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Optimizing concrete mixtures with minimum cement content for performance and sustainability

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Optimizing concrete mixtures with minimum cement content for performance and sustainability

by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The main purpose of this research is to investigate the minimum cement content required with an appropriate water-to-cement ratio (w/c) to meet given workability, strength, and durability requirements in a concrete pavement; and to reduce carbon dioxide emissions, energy consumption, and costs.

An experimental program was conducted to test 16 concrete mixtures with w/c ranging between 0.35, 0.40, 0.45 and 0.50; and cement content ranging from 400, 500, 600 and 700 lb/yd^3 (pcy). The fine aggregate-to-total aggregate ratio was fixed as 0.42 and the void content of combined aggregates was maintained the same for all the mixtures. Slump; setting time; 1, 3 and 28-day compressive strength; 28-day chloride penetration; and 1, 3, and 28-day air permeability were determined.

The test results showed that strength is a function of w/c and independent of cement content after the required cement content is reached, for a given w/c. Workability is a function of w/c and cement content: increasing w/c or cement content improves workability. Setting time is reduced when cement content is increased for a given w/c. Chloride penetration increases as w/c or cement content increases, when one parameter is fixed. Air permeability increases as cement content increases, for a given w/c.

Based on these findings, it is possible to reduce the paste content without sacrificing the desired workability, strength and durability, for a given w/c. When the overall effect of cement content on concrete properties is evaluated, 400 pcy of cement content is not recommended due to its high porosity caused by its low paste content. Furthermore, 700 pcy would also not be appropriate as increasing cement content does not improve the strength, after the required content is reached; and may decrease durability as high cement content both increases air permeability and chloride penetration. Moreover, for a w/c higher than 0.35, cement content of more than 500 pcy adversely affects the concrete performance by decreasing strength (increasing cement content from 500 pcy to 700 pcy approximately reduced the 28-day compressive strength by 15%) and may cause shrinkage related cracking problems.

Therefore, for a given w/c and for the aggregate system used in this study, the range of 500 pcy to 600 pcy is found to be the most appropriate cement content range that provides

the desired workability, strength, chloride penetration and air permeability. Mixtures with 500 pcy of cement content did not have a high workability (ranging from 0 in. to 3 in. depending on the w/c), but it may be improved by the addition of supplementary cementitious materials, water-reducing agents, or using a different aggregate gradation system.

The given cement content range was compared with the values obtained in accordance with the ACI 211 Report (2002): considering the high cement content range of 650 pcy to 930 pcy provided by the ACI 211 Report (2002) for the same given conditions, the recommended cement content range of 500 pcy to 600 pcy will have more significant impact and benefits on the concrete construction industry regarding the reduction of cement content.

In addition, to make the findings independent of the selected aggregate system, the relationship between paste volume and concrete properties is established. In order to meet the desired workability, strength and durability requirements; the paste volume should be within the range of 160% to 170% of the volume of voids. Exceeding this range will adversely affect the concrete performance by decreasing strength, and increasing chloride penetration and air permeability.

CHAPTER 1. INTRODUCTION

Cement, the main component of concrete, is one of the most important materials for all kinds of construction. Cement content is perceived to control concrete strength. Based on this perception, a minimum cement content is often specified that may exceed the amount needed to achieve the desired strength and durability. This excessive amount should be minimized to prevent its negative impact on costs and environment because:

- cement is the most expensive component in concrete
- cement contributes about 90% of the CO_2 burden of a concrete mixture
- cement production emits approximately 5% of global carbon dioxide (CO_2) and 5% of global energy consumption

Previous studies (Wasserman et al. 2009; Popovics 1990) suggest that a high cement content in a mixture does not contribute to greater strength than the required design strength. In addition, the high cement content will cause the concrete to become sticky as well as have shrinkage and cracking problems. Therefore, cement content should be balanced to achieve performance while minimizing risk of these problems. Despite the published studies and documentation, there continues to be a misconception that more cement in a mix design means a better performing mix.

This thesis study investigates how much cement content and paste volume is needed to achieve desired strength, durability and workability requirements in a concrete mixture through laboratory testing. The American Concrete Institute (ACI) 211 Report (2002) was used as a reference to determine the applicability and significance of the suggested cement content.

INDUSTRY PROBLEM

The annual growth rate of cement production is 4% due to rapidly increasing construction in developing countries (World Business Council for Sustainable Development 2005). Since using excessive cement content in concrete further increases this demand, the concrete industry aims to identify and use the most appropriate cement content for a given application.

Industry Concerns

Carbon Dioxide Emission

Approximately 80% of greenhouse gas emissions associated with concrete are released during the portland cement manufacturing process (Flower and Sanjayan 2007). In addition, cement is the third largest source of greenhouse gas pollution in the U.S. according to the U.S. Environmental Protection Agency (2004). Therefore, there is a demand on the industry to reduce its carbon footprint by the environmental agencies.

Energy Consumption

The energy consumption of the cement industry is estimated at about 5% of the total global industrial energy consumption (Hendriks et al. 2004). Cement content reduction is necessary if the environmental load due to the energy consumption is to be reduced.

Impact of Cement Content on Construction Industry

Cost

The low-bid contractual system used in most infrastructure construction demands that the cost of a concrete mixture be minimum. The cement used in concrete is the most expensive component in concrete. Therefore, using cement more efficiently will be beneficial in reducing project costs.

Sustainability

Considering the direct relation between the amounts of cement clinker produced and the CO_2 generated, the construction industry aims to reduce its carbon footprint by several techniques, including reducing the amount of cement in a mixture.

TECHNICAL PROBLEM

Any concrete pavement owner is inherently concerned with durability and performance issues. A high cement content can negatively impact performance and durability by increasing shrinkage, and the consequent risk of cracking. Although, workability is increased by increasing cement content, it causes higher internal temperatures in the concrete during the finishing and curing processes. In addition, increased cement content will increase the unit weight thereby increasing the curling and warping in the slabs. To prevent these problems, appropriate cement content should be used.

RESEARCH GOAL AND OBJECTIVE

The goal of this experimental project is to help the concrete industry use less cement with an appropriate water-to-cement ratio (w/c) to meet given workability, strength, and durability requirements; and so as to reduce carbon dioxide emissions, energy consumption, and costs.

The hypothesis that guided this study is, when other parameters are kept constant, after a required cement content is reached, concrete properties such as strength, chloride penetration, and air permeability will not be affected by adding additional cement. Figure 1 illustrates this hypothesis.

