Interactions of volumetrics as function of w/b, by mass

- First quadrant (RHS-Top): For a given A/B, there are ranges that would produce a compactable mixture. Only a narrow range of w/b will produce optimum compaction characteristics that will in turn manifest in highest strength. Similarly, for a given w/b, only typical ranges of A/B will produce good concrete. From the current study it can be seen (RHS-top quadrant) that the strength is optimized at w/b close to 0.3 for A/B = 4, 0.45 for A/B = 7 and 0.6 for A/B = 0.6. This implies that as A/B ratio increases the optimal w/b ratio from strength perspective also increases. Although the water demand of aggregates systems does not change significantly, the amount of binder changes; thus reflecting in terms of higher w/b ration with increasing A/B ratio. The smudged red area with higher w/b and lower

A/B cannot be fully explained based on available data. One explanation could be the presence of higher binder content, which in turn ensures reaching a certain minimal strength level. Juxtaposing this fact with the amount of water that higher w/b in this case would mean tends to overrule this argument at least at higher w/b ranges and also these concretes may be way beyond the regimes of RCC from consistency and compactibility perspectives. Hence, this red-bulb can be ignored while studying these plots.

- Second quadrant (LHS-Top): It appears that there is a two-way optimization going on. There is an inverse trend observed; higher A/B ratio mixtures have lower volume-of-paste/volume-of-aggregate-voids ratio (β) and vice versa. This fact has an intricate relation with A/B ratio and shall be explained in detail in the following section. It can be seen that the filling up of voids in aggregates by binder paste plays a crucial role in optimizing the strength behavior. It is not required to have the highest β values for an A/B ratio to achieve its potentially highest strength. From the obtained numbers, it can be seen that having paste volumes beyond a certain limit is actually leading to dropping down of strength, thus offering a testimony to the nuisance it creates. This can partially be explained based on the composition of paste. In the present study, the binder contents were kept constant for a given A/B ratio, while the water content was increased. This means that increasing paste volume implicitly means increase in the volume of water (and hence w/b). On the other hand, having lesser paste volume leads to incomplete filling up of aggregate voids and insufficient mobility (not close to optimal) required for full compaction thus restricting the realizing of full strength the existing binder quantity is capable of offering.
- Third quadrant (LHS-Bottom): The objective of this plot is clarify the role that the amount of water relative to binder content plays in deciding the quality of paste and their composite effect on the strength evolution of concretes. It can be seen that for every paste volume, there areone or more ranges of w/b ratios that would offer optimized strengths. There would certainly be interplay of other factors that would be considered in the subsequent sections. Analyzing this from another angle reveals that having a certain quantity of water in a mixture is not sufficient for achieving compatibility. There has to be commensurate amount of binder that

leads to a compactable mixture that could potentially achieve the highest strength.

- Fourth quadrant (RHS-Bottom): The objective of this plot is to explain the role of air content in RCC mixtures and the sensitivity of strength to air content vis-à-vis the w/b ratio. As expected, higher strengths are obtained at the bottom of the air content axis. Another perspective on this is that every w/b ratio has a range of *tolerable air content* for which the mixture strength will not be affected substantially; once this range is crossed, there will a dramatic drop in the strength. As a response to compaction effort a mixture can be compacted to various air contents, but individually, depending on the binder content and w/b ratio, the mixtures' responses to strength will differ. For example, the higher binder content mixtures (low A/B ratios) will be less sensitive to the changes in the air content than the corresponding mixtures with lower binder contents (higher A/B ratio).

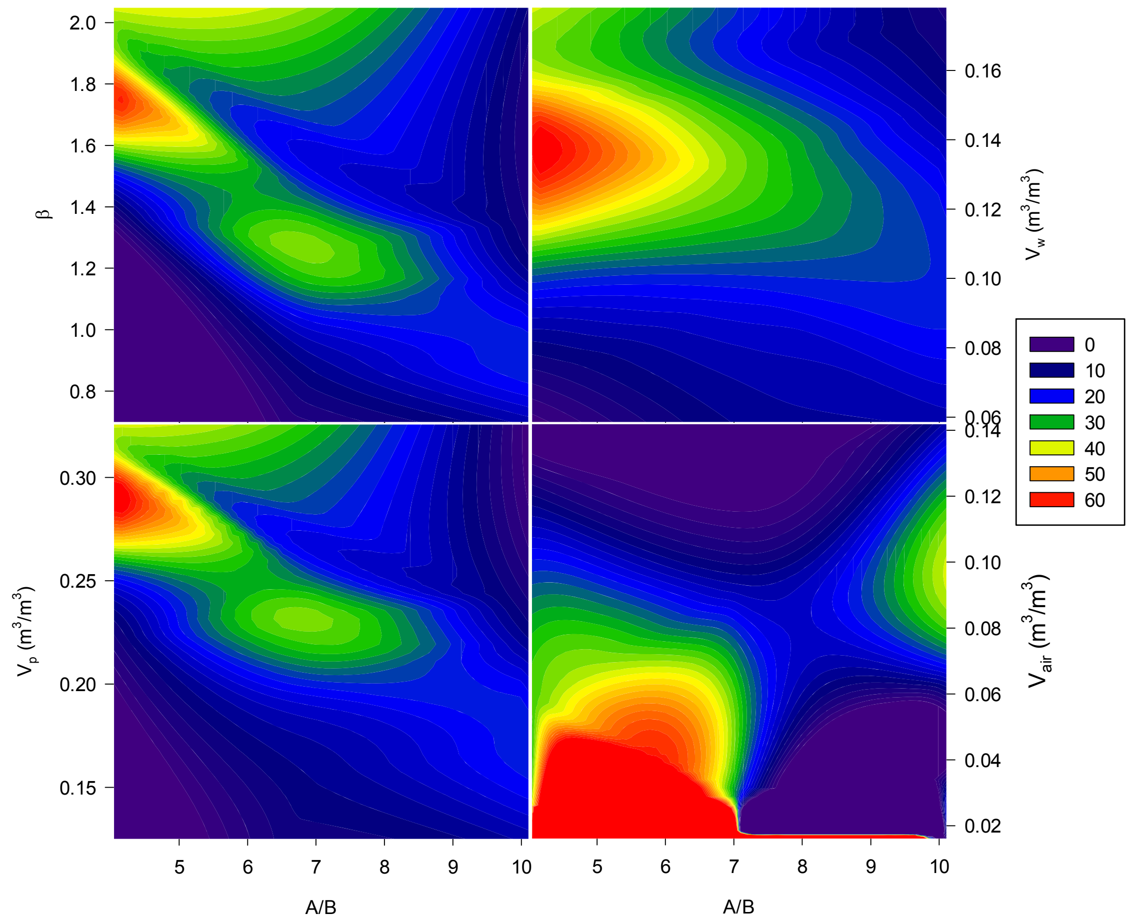


Figure J-22 UUCS: Interactions of volumetrics as function of A/B, by mass

Figure J-22 represents the influences of the interactions of various parameters and ratios with A/B ratio as a primary parameter on the 28d UUCS. Several interactions and optimizations can be observed. These plots are constructed to appreciate the influences and interactions caused due to the alterations in the aggregate contents of the mixtures. The following commentary is relevant:

- First quadrant (RHS-Top): This plot shows the interplay of A/B and volume of water. The remarkable fact that comes out of this plot is the water volume requirement for making compactable concrete that would in turn render strength commensurate to the amount of binder used in making a concrete mixture. For a fixed A/B ratio, the amount of water required to obtain highest possible strength reduces slightly, although the change may not be very perceptible from the plot. As explained earlier, having higher water is associated with corresponding nuisance value both in fresh state and from mechanical strength perspective. It can also be noticed that a fixed A/B ratio has its own robustness and tolerance band within which the strength is not much affected. This robustness seems to be a function of A/B ratio with higher robustness observed at higher A/B ration than at the lower end.

- Second quadrant (LHS-Top): The objective of this plot was to capture the influences of paste volume with respect to voids in aggregates on the measured UUCS. With an increase in the aggregate content, the volume of voids in aggregates also increases. The ratio, β should be carefully interpreted, since like w/b ratio it has two-fold meaning and can be altered by changing one parameter at a time or both. The effects however would be different for different changes. Nonetheless, with increasing A/B ratio the β for obtaining potentially maximum strength decreases and vice versa. Three distinct nebulae (one partially seen) can be observed, each showing its central core of maximized strength. An interesting thing that this plot reinstates is that not all combinations of binder-water-aggregate can make concretes, there are definite demarcations and limits to the amount an individual material can be added and in turn can meaningfully and effectively contribute to a concrete property, in this case UUCS.
- Third quadrant (LHS-Bottom): This plot was evolved simply assess the quantities of the paste volumes. It shows similar trends as the second quadrant and hence is not discussed further.
- Fourth quadrant (RHS-Bottom): The objective of this plot is to explain the role of air content in RCC mixtures and the sensitivity of strength to air content vis-à-vis the w/b ratio. As expected, higher strengths are obtained at the bottom of the air content axis. Another perspective on this is that every A/B ratio has a range of *tolerable air content* for which the mixture strength will not be affected substantially; once this range is crossed, there will a dramatic drop in the strength. Richer mixtures are quite sensitive to strength changes in response to changes in the air contents, while leaner mixes do not show such sharp responses. Due to the combined effect of the amount of paste and higher A/B ratio, higher air is caught up in these mixtures for a given compaction effort. An important note about the

large red bulb seen at the LHS bottom corner is that it would need further magnification to interpret the trends.

Figure J-23 presents the data on the volumetric basis. All the trends have been discussed in the previous two sections; hence, no further elaboration is presented here.

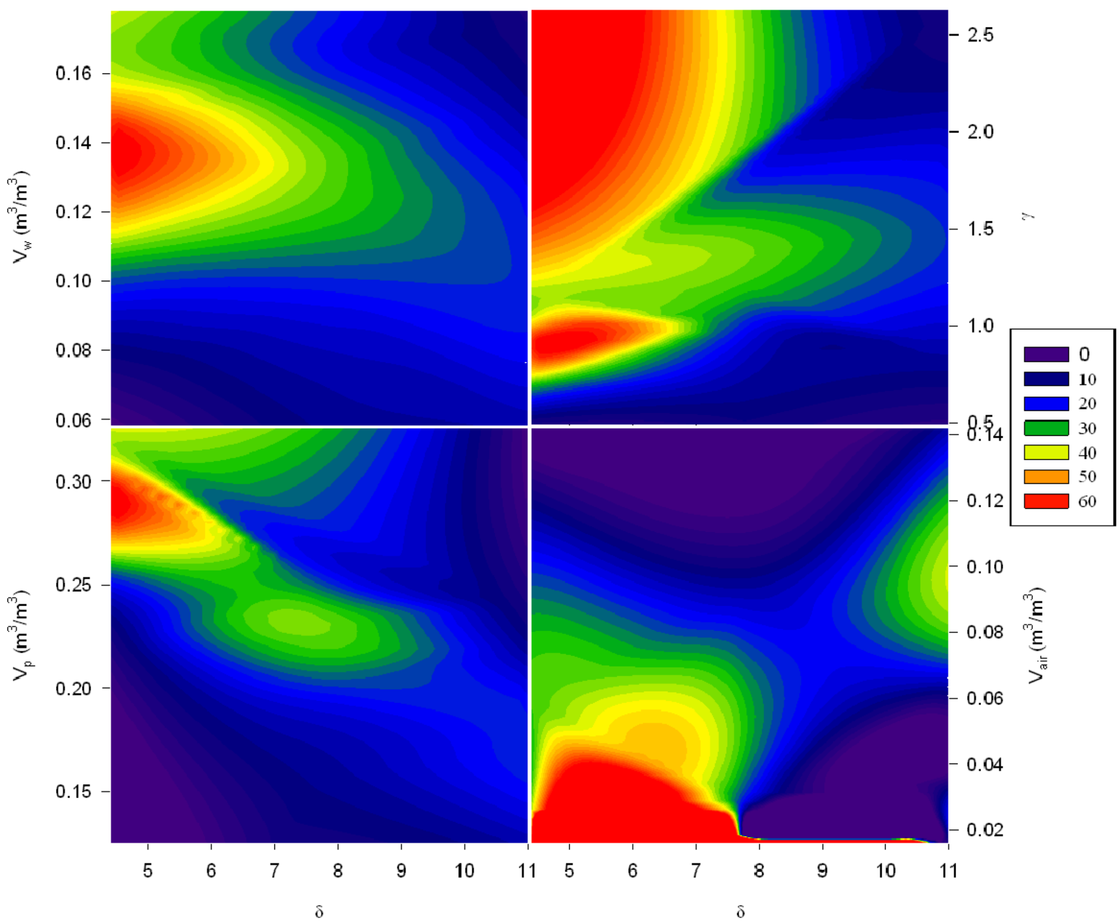


Figure J-23 UUCS: Volumetric relations and interactions influencing strength

Figure J-24 is not extensively discussed because many of the parameters and their effects have been discussed previously. The following points are relevant for the present discussion:

- There are combinations of A/B, binder content and w/b that produce optimal systems from a strength perspective. Having lower binder contents might yield higher binder efficiency, but lesser binder content limits their strength and the concretes may not render good finishibility. While with higher binder contents, the efficiency of the system does not increase significantly to offer an incremental advantage that justifies increasing binder content beyond a certain range. Hence, an optimum binder content and optimum A/B ratio would produce best strength results.

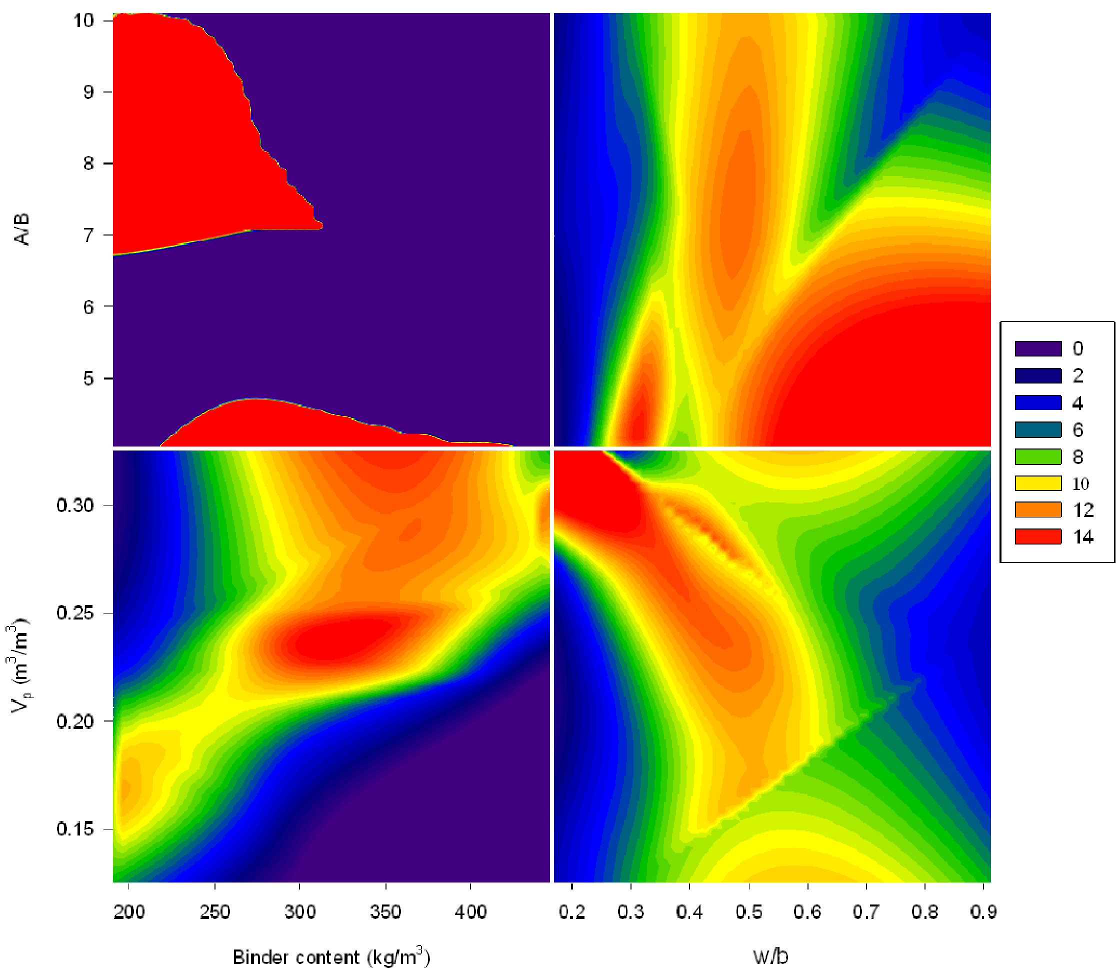


Figure J-24 Effects of paste volume, w/b, A/B on binder efficiency

- From the presented results, the optimal binder content range seems to be between 300-350 kg/m^3, the optimal paste volume is in the range of 0.20 to 0.25 m^3/m^3. From the A/B ratio perspective, optimization of binder efficiency takes place at different levels.
- From the paste volume perspective, it can be observed that the optimal paste volume increases with increasing binder content. This is a reflection of the composite effect produced by the amounts of binder, the corresponding water demand and the resulting w/b ratio required for achieving the matching compacted density. Although the volume of water does not change significantly with the changes in the A/B ratios, higher binder content mixtures are optimized at lower w/b ratios than the corresponding lower binder content mixtures. This happens because the w/b ratio reflects a quantity of water relative to the binder.

TEMPORAL EVOLUTION OF UUCS

The temporal evolutions of UUCS were modeled using the simple exponential model as discussed before. Figure J-25 shows the plots of coefficients a and b as a function of w/b.

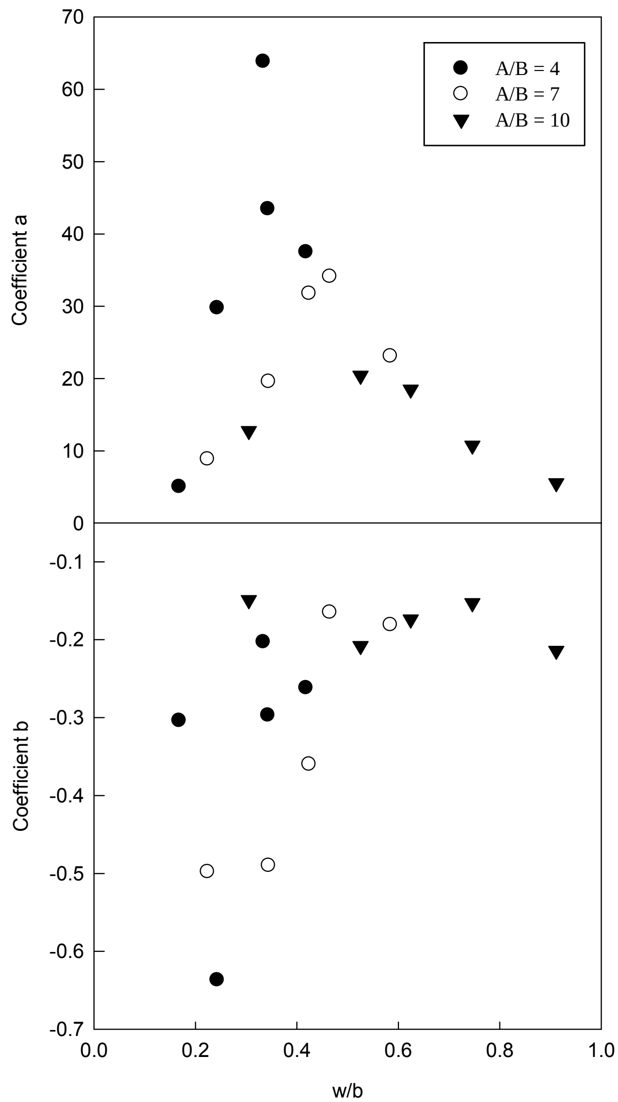


Figure J-25 Effects of w/b and A/B ratios on the strength coefficients a and b

RATE OF STRENGTH DEVELOPMENT

Figure J-26 shows the variation of rate of strength development as a function of curing age and binder content. Note that this diagram is developed for fully compactable mixtures (OMC) only. The rate of strength development is observed to increase with increasing binder contents and decrease with age. A composite diagram like this could help select the binder content based on the required rate of strength development and strength at a particular age. Moreover, it is anticipated that it would also help reduce excessive use of binders by helping select the right binder content.

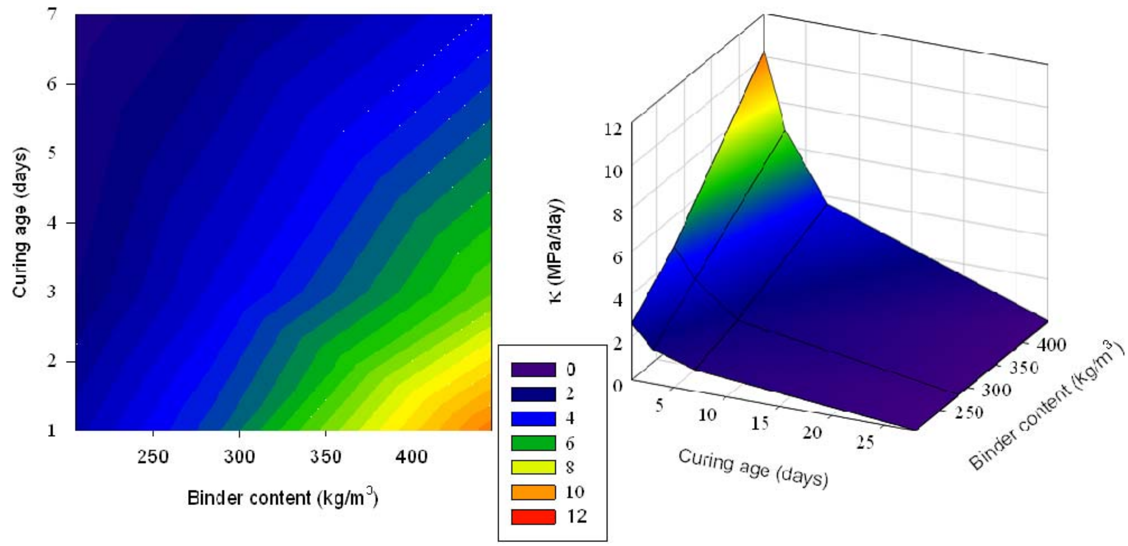


Figure J-26 Variation of the rate of strength development (κ) with binder content and curing age

J.4 Primarily water reducing admixture: a discussion

Water reducing admixtures may be used in at least three different ways as shown in Table 17-2. The range and extent of changes that can be brought with a given water reducer will depend on the cement and admixture characteristics. For the work under discussion, the consistencies of concretes at 15 min were kept constant while observing the reduction in water-to-cementitious (w/cm) ratio and keeping the cementitious content constant.

In this study, three primary chemical compositions of water reducer's viz. lignosulphonate based, polymer based and blends of ligno-polymer based were used. This section is divided into two parts. The first one offers a detailed analysis of polymer based water reducer. Similar analysis is performed for the remaining two chemicals. The second section offers a comparative statement based on admixture composition. The third and final section offers a perspective from an ASTM classification standpoint.

Table J-2 Ways of using water reducers [43]

Case	w/cm	Slump	Cement content
I	↓	~	~
II	~	↓	~
III	~	~	↓

It should be noted that the foregoing discussion relies on the assumption that all the mixtures are compacted to similar or comparable densities. The current state of testing as applied in this work is not capable of capturing differences. Moreover, density is quantified in terms of measured weight for a fixed volume and it may or may not be able to reflect the degree of compactness of a set of materials, especially when the process is confounded by suspensions of varying plasticity. This in turn also means that the vibration responses of these mixtures are quite different. As has been pointed out before, all mixtures were compacted at the end of 45 minutes after mixing, while the initial consistencies of the mixtures were kept constant, when characterized by an empirical test. Mechanistic characterization could be helpful for performing in-depth analysis. In addition, the vibration responses of these mixtures would tend to differ since the solids content of the cement suspensions are changing.

J.4.1 Water reducer: Type A for normal concrete

Type A admixture (P-06) was used in assessing the effectiveness of this admixture in different RCC mixtures. The manufacturer of this product claims more complete hydration of Portland cement with no effect on concrete air entrainment and a typical water reduction of 3-10%. The recommended dosage is in the range of 0.130 to 0.455 l/100kg of cement for normal concretes. Table 17-3 presents the experimental plan.

Table J-3 Experimental plan for a Type A water reducer

Binder content (kg/m^3)	A/B	Dosages (%, w/w of binder)					Remarks
		1	2	3	4	5	
205	4	0.00	0.50	1.50	3.00	--	Detailed investigation
282	7	0.00	0.19	0.75	1.50	3.00	
446	10	0.00	0.50	1.50	3.00	--	

EFFECT OF ADMIXTURE DOSAGE

As seen previously, the water reduction for this admixture ranged from zero to 30% depending on the dosage and the binder content in a mixture. Figure J-27 shows the trends in strength and percentage increase over the control mixtures for this water reducer along with the manufacturer recommended dosage bands. The percentage increase over control is shown with respect to the optimum moisture content. Due to an initial computation error, the first admixture dosage was less than what was thought off.

The trend indicates that the 28-day strength increases in the range of 12 to 57% over the control. Initially the strength shows an increase with the dosage reaches a maximum and then starts showing a decreasing trend. One of the things to note when using these curves is that the water content of the admixture is not taken into account. With increasing admixture dosage, the water content of the mixture also increases. The net amount of water reduction shown by these mixtures would then be the observed water reduction on a consistency basis less the water coming from the admixtures. However, such differentiation is not made in this analysis, because not all admixture manufacturers offered this information. Hence, to be consistent a simpler notion of computation has been used. A possibility of retarded strength gain manifesting into lower relative strength can also be offered. The explanation for such an increase in the strength is explained in the section on PC-based water reducer where detailed data is available.

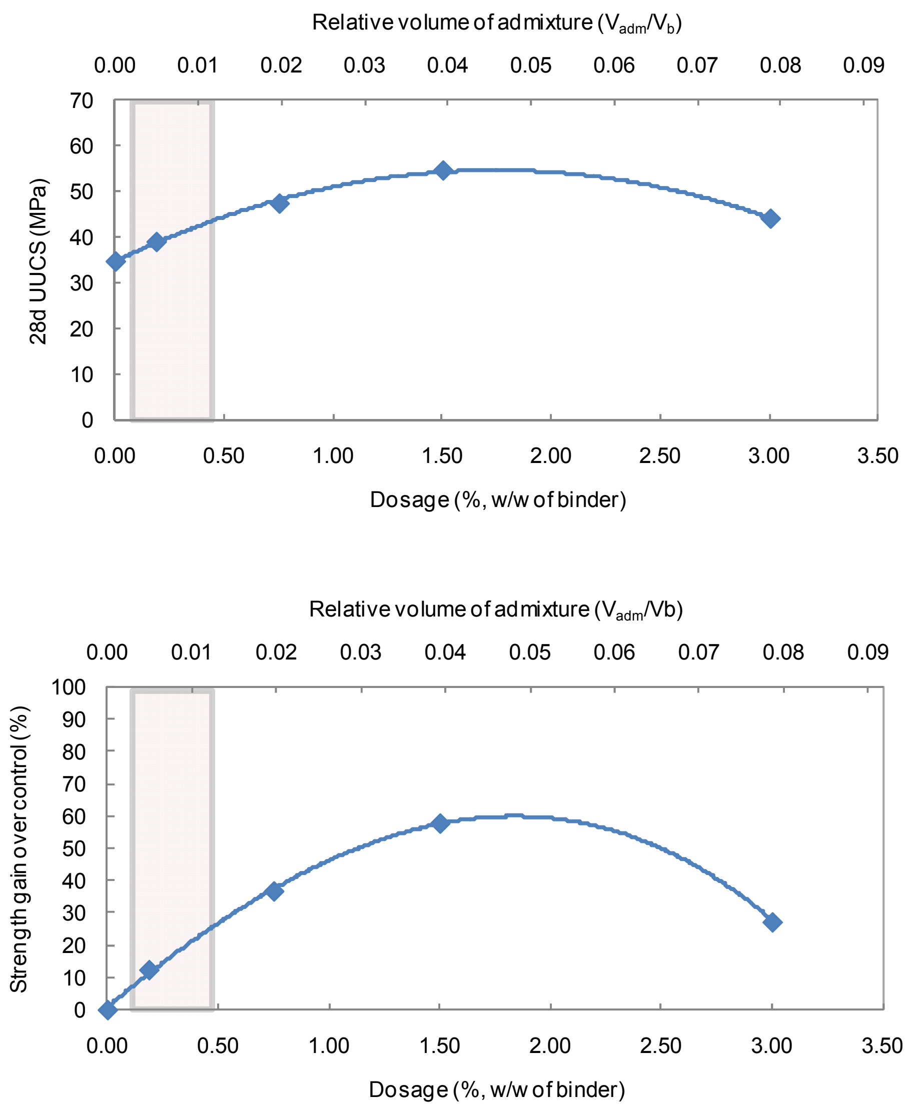


Figure J-27 Effect of water reducer (Type A) dosage on 28d UUCS. A/B = 7. Pink box marks the manufacturer recommended range.

EFFECT OF BINDER CONTENT

The effect of admixture dosages on mixtures with different binder contents are presented in Figure J-28. The 3D plot indicates that there is a binder content range over which this water reducer offers the most effective results. It is however not possible to argue this further based on the scale of this test program. Irrespective of the binder content, the general trend indicates that there is an optimization of strength vis-à-vis the admixture dosage and corresponding water reduction. When the aforementioned effects are combined together the interaction results into the most optimal dosage. This will be clear when the interaction effects are appreciated.

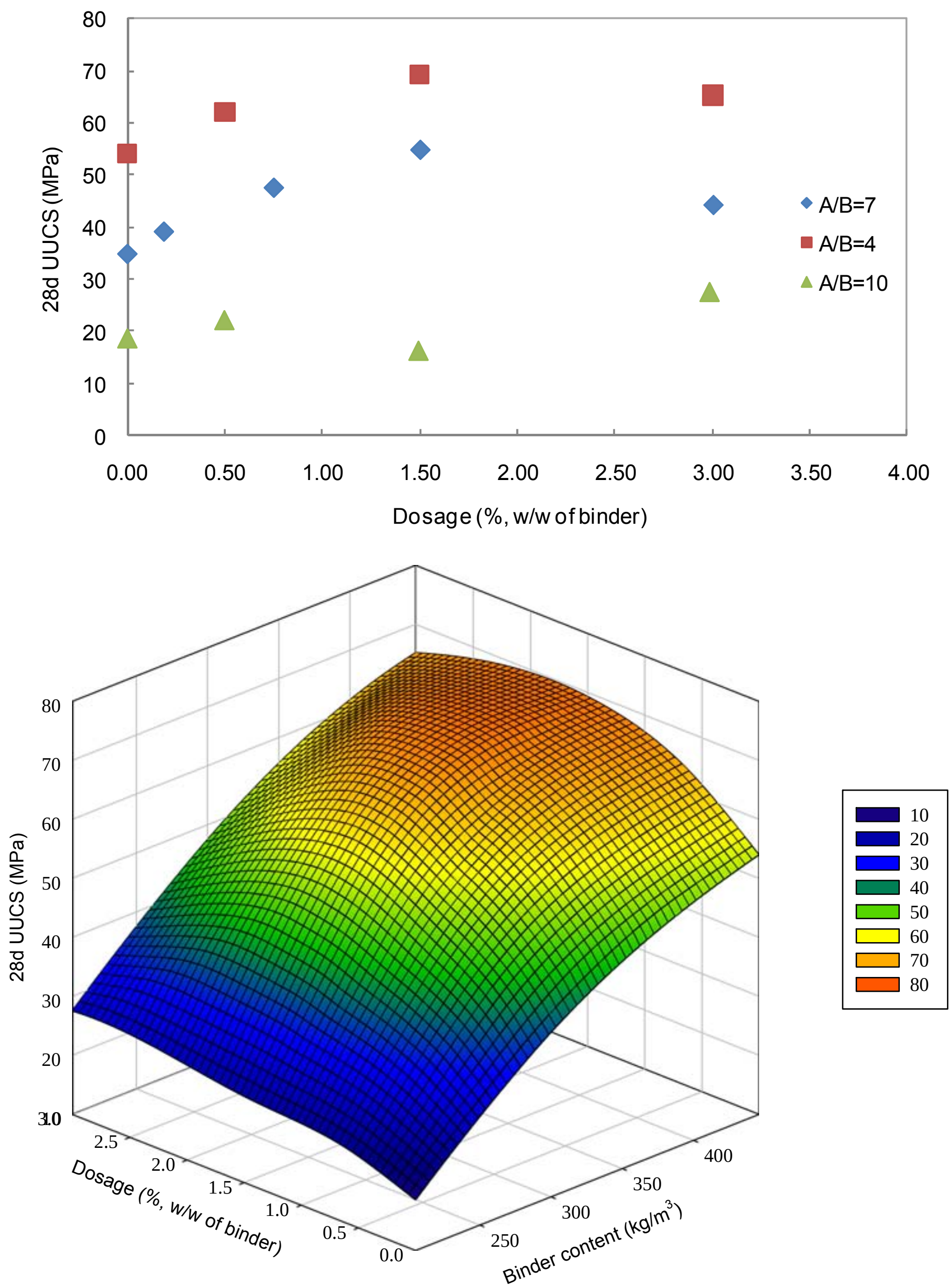


Figure J-28 Effects of binder content and Type A water reducing admixture dosage on 28d strength

TEMPORAL EVOLUTION

The temporal evolution of strength follows trends similar to control mixtures and are modeled using the same generalized equation. The coefficients are binder content and dosage dependent (refer to Figure J-29). In general, considering the coefficient, a, for a given binder content, there is an increase in the 28d strength with increase in the dosage; however the rate of increase decreases with higher dosages. In case of intermediate binder content, there is a peak in 28d strength as a function of admixture dosage and beyond this point, this strength shows a reduction.