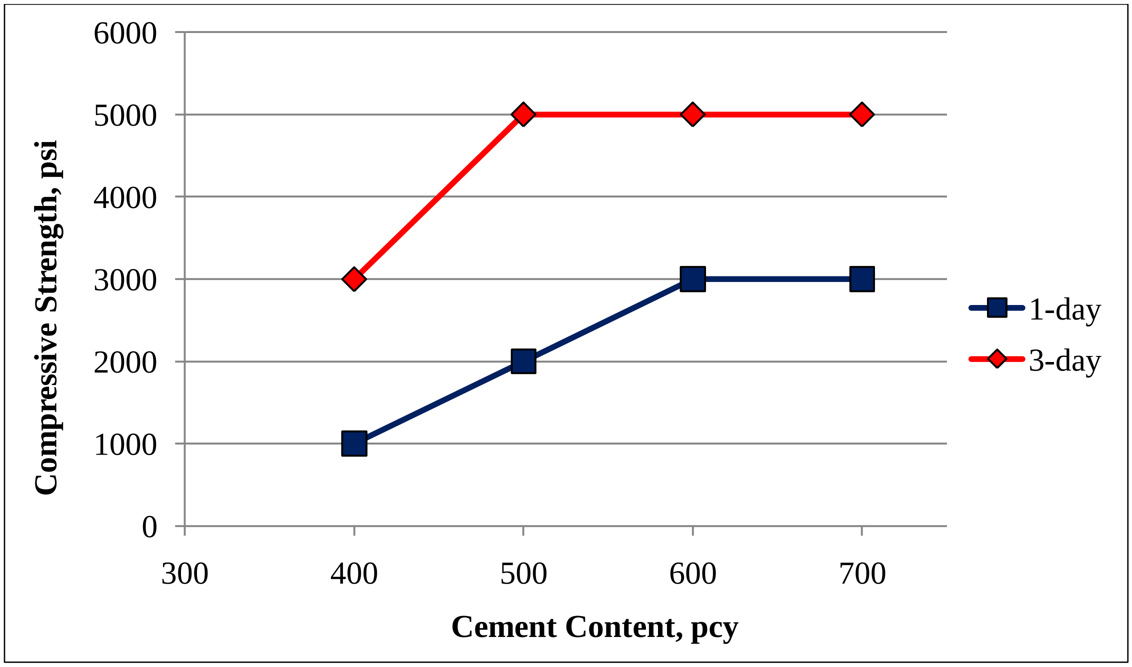


Figure 1. Effect of cement content on concrete compressive strength

The scope of this study is to investigate workability, air permeability, chloride penetration, and strength as indicators of performance of 16 concrete mixtures with 4 w/c and 4 cement contents. Setting time and air content are also tested to analyze the effect of cement content on overall concrete behavior.

SIGNIFICANCE OF THE RESEARCH

The findings of this research will indicate ways to use cement more efficiently by showing that strength is largely independent of cement content after a required cement content is reached, for a given w/c. These findings will have an impact on the concrete industry because minimizing the cement content in concrete will not only reduce costs but also may lead to more sustainable methods of concrete construction.

ORGANIZATION OF THE DOCUMENT

Following this introduction chapter, this thesis is organized into five chapters, namely literature review; materials and methods; results and discussion; conclusions; and recommendations.

CHAPTER 2: LITERATURE REVIEW

This chapter presents a review of literature focusing on five major areas:

- workability
- strength
- durability
- shrinkage
- sustainability

The literature is discussed about how each concrete property is affected by mixture composition. The five mixture characteristics covered include:

- cement content
- water-to-cement ratio (w/c)
- aggregates
- chemical admixtures
- supplementary cementitious materials

Although this research did not directly assess the effects of chemical admixtures and supplementary cementitious materials on concrete, it is important to consider their effects on fresh and hardened concrete properties to establish the context for the project. The term w/c was used instead of the water-to-binder ratio (w/b) throughout this report because no supplementary cementitious materials were used in this study.

A section on sustainability is also provided because the purpose of this study is to investigate methods for using cement more efficiently.

Concrete durability is commonly specified by defining minimum cement content, minimum strength, and maximum free w/c (Arachchige 2008). The w/c is the main factor affecting concrete strength where lower w/c provides higher strength. However, it is also perceived that concrete strength is controlled by the cement content. Based on this perception, a common specified design parameter is the minimum cement content which may exceed the amount required for the desired strength and durability.

Integrated Materials and Construction Practices for Concrete Pavement Manual (IMCP 2006) defines mix design as "the process of determining required and specifiable properties of a concrete mixture".

Information in the literature regarding the effect of mixture design decisions will be discussed in the following sections.

WORKABILITY

American Concrete Institute (ACI) 116R defines workability as "that property of freshly mixed concrete or mortar that determines the ease and homogeneity with which it can be mixed, placed, compacted and finished to a homogenous condition".

Workability can be identified by three main parameters (Kosmatka et al. 2002; Chen and Duan 2000):

- cohesiveness: the resistance to segregation,
- consistency: the ease of flow, and
- plasticity: the ease of molding.

Workability is commonly assessed by engineers using the slump test (ASTM C143). A number of factors can influence the workability of a mixture:

- Water content: For a given cement content, increasing water will make the mixture more fluid (IMCP 2006; Kosmatka et al. 2002; Ferraris and Gaidis 1992).
- Cement content: For a given water content, decreasing cement content will produce stiff mixtures with low workability. Concrete with high cement content shows high cohesiveness but becomes sticky (Lamond and Pielert 2006; Kosmatka et al. 2002; Mehta and Monteiro 1993).
- Water-to-cement ratio (w/c): Increasing w/c will increase workability (Kosmatka et al. 2002; Mindess et al. 2003).
- Gradation, shape, and surface texture of aggregates: Well-graded aggregates will increase workability. Increasing fine aggregate content increases workability but an excessive amount can cause mixtures to become sticky. Spherical, smooth surfaced aggregates will increase workability whereas angular, rough surfaced aggregates will decrease workability (IMCP 2006; Mindess et al. 2003; Mehta and Monteiro 1993).

- Admixture type and dosage: Water reducing agents are deliberately added to increase workability (IMCP 2006; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993). The effects of other admixtures on workability are complex and beyond the scope of this study.
- Supplementary cementitious materials: Increasing the supplementary cementitious materials content will generally increase workability (IMCP 2006; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993; Ferraris and Gaidis 1992).
- Type of cement: Increasing the cement fineness will decrease workability for a given w/c because finer cement will have a higher water requirement due to its increased specific surface area (IMCP 2006; Mindess et al. 2003).
- Entrained air: Increasing the entrained air will increase workability (IMCP 2006; Kosmatka et al. 2002).
- Duration of the mixing process: Increasing the mixing duration will decrease workability (IMCP 2006; Kosmatka et al. 2002).
- Ambient air temperature: Higher temperatures increase the rate of hydration which decreases workability (IMCP 2006; Kosmatka et al. 2002).

Although workability is typically quantified by the slump tests, these tests are of limited value because they do not fully characterize concrete flow (Ferraris and Gaidis 1992). For mixtures with different proportions, slump tests should not be used for comparison, but they indicate uniformity for similar mixtures (Kosmatka et al. 2002). However, mixtures with same slump value may not behave the same way during placement (Ferraris and Gaidis 1992).

Water Content

Water content is the most important factor for workability and increasing the water content in concrete will increase workability (Mindess et al. 2003). However, excessive water content should be avoided to prevent segregation and bleeding (IMCP 2006; Mindess et al. 2003; Mehta and Monteiro 1993).

For a given cement content, increasing water content will also increase w/c and that increased w/c will increase workability (Kosmatka et al. 2002).

Cement Content

Workability is affected by paste volume, because the paste lubricates the aggregates (Ferraris and Gaidis 1992; Dhir et al. 2004).

For a given water content, decreasing the cement content increases stiffness of concrete with having poor workability (Lamond and Pielert 2006; Mehta and Monteiro 1993). Concrete with high cement content shows high cohesiveness and becomes sticky (Lamond and Pielert 2006; Kosmatka et al. 2002; Mehta and Monteiro 1993). To prevent an adverse effect, appropriate cement content should be used to achieve the desired workability.

Aggregates

Aggregates constitute 60 % to 75 % of the total volume of concrete; therefore their selection is very important in the mix design process.

Gradation, shape, porosity, and surface texture of aggregates affect the workability of concrete (Kosmatka et al. 2002).

Aggregates should be well-graded to achieve the desired workability because fine aggregates have a high water requirement due to their high specific surface area and inadequate amount of fine aggregate causes mixtures to become stiff and segregate (IMCP 2006; Mindess et al. 2003; Shilstone 2002; Mehta and Monteiro 1993).

Aggregate shape and texture affect workability through their effect on cement paste requirements. Spherical, well rounded with smooth surfaced aggregates increase workability whereas angular, elongated, rough surfaced aggregates decrease workability and cause segregation (Mindess et al. 2003).

Chemical Admixtures

ASTM C125 (2003) defines an admixture as “a material other than water, aggregates, hydraulic cement and fibers that is used as an ingredient of concrete or mortar, and is added to the batch immediately before or during its mixing”.

There are different types of chemical admixtures but this thesis will only focus on the water-reducing agent because other admixtures are beyond the scope of this study.

Water-reducing agents make water available in concrete by neutralizing the surface charge of cement particles which causes flocculation and blocks water particles in those agglomerates as presented in Figure 2 (Mindess et al. 2003). Therefore, for a given water content, the addition of a water-reducing admixture will increase workability (IMCP 2006; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993).

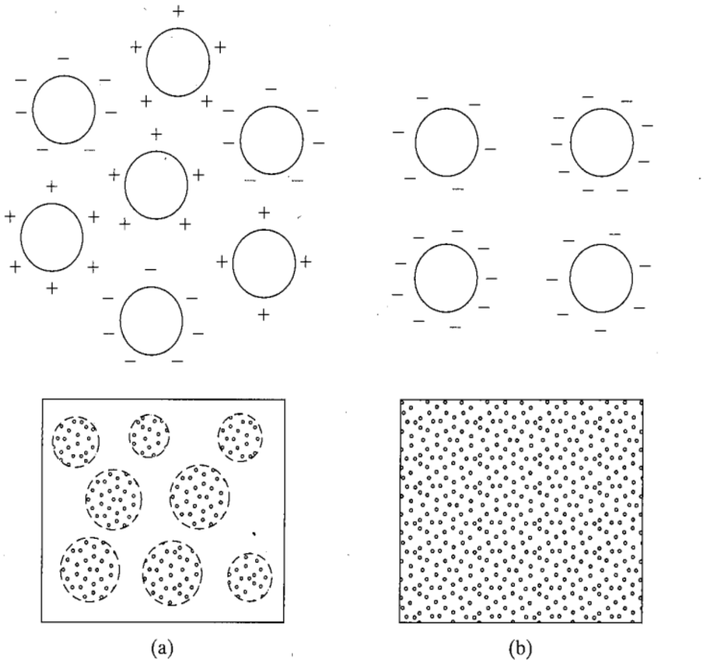


Figure 2. Dispersing action of water-reducing agents a) flocculated paste; b) dispersed paste (Source: Mindess et al. 2003)

Supplementary Cementitious Materials

Supplementary cementitious materials, especially fly ash, slag, calcined clay, metakaolin and shale generally improve the workability of concrete because their fine spherical morphology reduce interparticle friction (IMCP 2006; Mindess et al. 2003; Kosmatka et al. 2002; Wong et al. 2001; Collins and Sanjayan 1999; Lange 1997; Mehta and Monteiro 1993). However, silica fume increases the water requirement and stickiness of a concrete mixture because of its high surface area (IMCP 2006; Obla et al. 2003; Kosmatka et al. 2002; Ferraris et al. 2001; Chengzhi et al. 1996).

STRENGTH

Kosmatka et al. (2002) define strength as “the measured maximum resistance of a concrete specimen to axial loading”.

Although other parameters such as durability and shrinkage may be more critical to assess concrete quality, strength is still commonly used for this purpose, particularly in structural applications (IMCP 2006 p. 116).

Strength is affected by the following factors:

- Water-to-cement ratio (w/c): Increasing w/c will decrease strength (IMCP 2006; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993).
- Degree of hydration: Increasing the degree of hydration will increase strength (IMCP 2006; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993).
- Age: Strength increases as concrete age increases, initially rapidly and slowing over time (IMCP 2006; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993).
- Supplementary cementitious materials: Increasing the supplementary cementitious materials content will change strength (IMCP 2006; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993).
- Entrained air: Increasing the entrained air will decrease strength (IMCP 2006; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993).
- Admixture type and dosage: Water-reducing agents may have an indirect influence on strength (Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993). The effects of other admixtures on strength are beyond the scope of this study.
- Aggregates: Rough and angular aggregates will increase strength (IMCP 2006; Mindess et al. 2003; Mehta and Monteiro 1993).
- Type of cement: Increasing the cement fineness will increase the early strength (Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993).
- Cement content: For a given w/c, strength is reportedly independent of cement content (Wassermann et al. 2009; Dhir et al. 2004; Schulze 1999).

Cement Content

Strength is considered to be a function of w/c and independent of cement content for a given w/c, therefore increasing cement content does not affect strength (Wassermann et al. 2009; Dhir et al. 2004; Schulze 1999). Furthermore, according to Abrams rule, paste content does not affect strength although it is affected by the paste quality (Wassermann et al. 2009).

On the other hand, more cement needs to be added to meet the strength specification when the minimum cement content is not sufficient (American Society of Concrete Contractors 2005). Furthermore, achieving high strength by increasing the cement content is reportedly difficult when cement content is below 350 kg/m^3 (590 lb/yd^3) (Rixom and Mailvaganam 1999). These findings show a direct relationship between strength and cement content as opposed to the Abrams rule.

Water-to-Cement Ratio

The strength at any particular age is a function of w/c and the degree to which the cementitious materials have hydrated because they affect the porosity of both cement paste, and the interfacial transition zone between the coarse aggregate and cement paste (Wassermann et al. 2009; IMCP 2006; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993).

Strength decreases with increasing w/c (Figure 3) because the capillary porosity increases as presented in Figure 4 (Wassermann et al. 2009; IMCP 2006; Dhir et al. 2004; Mindess et al. 2003; Kosmatka et al. 2002; Schulze 1999; Mehta and Monteiro 1993). To increase strength, thus reduce w/c, it is more efficient to reduce the water content than to use more cement (Popovics 1990).