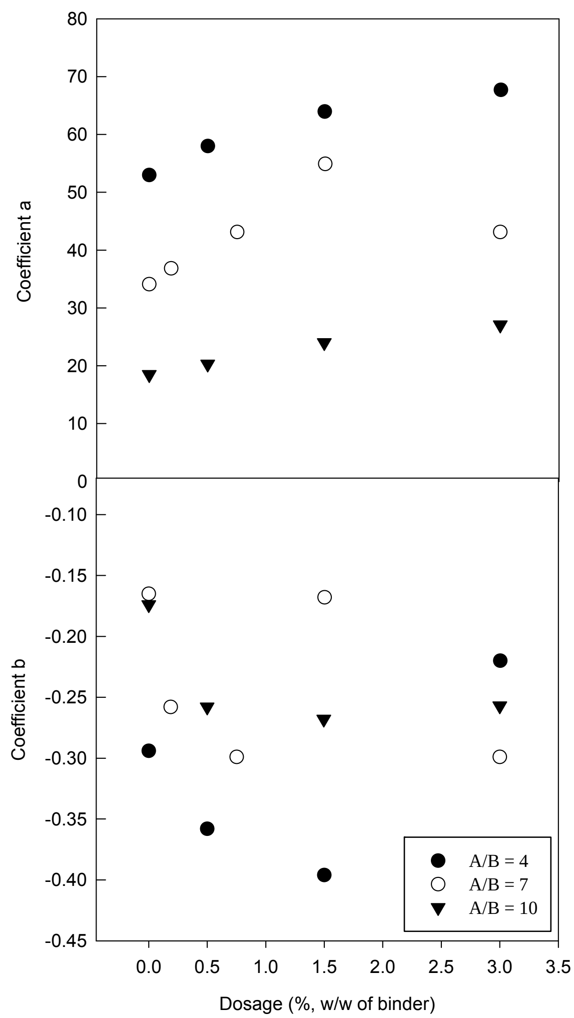


Figure J-29 Effect of Type A (P-06) admixture dosage on the strength development coefficients

Coefficient b, on the other hand represents the rate of strength development with age. In general, with the use of this water reducer there is an improvement in the time rate of strength increase. This rate however, either flattens out or reduces with higher dosages, implying that this admixture cannot accelerate the strength gain beyond a certain dosage and potentially offers a negative impact to the strength development. This becomes evident when the strength increase over control is plotted for different dosages for a given curing age.

BINDER EFFICIENCY

Figure J-30 shows the binder efficiencies of various A/B ratios at different dosages. It can be observed that the dosage of 1.5% offers the highest binder efficiency. Moreover, for this admixture the A/B ratio of 7 achieves the highest efficiency. There is definitely an interaction going on between the binder content and the admixture dosage. The binder efficiency increases with age and with the admixture dosage. These series of graphs indicate that the binder efficiency initially increases with the dosage, reaches a peak and then decreases. This can be partially explained on the basis of increased w/b ratio due to the water coming from the liquid admixture, which is not taken into account for this study. In addition to this, the air content could potentially increase at higher dosages.

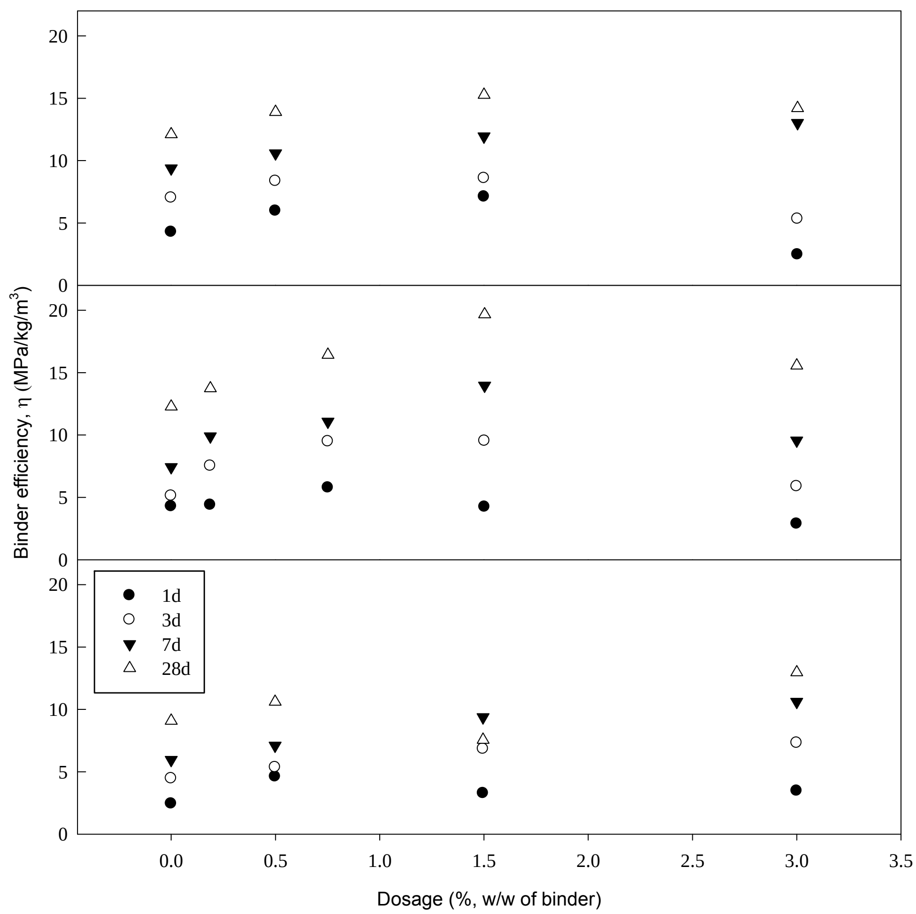


Figure J-30 Effect of admixture dosage and A/B ratio on the binder efficiency. A/B ratios for Top: 4, Middle: 7 and Bottom: 10

A 3D plot is constructed to illustrate the interaction of the binder content and the dosage of admixture on the binder efficiency. Figure J-31 offers such a representation. It is evident from this figure that the intermediate binder content and a dosage close to 1.5% offers the highest binder efficiency.

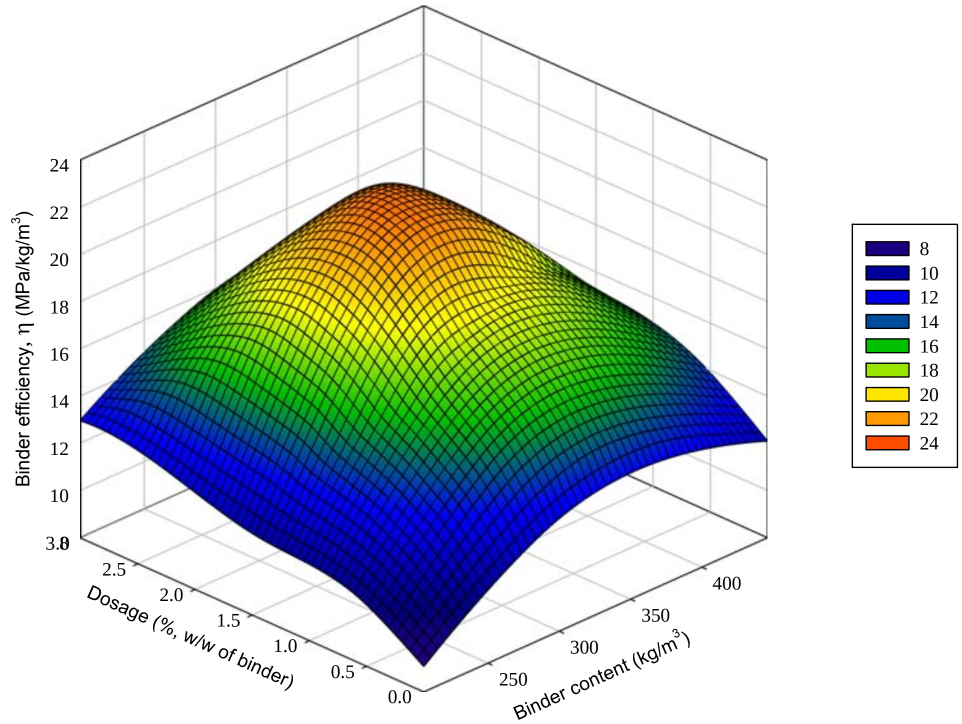


Figure J-31 Interaction of the binder content and the admixture dosage for Type A (P-06)

ABRAMS' LAW

With the use of this admixture, the Abrams' law is reinstated. It can be seen from Figure J-32 that the control mixtures were failing to follow the Abrams' law at the lower w/b ratios. With the use of water reducer, this law is partially reinstated. There are still points that show a drop in the strength with a reducing w/b ratio, quite similar to the control mixtures. One of the possible mechanisms combining the compaction and water reduction effects is explained in the section on PC-based admixtures.

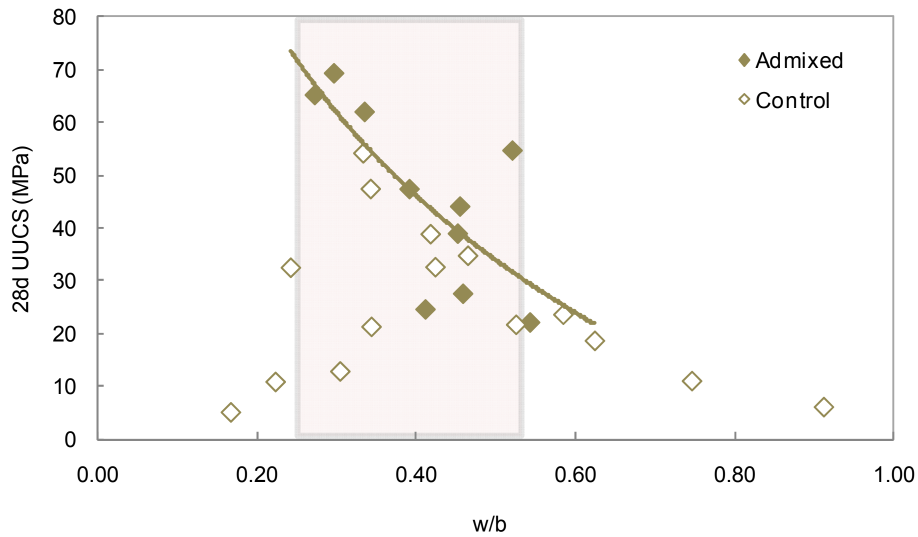


Figure J-32 Partial reinstatement of Abrams' law with the use of P-06 (Type A water reducer)

ASTM C494 CLASSIFICATION

Figure J-33 shows the strength of P-06 admixed concrete on the ASTM C494 template. It can be seen that this admixture with the lowest dosages (~0.25%) acts as a Type A water reducer, while it acts as a Type F at higher dosages. The strength gains with higher dosages (~3.00%) show strength retarding behavior at early ages, especially with higher binder content mixture. This effect reduces as the binder content is reduced with highest strength gains obtained for lean mixtures. Thus, this admixture is less efficient with higher binder contents than the intermediate and the lowest.

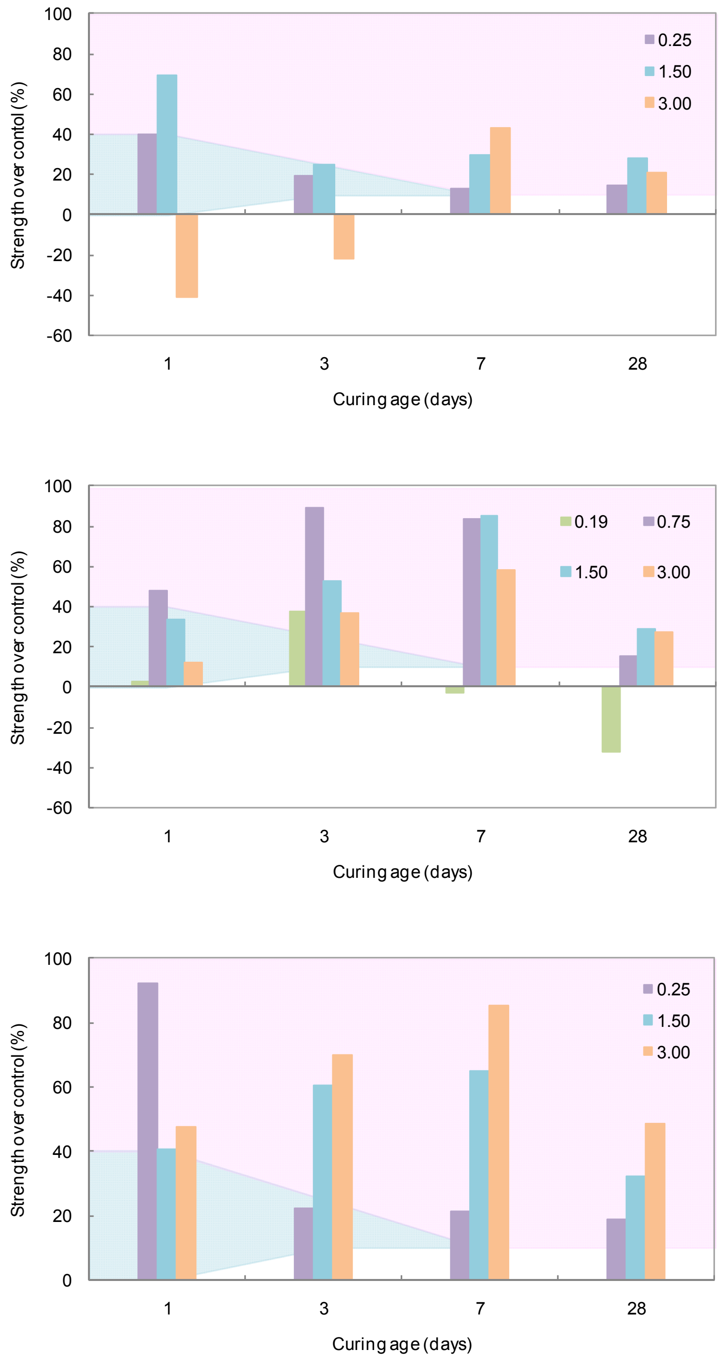


Figure J-33 ASTM C494 classification based on UUCS at different curing ages. A/B ratios for Top: 4, Middle: 7 and Bottom: 10. Blue and Pink regions show the ASTM strength requirements for Type A and Type F water reducers respectively

J.4.2 Water reducer: Type A, B and D for normal concrete

Admixture meeting the ASTM C494 requirements for Type A, B, D admixture (P-11) was used in assessing the effectiveness of this admixture in different RCC mixtures. The manufacturer recommended dosage is in the range of 0.130 to 0.399 lit/100kg of cement for normal concretes. Table 17-4 presents the experimental plan. The dosages were fixed at 0.25, 1.00 and 2.00% w/w of binder for all the binder contents. The corresponding water reduction, fresh properties and strength development were evaluated.

Table J-4 Experimental plan for a water-reducing cum retarding admixture: Type A, B, D (P-11)

Binder content	A/B	Dosage (%, w/w of binder)		
(kg/m^3)		1	2	3
205	4	0.25	1.00	2.00
282	7	0.25	1.00	2.00
446	10	0.25	1.00	2.00

EFFECT OF ADMIXTURE DOSAGE AND BINDER CONTENT

The changes in the 28d UUCS with the dosage and binder contents are shown in Figure J-34. There is an increase in the strength of admixed concrete with increasing dosage up to a dosage contingent on the binder content with a subsequent flattening or a dip. Lean mixtures however show an increasing trend and the present study does not capture its flattening point. This admixture has higher sensitivity for higher binder contents and acts more or less like a strength retarding and reducing admixture. Apparently, it seems that there seems to be an increase in the strength of admixed concrete with the increase in the admixture dosage, however this has to be appreciated vis-à-vis the water reduction and hence consequent reduction in the w/b ratio. Juxtaposing the argument in the chapter on fresh properties, it can be seen that for a fixed w/b ratio, increasing the dosage of this admixture would actually tend to reduce the strength.

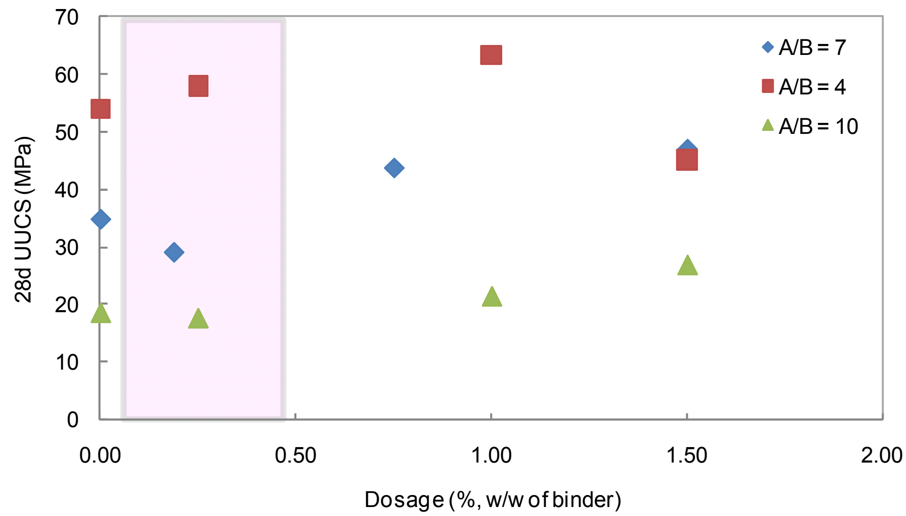


Figure J-34 Effects of binder content and dosage on the 28d UUCS of the admixed concrete (P-11)

TEMPORAL EVOLUTION

The increase in coefficient “a” shows that the 28d strength increases with the dosage depending on the binder content and admixture dosage. Refer to Figure J-35. The richer mixtures show an optimizing trend, initial increase, reaching or a peak and then a dip. Intermediate and lean binder content mixtures show a continual increase over the tested range. Coefficient “b” shows two different trends. In lean and intermediate mixtures an optimization trend is followed, implying the rate of strength gain improves up to a certain dosage and then drops down. For rich mixtures on the other hand, the time coefficient shows an initial increase, followed by a flattening effect. This implies that the rate of strength development is lowered in case of richer mixtures with increasing dosage of admixture. A caution thus needs to be exercised in opening the pavement to traffic if this kind of admixture is used, since it retards the strength development at early ages and more so in richer mixtures. A compromise on the natural setting and hardening of concrete results in the delay of opening of the pavement to traffic.

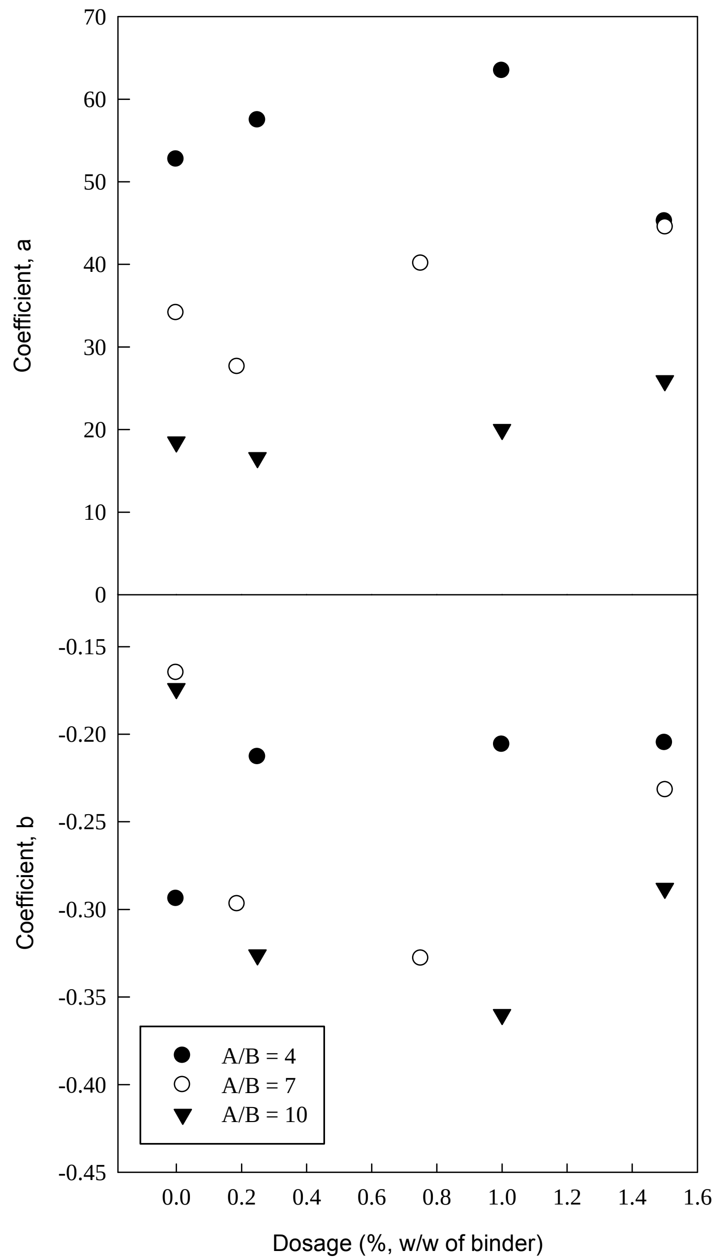


Figure J-35 Strength equation coefficients for P-11 admixed concretes at various dosages

BINDER EFFICIENCY

Figure J-36 represents the binder efficiencies of different mixtures at different dosages and ages. The binder efficiency is a composite function of the binder content and admixture dosage. For rich mixtures, the binder efficiency is reduced at early ages, most probably due to the retarding effect of the admixture. This effect gradually reduces with the age. Overdosing of admixture leads to a reduction in the binder efficiency potentially due to two reasons viz. water coming from the admixture leading to increase in the actual w/b ratio and the interaction of a retarder with class F fly ash causing further delay.

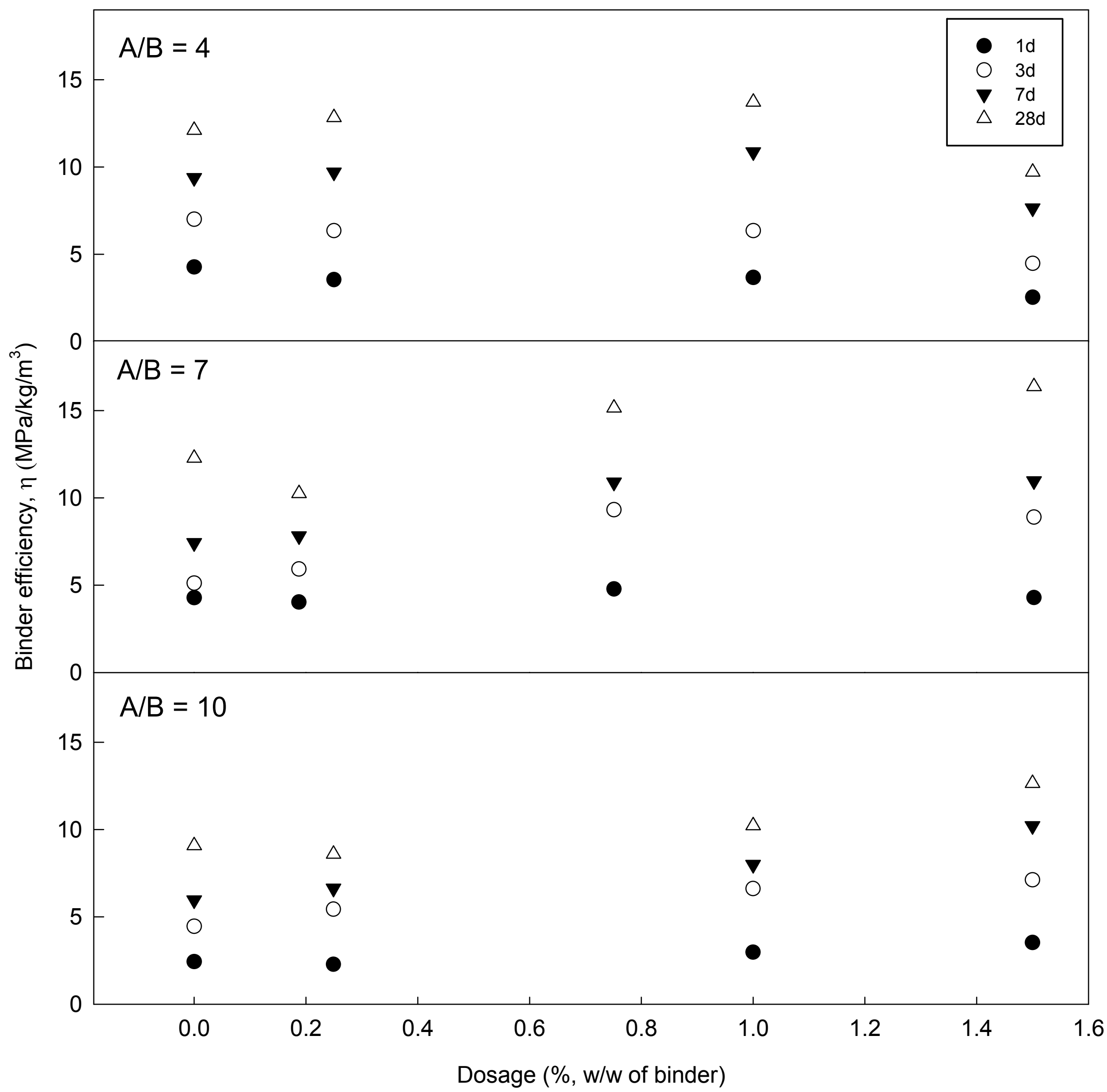


Figure J-36 Binder efficiencies for P-11 admixed concretes

For intermediate binder content, the binder efficiency compared to the control mixture improves with age. Slight reduction in compressive strength accompanied by retardation of early age strength is observed for lower dosage. As the dosage is increased, the binder efficiency reaches it maximum beyond which the incremental increase with dosage is reduced. In case of leaner mixtures, the binder efficiency shows a continuously increasing trend over the tested range of dosages. There is a definite retarding effect shown at the early ages, which reflects in the similar to control efficiency in admixed concretes, despite of the fact that there is a concurrent water reduction.

ABRAMS' LAW

Figure J-37 shows the reinstatement of Abrams' law using P-11 admixture. Possible mechanisms of the increase in the strengths are explained in the section on PC-based water reducing admixture. At lower w/b ratio, the maximum increase in the strength is approximately four times that of the control mixtures. This increase reduces with the increase in the w/b ratio. Although there is not much increase in the strength at these w/b ratios, there is a definite advantage gained in terms of the fresh properties resulting in extended compaction time window.

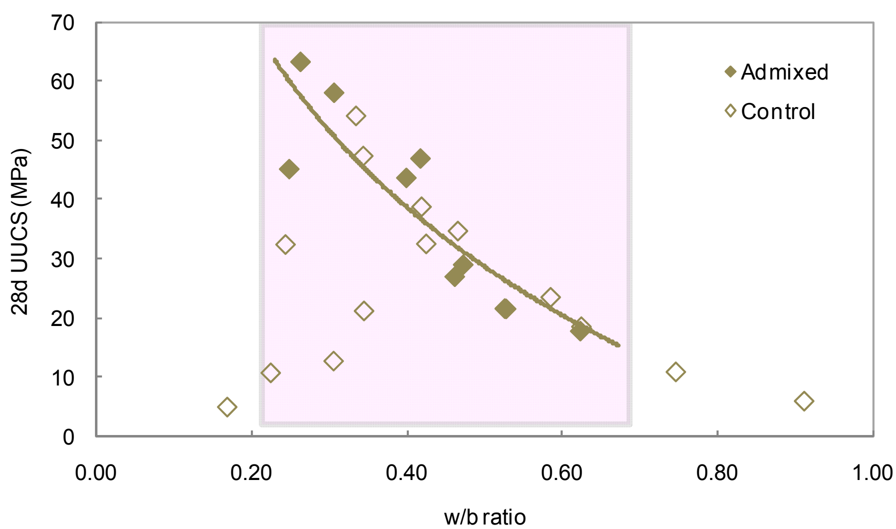


Figure J-37 Partial reinstatement of Abrams' law using P-11 admixture

ASTM C494 CLASSIFICATION

This admixture shows sensitivity to the binder content and hence different classification schemes are applicable vis-à-vis ASTM C494 classification system. In general at lower dosage (~0.25%), this admixture satisfies requirements for type B admixture, while at higher dosages and for intermediate and lean mixtures, it satisfies the strength requirements for both type A and D admixtures. Refer to Figure J-38.