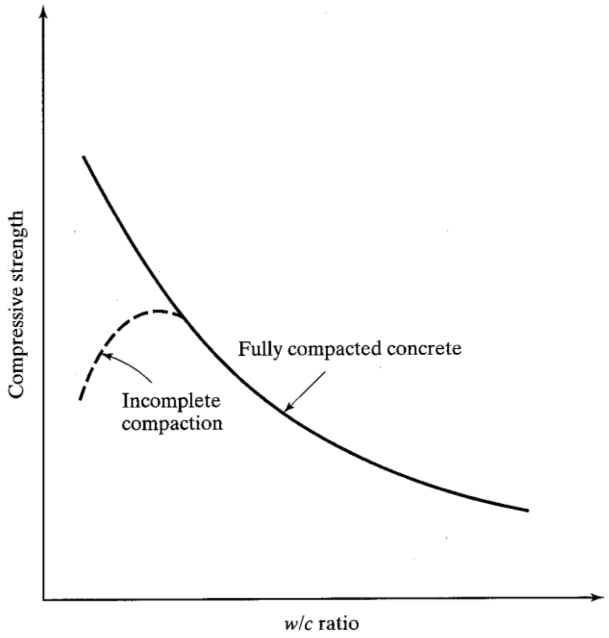


Figure 3. Relationship between compressive strength and water-to-cement ratio (Source: Mindess et al. 2003)

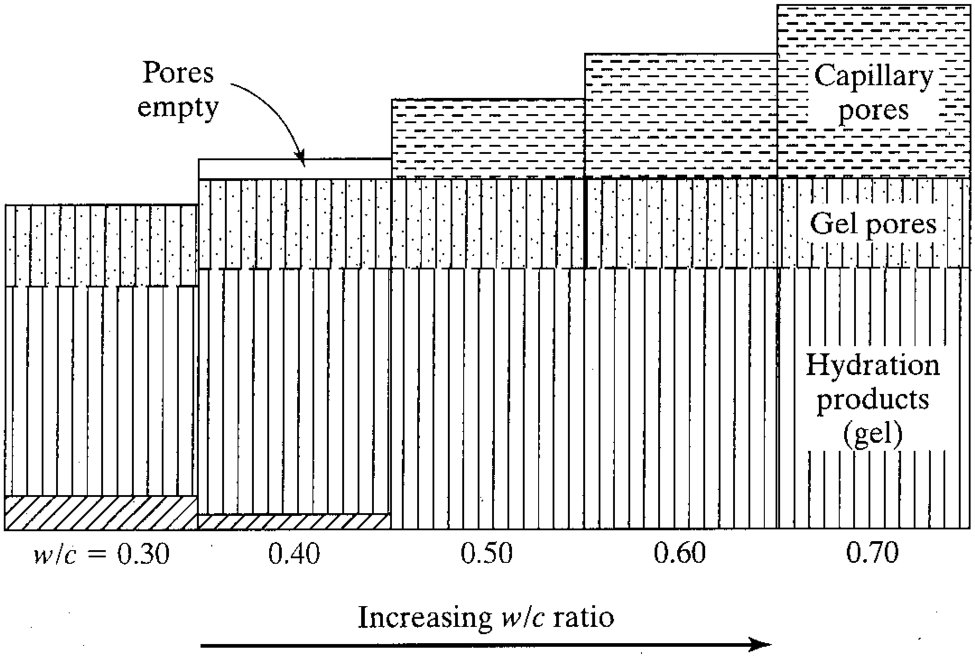


Figure 4. Relationship between porosity and w/c (Source: Mindess et al. 2003)

When durability is not the control parameter, w/c should be selected according to the compressive strength (Kosmatka et al. 2002). The range of w/c varies based on the project's purpose and structural requirements; type of the construction (for example, normal strength concrete (3,000-6,000 psi) is used for rigid pavement construction whereas high strength concrete (6,000-9,000 psi) is used in structural elements; and conditions (e.g., weather and curing conditions).

Aggregates

Rough and angular aggregates will increase strength because they bond better to the cement paste (IMCP 2006; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993). However, once the chemical interaction between aggregate and cement paste is effective at later ages, the surface texture of aggregate reduces its influence on strength (Mehta and Monteiro 1993).

The maximum size of aggregate also affects the concrete strength (Figure 5). For example, large aggregate particles reduce compressive strength by exhibiting a high stress concentration when they are subjected to compressive load (Mindess et al. 2003). Moreover, large aggregate particles forms interfacial transition zones exhibiting more microcracks compared to the smaller aggregate particles (Mehta and Monteiro 1993).

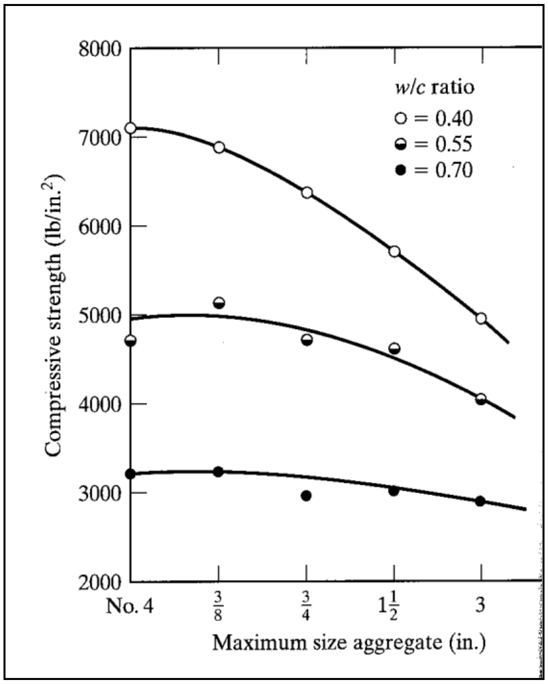


Figure 5. Effect of maximum size of aggregate on compressive strength (Source: Cordon and Gillespie 1963)

Chemical Admixtures

Water-reducing agents may indirectly increase strength because w/c is reduced (Kosmatka et al. 2002). In addition, at a given w/c, water-reducing admixtures may increase the rate of strength gain; however the ultimate strengths are not significantly affected (Mindess et al. 2003; Mehta and Monteiro 1993).

Supplementary Cementitious Materials

The addition of supplementary cementitious materials such as silica fume, limestone, slag, metakaolin, and fly ash reduce both pore sizes and porosity, and increase strength (Barbhuiya et al. 2009; IMCP 2006; Mindess et al. 2003; Bonavetti et al. 2003; Obla et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993). However, the chemistry, fineness and dosage of the supplementary cementitious material affect the early strength development of concrete as presented in Figure 6 (IMCP 2006; Mindess et al. 2003). For example, silica fume is very reactive therefore it increases both the early and later age strength by affecting cement hydration immediately (IMCP 2006; Mindess et al. 2003; Mehta and Monteiro 1993).

In contrary, although Class F fly ash and ground granulated blast-furnace slag increase the ultimate strength, they decrease the early strength up to 28 days (IMCP 2006; Mehta and Monteiro 1993).

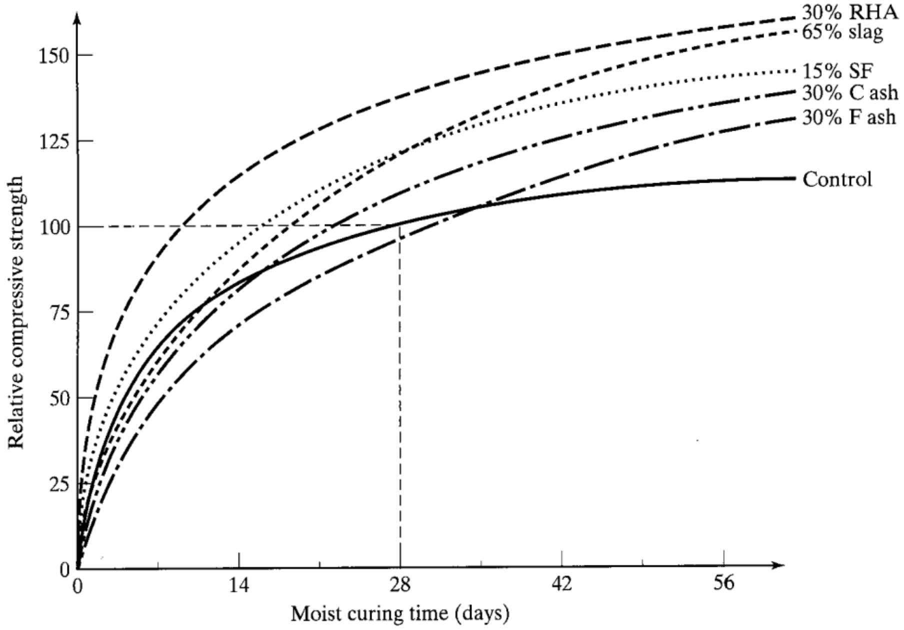


Figure 6. Relationship between relative compressive strength and supplementary cementitious materials (Source: Mindess et al. 2003)

RHA = rice husk ash

SF = silica fume

DURABILITY

ACI Committee 201 (2008) defines durability of concrete as “the ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration and retain its original form, quality, and serviceability when exposed to its environment”.

Environmental conditions, concrete components, mix design, placement and curing determine the required degree of ultimate durability and life of different concretes (Kosmatka et al. 2002).

The following factors influence the concrete durability:

- Water content: Decreasing water content will increase durability (IMCP 2006; Mindess et al. 2003; Mn DOT 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993).
- Water-to-cement ratio (w/c): Decreasing w/c will increase durability (IMCP 2006; Dhir et al. 2004; Mindess et al. 2003; Mn DOT 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993).
- Cement content: For a given w/c, increasing cement content may decrease durability (Wassermann et al. 2009; Dhir et al. 2004).
- Supplementary cementitious materials: Increasing the amount of supplementary cementitious materials will generally increase durability (IMCP 2006; Obla et al. 2003; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993).
- Degree of hydration: Increasing the degree of hydration will increase durability (IMCP 2006; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993).
- Age: Durability increases as concrete age increases (IMCP 2006; Obla et al. 2003; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993).
- Aggregates: Use of hard, dense and strong aggregate that is free of reactive silica will improve durability (IMCP 2006; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993).
- Air void system: Having a good air void system increases durability when concrete is subjected to the freeze-thaw conditions (IMCP 2006; Mindess et al. 2003; Mn DOT 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993).

- Admixture type and dosage: A water-reducing agent may indirectly increase durability by reducing w/c and providing a more uniform pore structure (Mindess et al. 2003; Mehta and Monteiro 1993).
- Consolidation and curing: Adequate consolidation and proper curing will increase durability (IMCP 2006; Mindess et al. 2003; Mn DOT 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993).

Cement Content

For a given w/c, increasing cement content may decrease durability because high cement content increases both chloride penetration and shrinkage (Wassermann et al. 2009; Dhir et al. 2004). Increasing shrinkage will cause crackings in concrete which will shorten the longevity of concrete thus decrease its durability (Mehta and Monteiro 1993).

Durability and finishability of concrete should be ensured according to the minimum cement content requirements (Kosmatka et al. 2002). ACI 302 recommends the minimum cementitious materials content to be more than the values shown in Table 1 to achieve the desired workability, finishability, abrasion resistance, and durability (Kosmatka et al. 2002).

Table 1. Minimum requirements of cementitious materials for concrete used in flatwork

Nominal maximum size of aggregate, mm (in.)	Cementitious content, kg/m^3 (lb/yd^3)*
37.5 (1½)	280 (470)
25 (1)	310 (520)
19 (¾)	320 (540)
12.5 (½)	350 (590)
9.5 (3/8)	360 (610)

* Cementing materials quantities may need to be greater for severe exposure. For example, for deicer exposures, concrete should contain at least 335 kg/m^3 (564 lb/yd^3) of cementitious materials.

Source: ACI 302

Water-to-Cement Ratio

An important parameter for durability is the w/c (IMCP 2006; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993). As w/c decreases, the porosity of the paste decreases and concrete becomes less permeable thus reducing passage of water and aggressive compounds such as chlorides and sulfates (IMCP 2006; Dhir et al. 2004; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993).

Aggregates

Increasing the maximum size of aggregate will increase durability by decreasing the cement paste content that will be under the physical or chemical attack (Mindess et al. 2003). However, reducing the aggregate size will increase durability when concrete is subjected to freeze-thaw condition (Mindess et al. 2003).

Aggregates should be unsound to prevent volume change by resisting a high internal stress when water inside the aggregate is frozen. The degree of saturation, porosity, permeability, and size of aggregate determines this stress (Mindess et al. 2003).

Use of hard, dense and strong aggregate will improve durability by providing good wear resistance (IMCP 2006; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993).

In addition, aggregates should be free of reactive silica that causes a chemical reaction between the alkali in the cement paste and silica in the aggregate. Because alkali-silica reaction is very damaging for concrete and it significantly decreases the durability of concrete by causing map cracking, popouts and staining (Mindess et al. 2003).

The effect on various aggregate properties on durability is presented as shown in Table 2.

Table 2. Durability of concrete influenced by aggregate properties

Durability	**Relevant Aggregate Property**
Resistance to freezing and thawing	Soundness, porosity, pore structure, permeability, degree of saturation, tensile strength, texture and structure, clay minerals
Resistance to wetting and drying	Pore structure, modulus of elasticity
Resistance to heating and cooling	Coefficient of thermal expansion
Abrasion resistance	Hardness
Alkali-aggregate reaction	Presence of particular siliceous constituents

Source: Mindess et al. 2003

Chemical Admixtures

Water-reducing agents are used to decrease w/c so they reduce the concrete porosity and improve resistance to de-icing salts and acidic waters. When more uniform pore structure is provided, permeability is decreased while durability is increased (Mindess et al. 2003; Mehta and Monteiro 1993).

Supplementary Cementitious Materials

Increasing the supplementary cementitious materials content will generally increase concrete durability in terms of improving impermeability, resistance to thermal cracking, and alkali-aggregate expansion (IMCP 2006; Obla et al. 2003; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993).

In addition, using supplementary cementitious materials in concrete usually improves the resistance to sulfate water, seawater and acidic water by reducing pore size, permeability and calcium hydroxide content of the hydrated product during pozzolanic reaction (Mindess et al. 2003; Mehta and Monteiro 1993).

In this study, permeability, chloride penetration and carbonation are evaluated as potential durability indicators as discussed below:

Indicators of Durability

Permeability

Kosmatka et al. (2002) define permeability as “the amount of water migration through concrete when the water is under pressure or to the ability of concrete to resist penetration by water or other substances (liquid, gas, or ions)”.

The overall permeability is a function of:

- the permeability of the paste,
- the permeability and gradation of the aggregate,
- the quality of the paste and aggregate transition zone, and
- the relative proportion of paste to aggregate (Kosmatka et al. 2002).