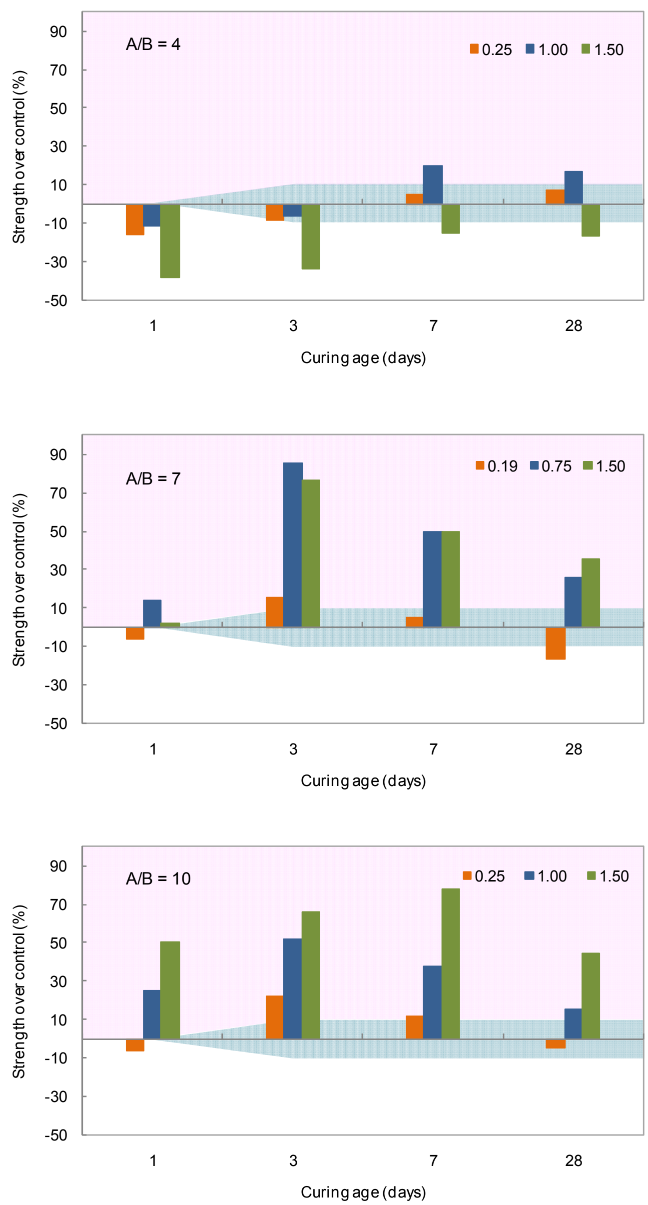


Figure J-38 ASTM C494 classification for P-11 admixture. Blue shaded area denotes requirements for type B admixture, while pink shaded area represents requirements for type A/D admixture

J.4.3 Water reducer: Type B and D for normal concrete

Admixture meeting the ASTM C494 requirements for Type B (retarding) admixture (P-13) was used in assessing its effectiveness in different RCC mixtures. The manufacturer recommended dosage is in the range of 0.130 to 0.266 l/100kg of cement for normal and mass concretes. This admixture is a strong retarder and is expected to delay the setting times, reduce w/b ratio and improve the density of the mixtures. Table 17-5 presents the experimental plan. The dosages were fixed at 0.20, 0.60 and 1.20% w/w of binder for all the binder contents. The corresponding water reduction, fresh properties and strength development were evaluated.

Table J-5 Experimental plan for a retarding admixture: Type B (P-13)

Binder content (kg/m^3)	A/B	Dosage (%, w/w of binder)		
		1	2	3
205	4	0.20	0.60	1.20
282	7	0.20	0.60	1.20
446	10	0.20	0.60	1.20

A detailed presentation of the strength test results is avoided here. Figure J-39 presents the relative strength gains of admixed concretes at different ages and for different binder content mixtures. No classification scheme is applied because the strength reduction in some cases does not allow a strong case for classifying it under one category or another. This admixture offers a strong retardation and reduction in the strength. It is relatively more sensitive to higher binder content mixtures and at higher dosages. It possibly leads to strength increase due to the combined effect of improved density and water reduction effects.

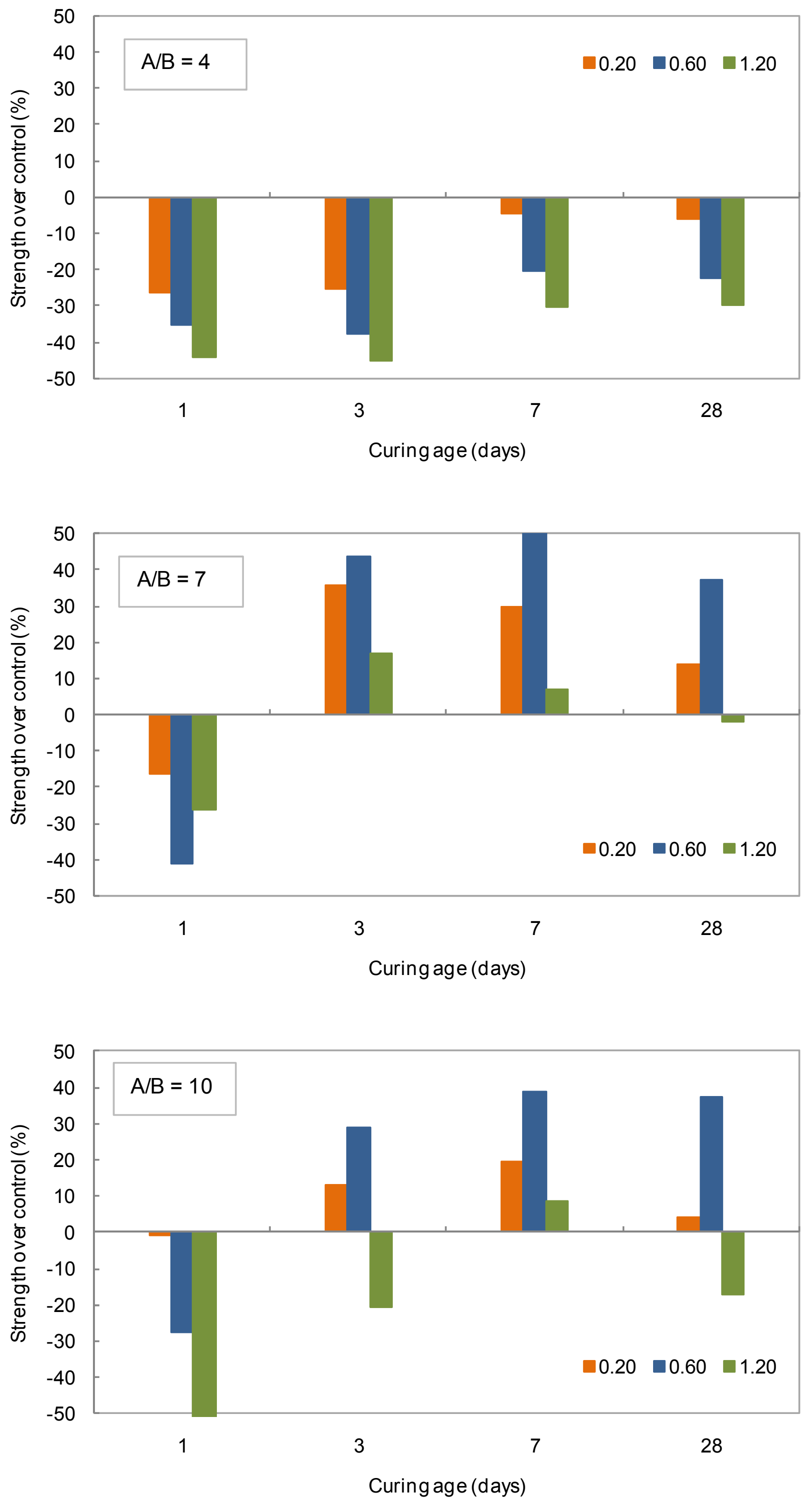


Figure J-39 Relative strength with P-13 (Type B) admixture

J.4.4 PC based: A detailed presentation

REVISITING EXPERIMENTAL PLAN

Table 17-6 describes the experimental plan for this phase of the work. It should be noted that the initial consistency as measured by Cabrera slump value was kept constant; corresponding water reduction was recorded along with the resulting properties of the mixtures including the fresh and hardened.

Table J-6 Experimental plan for PC-based water reducer

Binder content (kg/m^3)	A/B	Dosages (%, w/w of binder)							Remarks
		1	2	3	4	5	6	7	
205	4	0.00	0.25	1.50	3.00	--	--	--	
282	7	0.00	0.19	0.56	1.13	1.69	2.25	3.00	Detailed investigation
446	10	0.00	0.25	1.50	3.00	--	--	--	

EFFECT OF ADMIXTURE DOSAGE

As described previously this admixture can be used as a plasticizer and a superplasticizer at different dosages. All the mixtures were formulated with similar initial consistency characterized by Cabrera slump value (CSV). Corresponding water reductions were recorded and are already discussed in one of the earlier chapters.

Figure J-40 shows the trend in 28d UUCS for admixture dosages ranging from 0 to 3% weight by weight of binder. The same information on volume basis is also presented. There are multiple implications of using a water reducer. The trend shows that initially the strength increases with increase in the admixture dosage (or content per unit volume), reaches a peak and then starts dropping down. The dosage that renders maximum UUCS is 2.2%, by weight. All the admixed mixtures showed increase in the strength over control depending on the dosage of admixture used. The % increase over control ranged between 19.9 and 76.7 %. It is interesting to note that the maximum admixture dosage used in this work was almost five times the maximum value recommended by the manufacturer. Moreover, it did not produce any serious negative effects on concrete strength.

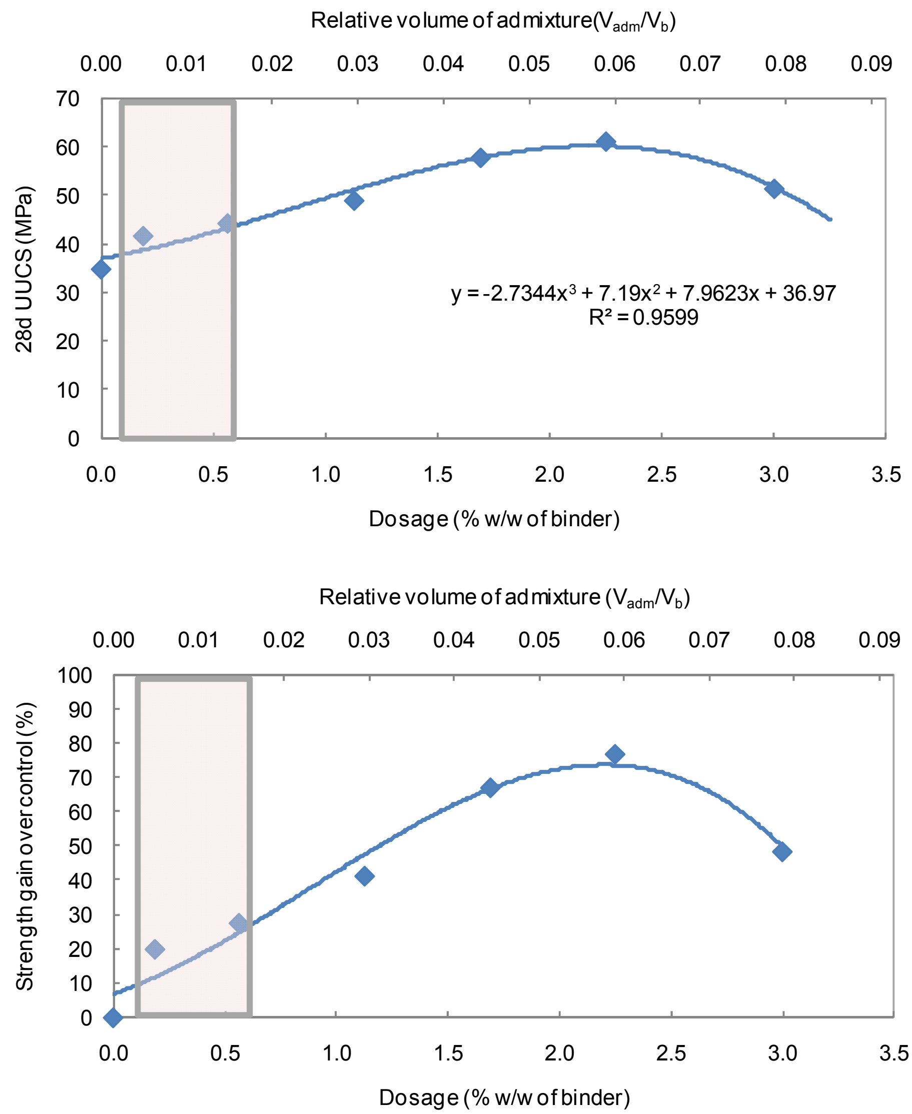


Figure J-40 Effect of admixture dosage on 28d UUCS. Pink box marks the manufacturer recommended range for low-, mid- and high range water reduction

The admixed concrete follows Abrams' law up to a certain limit. Refer to Figure J-41. Due drier consistency, resulting in incomplete compaction, the control mixtures were not achieving their potentially maximum density and hence strength. Considering the control mixtures as benchmarks, the admixed mixtures have actually produced strength increases of up to 200% for a given w/b ratio at 28 days. For example, if we consider a w/b = 0.35, the jump observed in the strength is from 20 MPa to 60 MPa.

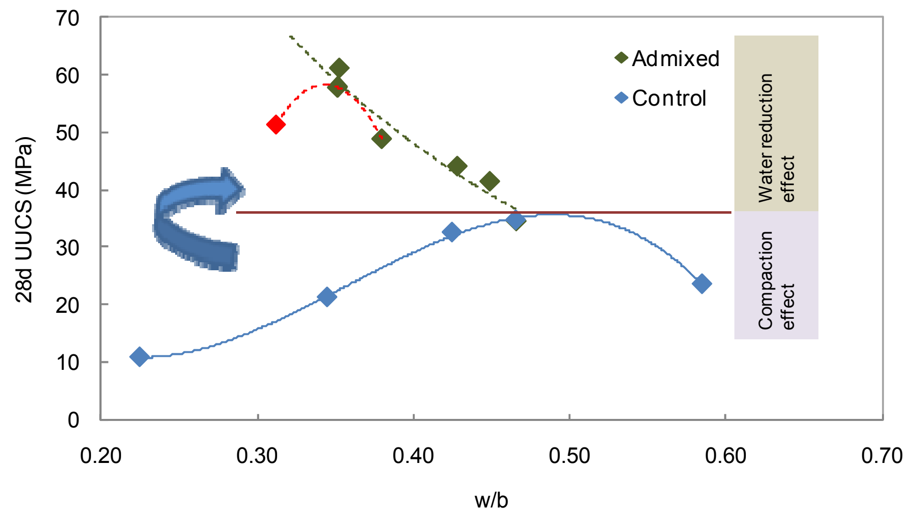


Figure J-41 Partial reinstatement of Abrams law. Compaction and water reduction effects

From the admixture dosage perspective, this water reducer can produce strength increase up to a certain limit only. Beyond a particular admixture dosage, the strength actually starts dropping down. It can be hypothesized that this drop is not due to incomplete compaction, but appears to be more due to the beginning of reduction in the effectiveness of the admixture at that w/b to manifest a commensurate increment in the measured strength.

The strength needs to be analyzed and understood from two distinct perspectives. The first is the *compaction response* while the second is *water reduction response.* These two composite actions decide the total increase in the compressive strength observed for a given w/b and curing age. As is shown in the above figure, the drier mixtures are initially plasticized so that they could come to a level of maximum possible compacted density. Some of the admixture power or efficiency is consumed in mobilizing this plasticity required for compacting a mixture to its potentially maximum density. Up to the point of optimum moisture content (OMC), the mixture has the potential and composition (in terms of binder content at a fixed Aggregate/Binder ratio) to produce maximum strength comparable to that obtained by the mixture at OMC and compacted to its maximum density. It is just due to the lack water resulting into reduced or no plasticity and mobility of binder paste that the mixture cannot be compacted fully in its non-admixed form. Adding a plasticizing effect through the via-medium of a water reducer assists in overcoming this barrier. Consequently, a mixture's strength is initially raised that achieved by the mixture at OMC. The drier the mixture, the higher is the expenditure of a water-reducer's power to plasticize and vice versa. If all these mixtures were to be admixed at OMC, the strength increase that would be produced will show quite a different trend.

Along with the plasticizing role, the water reducer also produces water reduction effects. The exact demarcation may not be possible based on available data. At this point, the water reducer is starting to increase the strength. Again the higher the w/b ratio, the higher is the % power used in producing the water reduction effect. Thus differentiating the two roles can help assess the actual water reduction produced by a water reducer. For example, if we consider w/b = 0.35, the overall strength increase was about 40 MPa, of which approximately 14.65 MPa (Strength at OMC minus that at w/b = 0.35) comes from plasticizing effect, while the rest comes from water reduction effect. It should be noted that this analysis was based on the available strength data. Further studies pin pointing the exact origins and mechanisms of the composite action were beyond the scope of this work.

Figure J-42 shows a composite plot of w/b versus UUCS. It can be seen that the Abrams law is reinstated with the use of this water reducing admixtures.

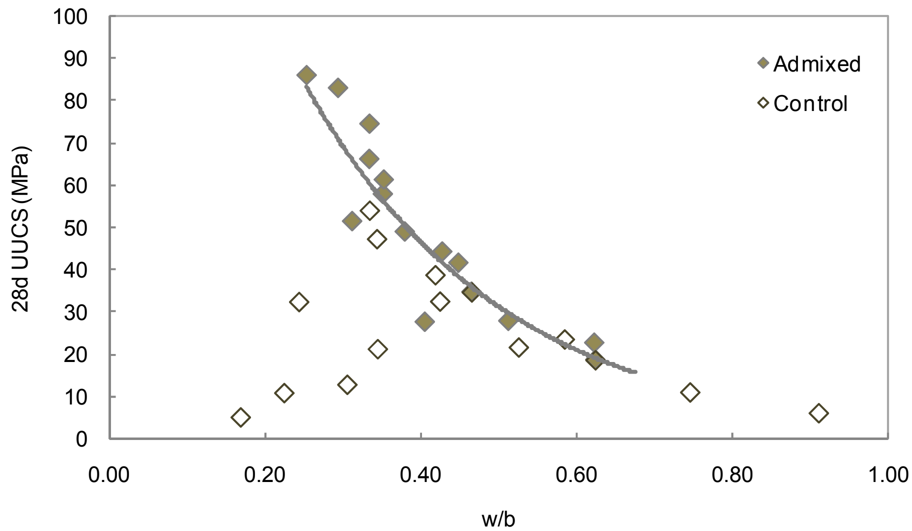


Figure J-42 Partial reinstatement of Abrams' law

EFFECT OF BINDER CONTENT

The effect of different binder contents for various admixture dosages is shown in Figure J-43. No specific trends are constructed for A/B ratio of 4 and 10. The interaction effects will be plotted and described in the subsequent section. The effectiveness of this admixture appears to be binder content specific or in other words for a given dosage of admixture, there is a w/b ratio that would manifest highest efficiency. The effectiveness of admixture is less at A/B ratios of 4 and 10 while it appears to be relatively higher with A/B ratio of 7. A clearer description will evolve when 3D and contour plots are generated and the paste quality is analyzed.

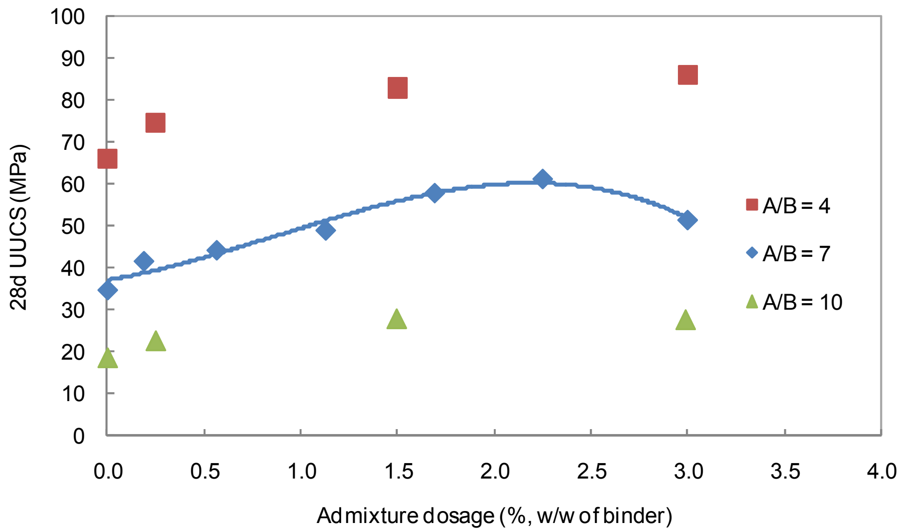


Figure J-43 Effect of binder content on the effectiveness of different dosages

INTERACTION EFFECTS: BINDER CONTENT AND ADMIXTURE DOSAGE

The data was analyzed for interaction effects using a least squares model to understand interaction effects of binder and admixture dosages. Three binder contents (205, 282, 446 kg/m^3) and four admixture dosages (0, 0.5, 1.5, 3.0 %) were used in this analysis. A model consisting of binder content, admixture dosage and the interaction term of binder content *admixture dosage was used in constructing the model. The resulting model showed a very good fit (R^2 = 0.99) is plotted against actual values and is shown in Figure J-44. A residual plot showing good distribution is also obtained and shown along with the model plot. With the available data the objective was to

- Effects of binder content (CC)
- Effects of admixture content (Adm)
- Obtain optimal mixture parameters
- Trace the interaction effects and
- Rank the mixtures

The effects of binder contents and admixture dosages are individually shown in Figure J-44. This figure also shows the desirability profiles for the highest UUCS. The binder content of 446 kg/m^3 and admixture dosage of 1.5% produce the maximum UUCS.

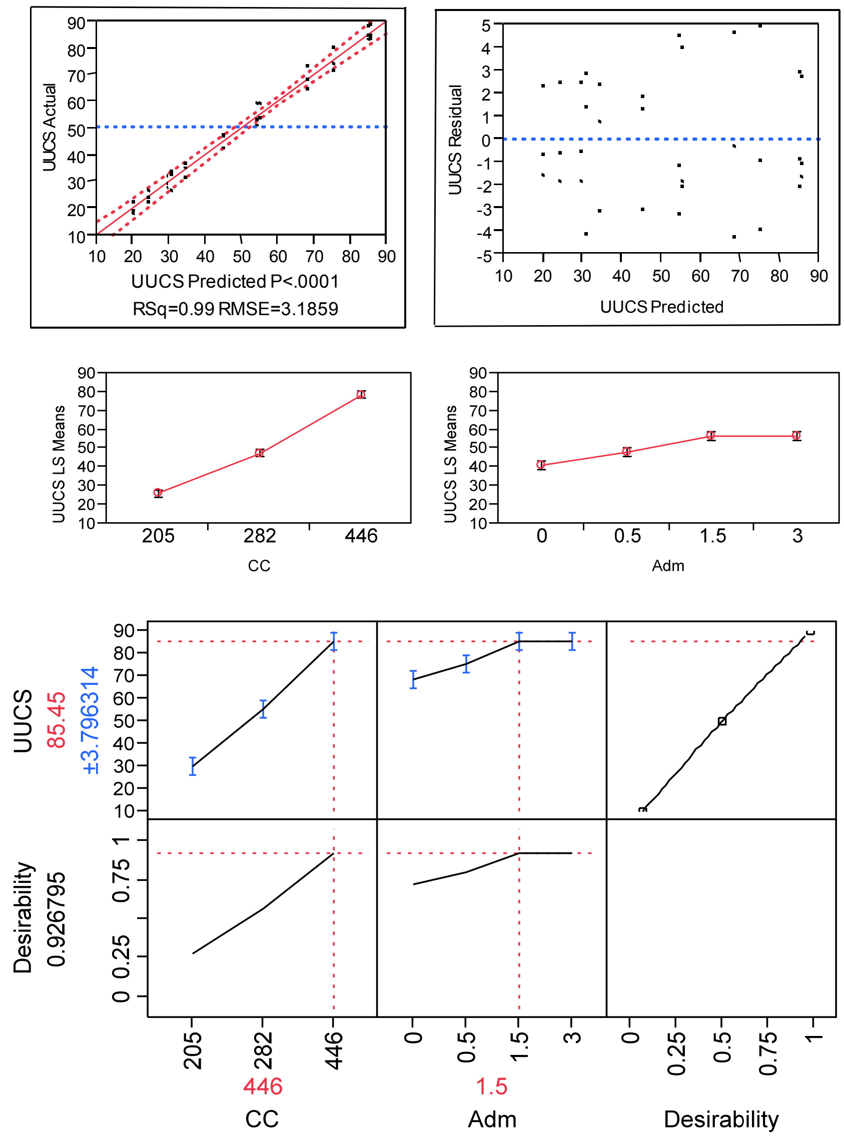


Figure J-44 Prediction models attributing individual and interaction effects. Desirability trends obtained for maximum strength

Analysis of variance (ANOVA) and F-tests were used to check for differences and to assess whether they were statistically significant or not. Refer to Table 17-7. Different letters here mean that the effects produced by the binder contents on the strength are different and are statistically significant.

Table J-7 Establishing statistical difference in binder contents

Binder content (kg/m^3)	Designation	Least squares mean
446	A	78.58
282	B	47.35
205	C	26.15

Similarly, admixtures were individually checked for differences. The results of the analysis are shown in Table 17-8. In this case, however, the admixture dosages of 1.5 and 3.0 % were not found to produce statistically significant differences. The values of least square means were quite close to one another.

Table J-8 Establishing statistical differences in admixture dosages

Admixture dosage (%)	Designation	Least squares mean
3.0	A	56.84
1.5	A	56.83
0.5	B	48.24
0.0	C	40.86

Further to this, statistical analysis of different dosages and binder contents together was conducted in order to trace the interaction effects produced on the strength. Table 17-9 offers the summary.

Table J-9 Establishing statistical difference due to interaction effects

Binder content (kg/m^3)	Admixture dosage (%)	Classification A	B	C	D	E	F	G	Least Squares Mean
446	1.5	X							85.45
446	3.0	X							85.23
446	0.5		X						75.14
446	0.0			X					68.53
282	1.5				X				55.37
282	3.0				X				54.44
282	0.5					X			45.36
282	0.0						X		34.24
205	3.0						X		30.86
205	1.5						X		29.69
205	0.5							X	24.24
205	0.0							X	19.83

Figure J-45 shows the least squares mean plot for the interaction effects. The following is a summary:

- Irrespective of the binder content, there is no statistically significant difference between 1.5 and 3.0% admixture dosages
- In mixtures with higher A/B ratio, there is no significant effect produced by adding 0.5% admixture dosage. Statistically the strength produced by the control mixture and the mixture with 0.5% water reducer produces similar compressive strengths
- The strengths produced by the control mixture with A/B = 7 are similar to the strengths produced by mixtures with A/B = 10 and admixture dosages above 1.5%

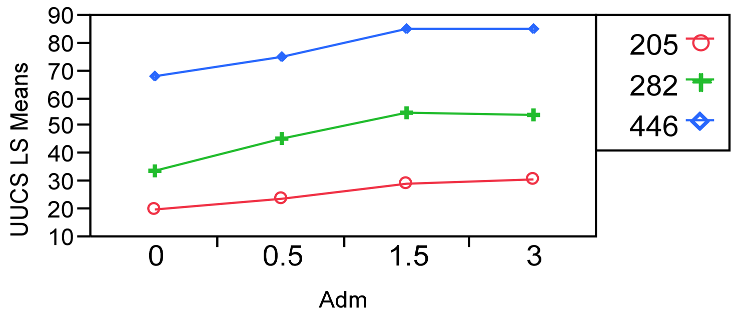


Figure J-45 Least squares mean plots for the interaction effects produced by binder content and admixture dosages

BINDER EFFICIENCY

Figure J-46 shows the effects of binder content, admixture dosage and curing age on the binder efficiency. Depending on the binder content and admixture dosage, the binder efficiency is enhanced by the use of this water reducer. In terms of quantification, the increase in the binder efficiency was nil to 177% compared to control mixtures. The exact mechanism of this increase in the efficiency of binder is not investigated.

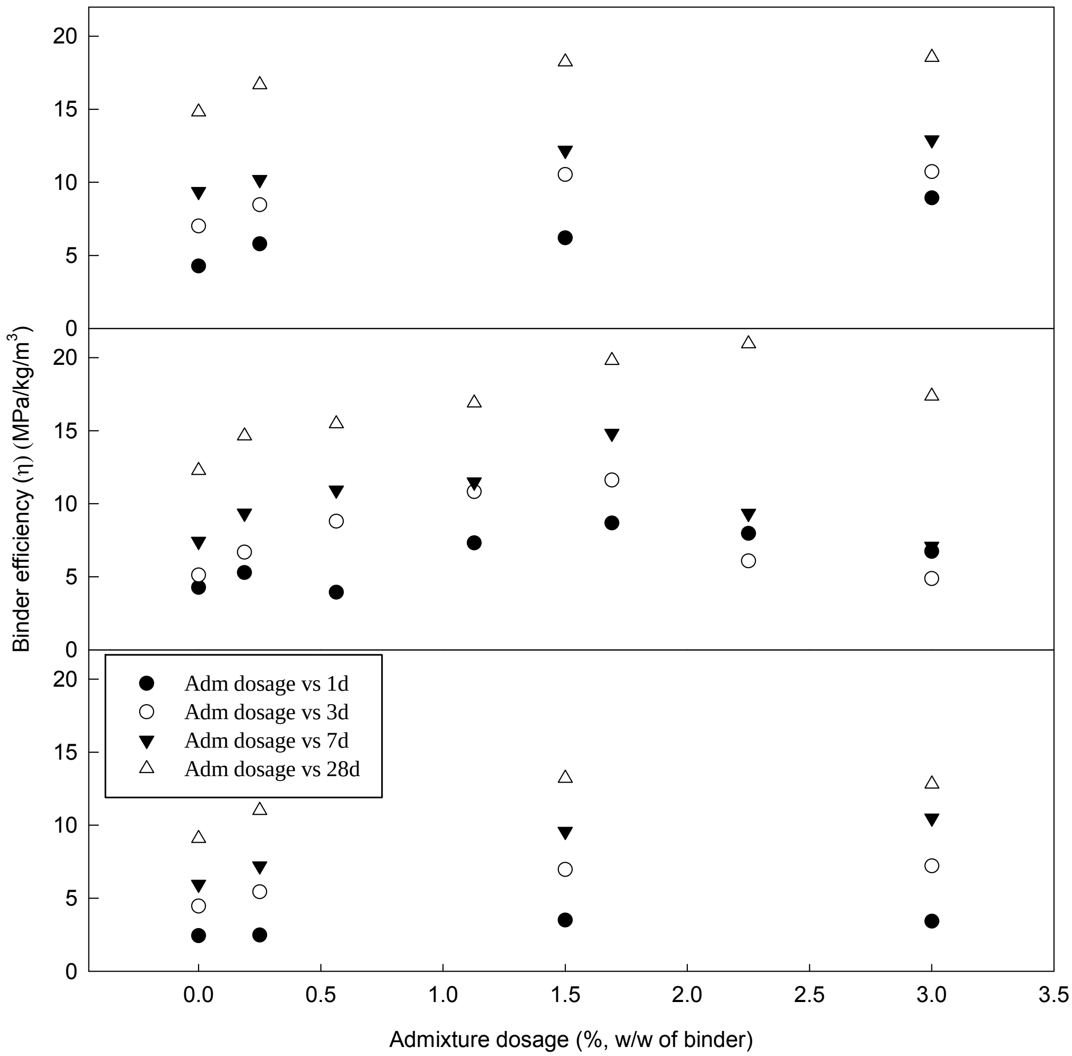


Figure J-46 Effect of admixture dosage on binder efficiency

TEMPORAL EVOLUTION

Figure J-47 shows the effect of curing age on the effectiveness of admixtures for a fixed A/B = 7. It can be seen that the optimal admixture for getting maximum strength did not remain the same but varied. It is difficult to propose a plausible solution based on the available data and scale of work and hence it is not discussed further.

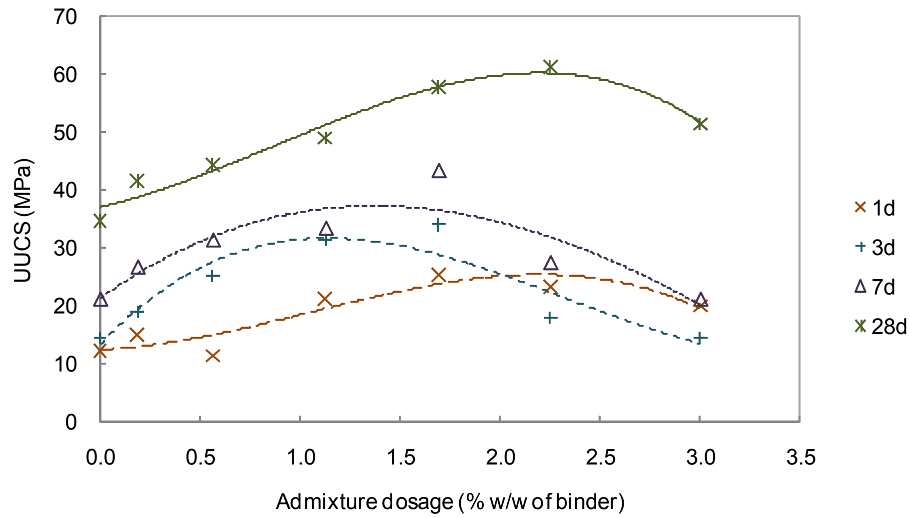


Figure J-47 Strength trends as functions of admixture dosages at different ages. A/B = 7

Figure J-48 shows the evolution of strength as a composite function of the binder content and admixture dosages at four different curing ages. Two way interaction and effectiveness of water reducer can be easily seen. There are combinations of binder content and admixture content that lead to optimized results when one parameter is fixed at a time. The exact nature and mechanism of this effect is considered to be beyond the scope of this work.

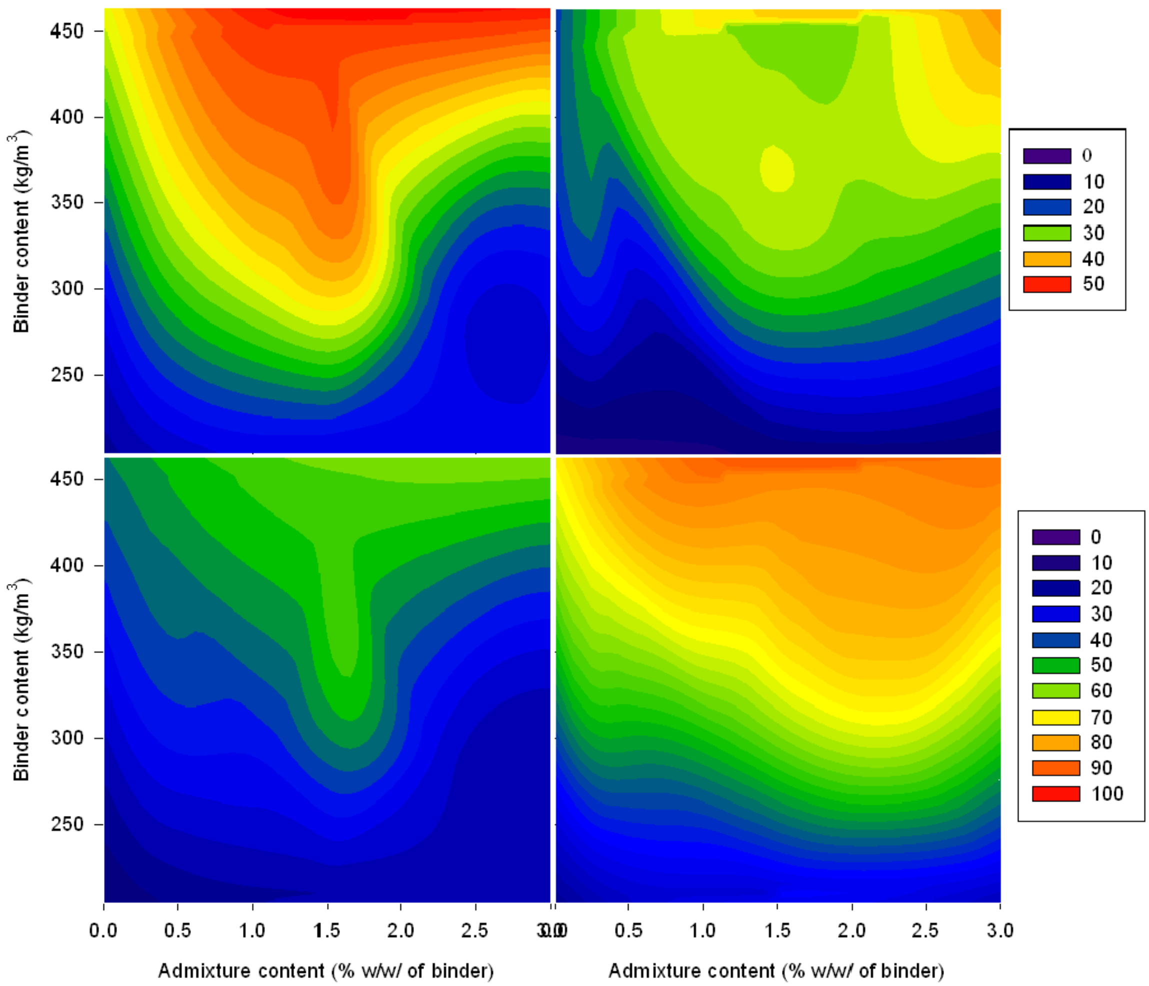


Figure J-48 Temporal evolution of admixed concretes. Curing ages start at Top-RHS corner and go counter-clockwise for 1, 3, 7 and 28 days.

Figure J-49 shows the strength coefficients obtained from strength-age modeling using equation shown above. In general, the coefficients increase for a given A/B and w/b ratios while the decay coefficient for time decreased. Furthermore, increased values of coefficient ‘a’ indicate higher ultimate strength while reduced values of coefficient ‘b’ indicate higher rate of strength development. A higher rise in the initial strengths up to 7 days is observed followed by more or less flat line indicating a boost in the initial reactivity of binders.

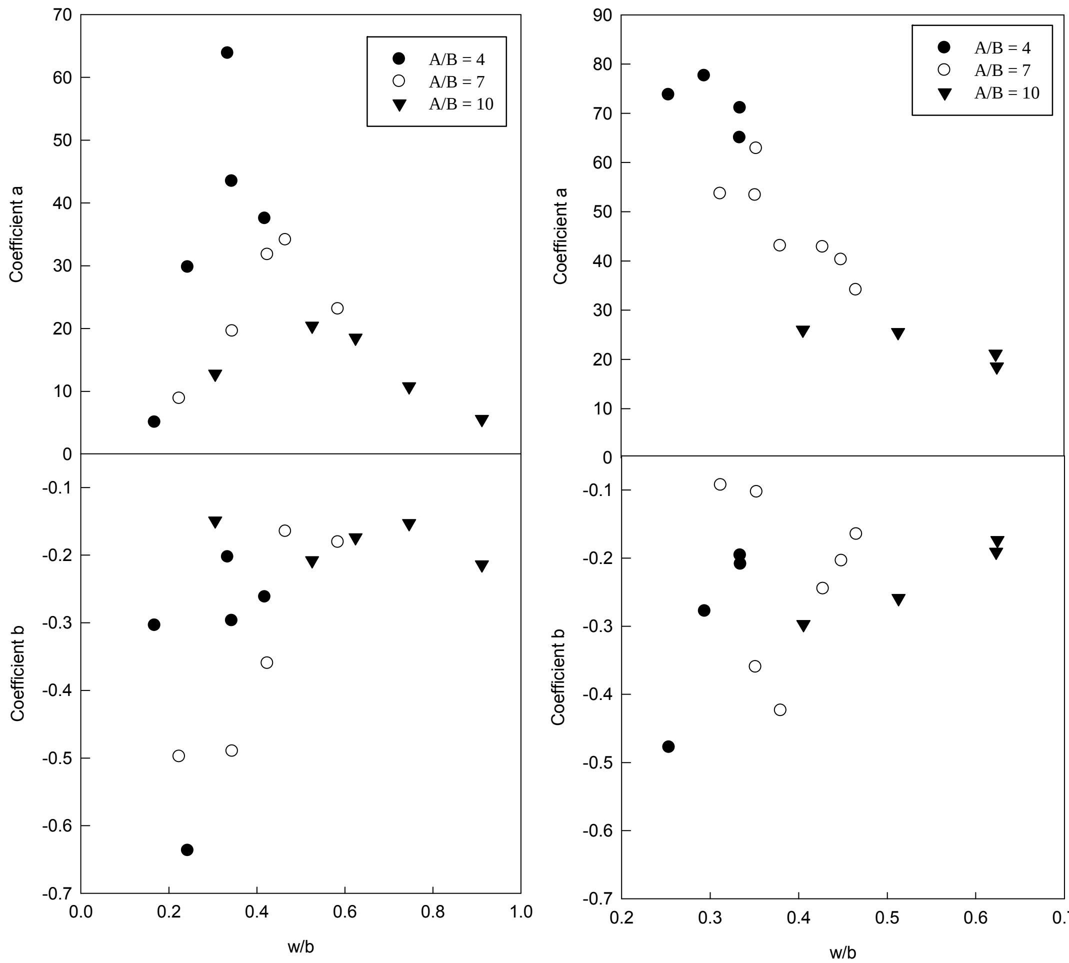


Figure J-49 Composite effect of admixture and w/b ratio on the strength coefficients

The rate of UUCS development for various dosages at a fixed A/B ratio of 7 is shown in Figure J-50. It can be seen that the rate of strength development for all dosages is higher than the control mixtures. At the end of first day, the rates for admixed concretes are much higher than the control mixture.

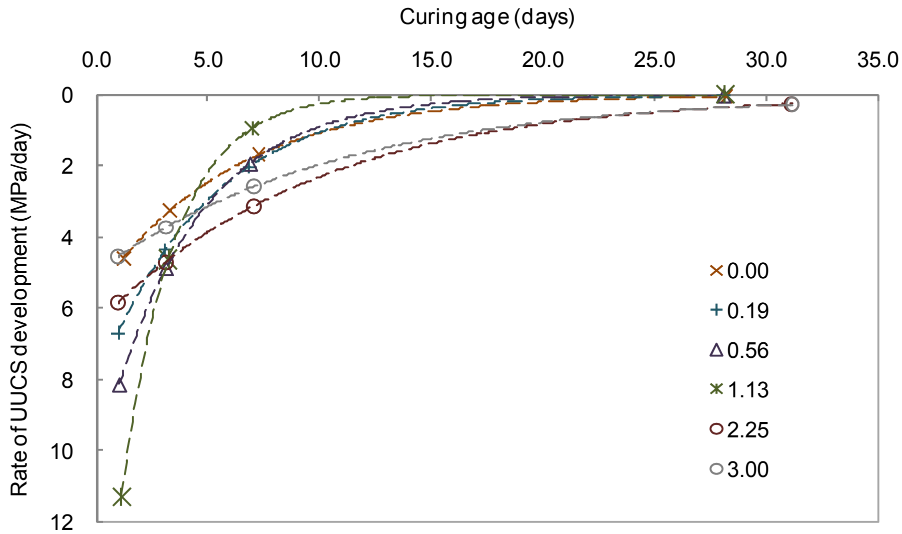


Figure J-50 Rate of UUCS development for different dosages

IMPROVISATION IN PASTE QUALITY

This section addresses the analysis from the mixture composition and improvisation of paste quality perspectives. Figure J-50 shows the strength transitions brought about by the use of this water-reducing admixture in comparison to the control mixtures. The scales have been retained the same in order to highlight the effective areas in these plots. There are local and individual optimizations and trends and could be discussed at length. However the focus of this discussion on the improvisation in the paste quality with the use of this water reducer. Following are important observations:

- In general, the efficiency of the binder seems to have improved; the exact picture is presented in the earlier section.
- Additionally the overall efficiency of a concrete composition is also improved. In a limited sense, it could be said that for a given set of A/B and w/b ratios, the mixture achieves higher efficiency.
- The range of w/b ratios over which mixtures could be compacted and would render meaningful strengths narrows down due to the use of water reducer. For a given w/b ratio, the strength that could be achieved is raised, depending on the

mixture composition and admixture content. The later part will be clarified in the following section.

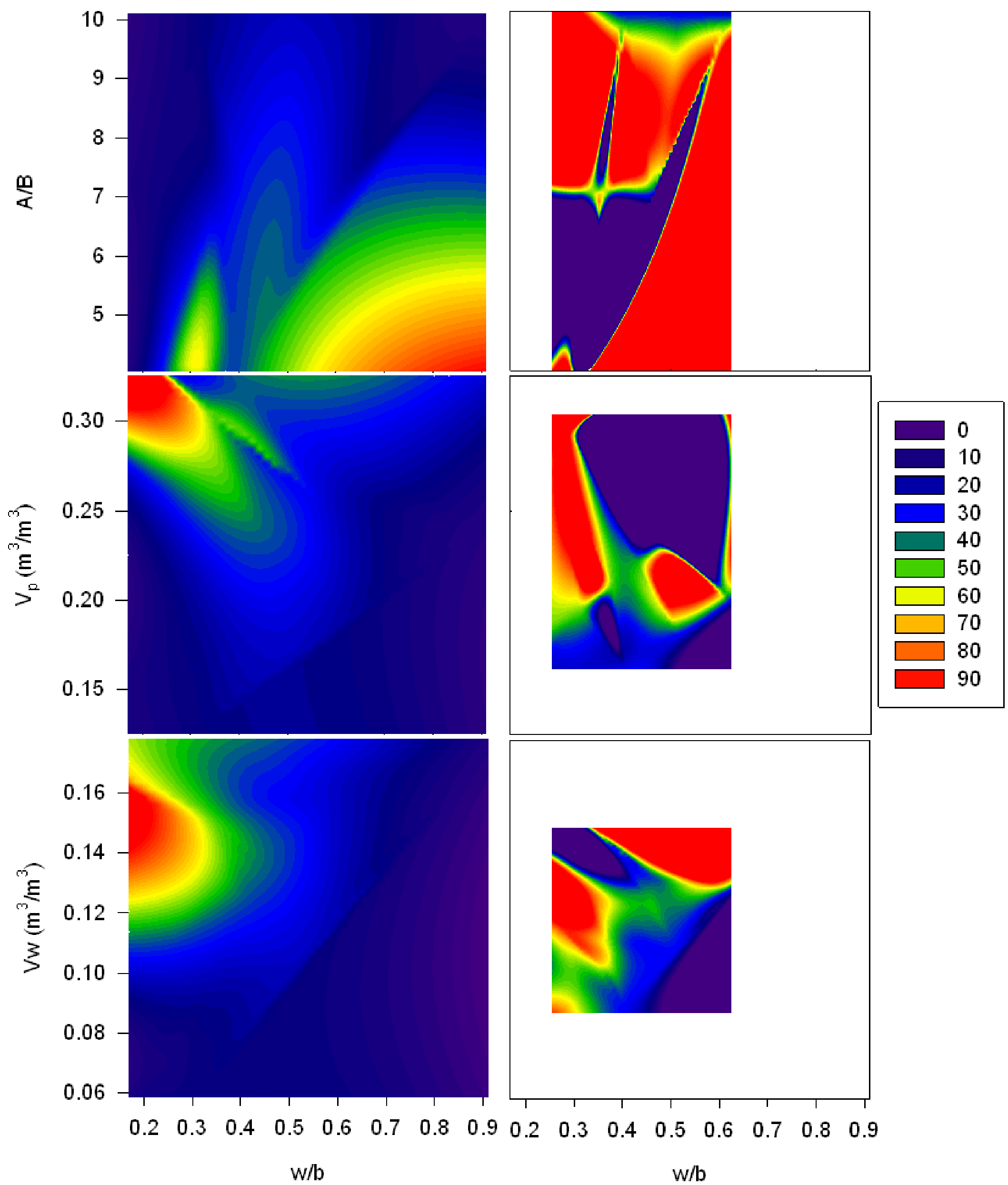


Figure J-51 Comparison of strengths in control and admixed concretes for 28d UUCS

- It can also be seen that there is a distinct zone (marked by viol defined by A/B and w/b ratios in which there is no improvement. This implies that the use of admixture over this region is not offering any help in improving the strengths.
- The efficiency of paste is also improved in turn. For a given w/b (used in this work), there are dramatic transitions in strengths, most of which must be resulting from the improvement in the paste quality brought about by the reduction in the water contents. It is interesting to note that with the use of this admixture the optimization zones change their loci and also take different paths to the optimized values
- Within a narrow range of w/b ratio, a large variation in strength can be covered by the use of this water reducer. Again the paths to and the loci of optimized strength values are quite different from the control mixtures.
- It is critical to note that the air contents of most of the admixed mixtures were comparable to the OMC mixtures and hence the negative effects of larger volumes of air content of entrapped and entrained air are overcome. Therefore, no plot for air content is constructed.

Figure J-52 shows the strength plots as functions of admixture dosages on weight and volume basis. Different ratios and volume concentrations are plotted as second variables. Comparisons with previous figures constructed for control mixtures are discussed. The following are some salient observations:

- In terms of the ratio of paste volume and voids in aggregates, it could be seen that less paste is required to produce similar or higher strengths. This is however subject to production of aesthetically acceptable concrete.
- There are combinations of quantities of water and admixture dosages that would not render any strength. This fact is to be viewed in the light of A/B ratio used for these combinations. With increasing admixture dosages, the corresponding volumes of water reduce. The exact mechanism of these transitions is considered to be beyond the discussion of this work.

The paste composition plays a decisive role in influencing the strength properties of concretes in general. A volumetric ratio of the volumes of admixture and paste, ξ is used in obtaining the second set of plots and to appreciate the transitions in strengths while being cognizant of other ratios and volumes. The following observations are salient:

- For a fixed γ ($V_p/V_{voids\ in\ aggr.}$), there could be more than one combination of admixture volume and paste content that would produce highest possible strengths.
- It is interesting to note that even with γ less than one, much higher strengths can be produced.
- There are optimal combinations of δ and ξ that would render highest possible strengths. There are specific trends and pathways to this optimization. If we consider an iso-strength line in this plot, we could see that there are two pairs of such combinations that would render similar strengths. The first pair will have relatively lower admixture volume when compared with the paste volume and second pair will have a relatively higher admixture volume. This fact needs to be juxtaposed with the volume of water in the paste, since this could have a decisive influence on the strength of concrete.
- One of the interesting things to note from the plot of ξ versus volume of water is the revelation on of the minimum water required for mobilizing the effect of water reducer. From this plot and a corresponding plot on the dosage of the admixture, it can be seen that some combinations of volume of water and admixtures will not produce strength, while slight changes in the relative volumetric composition of admixture and water. Similarly there are distinct combinations for a given paste composition that produce the highest strength thus reflecting on the range of water volumes over which this admixture is most efficient.

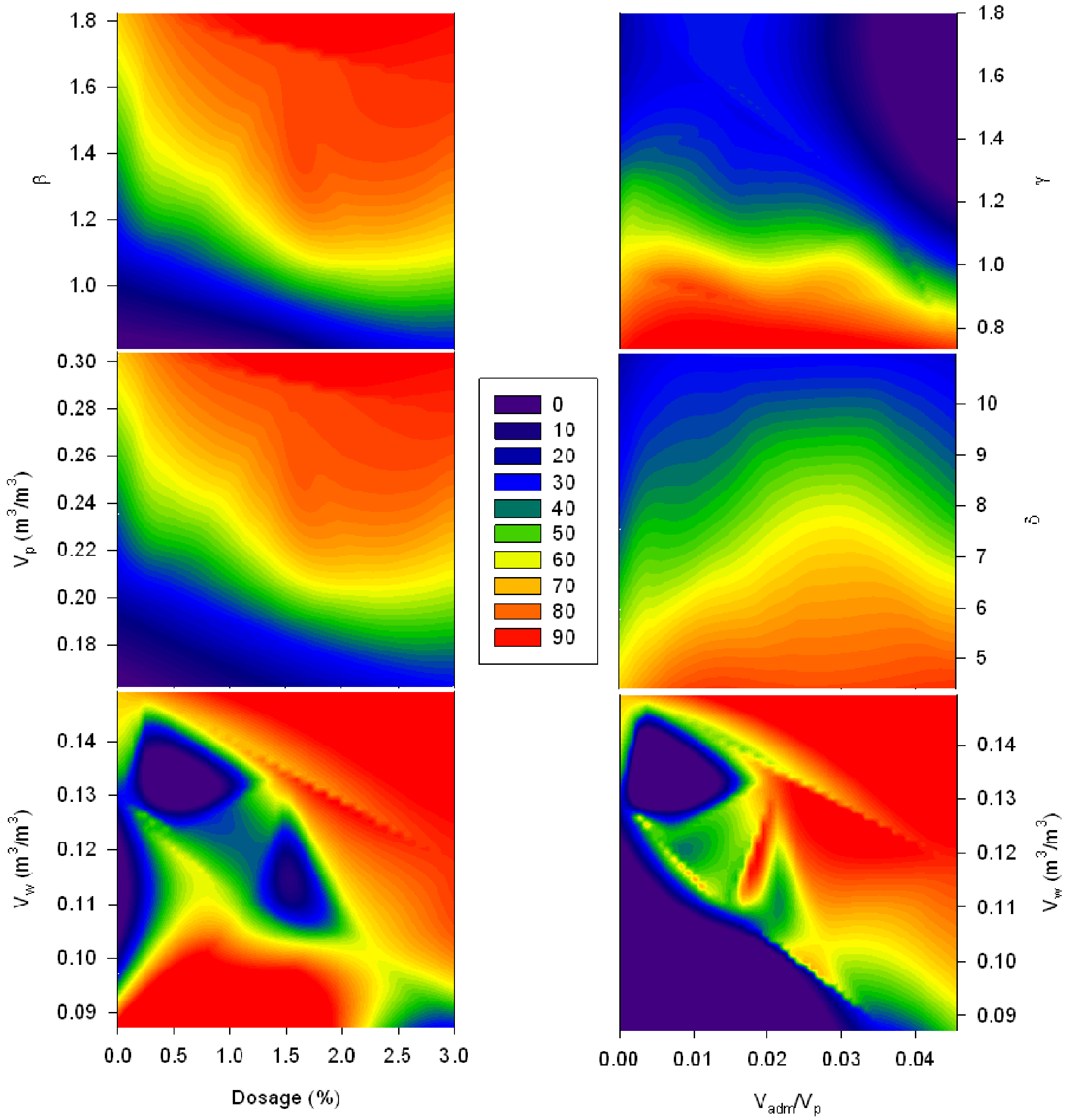


Figure J-52 Trends of 28d UUCS as a function of admixture dosages and relative volumes

ASTM C494 CLASSIFICATION

Based on the strength gain over the control the admixtures at different dosages could be classified as either fulfilling the role of type A or type F water reducers. Figure J-53 was constructed with this objective. It can be seen that this water reducer varying performance based on the dosage and binder contents. It is interesting that a clear distinction into types mentioned by ASTM C494 cannot be applied.

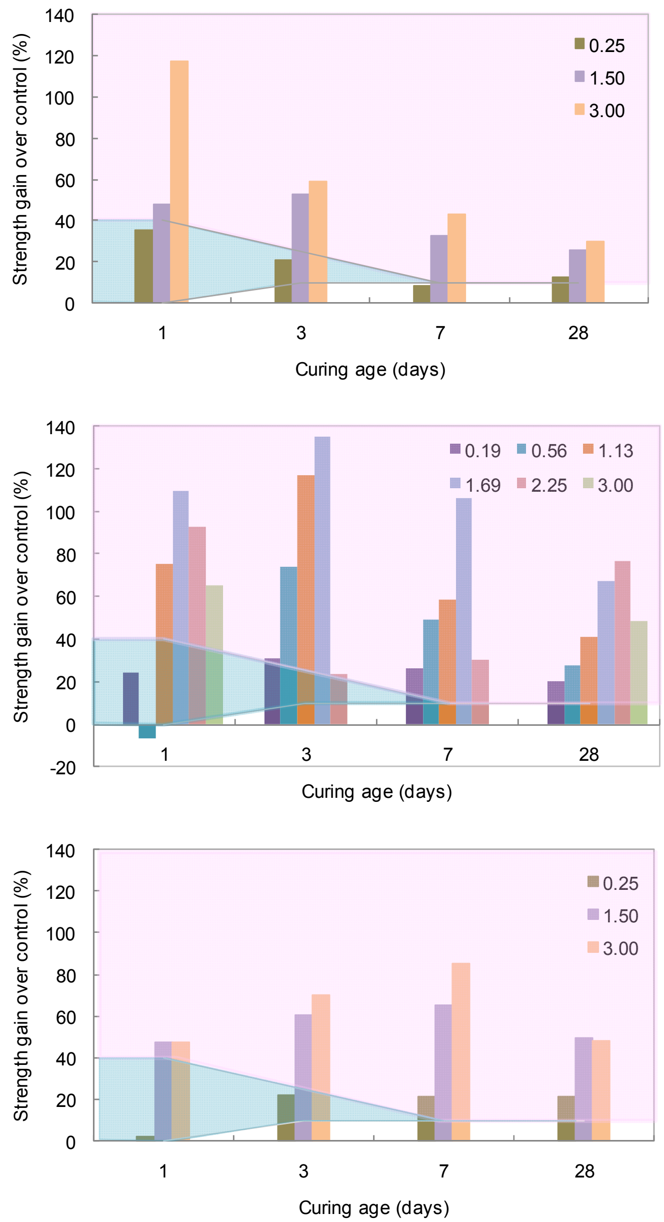


Figure J-53 ASTM C494 classification based on UUCS. A/B for Top: 4, Middle: 7 and Bottom: 10. Blue region shows requirements for type A while Pink region shows requirements for type F water reducers. No strength requirement for one-day tests for type A water reducer.

J.4.5 Role of admixture composition

A detailed investigation was undertaken to compare the PC-based with a ligno-based water reducer. The selected ligno-based water reducer was claimed by the manufacturer to behave as type A, B, D and F and for extended applications as type G admixture. Table 17-10 revisits the dosage comparison.

Table J-10 PC-, Ligno-based admixture dosage comparison

Product chem.		Dosages in %, w/w of binder														
	A/B	4				7							10			
	Prod.	1	2	3	4	1	2	3	4	5	6	7	1	2	3	4
PC-	P-05	0.00	0.25	1.50	3.00	0.00	0.19	0.56	1.13	1.69	2.25	3.00	0.00	0.25	1.50	3.00
Ligno-	P-10	0.00	0.25	1.50	3.00	0.00	0.25	0.75	--	1.50	2.25	3.00	0.00	0.25	1.50	3.00
Remarks						Detailed investigations										

Rather than presenting a detailed investigation here, a synoptic comparison between the two admixture chemistries is presented. The details of this and other admixtures can be found in the appendix. Following points shall be used for comparison:

- Comparison of strength at similar dosages
- Binder efficiency
- Temporal evolution of strength
- Strength vis-à-vis the volumetric composition
- ASTM classification

COMPARISON OF STRENGTH AT SIMILAR DOSAGES

Figure J-54 shows paired comparison for the two admixtures. This plot is constructed for strengths at similar dosages. Paired t-tests were not performed due to lack of sufficient repeats for rendering statistically meaningful inferences. Instead, simple linear regression equations expressing the strengths at similar dosages are presented. Other details of the model are provided in the appendix. A good correlation with R-squared value of 0.97 is obtained and the strength of PC based admixtures is consistently found to be greater than the ligno-based admixtures. The process that the PC-based admixture used in this work is more effective in rendering strength increases than its Ligno-based counterpart. It should however be noted that the presented correlation is for 28 days strength and it does not remain valid for earlier ages, where even linear relations cannot be proposed. Furthermore, unlike the PC-based water-reducer, there are strong interaction effects between the binder content and the admixture dosage. These effects are covered in detail in the appendix.

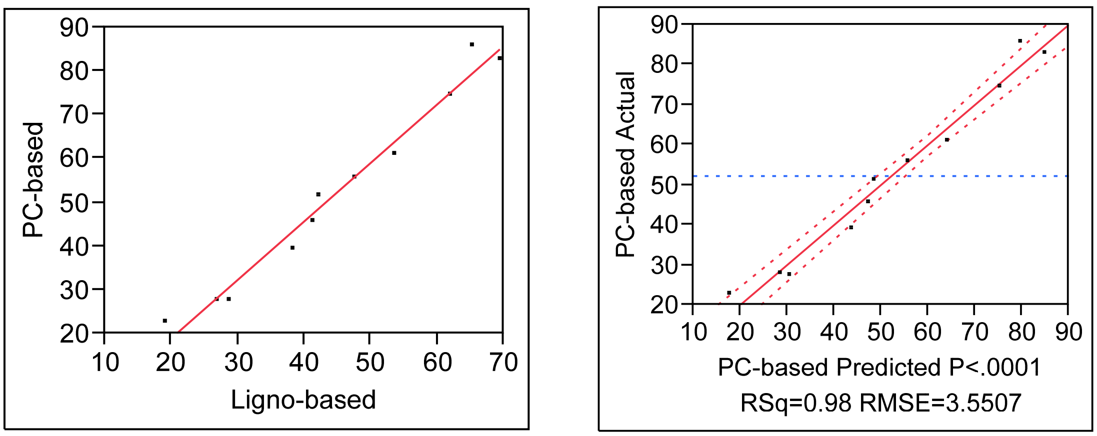


Figure J-54 Comparison between 28d PC-based and Ligno-based water reducer at similar dosage

BINDER EFFICIENCY

Figure J-55 shows the ratio of binder efficiencies of PC-based to Ligno-based water reducers. It can be seen that the binder efficiency for PC-based WR is higher in binder rich mixtures while it tends to be lower in leaner mixtures.

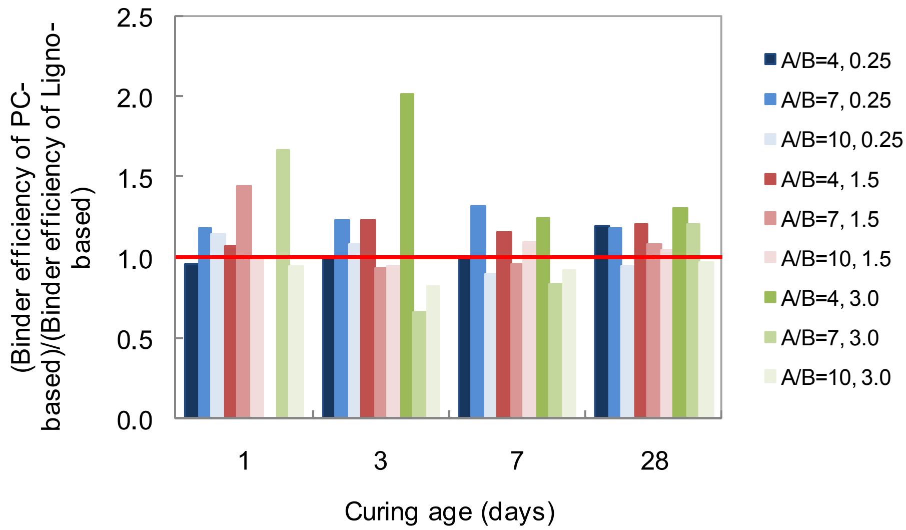


Figure J-55 Comparison of binder efficiencies at different ages

TEMPORAL EVOLUTION OF STRENGTH

The temporal evolution as modeled using above mentioned equation is compared for the two admixtures in Figure J-56. It can be seen that for similar w/b ratio, the PC based admixture is potent of producing higher ultimate strength as shown by the coefficient a. On the other hand, lower b values for ligno-based admixture; indicate that the rate of strength development for this admixture is comparatively lower than the corresponding PC-based admixture dosage.