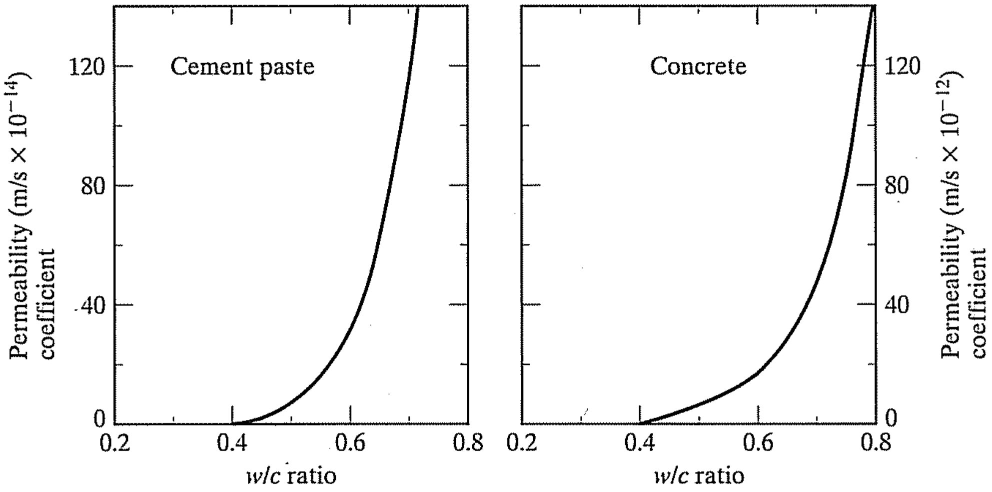
Concrete durability increases as concrete permeability decreases and that reduced permeability increases the concrete resistance to freeze and thaw, sulfate penetration, chloride-ion penetration, and chemical attack (IMCP 2006; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993).

The following factors are known to influence permeability:

- Water-to-cement ratio (w/c): Decreasing w/c will decrease permeability (IMCP 2006; Dhir et al. 2004; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993).
- Cement content: For a given w/c, decreasing cement content reportedly decreases permeability (Wassermann et al. 2009; Dhir et al. 2004).
- Water content: For a given w/c, decreasing water content will decrease permeability (Malisch 1992).
- Supplementary cementitious materials: Increasing the amount of supplementary cementitious materials will generally decrease permeability, up to a limit, depending on the type of material used (Barbhuiya et al. 2009; IMCP 2006; Obla et al. 2003; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993; Collepardi and Biagini 1989).
- Degree of hydration: Increasing the degree of hydration will decrease permeability because the size of the pores will be reduced and lose their interconnections (IMCP 2006; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993).
- Age: Permeability decreases as concrete age increases (IMCP 2006; Obla et al. 2003; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993).
- Aggregates: Increasing the maximum size of aggregates will increase the concrete permeability because the coarse aggregate size affects the microcracks in the interfacial transition zone (IMCP 2006; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993).
- Porosity: Increasing the porosity of cement paste increases permeability because paste with increased porosity will contain a relatively high number of big and well-connected pores (IMCP 2006; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993).
- Admixture type and dosage: A water-reducing agent may decrease permeability by reducing w/c and the porosity of concrete (Mindess et al. 2003; Mehta and Monteiro 1993).

- Consolidation and curing: Adequate consolidation and proper curing will decrease permeability (IMCP 2006; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993).

When w/c decreases, the porosity of the paste decreases and this reduction reduces the concrete permeability as presented in Figure 7 (Mindess et al. 2003).



(a) (b)

Figure 7. Influence of w/c on the permeability of (a) cement paste, (b) concrete (Source: Mindess et al. 2003)

The effect of w/c on the capillary volume is presented in Figure 8. Large capillary porosity is the reason why w/c affects permeability (Mindess et al. 2003). Permeability increases for concrete with w/c greater than 0.42 as a result of the increased capillary volume (Mindess et al. 2003).

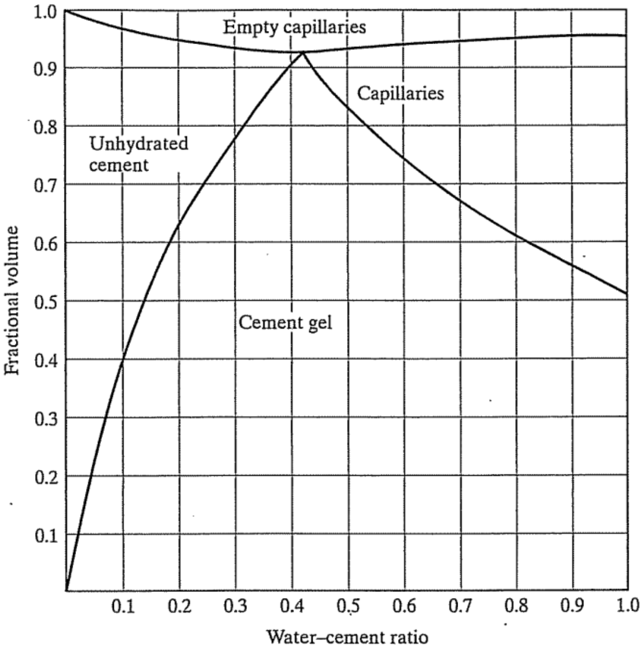


Figure 8. Composition of sealed and fully hydrated portland cement paste (Source: Hansen 1986)

Chloride Penetration

Chloride ions can penetrate into concrete by capillary absorption, hydrostatic pressure, and diffusion (Stanish et al. 1997). Chloride attacks steel in reinforced concrete structure and causes the concrete deterioration which reduces the concrete durability (Mehta and Monteiro 1993). Therefore, concrete durability increases as chloride penetration decreases (Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993; Collepardi and Biagini 1989).

The following factors affect the chloride penetration:

- Water-to-cement ratio (w/c): Decreasing w/c will decrease the chloride penetration (Dhir et al. 2004; Mindess et al. 2003; Kosmatka et al. 2002; Stanish et al. 1997; Mehta and Monteiro 1993; Collepardi and Biagini 1989).
- Supplementary cementitious materials: The presence of supplementary cementitious materials will decrease the chloride penetration as presented in Figure 9 (Mindess et al. 2003). Increasing the amount of supplementary cementitious materials will decrease the chloride penetration (Barbhuiya et al. 2009; Dhir et al. 2006; IMCP

2006; Dhir et al. 2004; Obla et al. 2003; Mindess et al. 2003; Kosmatka et al. 2002; Stanish et al. 1997; Mehta and Monteiro 1993; Collepardi and Biagini 1989).

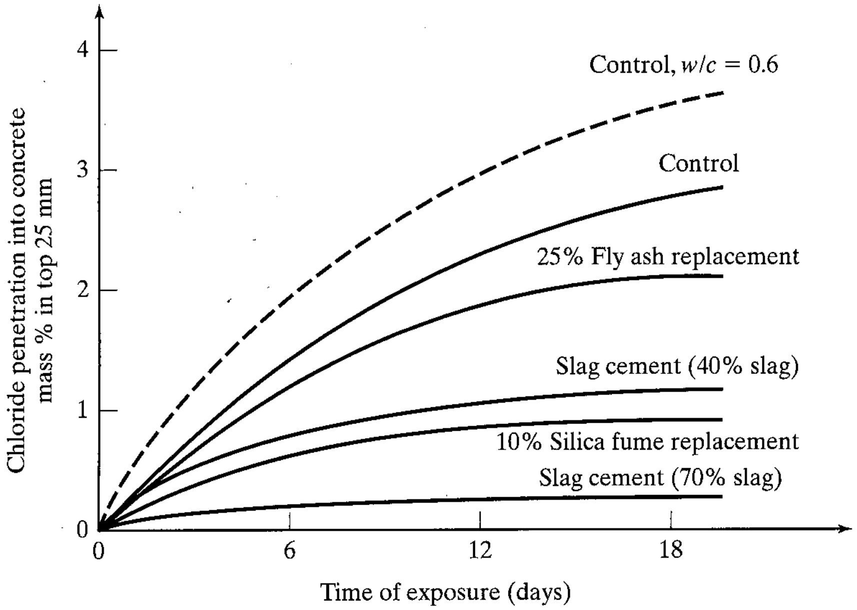


Figure 9. The effect of supplementary cementitious materials on chloride penetration (Source: Mindess et al. 2003)

- Degree of hydration: Increasing the degree of hydration will decrease the chloride penetration (Mindess et al. 2003; Obla et al. 2003; Kosmatka et al. 2002; Stanish et al. 1997; Mehta and Monteiro 1993).
- Age: Chloride penetration decreases as concrete age increases (Obla et al. 2003; Mindess et al. 2003; Kosmatka et al. 2002; Stanish et al. 1997; Mehta and Monteiro 1993).
- Cement content: For a given w/c, increasing cement content increases the chloride penetration because cement content controls the chloride binding capacity in concrete. Therefore, increased cement content will provide more binding to chlorides (Wassermann et al. 2009; Arachchige 2008; Buenfeld and Okundi 1998; Stanish et al. 1997; Collepardi and Biagini 1989).