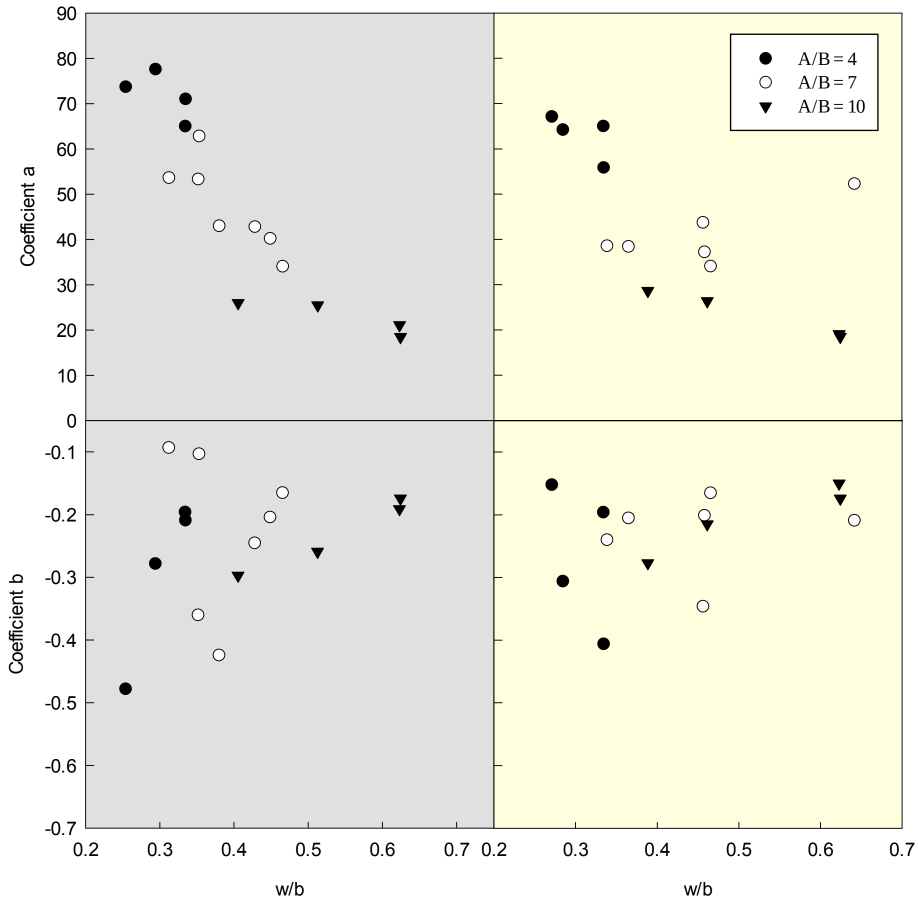


Figure J-56 Strength development coefficients: Effects of different admixtures. Gray: PC, Yellow: Ligno

STRENGTH VIS-À-VIS THE VOLUMETRIC COMPOSITION

Figure J-57 shows a comparison of PC-based and Ligno-based water reducers on the strengths as a composite function of A/B, V_p, ξ and w/b ratio. It can be seen that these water reducers follow distinctly different trends towards optimization. The following are the salient inferences:

- The range of w/b ratios over which these water reducers are effective is distinct. Similarly, the amount of binder relative to the aggregate content over which these two admixtures are most effective is also distinct.
- In terms of the paste volume optimization, the optimal range of effectiveness of Ligno-based superplasticizer is different as well. However, at similar paste vo-

lumes, the PC based water reducers tend to produce higher strengths than their counterparts with Ligno-based water reducers did.

- The plot of ξ vs. w/b ratio shows that the PC-based admixture remains effective over a wider w/b ratio range. In case of Ligno-based water reducer, at higher w/b ratio, the effectiveness reduces dramatically. It is also interesting to note that unlike clear trends observed in PC-based admixture, there is a distinct nebula of high strength over a specific zone bound by w/b ratio and ξ.

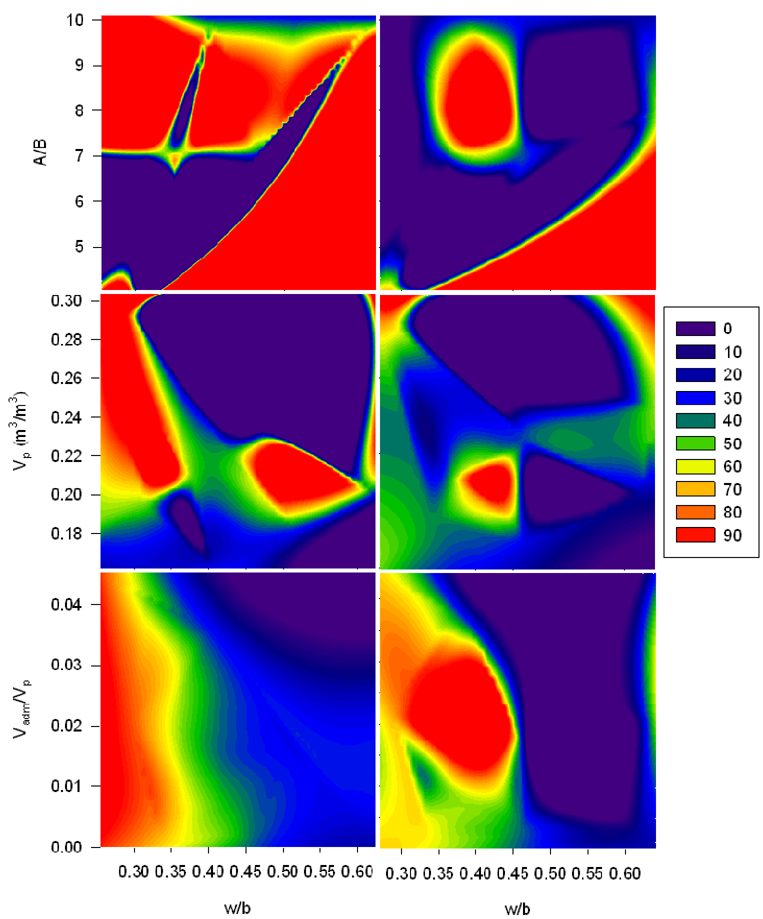


Figure J-57 Comparison of strengths achieved by PC-based and Ligno-based water reducers

ASTM CLASSIFICATION

Figure J-58 was constructed shows strength development vis-à-vis the ASTM C494 classification for admixture types A, B, D and F. it should be noted that all the mixtures have 25% F fly ash of the total binder. Unlike PC-based admixture, the ligno-based water reducer is quite sensitive to the binder content and shows quite distinct behavior. Lower dosages appear to have higher effectiveness in binder rich mixtures while they are not so effective in leaner mixtures. Higher dosages invariably affect not only the early strength but also the later age strength development.

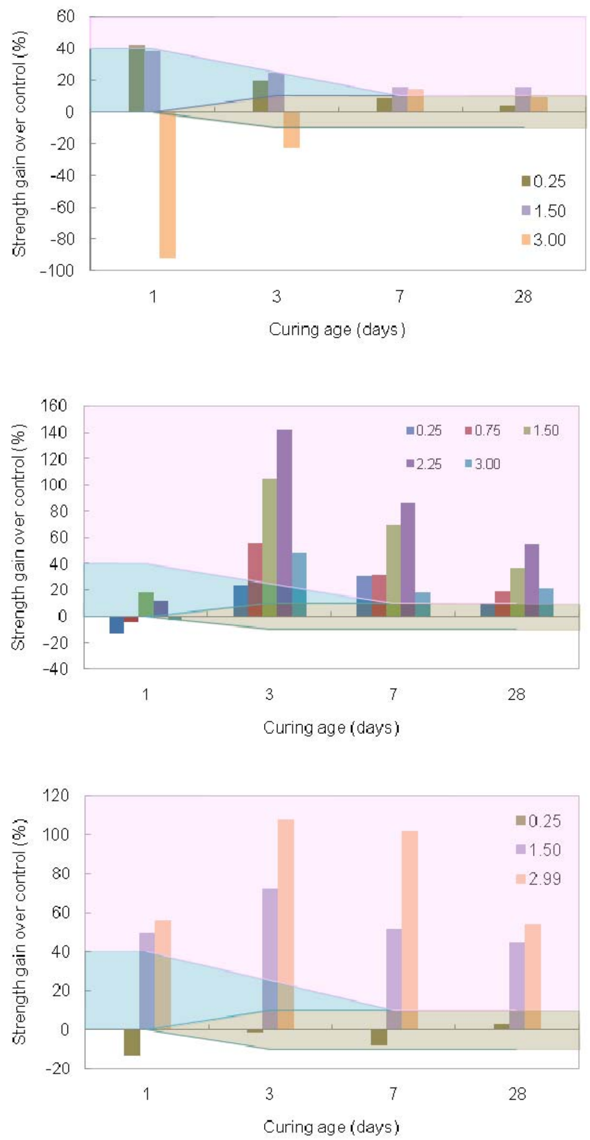


Figure J-58 ASTM C494 classification for Ligno-based water reducer

REINSTATEMENT OF ABRAMS' LAW

Figure J-59 shows that both the admixtures reinstate Abrams' law for strength. It can be seen that the Ligno-based admixture offers comparatively lesser strength at lower w/b ratios while it offers relatively higher strength at higher w/b.

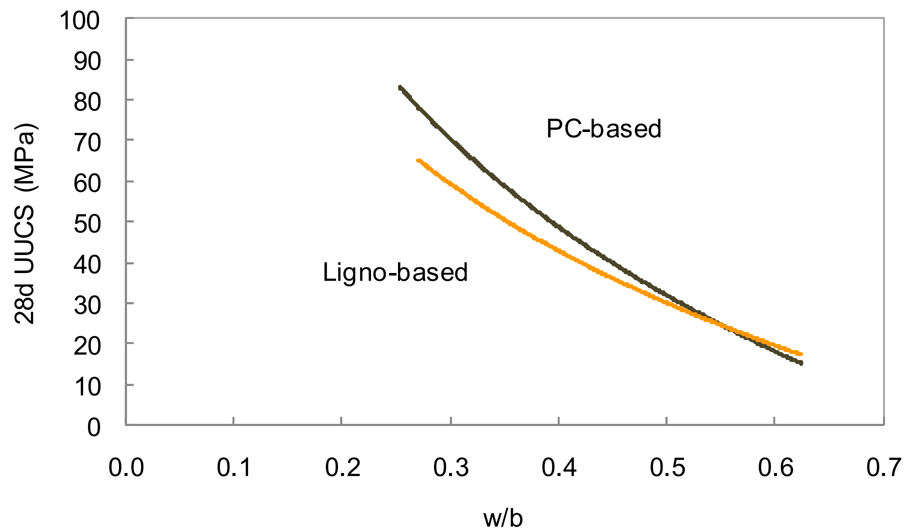


Figure J-59 Reinstatement of Abrams' law: a comparison

J.5 A presentation on air entraining admixtures

The objective of this part of the work was twofold (Table 17-11):

- To find the best admixture chemistry from strength perspective and
- On the selected chemistry, the effect of binder content was to be studied

Table J-11 Experiments on AEA's

A/B	SD (P-19)				WH (P-20)			MR (P-21)		
	1	2	3	4	1	2	3	1	2	3
4	0.10	0.35	0.70	--	--	--	--	--	--	--
7	0.076	0.188	0.376	0.700	0.150	0.300	0.750	0.076	0.188	0.376
10	0.10	0.35	0.70	--	--	--	--	--	--	--

J.5.1 Caveats

The following points are relevant in the following discussion:

- The binder composition and characteristics, the aggregate content and characteristics, and the mixing procedures were kept the same. No other chemical admixtures were added for this part of the study. The air content of fresh concrete was measured using routine pressure-meter test (ASTM C 231).
- No attempts were made to characterize the air void structure in hardened concrete. Since this characterization was not undertaken, the influence of entrapped and entrained air voids cannot be differentiated. In addition, the stability of air void system in fresh concrete and during its transition towards hardened state was not studied. Direct correlations with the air content as measured on the fresh compacted concrete at 15 min. is used in this analysis.
- Moreover, it is assumed that the air voids are distributed randomly but statistically uniformly.
- The following are chemistry specific considerations:
    - Synthetic detergent (SD): P-19; generates air rapidly, coarser bubbles
    - Water soluble hydrocarbon (WH): P-20; generates air rapidly, mid-sized bubbles
    - Modified resin (MR): P-21; slower air generation, smallest air voids amongst AEA's [44]
- For most AEA's the air content increases with the dosage following a parabolic trend leveling off at higher dosages.
- A ratio proposed by Feret and later used by Talbot and Richart [45-46], cement paste ratio (or cement space ratio), r_F can be used in estimating the strength of concrete. It should however be noted that the Faret's concept tends to over-estimate concrete strength at higher cement contents and under-estimates them at lower cement contents. Following formula is relevant to this discussion,

$$f = K r_F^2$$

where,

f is the concrete strength

K is an empirical constant

r_F = C/(C+W+V_a), C and W are weights or absolute volumes of cement and water and V_a is the volume of air in compacted concrete

- Compressive strength of comparable concretes are reduced by approximately five percent of air-free strength for every one percent of air in the fresh concrete [47] and is given by the following formula

$$f = f_0(1 - 0.05V_a)$$

- It is essential to recognize that the composite action of w/b ratio and the volume of air voids influence the strength of concrete. A unit volume of capillary pores, in general, does not have a similar effect as the same volume of initial air voids (reference). Moreover, the capillary porosity is age-dependent and reduces with continuing hydration. On the other hand, air voids once created, either due to entrainment or lack of compaction are stable over time [46]. Therefore, age-specific effects on strength will not form a part of this discussion. Figure J-60 shows typical examples of admixed concretes in comparison with control mixture.

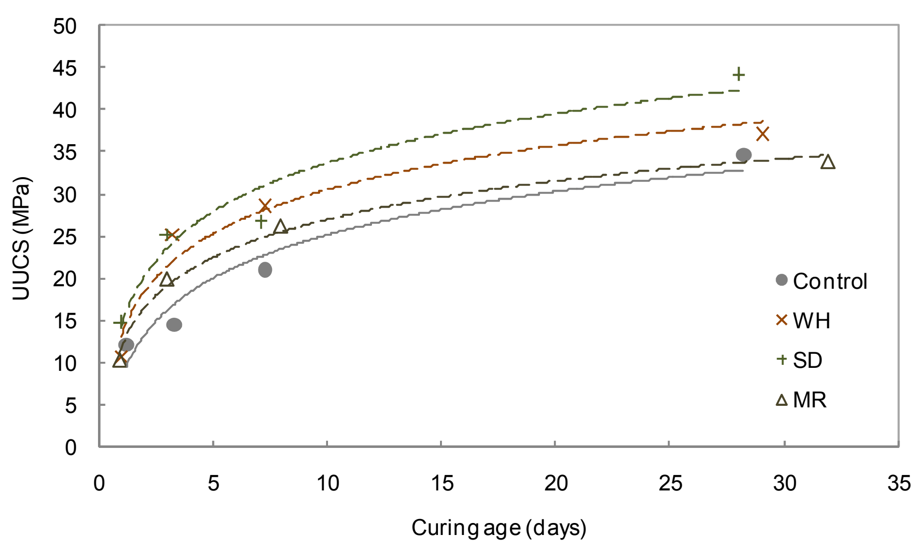


Figure J-60 Comparison showing no effect on rate of strength development with the use of different AEA's

- Cement content has an influence on the strength due to w/b ratio effects. It is claimed there is a range of cement content in which the effects of water and air contents on the strength of concrete are similar on a volumetric basis. At higher cement contents, the effect of air content is reported to be be greater, while it will be lower at lower cement contents than the corresponding effect produced by water on the strength [46, 48-49]. However, it should be borne in mind that these arguments are valid for concretes with measurable slump. No specific research has been reported on drier concretes.

J.5.2 Effects of AEA chemistry

Figure J-61 revisits the plot of measured air content in fresh concrete as a function of admixture dosages for different AEA chemistries. For a fixed dosage, SD based AEA seems to entrain the highest air followed by MR and WH. All the AEA's produce a parabolic trend; the flattening effect with increasing dosage could not be captured with the used dosage ranges.

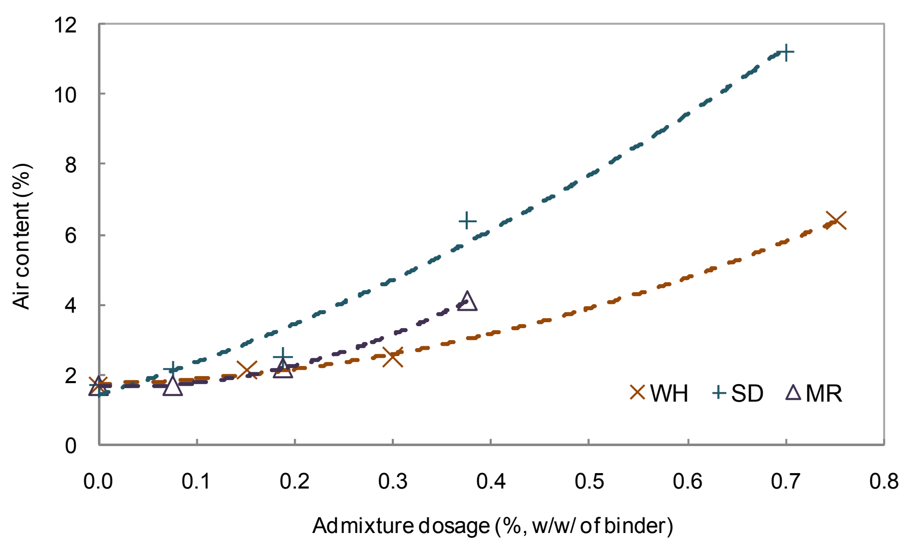


Figure J-61 Effect of AEA chemistry and dosage on the measured air content of fresh compacted concrete

Figure J-62 shows the effect of dosages on the relative strengths of different mixtures at 28 days. The maximum dosages used for SD, WH and MR were approximately 15, 8 and 3 times the average recommended dosages, respectively. In general, with the increase in the dosage of the admixture the strength increases, reaching a maximum and then starts to reduce. Since the initial consistency was kept constant, the explanation of this phenomenon is two-fold. It is known that in drier concretes, the compaction response of a mixture improves with the presence of entrained air [50]. Better compaction leads to reduction in the entrapped air voids with a corresponding improvement in the density and an increase in the mechanical strength. As the dosage is further increased, this effect is reduced while the presence of a network of entrained air bubbles resulting in the increase in the volume of air starts to be manifested. The effect thus produced supersedes the water reduction effect, resulting in a decrease in the strength.

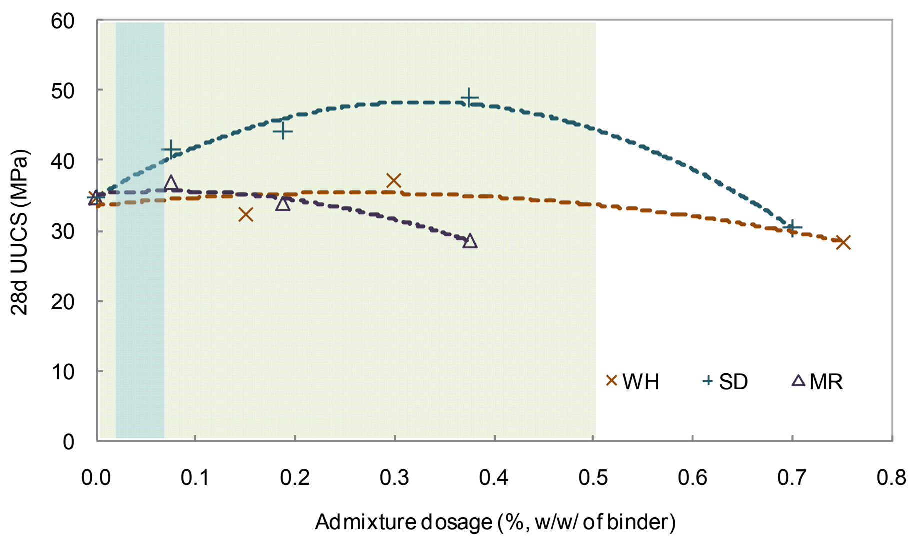
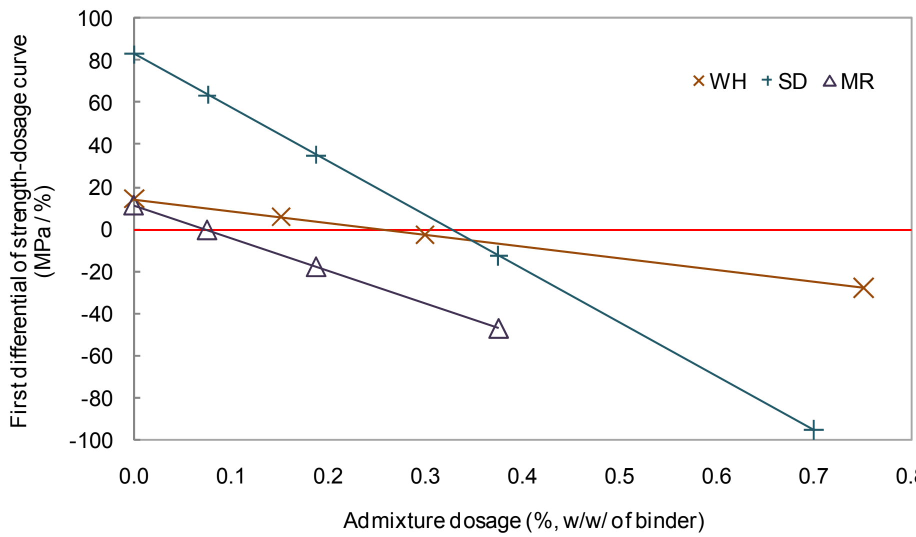


Figure J-62 Effects of dosage on the strength of admixed concrete mixtures.Green rectangle represents the recommended dosage range for WH, while the Acqua color strip represents the receommended range for SD and MR.

Quite interestingly, the effect of SD based AEA is to yield higher content and strength compared to other AEA's. The mixtures produced using this AEA are less robust when compared to the mixtures with WH or MR. It is also important to recognize that the initial consistencies of these mixtures were kept constant, while observing the water reduction. As such, the mutually competing effects of w/b ratio and air content as discussed above cannot be fully appreciated. Another caveat to this is the mixtures have different air contents, thus qualitatively representing a different internal structure.



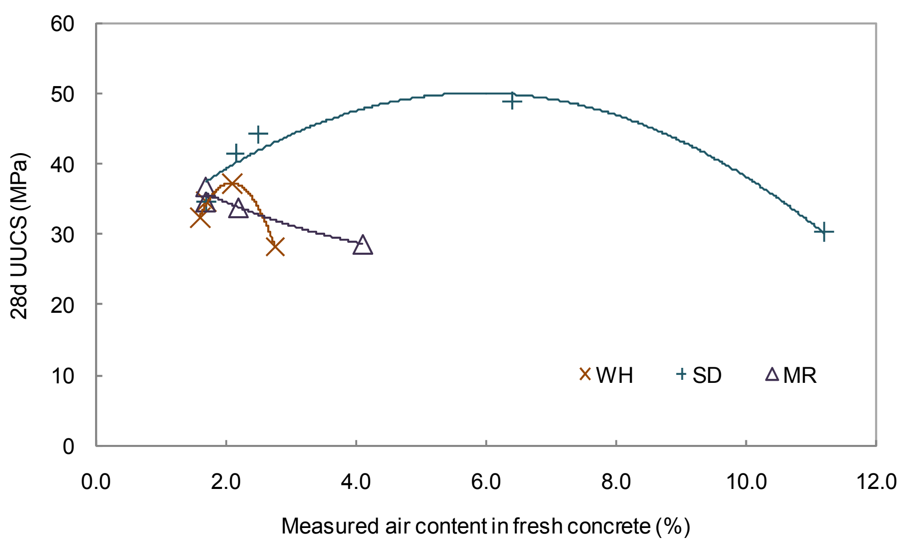


Figure J-63 Perspectives on strength-air content-admixture dosage

Figure J-63 presents another perspective on the strength-air content-admixture dosage relationship. The upper part of this figure represents the first differential of the strength-dosage plot as a function of admixture dosage. It can be seen that the SD based admixture has the greatest slope implying the highest rate of change of strength with increasing dosage resulting in a highly admixture sensitive system. MR and WH. The optimal dosage at which the highest strength (where the differential cuts the horizontal axis) is obtained is a function of admixture chemistry. In the lower part of this Figure, the trend of strength as a function of the measured air content in the fresh concrete is plotted. WH and SD follow a parabolic trend, while MR follows a non-linear inverse trend. This perspective proves that SD based mixtures are more robust than the WH or MR based systems.

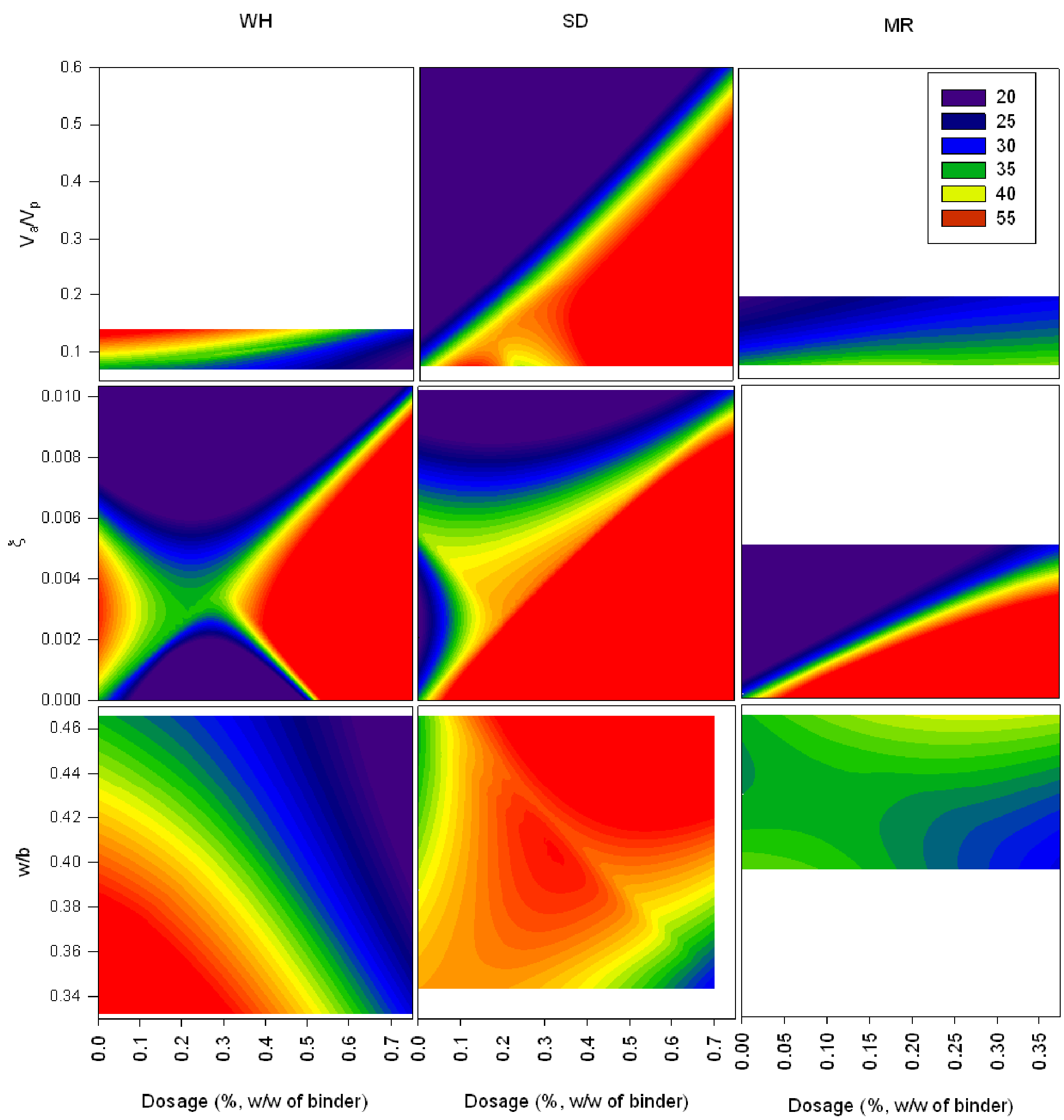


Figure J-64 Strength as a function of different ratios dosage of AEA's

J.5.3 SD-based AEA: Detailed study

Figure J-65 shows the effect of the AEA dosage on the entrained air in fresh concrete as measured using pressure-meter test. This has been discussed previously and is just re-produced here to lay the foundation of the following discussion. Of relevance is the point that the volume of air content is at a maximum for the intermediate binder content.

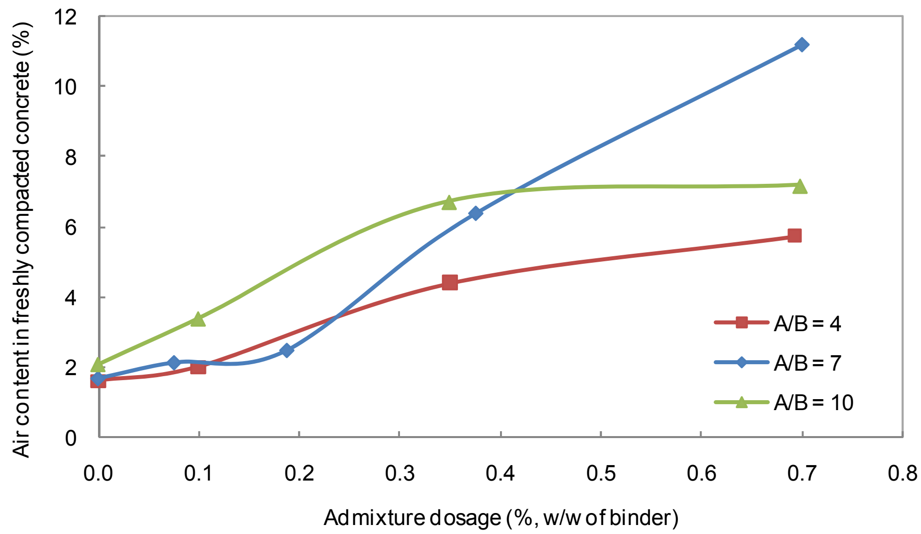


Figure J-65 Effect of SD-based AEA on the air content of fresh concrete: Effects of binder content

Figure J-66 shows the trends of strength in response to the admixture dosage for various binder contents or A/B ratios. For leaner mixtures, the strength increases initially and then follows a decreasing trend with increasing admixture dosage. Richer mixtures however show no increase in the strength at lower dosage, but show a decreasing trend overall. Intermediate binder content on the other hand show a different pattern altogether. Initially the mixture shows increasing strength in response to increasing admixture dosage. The strength then reaches a peak and then shows a decreasing trend. Although the initial consistencies were kept constant, and water reduction was observed, the phenomenon resulting due to composite action of w/b ratio and air content can be partially seen here. This binder content may be close to that range where w/b ratio and the volume of air have similar quantitative effect on strength of concrete.

Figure J-67 (upper) shows the first derivative of the strength equation with respect to the admixture dosage. The rate of change of strength for leaner and richer mixtures indicates an overall strength reduction with increasing admixture dosage. At higher dosage end, there is a transition from decreasing trend shown by the intersection of the derivative line with the horizontal axis. Practically this would imply that the effect of air content on strength has started to flatten out. In case of intermediate binder content, the transitioning from a positive value of the derivative to the negative domain indicates that strength is optimized as a function of admixture dosage. The dosage at which the derivative line crosses the horizontal line is the optimal dosage that offers a balance of water reduction and air content rendering the highest possible strength. Figure shows iso-strength plots as a function of air content and binder content. It appears that the optimal dosage at which the strength reaches its peak with this admixture varies with the binder content. In this case, it is the lowest for the richest mixture, reaches the highest range for intermediate mixture and then drops down for the lowest binder content.

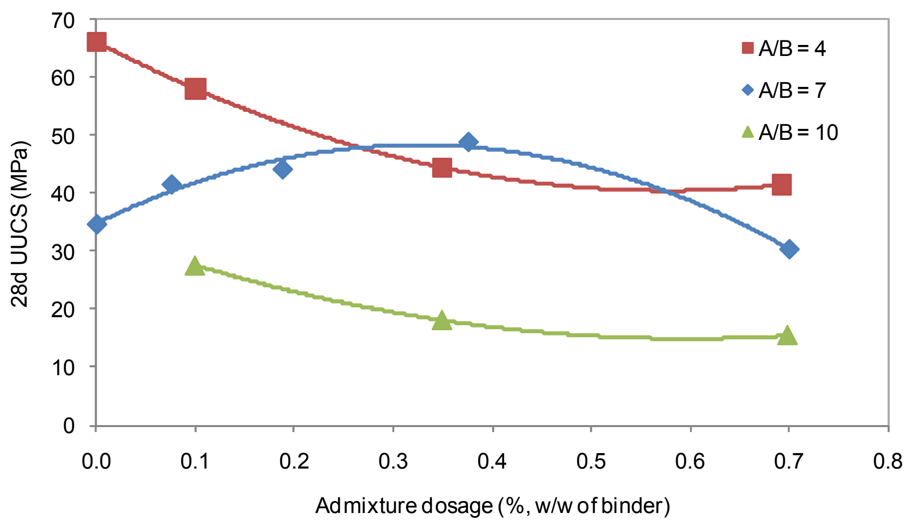


Figure J-66 Effect of binder content and admixture dosage on strength

The lower part of this figure shows the trends in strength as a function of volume of air in compacted concrete. Richer mixtures tend to show a strength reduction behavior with increasing volume of air content. Intermediate and leaner mixtures however, show follow a parabolic path of optimization. Initially with increasing air content the strength increases followed by a peak and then reduction. The air contents at which the optimization take place depends on the binder content or A/B ratio of the mixtures.