- Porosity: Reducing porosity decreases the chloride penetration (Wassermann et al. 2009; Mindess et al. 2003; Kosmatka et al. 2002; Stanish et al. 1997; Mehta and Monteiro 1993; Collepardi and Biagini 1989).
- Admixture type and dosage: A water-reducing agent may indirectly decrease the chloride penetration by reducing w/c and the porosity of concrete (Mindess et al. 2003).
- Curing: Increasing the curing time decreases the chloride penetration (Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993; Collepardi and Biagini 1989).
- Concrete cover: Increasing the concrete cover will slow down the chloride penetration (Mindess et al. 2003; Kosmatka et al. 2002; Stanish et al. 1997; Mehta and Monteiro 1993).
- Aggregates: Aggregate type does not affect the chloride penetration (Arachchige 2008).

Carbonation

Kosmatka et al. (2002) define carbonation as “the process by which carbon dioxide in the ambient air penetrates the concrete and reacts with the hydroxides, such as to form carbonate” (Kosmatka et al. 2002). Carbonation decreases the alkalinity (pH) of concrete which will reduce its resistance to protect steel from corrosion (Mindess et al. 2003; Kosmatka et al. 2002). Therefore, carbonation of concrete plays an important role on the service life of reinforced concrete structure.

The following factors influence carbonation:

- Water-to-cement ratio (w/c): Decreasing w/c will decrease carbonation (Kosmatka et al. 2002).
- Water content: Decreasing water content will decrease carbonation (Mindess et al. 2003)
- Cement content: There are different findings regarding the effect of cement content on carbonation. Kosmatka et al. (2002) reported that for a given w/c, decreasing cement content will decrease carbonation. Although, Wassermann et al. (2009) reported that for a given w/c, carbonation is independent of cement content.

- Supplementary cementitious materials: The addition of supplementary cementitious materials may increase the carbonation depth by reducing the calcium hydroxide amount. The rate of carbonation increases by the addition of silica fume and fly ash because the total amount of components that is able to carbonate decreases as a result of reduction in total carbon monoxide (Papadakis 2000).
- Curing: Increasing the curing time will decrease carbonation (Kosmatka et al. 2002).
- Porosity: Reducing porosity will decreases carbonation (Kosmatka et al. 2002).
- Temperature: Decreasing the temperature will decrease carbonation (Kosmatka et al. 2002).

SHRINKAGE

IMCP 2006 defines shrinkage as “a decrease in length or volume of the concrete. Concretes with low w/c and those exhibiting large amount of autogenous shrinkage will develop cracking (Kosmatka et al. 2002). Shrinkage adversely affects the service life of concrete by causing cracks therefore preventing shrinkage is essential (Kosmatka et al. 2002).

There are five types of shrinkage:

- Autogenous shrinkage: autogenous shrinkage occurs as a result of cement hydration causing visible volume reduction of cement paste, mortar, or concrete (Kosmatka et al. 2002).
- Plastic shrinkage: plastic shrinkage occurs when fresh concrete has volume change before hardening (Kosmatka et al. 2002).
- Drying shrinkage: drying shrinkage occurs when the loss of water from the hardened material causes strain (Mindess et al. 2003).
- Thermal shrinkage: thermal shrinkage occurs when concrete is subjected to cooling (Mehta and Monteiro 1993).
- Carbonation shrinkage: carbonation shrinkage occurs when hardened cement paste reacts with CO_2 (Mindess et al. 2003).

The rate of the shrinkage depends on the size and shape of the concrete mass. Increasing the concrete mass will decrease the rate and amount of shrinkage while increasing the shrinkage duration (Kosmatka et al. 2002).

The following factors affect the overall shrinkage:

- Water-to-cement ratio (w/c): For a given cement content, increasing w/c will increase drying shrinkage. In contrary, low w/c (below 0.40) will cause autogenous shrinkage (IMCP 2006; Mindess et al. 2003; Kosmatka et al. 2002; Schulze 1999; Mehta and Monteiro 1993).
- Water content: Increasing the water content will increase the total shrinkage (primarily the drying shrinkage) (IMCP 2006; Kosmatka et al. 2002).
- Cement content: For a given w/c, total shrinkage (both drying and autogenous shrinkage) increase with increasing cement content (Kapelko 2006; IMCP 2006;

Dhir et al. 2004; Su and Miao 2003; Kosmatka et al. 2002; Schulze 1999; Mehta and Monteiro 1993).

- Supplementary cementitious materials: Increasing the supplementary cementitious materials content, especially silica fume will increase the total shrinkage (both drying and autogenous shrinkage) (Obla et al. 2003; Mindess et al. 2003; Tazawa and Miyazawa 1995; Mehta and Monteiro 1993).
- Aggregates: Increasing the amount of hard and rigid aggregates will increase the resistance to drying shrinkage because these aggregates are difficult to compress (Kosmatka et al. 2002).
- Admixture type and dosage: Some water-reducing agents may increase drying shrinkage because they improve the porosity of the hydration product (Wassermann et al. 2009; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993). The effects of other admixtures on strength are beyond the scope of this study.
- Moisture loss: The evaporation of water from the surface causes both drying and plastic shrinkage (IMCP 2006; Mindess et al. 2003).
- Degree of hydration: Increasing the rate of hydration will increase shrinkage (IMCP 2006; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993).
- Relative humidity: Increasing the relative humidity will decrease the carbonation shrinkage because water fills the pores and prevents penetration of CO_2 into paste (Mindess et al. 2003; Kosmatka et al. 2002).
- Specimen geometry: The size and shape of a concrete specimen affects the rate of moisture loss and the drying shrinkage magnitude. Increasing the volume-to-surface area ratio will decrease the drying shrinkage. However, increasing the surface area will increase the carbonation shrinkage (Mindess et al. 2003; Kosmatka et al. 2002).
- Temperature: Concrete shrinks as the temperature cools (IMCP 2006; Kosmatka et al. 2002; Mehta and Monteiro 1993).

- Curing: Sealers, coatings and fogging decrease and delay shrinkage. Steam curing and increasing the coolness of initial curing temperatures will decrease shrinkage (Henkensiefken et al. 2009; Kosmatka et al. 2002).
- Cement type: Cement type does not directly affect shrinkage (IMCP 2006).