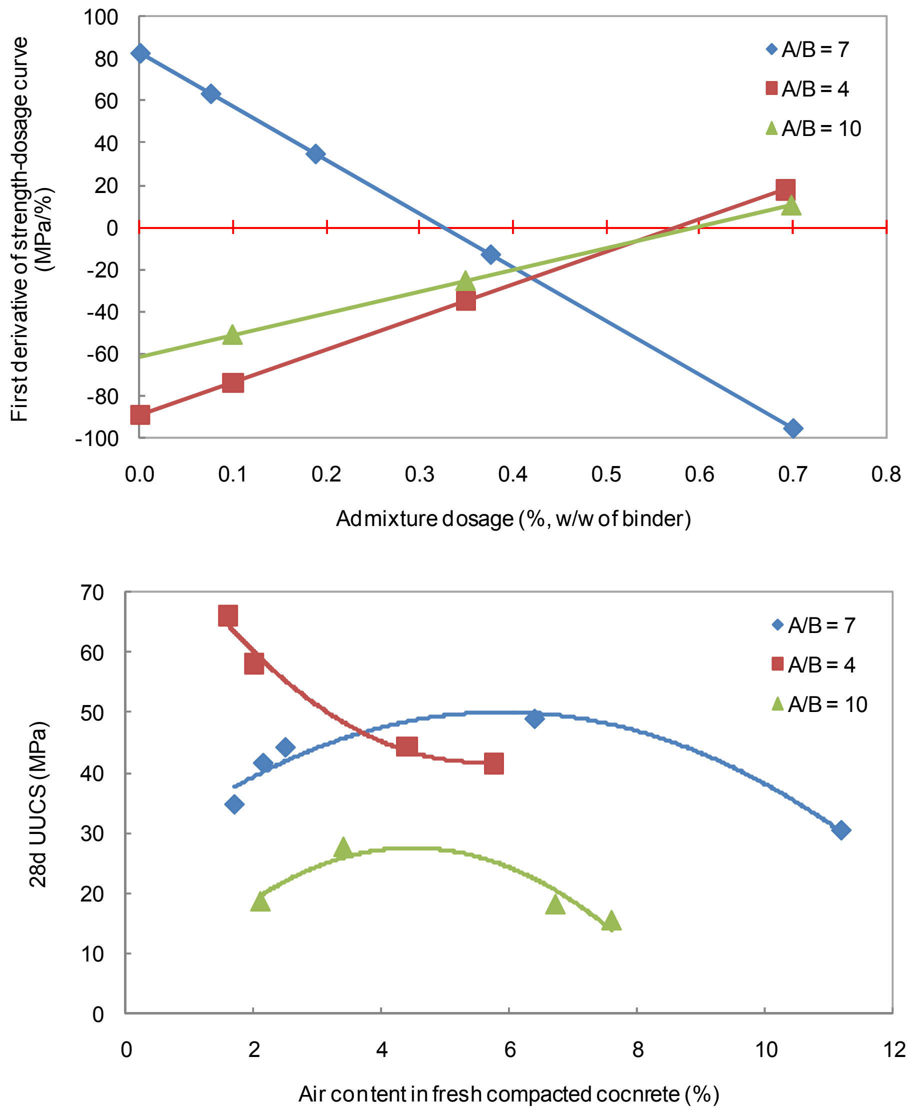


Figure J-67 Perspectives on strength-air content-admixture dosage and binder content

Figure J-68 shows two plots with their respective trends and 95% confidence limit bands. The plot on the left hand shows the relationship of strength to the volumetric ratio of (water+air)/binder. This relationship is analogous to Abrams' law and takes into account the combined effects produced by the volume of air and w/b ratio on the strength of concrete. Similar relations were developed by Feret and are reported by Popovics [46]. Similarly as discussed above, the relationship between strength and the square of cement-space ratio (r_F) is given by a straight line. For the test data, there is a negligible intercept and the value of k is -241.95.

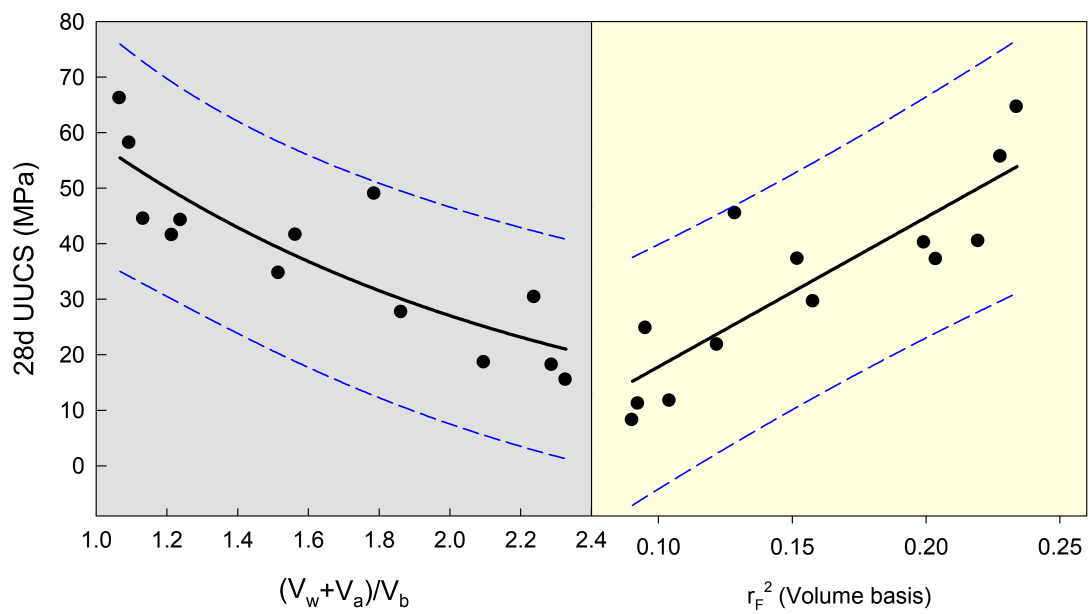


Figure J-68 Strength-w/b-air content interaction effect and strength cement-space ratio effect

Figure J-69 shows the iso-strength lines as functions of admixture dosages and other ratios taken a pair at a time. For every w/b ratio, there will be an optimal dosage of admixture that will render the maximal strength. For each combination of water and binder content, there will be a tolerance limit for accepting a certain range dosage of admixture without affecting the strength much. This tolerance decreases as the dosage increases. The relative volume of air content to paste offers a great deal of information. A paste can tolerate only a certain range of air content in it without actually starting to affect the strength. This can be seen where this ratio is relatively low. With lower ratios (implying lower air content) higher dosages can be accommodated and vice versa. As this ratio increases, the strength dramatically drops down.

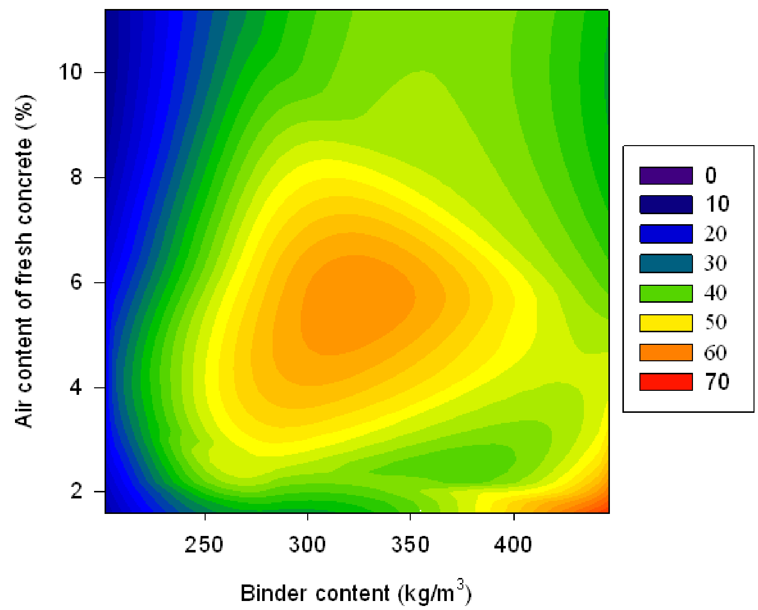


Figure J-69 Iso-strength plots as functions of binder content and air content in fresh concrete

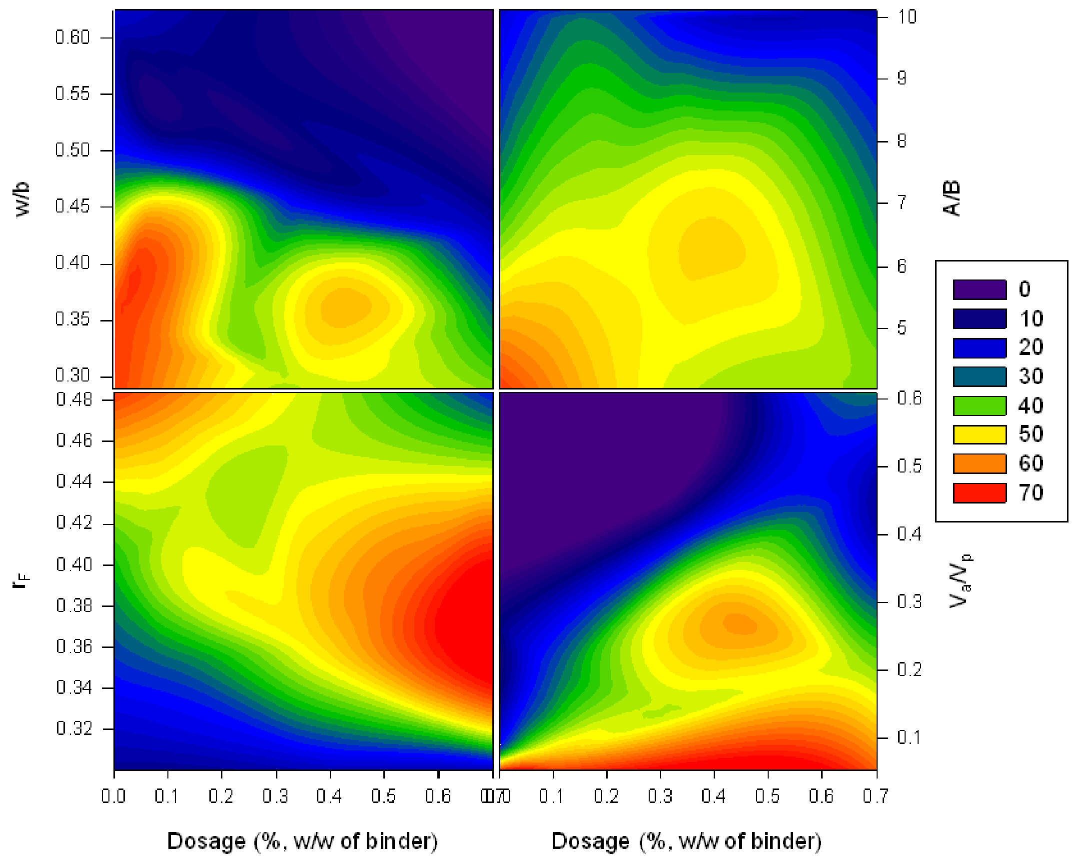


Figure J-70 Iso-strength plots of strength as functions of admixture dosage and various ratios

Figure J-71 shows the above trends in 3D plots with an objective to bring out the interaction effects taking place in the admixed systems. From the LHS plot, for a given dosage, as the volume of air in the paste increases, the strength decreases. However, the trend is different for some intermediate admixture dosages. This cannot be understood alone as a function of dosage. These dosages are primarily coming from the intermediate binder contents, where the strength response due to the combined effect of water reduction and air content is significantly different from the richer and leaner mixtures. In this range of admixture dosage, there is an interaction effect of water reduction and the volume of air. Although the relative volume of air increases in the paste, the strength keeps increasing, reaches a peak and then drops down for a certain range and then again starts rising up. The composition of the paste must be playing a very vital role in deciding this interaction. The rising of strength at lower air content is quite straightforward to understand. A better appreciation of the physio-chemical behavior and the consequent actions resulting into this anomalous behavior cannot be offered based on the scale of this study. The RHS figure shows the trend with A/B content and dosage. For a given dosage, as the binder content increases the ability of the admixture to entrain air decreases. Again, the unusual behavior with respect to the binder content is easily seen in the form of a hump in the middle.

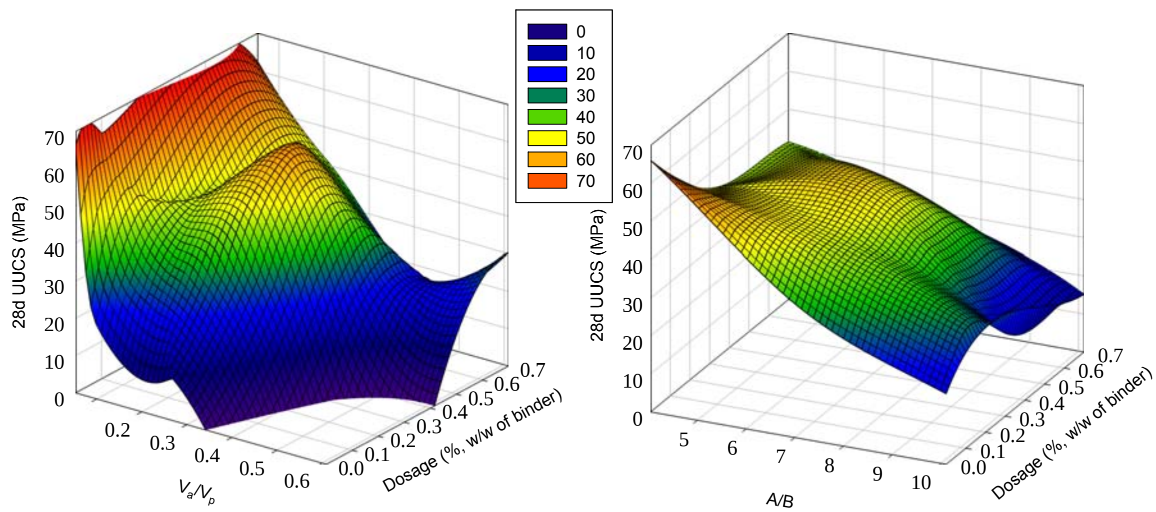


Figure J-71 Interaction effects of AEA dosage on strength

It is interesting to appreciate the water reduction and air entraining power of this admixture as a function of its dosage in RCC mixtures. It is not the total volume of the admixture, but its relative volume with respect to the binder volume that is causing any changes in the measured properties. Figure J-72 depicts the changes in the air content and water reduction with dosage. The dark blue region should be cautiously evaluated, since due to the graphing package's limitation it is constructing the plot in the shown manner. Physically the blue region may not the depicting the truth. Nevertheless, the red-yellow nebular region shows the variations in the air content and water reduction capability of this admixture. If the water reduction is fixed, then the air content increases with the increasing dosage. While if the air content is held constant, there are two different water reductions that can be obtained.

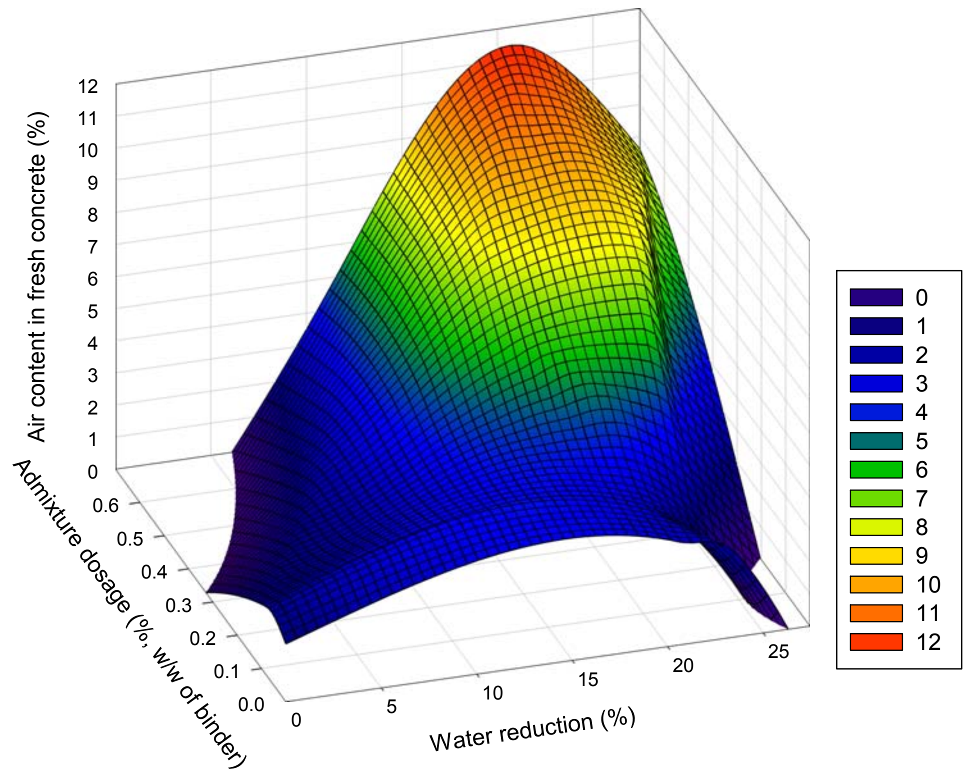


Figure J-72 Air content of fresh concrete as a function of its dosage and water reduction

Similar effects are shown in Figure J-73 plotting two factors at a time to get the trends in the strength. Again, the red areas on the right hand side corners may not make physical sense. Quite interestingly, for fixed air content, at higher water reductions, the strength is lower. It can be hypothesized with higher water reduction; there is insufficient water present in the concrete system leading to higher volume of compaction voids, which in turn are reducing the strength. On the other hand, with lesser water reduction, there is sufficient water to entrain air, which in turn is reducing the strength.

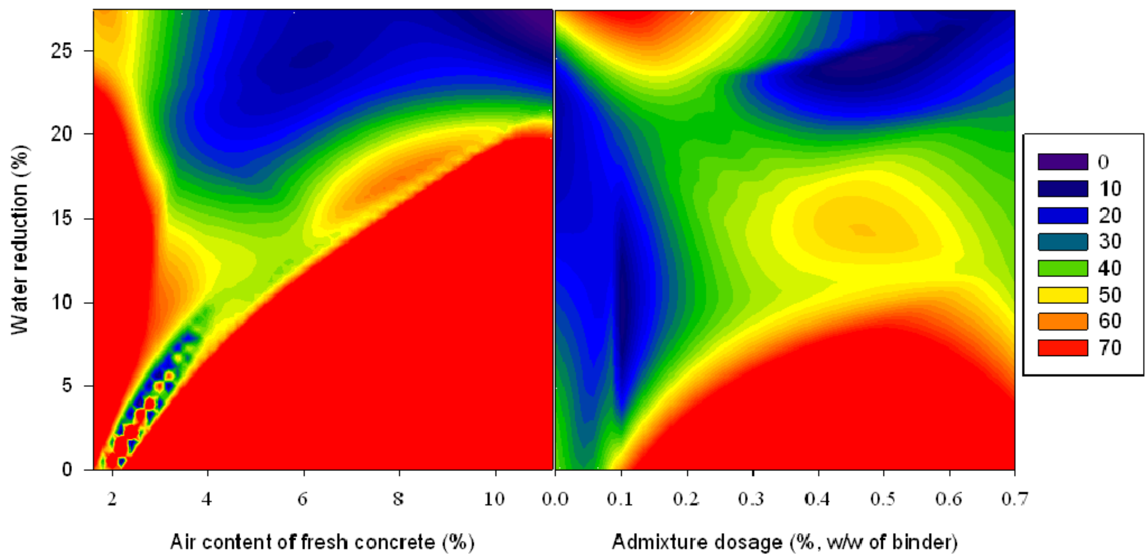
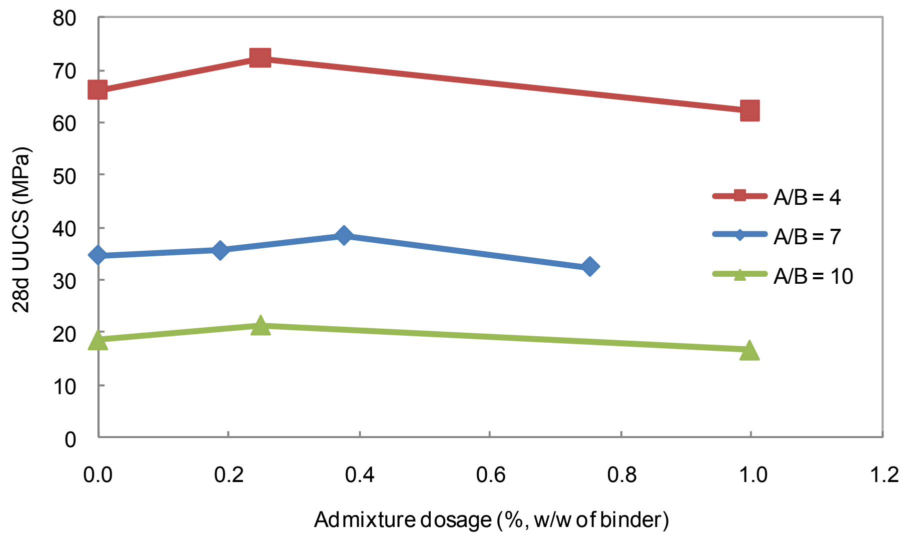


Figure J-73 Iso-strength (MPa) plots as functions of water reduction, admixture dosage and air content of fresh concrete

J.6 Rheology modifiers

Rheology modifiers are primarily added for the purposes of changing the fresh state behavior of concrete. They may or may not have any physio-chemical effects that may in turn affect the mechanical properties of concrete. In the case of dry concretes, this may be a reflection of incomplete compaction primarily resulting due to the relatively drier nature of concrete and lack of cohesiveness. Moreover these admixtures are not intended for water reduction and hence strength changes. As such, a detailed discussion is avoided here.

Figure J-74 shows the 28-day strengths of products P-24 and P-25 admixed concrete mixtures at different dosages and for different binder contents. The strength development starting from one-day strength was not affected by the presence of these admixtures in concrete mixtures. Although the effect of product P-25 on strength is relatively lesser, this may or may not be statistically significant.



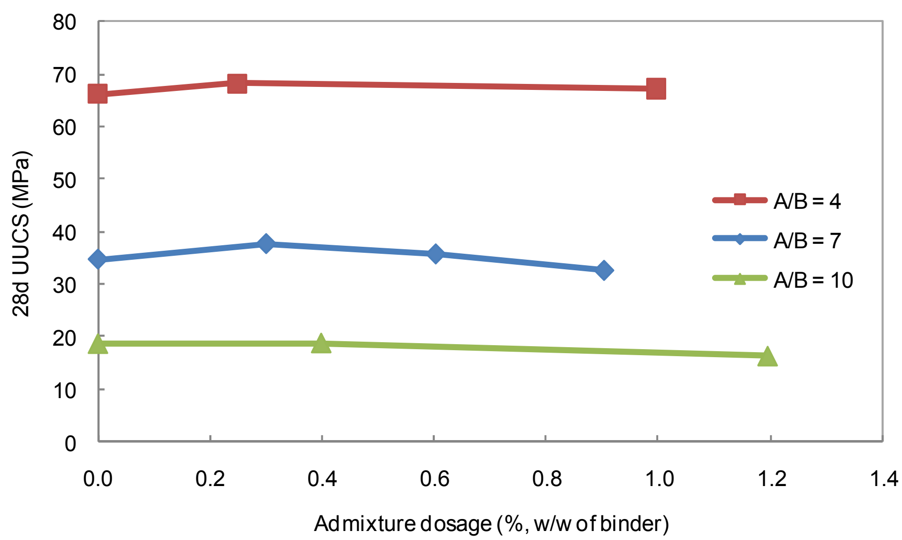


Figure J-74 Effects of RM dosages on the 28-day strength for various A/B ratios. Top: P-24, Bottom: P-25

J.7 Dry cast products

One surfactant based (P-28) and one PC-Glycol based (P-29) dry cast product were used in this study. A detailed report is presented in one of the appendices. Figure J-75 presents the strength responses of these two products at 28 days. The relative increase in the strength offered by these admixtures is not comparable to water reducers. The advantages are primarily observed in terms of fresh concrete properties and hence no elaborate descriptions are offered here.

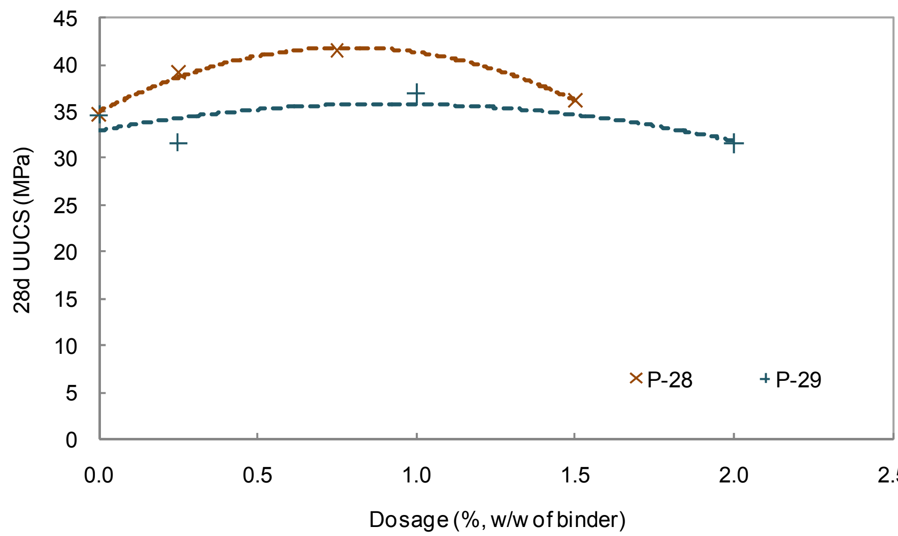


Figure J-75 28d UUCS with surfactant based (P-28) and PC-glycol based (P-29) dry cast products

The surfactant-based product is more or less like an air-entraining agent that fluidizes the paste, helping compaction within a short time window. Due to the action of surfactants, they are not good dispersants, but to a certain extent can reduce the water demand of a mixture. The PC-glycol based product, however, has relatively less water reducing effect. Hence, in both cases, no substantial change vis-à-vis the corresponding water reduction is obtained.

J.8 The omega index factor (O.I.F.)

This section presents a series of figures showing the O.I.F's (strength divided by water/binder ratio for different chemical admixtures described above.. Regression lines are shown for which the R^2 > 0.70 and the Y-axis is kept the same for all plots for providing a comparative view of different mixtures.

J.8.1 Mixtures without admixtures

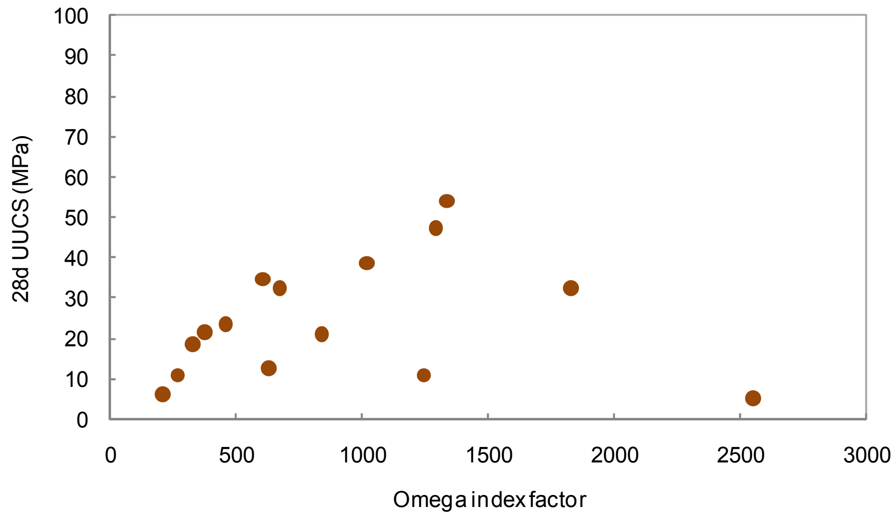


Figure J-76 O.I.F. for non-admixed mixtures

J.8.2 Water reducers: Ligno-, PC- based

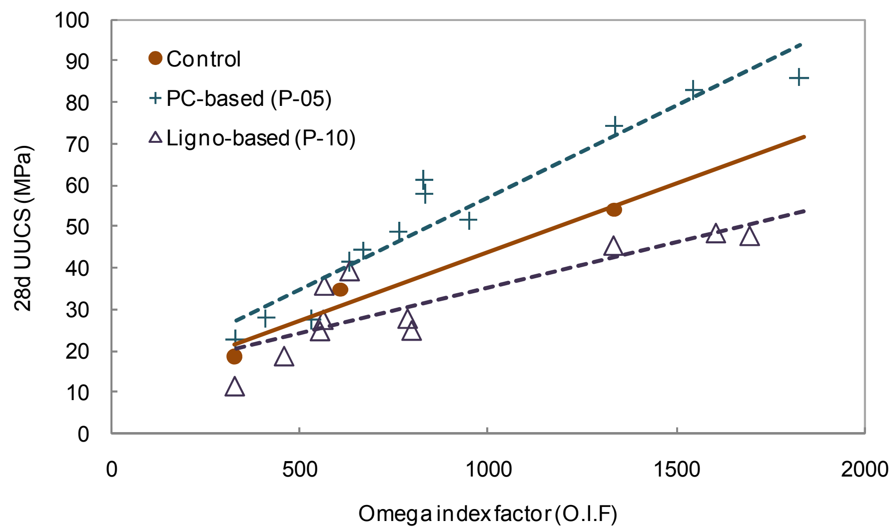


Figure J-77 O.I.F. for Ligno-, PC-based water reducers (P-05, P-10)

J.8.3 Retarding water reducers

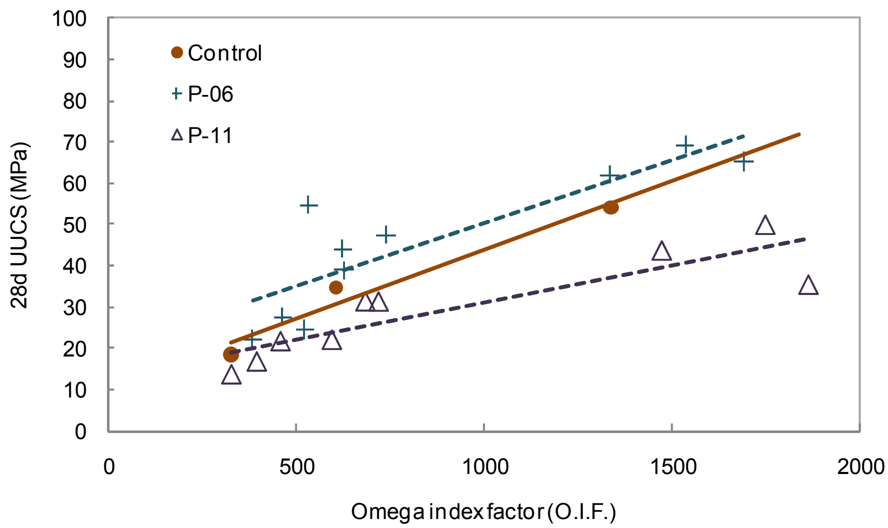


Figure J-78 O.I.F. for retarding water reducers (P-06, P-11)

J.8.4 Strong retarder and surfactant based dry cast product

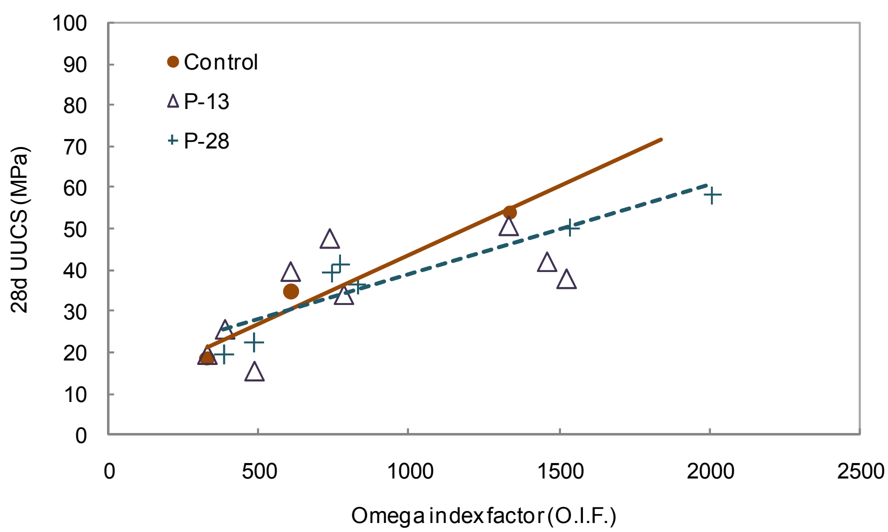


Figure J-79 O.I.F for a strong retarder (P-13) and surfactant based dry cast product (P-28)

J.8.5 AEA's

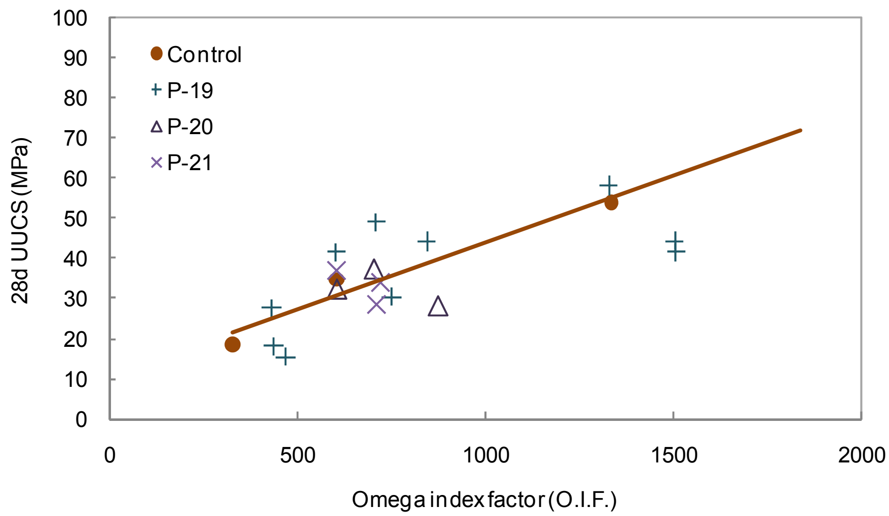


Figure J-80 O.I.F for different AEA's. Synthetic detergent (P-19), water-soluble hydrocarbon (P-20) and modified resin (P-21)

J.9 Composite view

J.9.1 Strength gain over control

From the practical perspective, a contractor would be interested in a comparative composite picture that will help him select the most suitable admixture for some specified strength. Figure J-81 represents the improvement in strength over control for the series of mixtures cast with A/B = 7, binder content of 282 kg/m^3 and water reducing or water reducing cum retarding admixtures. It can be seen that the PC-based product offers a wide range of applicability in terms of dosages and can potentially increase the strength up to the maximum possible within the tested set of admixtures. The Calcium lignosulfonate based water reducer and product P-06 offer similar potential, however their abilities to increase the strength are relatively lesser than the PC-product. This is a consequence of the water reducing abilities of these admixtures, which is compared in an earlier chapter.

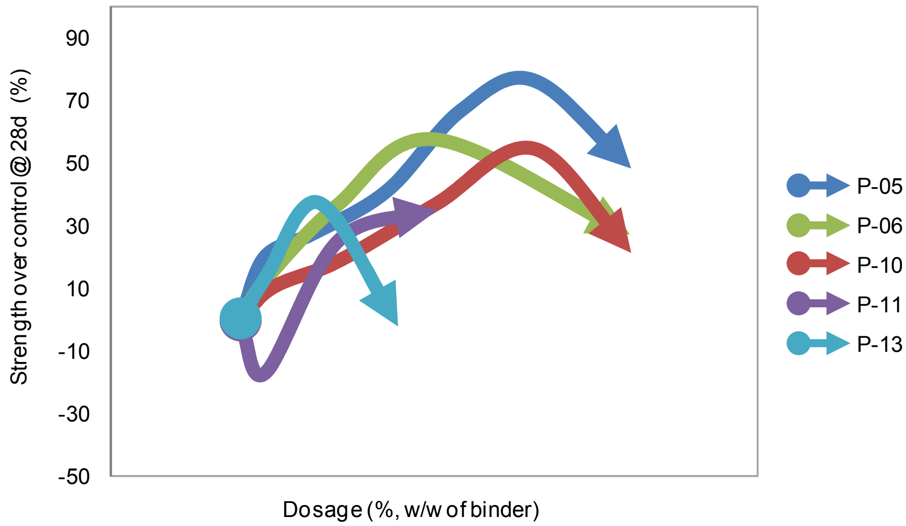


Figure J-81 Relative strength gain over control as a function of the admixture type (ASTM C494 types A, B, D and F for normal concretes) and dosage

Retarding/water reducing admixtures, under tested conditions, show a mixed trend. These products exhibit strength improvement over a limited range of dosages, beyond which their effectiveness in reducing the water while overcoming their hydration retarding action is reduced. However, they offer manifold benefits in terms of fresh concrete properties and hence can be applied where reaching minimum strength is not an issue. This comparison assumes that qualitatively mixtures produced with different concretes are similar at the microscopic level. Although the amount of charge stabilization of binder particles achieved by each of these admixtures and the consequent dispersions and their nature could be different. This cannot be elaborated further based on the studied parameters. Since this mixture has an intermediate binder content and is most proximal to typical pavement mixtures, therefore the results of this A/B ratio are presented. Similar curves can be constructed for other binder contents as well; however, their behaviors are different and are described in one of the appendices. It can also be seen that the water reducing admixtures are relatively more robust in their compressive strength response to dosage than the retarding-cum water reducing admixtures.

Opening the pavement for traffic depends on the early strength development. Use of water reducers alone may help achieve this, contingent on proper curing. Figure J-82 represents the relative strength gains at the end of the first day of curing for admixed concretes. It can be seen that the use of PC-based admixtures could be beneficial in improving the early age strengths and in turn could help early opening of the pavement to traffic. Other admixtures have a somewhat retarding effect on the strength development and hence would need extended times to gain the strength required for opening the pavement to traffic.

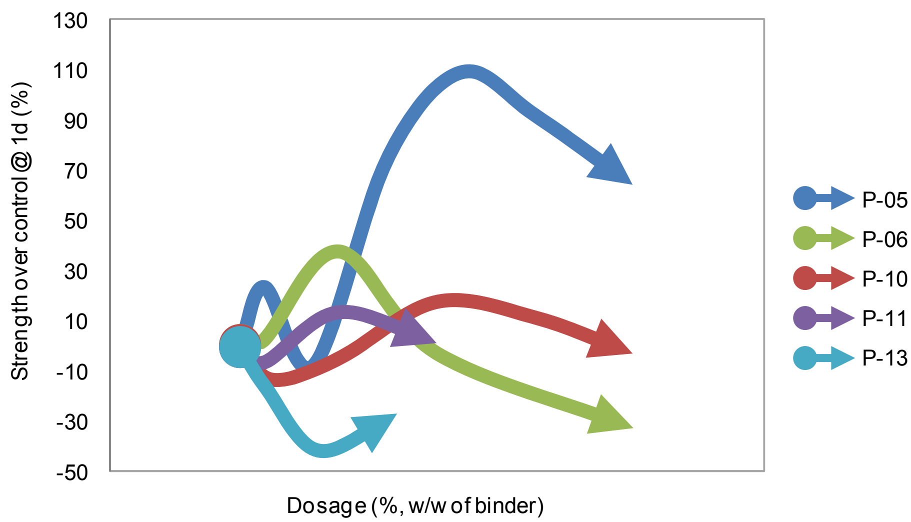


Figure J-82 24 hr relative strength gain over control for different retarding-/normal-water reducers

The air entraining agents (AEA's) used in this work showed some potential for improving the compressive strength of concrete mixtures. AEA's do not reduce water demand directly, the air bubbles lubricate the system. As discussed before, when an AEA is used, water reduction and air entrainment could go hand in hand or compete to reduce the overall effect produced on compressive strength. In the present study, the synthetic detergent based AEA (P-19) showed the highest and continual strength gain (refer to Figure J-83) the water-soluble hydrocarbon (P-20) and modified resin (P-21). The latter two AEA's showed an initial increase in strength at lower dosages, reaching a peak and then showing a reduction. Their performance compared to the retarding-/normal-water reducers is less effective in enhancing the strengths, which primarily comes from the improvement in the compactibility of the mixtures.

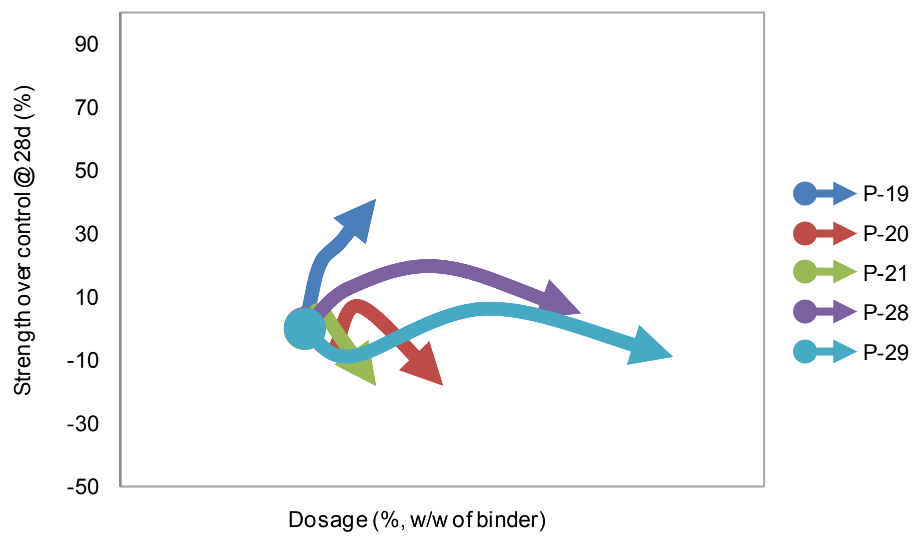


Figure J-83 Relative strength gain over control as a function of the AEA chemistry and typical rheology modifiers and their dosages

It is also interesting to note that the strength response of synthetic detergent based AEA is highly sensitive to admixture dosage and a slight over- or under-dosing may cause substantial alteration in the compressive strength, indicating a less robust system. Modified resin based AEA also shows similar sensitivity, however, the path it follows in changing the strength is different. The water-soluble hydrocarbon based AEA offers a relatively higher robustness in its compressive strength response.

The above figure also shows the strength responses of the surfactant based dry cast product (P-28) and PC-glycol blended dry cast product (P-29). Both of these admixtures offer a consistent response over the tested range of dosages. The surfactant-based product improves the finishibility of the mixtures while following a parabolic path leading to a maximum strength gain at an intermediate dosage followed by a decreasing trend in response to the increase in the dosage. In case of the PC-glycol blend, due to a limited water reducing capability this admixture also shows a parabolic trend, however leads to relatively gentler increase in the strength when compared to the corresponding dosages of the surfactant based product.

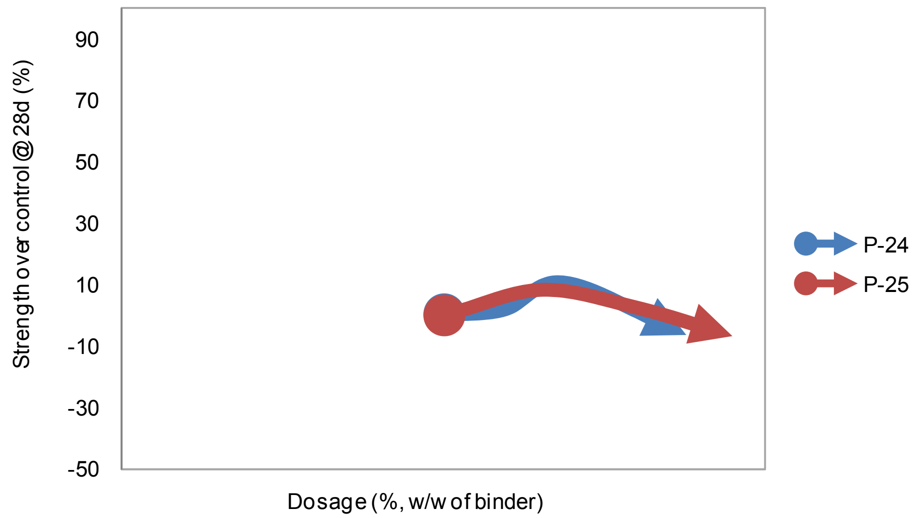


Figure J-84 Relative strength gain over control as a function of the typical rheology modifiers and their dosages

Figure J-84 shows the strength responses of the starch based (P-24) and Welan-gum (P-25) based rheology modifiers. Both of these admixtures offer a robust response over the tested range of dosages.

BINDER SAVINGS

From the cost perspective, the additional advantage of using admixtures could be binder content reduction. A simple analysis is presented here with an objective of appreciating an aspect of cost reduction. Reducing the binder content will also make the concrete systems more sustainable by reducing the carbon-footprint. It can be recalled that the binder efficiency is computed using the following formula

$$Binder\ efficiency\ (\eta) = \frac{UUCS\ (MPa)}{Binder\ content\ (\frac{kg}{m^3})}$$

Say, the target strength is kept constant, that of control mixture. The use of admixtures leads to changes in the binder efficiencies. Using the following symbols:

η_c: binder efficiency of the control mixture at a given age
$\eta_{a:}$ binder efficiency of the admixed mixture at the same age as the control mixture
B_c: binder content of the control mixture
B_a: binder content of the admixed mixture

For a fixed strength, the following equivalence can be established from the above relation

$$(UUCS)_{age} = B_c\eta_c = B_a\eta_a$$

For a given admixture, there is certain binder efficiency at a given age and with this changed efficiency (w.r.t. control); the binder content can be changed. The % change of binder content with respect to control can then be given by the following formula:

$$\frac{(B_a - B_c)}{B_c} \times 100 = \frac{(\eta_a - \eta_c)}{\eta_a} \times 100$$

It should be noted that this is a quantitative comparison based primarily the assumption that the reduction in the binder contents will not produce any unwanted effects of the fresh behavior and compactibility to the extent that it affects the compressive strength.

Above mentioned analysis is presented in the following discussion. 28d compressive strength is considered the base strength. Figure J-85 shows the potential scope of reduction in the binder content of concrete mixtures due to use of different retarding-/normal-water reducing admixtures. Assuming the finishibility offered by all the admixed mixtures is the similar, the binder content reduction offered by the PC-based and lignosulfonate based water reducers is comparable. Product P-06 is also offers comparable reduction; however, it is effective at lower dosages. Retarding water reducer's offer limited advantage over a relatively narrower dosage range.

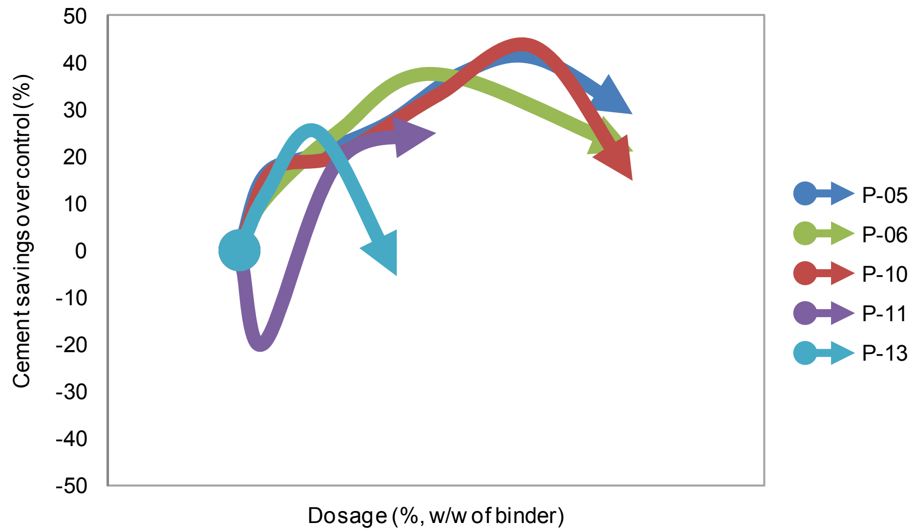


Figure J-85 Potential for binder reduction with the use of different retarding-/normal-water reducing admixtures conforming to ASTM C494 types A, B, D and F.

Similar plots for binder savings could be constructed for AEA's that have shown water reducing and hence strength improving potential. Again, with a less robust system, the synthetic detergent based system offers a potential case of good cement savings. The other AEA's offer a poor to negative savings potential. This is shown in Figure J-86. Other binder contents are shown in one of the appendices.

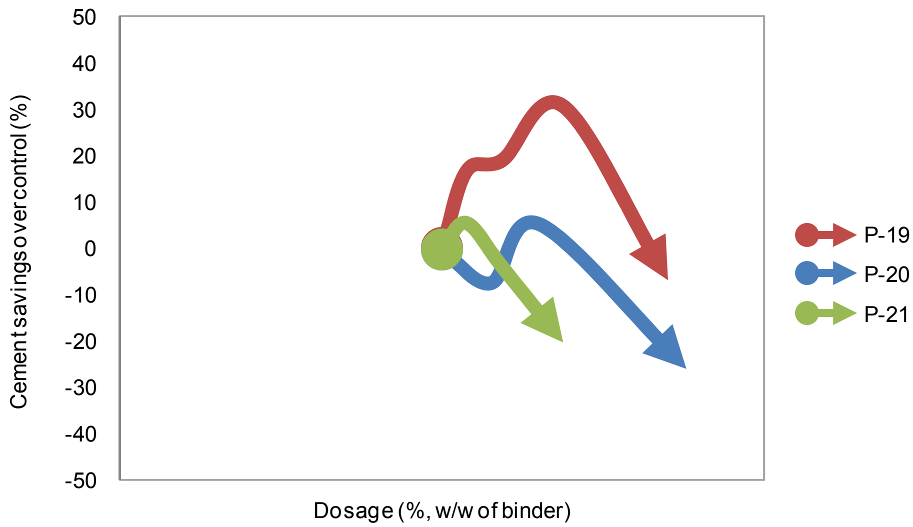


Figure J-86 Binder reduction potential of different AEA's

J.10 Compressive strength: Effects of admixture cocktails

J.10.1 Binary Systems

The primary objective of using duets is to improve the fresh properties of concretes. Strength measurement was not the primary objective of this test program. One admixture having water reducing properties can be combined with another admixture to extract the beneficial effects of the latter one. The combined dosages were selected with the idea that the water reduction for the first would be in the normal water reduction range, while that for the second would be in the high range. In the forthcoming section, three sets of results are presented. The first case discusses the effects of combining a ligno-based water reducer with a SD-based AEA. The second case talks about the combination of surfactant based dry cast product and a retarding-water reducer.

CASE I: LIGNO-BASED WATER REDUCER AND SD BASED AEA

As stated previously, this combination was attempted for the purpose of improving the finishibility of concretes admixed with only ligno-based water reducer. Two dosage levels of the mixed products (0.75 and 2.00%) were selected and the composition was varied. Figure J-87 represents the 28-day compressive strength results.

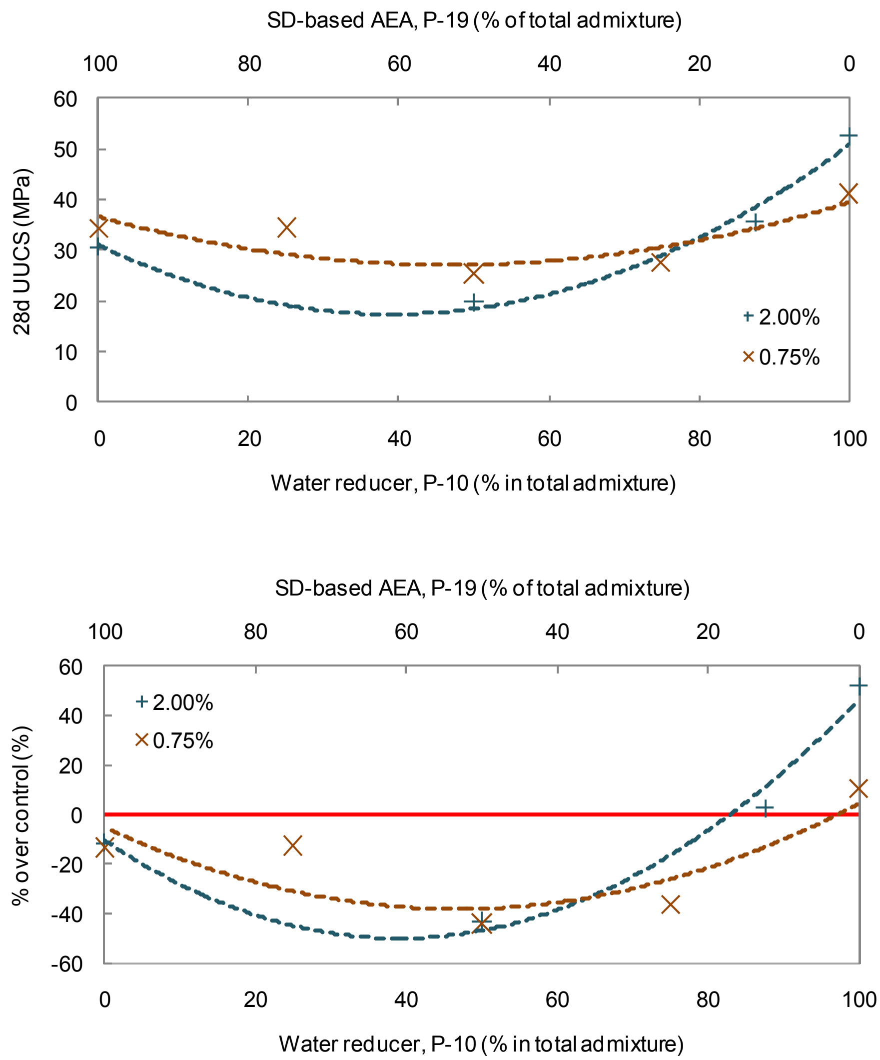


Figure J-87 28d UUCS of the admixture duet: Ligno-based water reducer and SD-based AEA. Total admixture dosage is in percentage, w/w of binder

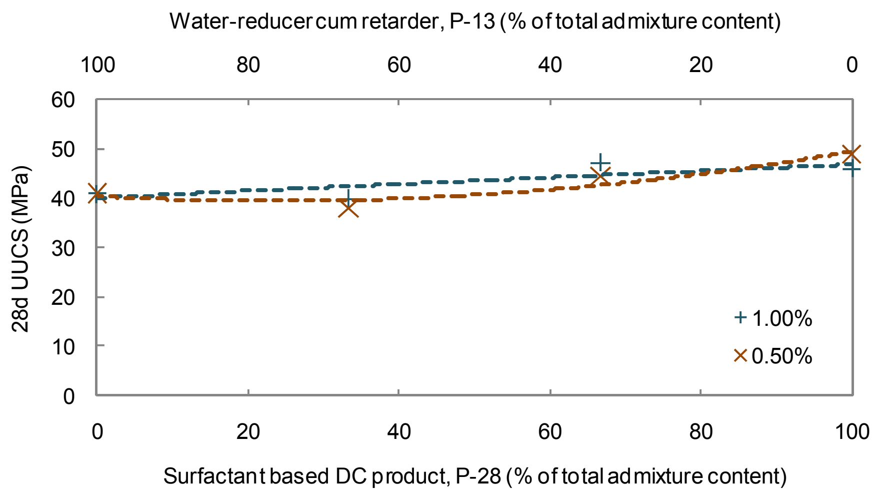
It can be seen that the combined dosage does not make a difference in the 28-day compressive strength. The results show a comparable trend as the composition is varied at two different dosages. Compared with the control mixture, the use of this combination of admixture did not produce any increase and in-fact the strength reduced, except when only water reducer used. The possible reasons of such a manifestation could be the use of a combination of admixtures that have the potential to entrain air. As discussed previously the lingo-based admixtures, although highly refined have a tendency to increase entrained air volume. At lower dosage, the air is entrained only from the AEA. On the other hand, at higher dosages, the air is entrained by both the lingo-based water reducer and the AEA. The effect of increased air entrainment masks the effect of water reduction. The percussions of this could be seen in the fact that the Abrams' law is not followed. This could also mean the increased dispersion is superseded by the increased porosity of the concrete mixture.

Similar results are produced by combining a PC-based product (P-05) and SD-based AEA (P-19); however, the % reduction in strength is smaller. This may be due to the electro-steric dispersion that might have to lead to a more stable and denser system.

CASE II: SURFACTANT BASED DRY CAST PRODUCT AND RETARDING WATER REDUCER

This combination was attempted to improve the compaction time window of concretes dosed with surfactant based dry cast product. Two dosage levels (0.50 and 1.00%) were selected and the composition was varied with a fixed total dosage. Figure J-88 represents the 28-day compressive strength results.

It can be seen that the combined dosage does not make a difference in the 28-day compressive strength. The results show a comparable trend as the composition is varied at two different dosages. Despite using a strongly retarding admixture, there is a sizeable increase in the 28-day strength, however with the increasing dosage of the retarding water reducer the % increases in strength reduces.



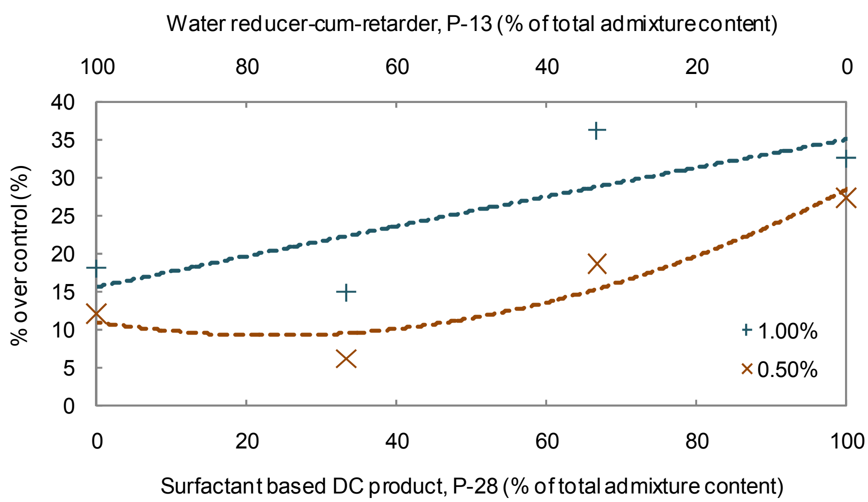


Figure J-88 28d UUCS of the admixture duet: Surfactant based dry cast product and retarding water reducer. Total admixture dosage is in percentage, w/w of binder

The combinations of PC-based water reducer and rheology modifiers did not produce any substantial strength gains over the control. Hence, these results are reported in the appendix.

J.10.2 Ternary Systems: Effect of composition

In this section, a description of strengths for different combinations of triplets is provided. The primary objective of formulating triplets was to improve the fresh properties of RCC. In this section some proofs of concepts of using the concept of method of mixtures is presented. Of the three triplets, the first one is described in detail along with the JMP analysis of the method of mixtures, prediction equations and ternary plots. For the remaining two combinations, only contour plots are presented with brief descriptions. No temporal evolution of strength is presented.

COMBINATION 1: PC-BASED WATER REDUCER-HYDRATION STABILIZER-RHEOLOGY MODIFIER (WR-HS-RM)

This combination is typically recommended for pervious concrete and is used at a fixed combined dosage of 1.5%. The combinations of the admixtures were changed with design of experiment concepts using the mixture modeling as described in the literature review section of the thesis. Table 17-12 offers a summary of the test variables, admixture combinations and the 28d compressive strength.

Table J-12 Triplet combination-1: Compositions and 28d UUCS

Mixture ID		A	B	C	D	E	F	G	H	I	J
WR	(%, w/w)	1.50	0.00	0.00	0.75	0.00	0.75	1.00	0.25	0.25	0.50
HS	(%, w/w)	0.00	1.50	0.00	0.75	0.75	0.00	0.25	1.00	0.25	0.50
RM	(%, w/w)	0.00	0.00	1.50	0.00	0.75	0.75	0.25	0.25	1.00	0.50
WR	(%)	100.00	0.00	0.00	50.00	0.00	50.00	66.67	16.66	16.66	33.33
HS	(%)	0.00	100.00	0.00	50.00	50.00	0.00	16.66	66.67	16.66	33.33
RM	(%)	0.00	0.00	100.00	0.00	50.00	50.00	16.66	16.66	66.67	33.33
28d UUCS		62.77	56.93	40.65	53.95	43.15	45.89	51.96	46.42	44.51	46.55

Figure J-89 represents the contour plot for the mixture of admixtures used. Being PC based, the water reducer produces substantial water reduction leading to higher strength gains. Hydration stabilizer retards the strength a little bit and with its increase in the admixture composition, the strength reduces. The rheology modifier improves the viscosity of the paste a bit potentially leading to increase in the compressive strength, but to the least possible amongst the three admixtures when used alone. When combined together, there are admixture interactions and their individual and combined interactions with the binders those results into different strengths. The strength produced depends on the dominating action in the admixture combinations.

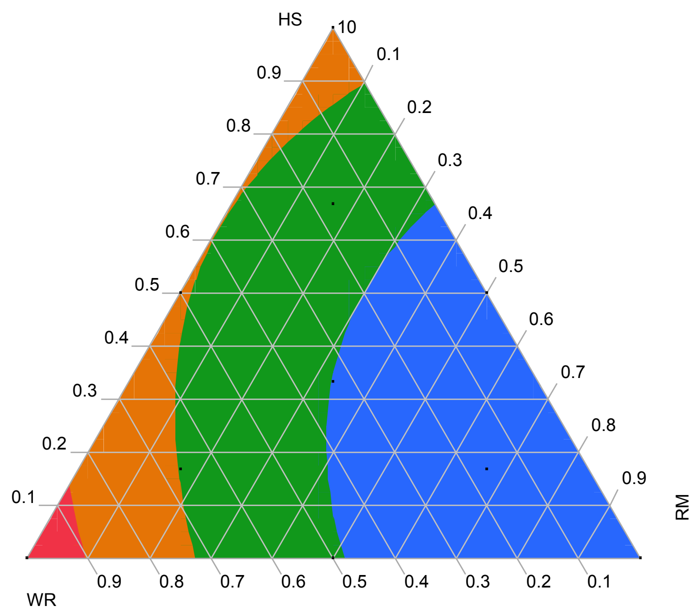


Figure J-89 Strengths of ternary blends of admixtures. Blue (40 MPa), Green (46.25), Orange (52.5), Red (58.75) and Pink (65)

A JMP analysis employing the method of mixtures was conducted and is presented here. Figure J-90 shows the correlation between the actual tested and predicted strengths. The prediction equation (R^2 = 0.96) is as follows:

$$28d\ UUCS = 62.64*WR+56.08*HS+41.49*RM-25.54*WR*HS-21.84*WR*RM-22.56*HS*RM+14.86*WR*HS*RM$$

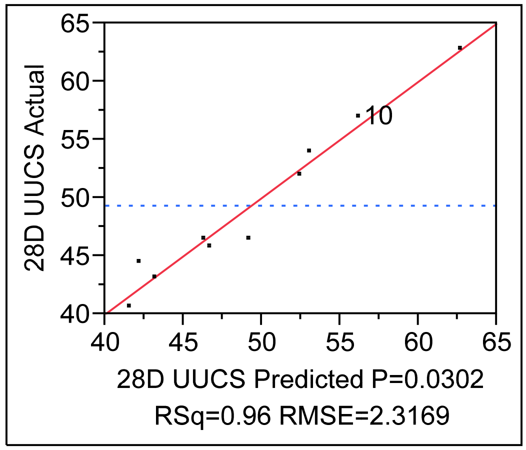


Figure J-90 Actual by predicted 28d UUCS plot of the ternary blend of admixtures: combination 1

The table (refer to Table 17-13) for parameter estimates indicate that the interaction parameter of the three admixtures plays an important role in influencing the compressive strength of concrete mixtures.

Table J-13 Parameter estimates for the model of mixtures for the first ternary blend of admixtures

Term	Estimate	Std Error	t Ratio	Prob>|t|
WR	62.647059	2.239685	27.97	0.0001*
HS	56.084332	2.239685	25.04	0.0001*
RM	41.494786	2.239685	18.53	0.0003*
WR*HS	-25.53722	11.27411	-2.27	0.1084
WR*RM	-21.83631	11.27411	-1.94	0.1482
HS*RM	-22.56176	11.27411	-2.00	0.1392
WR*HS*RM	14.860588	74.32658	0.20	0.8543

Furthermore, a prediction profiler was also constructed for estimating the strength of concrete mixtures. Figure J-91 shows such a plot along with the desirability plot set at 1/3rd of each component of the blend. These plots can also be set at any required strength

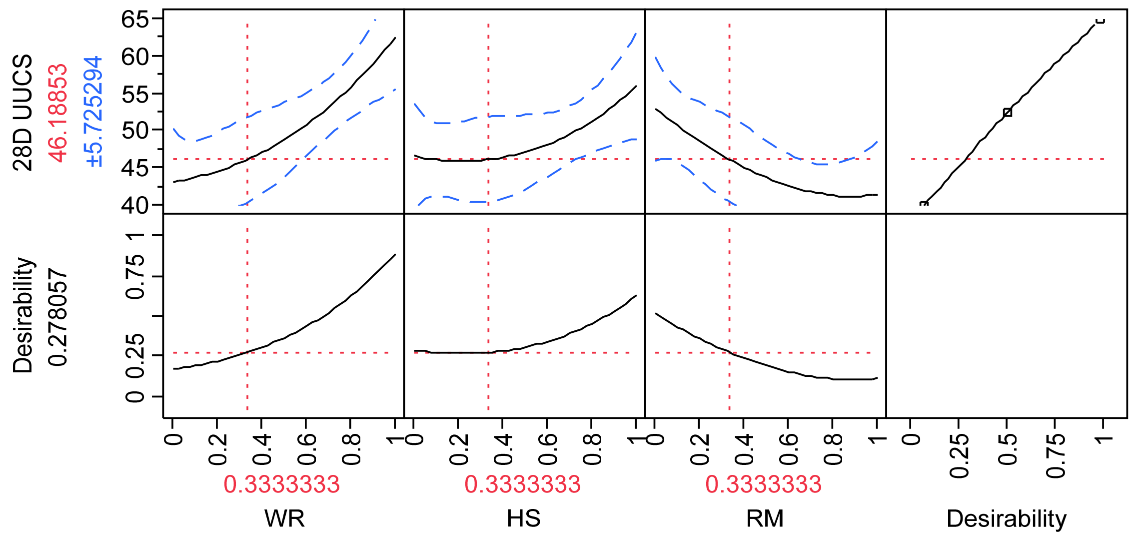


Figure J-91 Prediction and desirability profiler for the first ternary blend of admixtures

Similarly, the % strength increase over the control is plotted using mixture modeling concept and is shown in Figure J-92. It is interesting to observe that the strength increases using combined admixture system results into different trends than those obtained with strength representation. The strength increases range between 20 and 90% over control. Although the PC-based WR reducer produces a substantial increase in the strength, in the areas of combined actions of HS and RM, the strength increase is relatively less and this region occupies a significant portion of the plot. Figure J-93 and 17-94 and Table 17-14 offer the statistical information.

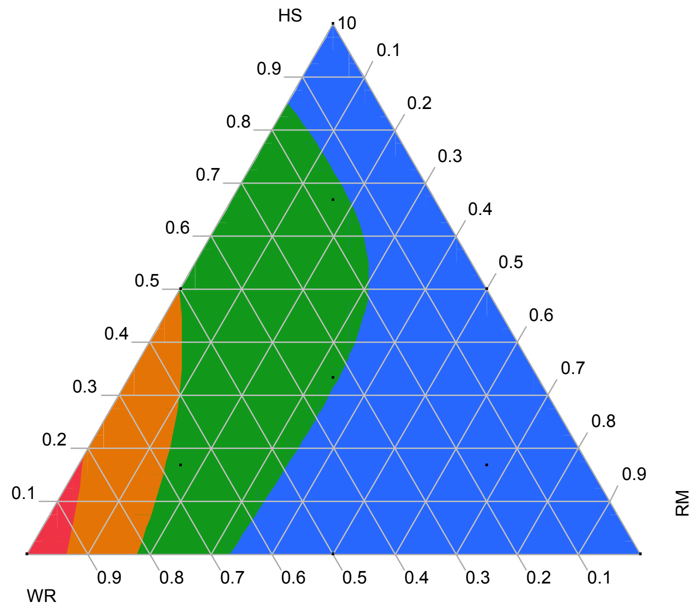


Figure J-92 % strength over control for ternary mixtures of admixtures. Blue (20 %), Green (37.5), Orange (55), Red (72.5) and Pink (90)

The output from JMP for the % strength over control is directly presented here. The prediction equation (R^2 = 0.75) is as follows:

% 28d UUCS over control = 83.66*WR+30.88*HS+33.80*RM-10.04*WR*HS-134.12*WR*RM+14.18*HS*RM+76.43*WR*HS*RM

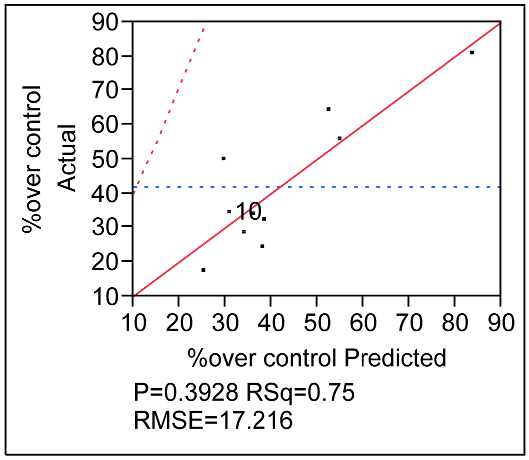


Figure J-93 Actual by predicted % over control plot of the ternary blend of admixtures: combination 1

Table J-14 Parameter estimates for strength over control for ternary blend: combination 1

Term	Estimate	Std Error	t Ratio	Prob>|t|
WR	83.65659	16.64265	5.03	0.0152*
HS	30.888966	16.64265	1.86	0.1605
RM	33.805859	16.64265	2.03	0.1352
WR*HS	-10.03754	83.77561	-0.12	0.9122
WR*RM	-134.1194	83.77561	-1.60	0.2077
HS*RM	14.182049	83.77561	0.17	0.8763
WR*HS*RM	76.426751	552.3057	0.14	0.8987

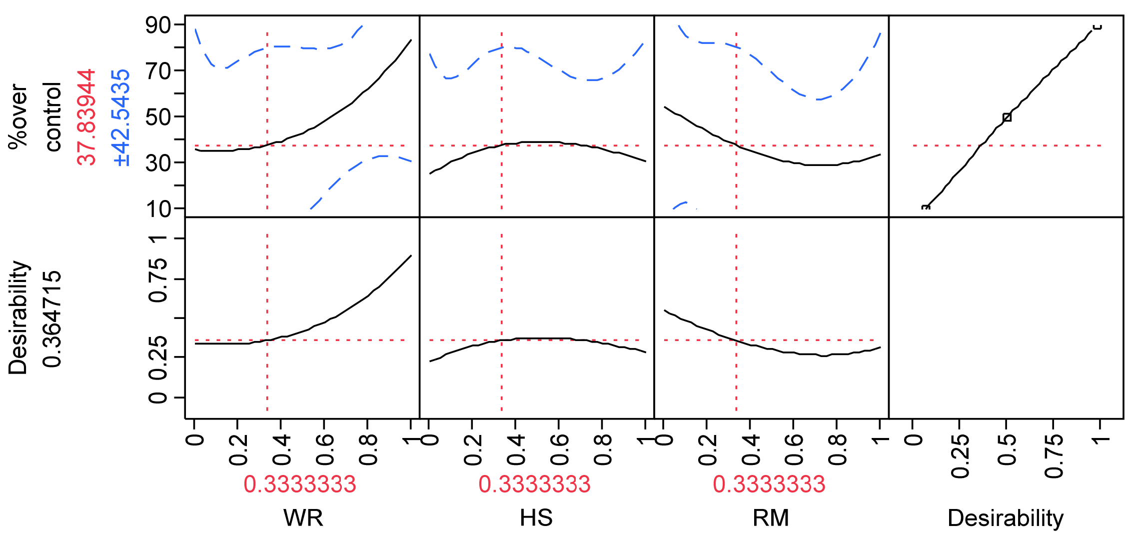


Figure J-94 Prediction and desirability profiler for % over control for ternary admixture blend-1

Similarly, binder efficiency is plotted on the ternary plot (refer to Figure J-95), which comes out to be quite similar to previous analysis with an only exception that there is a region close to the rheology modifier that die to a software discrepancy comes out to be white.

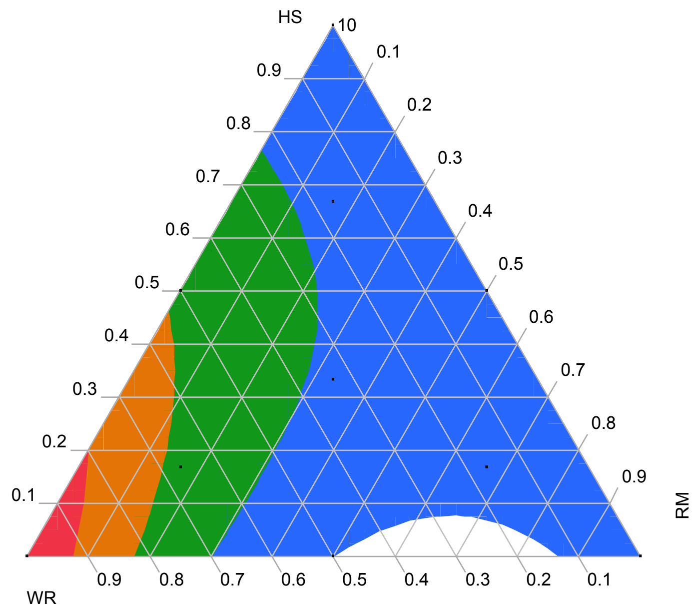


Figure J-95 Binder efficiency of ternary mixed admixtures. . Blue (15 MPa/kg/m^3), Green (16.75), Orange (18.5), Red (20.25) and Pink (22)

Figure J-96 shows the prediction and desirability profiles

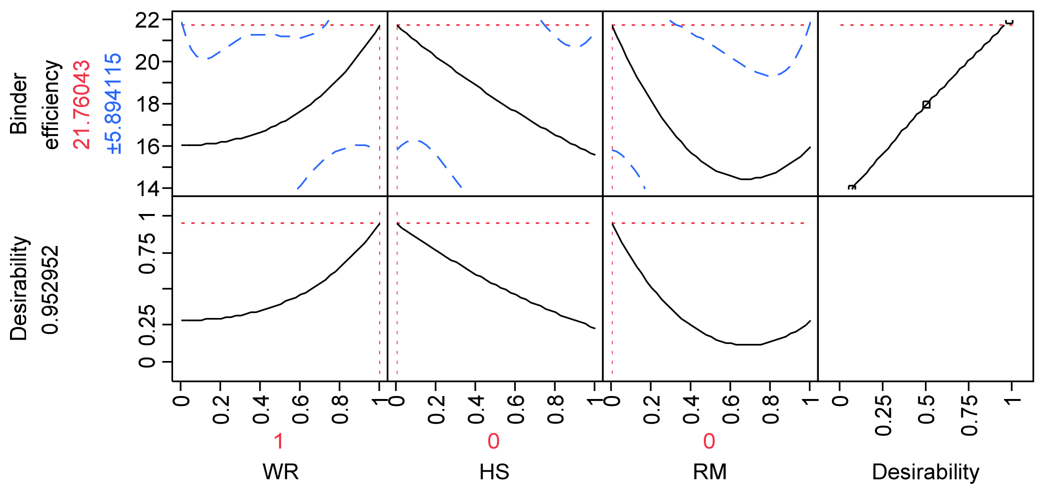


Figure J-96 Prediction and desirability profiler for 28d UUCS binder efficiency for ternary admixture blend-1

COMBINATION 2: LIGNO-BASED WATER REDUCER (P-10)-SD BASED AEA (P-19)-STARCH BASED RHEOLOGY MODIFIER (P-24)

This combination was tried with an objective of reducing the cost, improving the finishibility and rheology of fresh concrete. Table 17-15 offers a summary of admixture combinations and 28d UUCS.

Table J-15 Triplet combination-2: Compositions and 28d UUCS

Mixture ID		A	B	C	D	E	F	G	H	I	J
WR	(%, w/w)	1.50	0.00	0.00	0.75	0.00	0.75	1.00	0.25	0.25	0.50
AEA	(%, w/w)	0.00	1.50	0.00	0.75	0.75	0.00	0.25	1.00	0.25	0.50
RM	(%, w/w)	0.00	0.00	1.50	0.00	0.75	0.75	0.25	0.25	1.00	0.50
WR	(%)	100.00	0.00	0.00	50.00	0.00	50.00	66.67	16.66	16.66	33.33
AEA	(%)	0.00	100.00	0.00	50.00	50.00	0.00	16.66	66.67	16.66	33.33
RM	(%)	0.00	0.00	100.00	0.00	50.00	50.00	16.66	16.66	66.67	33.33
28d UUCS		47.46	16.60	37.57	26.60	32.02	36.63	35.48	19.35	32.84	33.99

In general, this composition did not produce any substantial strength gains except for those obtained by the water reducer alone. The presence of AEA reduces the strength substantially and potential possibility of chemical incompatibilities within the admixture triplets cannot be denied. Figures 17-97 through 17-100 represent the experimental data in different forms.

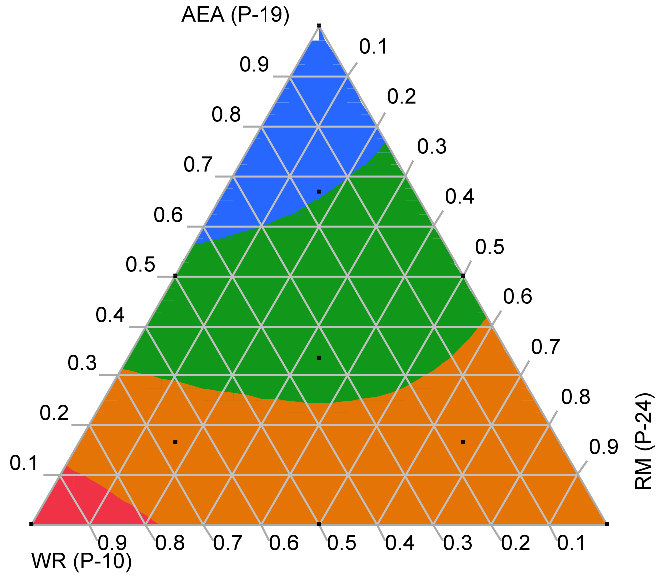


Figure J-97 Strengths of ternary blends of admixtures. Blue (15 MPa), Green (23.75), Orange (32.5), Red (41.25) and Pink (50)

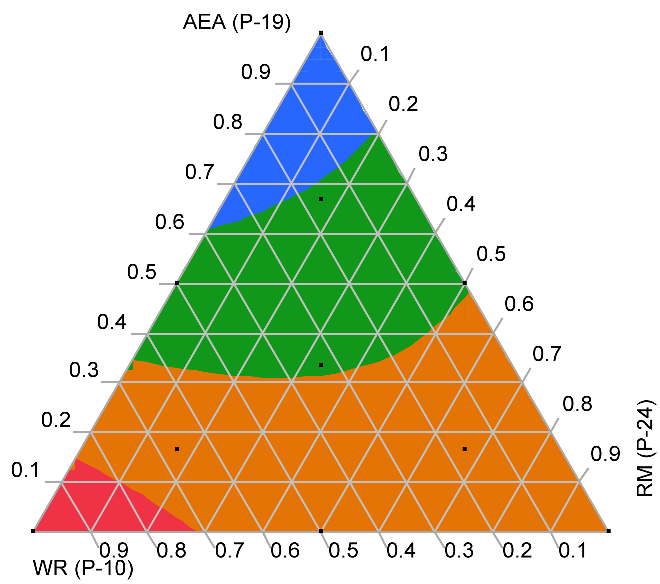


Figure J-98 % strength over control for ternary mixtures of admixtures. Blue (-60 %), Green (-35), Orange (-10), Red (15) and Pink (40)

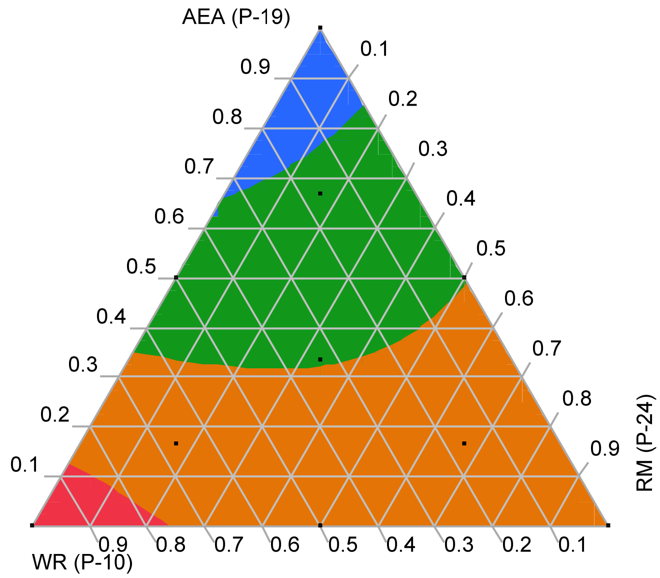


Figure J-99 Binder efficiency of ternary mixed admixtures. . Blue (4 MPa/kg/m3), Green (7.5), Orange (11), Red (14.5) and Pink (18)

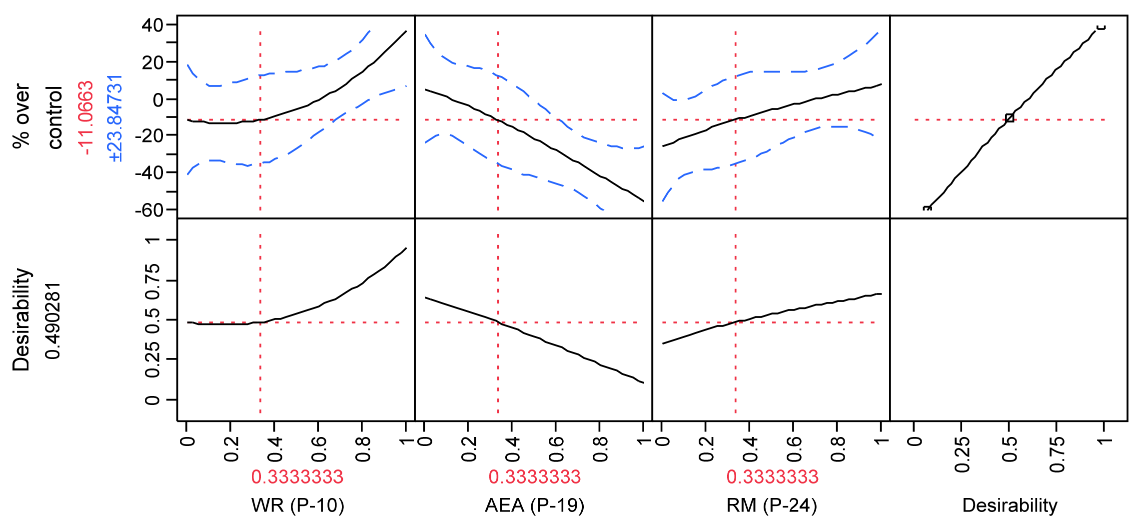


Figure J-100 Prediction and desirability profiler for % over control for ternary admixture blend-2

COMBINATION 3: LIGNO-BASED WATER REDUCER-AEA-RHEOLOGY MODIFIER

This combination was tried with an objective of reducing the cost, improving the finishibility and rheology of fresh concrete. Table 17-16 offers a summary of admixture combinations and 28d UUCS.

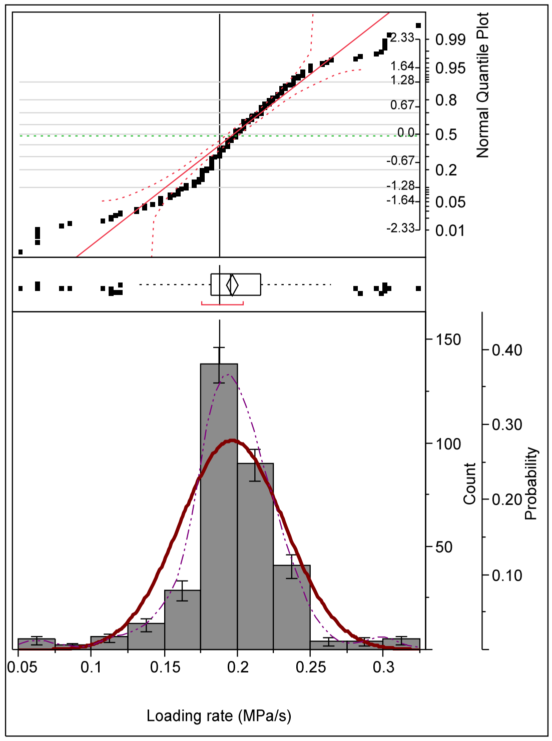
Table J-16 Triplet combination-3: Compositions and 28d UUCS

Mixture ID	A	B	C	D	E	F	G	H	I	J
WR (%, w/w)	1.50	0.00	0.00	0.75	0.00	0.75	1.00	0.25	0.25	0.50
AEA (%, w/w)	0.00	1.50	0.00	0.75	0.75	0.00	0.25	1.00	0.25	0.50
RM (%, w/w)	0.00	0.00	1.50	0.00	0.75	0.75	0.25	0.25	1.00	0.50
WR (%)	100.00	0.00	0.00	50.00	0.00	50.00	66.67	16.66	16.66	33.33
AEA (%)	0.00	100.00	0.00	50.00	50.00	0.00	16.66	66.67	16.66	33.33
RM (%)	0.00	0.00	100.00	0.00	50.00	50.00	16.66	16.66	66.67	33.33
28d UUCS	47.46	16.60	25.72	26.60	33.11	26.64	28.32	19.97	28.51	29.07

In general, this composition did not produce any substantial strength gains except for those obtained by the water reducer alone. The presence of AEA reduces the strength substantially and potential possibility of chemical incompatibilities within the admixture triplets cannot be denied. Since this combination produced similar results to ternary blend-2, no further analysis is reported here.

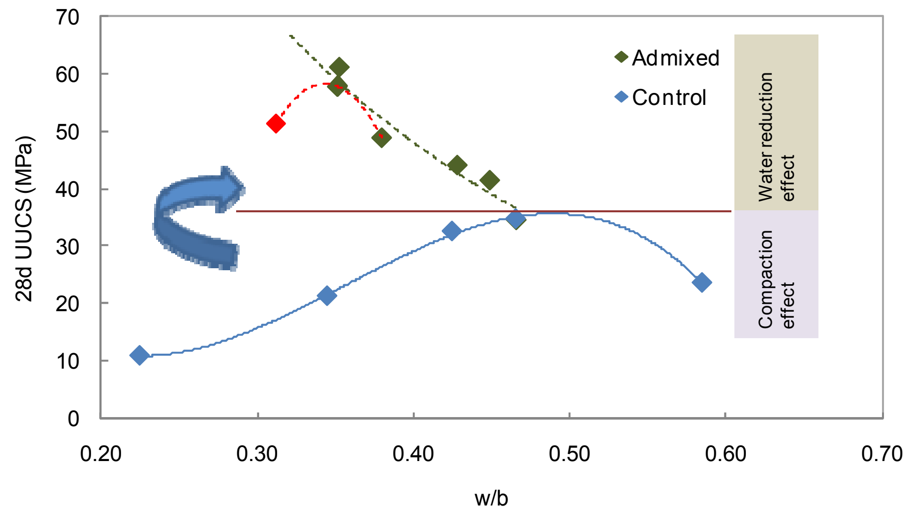
SUMMARY

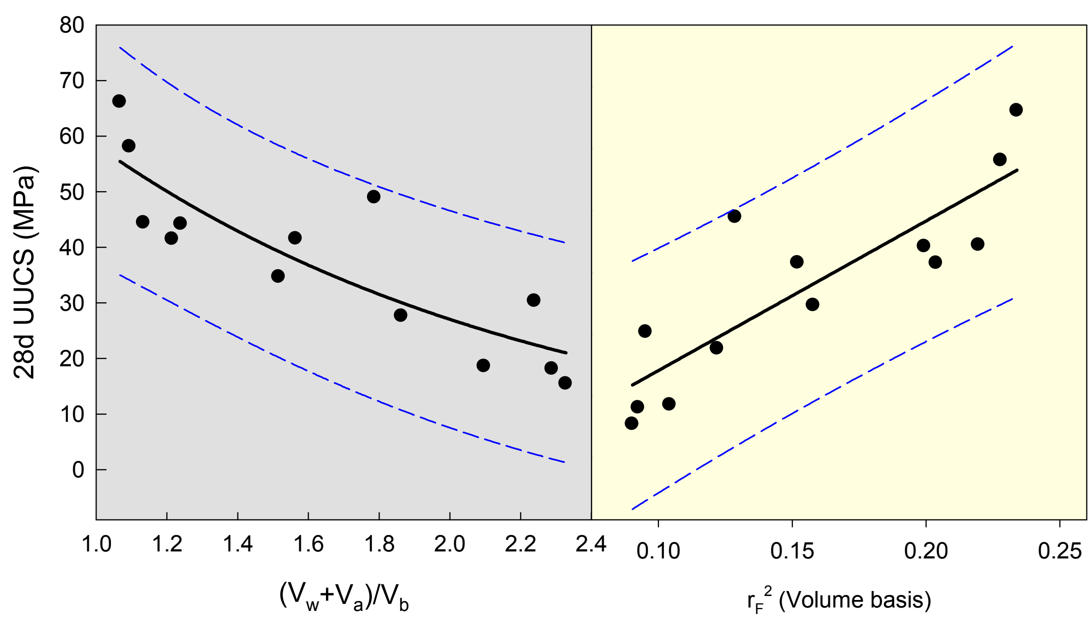
This chapter described the evolution of strength in different concrete mixtures including the control mixtures. Statistical analysis of the test methods indicated that there was a good control over testing. This analysis will also help in estimating the possible range and variability these results would produce. Maintaining the ASTM prescribed loading rate for early ages and for concretes with higher strengths was a bit challenging and hence the distribution so obtained is skewed to the right.



Strength was analyzed from various perspectives, including paste quality, quantity, the volumetric composition of concrete and age. Various new indices were developed and used in characterizing the strength development. An interesting outcome of this work was checking of validity of Abrams' law and tracing possible reasons for the deviant behavior in RCC mixtures.

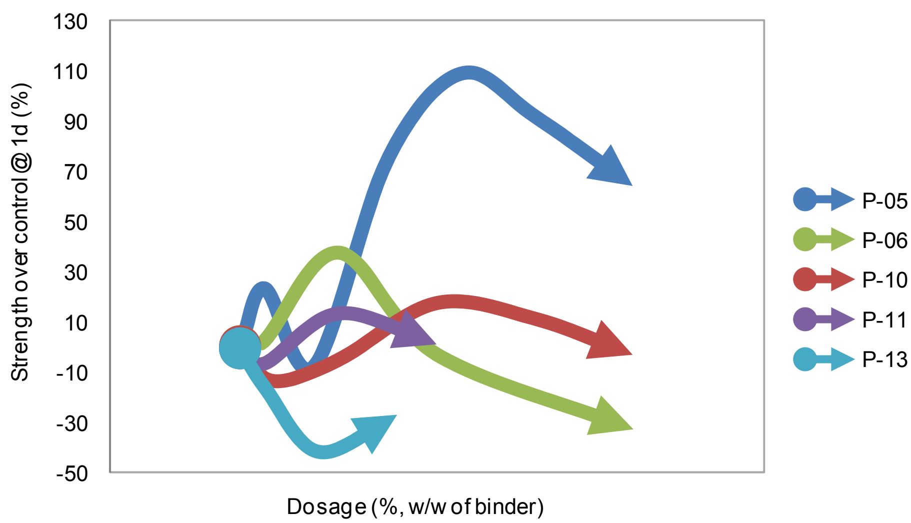
Comparisons were made between various water reducing and retarding admixtures and relationships and comparative statements were offered. The PC based water reducers were found to be most effective over a wider range than the other admixtures. Ligno-based admixtures followed closely, although their early age strength development was relatively poorer. The blends of ligno-PC showed intermediate performances.





Mixtures entrained with air followed different trends and had to be analyzed while taking into account the air content in the water/binder ratio. The strength RCC, in fact increased with some air entraining admixtures. There is a competing tendency between the air entrainment and water reduction by an AEA and the superior of these two manifestations leads to more pronounced effect respectively.

The results for dry cast and other products were also presented. The results indicate that the rheology modifiers have no significant effects on the strength evolution of different mixtures. Finally composite diagrams to illustrate the relative performances of different admixtures were developed. These diagrams will help choose the right admixture depending on the intended strength goal for a particular site.



Binary and ternary combinations of admixtures were tested primarily to improve the fresh properties of concrete. Some of those showed improvements in the strengths of mixtures as well. Ternary plots were evolved in order to offer proof of concepts used for this work.

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APPENDIX K GREEK ALPHABET IN ROMAN AND ITALIC TYPE

Reference: Thompson, A. and B. Taylor, N., *Guide for the use of the international system of units (SI)*. 2008, Gaithersburg, MD, USA: NIST, U.S. Department of Commerce.

Name	Capital Roman	Lower Case Roman	*Capital Italic*	*Lower Case Italic*
alpha	Α	α	*Α*	*α*
beta	Β	β	*Β*	*β*
gamma	Γ	γ	*Γ*	*γ*
delta	Δ	δ	*Δ*	*δ*
epsilon	Ε	ϵ, ε	*Ε*	*ϵ, ε*
zeta	Ζ	ζ	*Ζ*	*ζ*
eta	Η	η	*Η*	*η*
theta	Θ, Θ[a]	θ, ϑ[b]	*Θ, Θ*[a]	*θ, ϑ*[b]
iota	Ι	ι	*Ι*	*ι*
kappa	Κ	κ, ϰ[b]	*Κ*	*κ, ϰ*[b]
lambda	Λ	λ	*Λ*	*λ*
mu	Μ	μ	*Μ*	*μ*
nu	Ν	ν	*Ν*	*ν*
xi	Ξ	ξ	*Ξ*	*ξ*
omicron	Ο	ο	*Ο*	*ο*
pi	Π	π, ϖ	*Π*	*π, ϖ*
rho	Ρ	ρ, ϱ[b]	*Ρ*	*ρ, ϱ*[b]
sigma	Σ	σ	*Σ*	*σ*
tau	Τ	τ	*Τ*	*τ*
upsilon	Υ	υ	*Υ*	*υ*
phi	Φ	φ, ϕ	*Φ*	*φ, ϕ*
chi	Χ	χ	*Χ*	*χ*
psi	Ψ	ψ	*Ψ*	*ψ*
omega	Ω	ω	*Ω*	*ω*

APPENDIX L UNIT CONVERSION FACTORS

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)