Water Content

Water content is the primary parameter that affects drying shrinkage (IMCP 2006; Kosmatka et al. 2002). Decreasing the water content of concrete will decrease shrinkage (Figure 10).

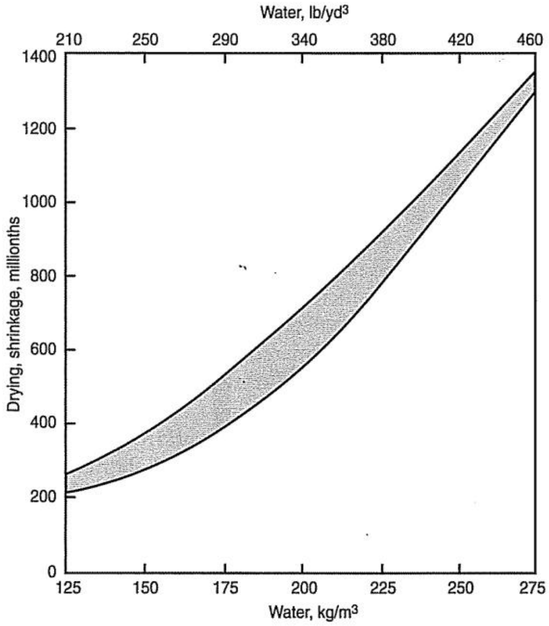


Figure 10. Relationship between total water content and drying shrinkage (Source: Kosmatka et al. 2002)

Cement Content

For a given w/c, both drying and autogenous shrinkage increase with increasing cement content (Kapelko 2006; IMCP 2006; Dhir et al. 2004; Su and Miao 2003; Kosmatka et al. 2002; Schulze 1999; Mehta and Monteiro 1993). However, Wassermann et al. (2009) reported that for a given w/c, the effect of cement content on shrinkage is small.

Water-to-Cement Ratio

In contrast to drying shrinkage, autogenous shrinkage increases as w/c decreases (especially below 0.40) and the density of cement microstructure increases (Mindess et al. 2003; Kosmatka et al. 2002; Schulze 1999; Mehta and Monteiro 1993).

Aggregates

Coarse aggregates resist the drying shrinkage of hydrating cement paste (Kosmatka et al. 2002).

The following aggregate properties affect the drying shrinkage:

- Increasing the maximum size of aggregates will increase drying shrinkage because the internal stress between cement paste and aggregate will increase and cause and increased amount of cracking (Mindess et al. 2003; Kosmatka et al. 2002).
- Increasing the amount of hard and rigid aggregates will increase the resistance to shrinkage (Kosmatka et al. 2002).
- Increasing the elastic modulus of aggregates will decrease the elastic deformation of concrete and decrease shrinkage (Mindess et al. 2003; Mehta and Monteiro 1993).
- Increasing the aggregates containing excessive clay content will increase drying shrinkage by increasing the water requirement because clay particles have high surface area and absorb high amount of water (IMCP 2006; Kosmatka et al. 2002).
- Increasing the aggregate content will decrease the drying shrinkage of concrete as presented in Figure 11 (Mindess et al. 2003).

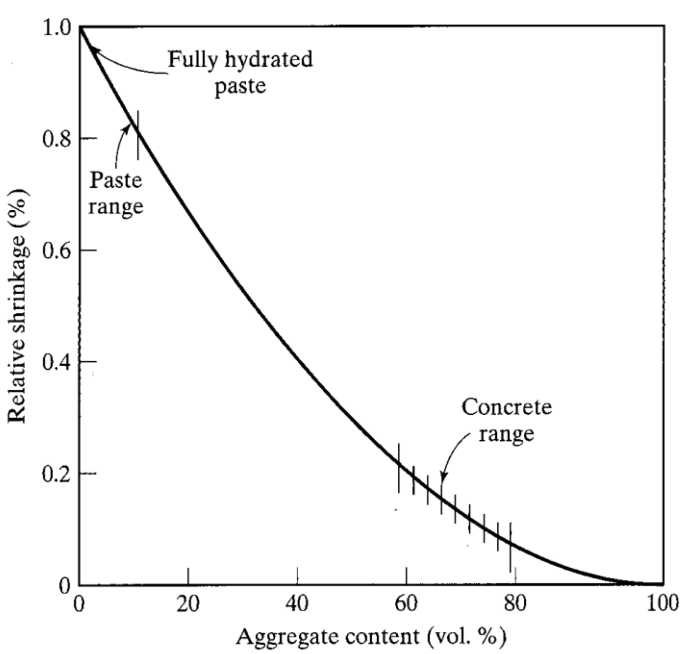


Figure 11. The effect of aggregate content on the drying shrinkage of concrete (Source: Mindess et al. 2003)

Chemical Admixtures

Some water-reducing agents may increase shrinkage because they improve the porosity of the hydration product (Wassermann et al. 2009; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993).

In contrary, Tazawa and Miyazawa (1995) reported that autogenous shrinkage is slightly reduced by water-reducing agents due to their effect on the rate of hydration.

Supplementary Cementitious Materials

Increasing the supplementary cementitious materials content, especially silica fume will increase drying and autogenous shrinkage due to having low bleeding characteristics (Khatib et al. 2009; Obla et al. 2003; Mindess et al. 2003; Tazawa and Miyazawa 1995; Mehta and Monteiro 1993).

The effect of fly ash, ground granulated blast-furnace slag, calcined clay and calcined shale is reportedly small on shrinkage as presented in Figure 12 (IMCP 2006; Mindess et al. 2003; Kosmatka et al. 2002).

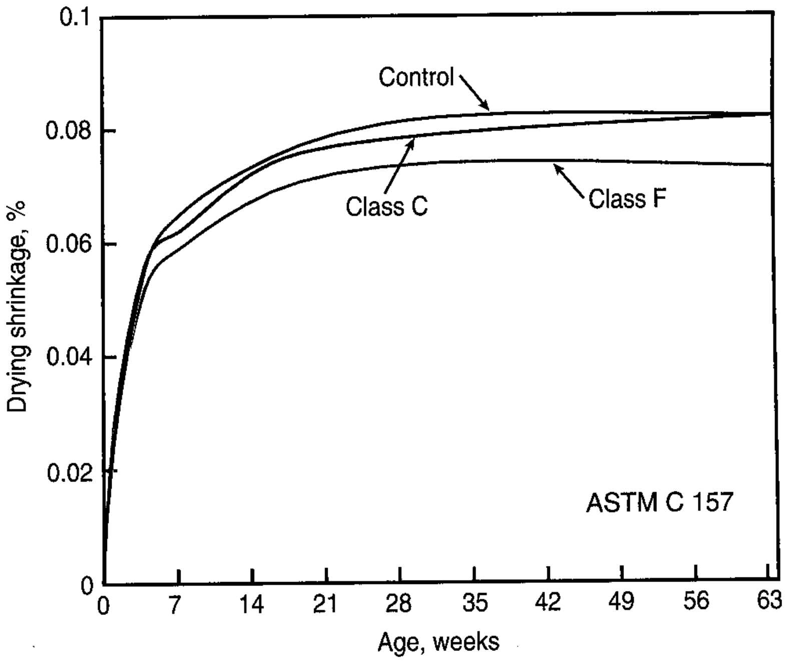


Figure 12. Drying shrinkage of fly ash concretes compared to a control mixture (Source: Gebler and Klieger 1986)

SUSTAINABILITY

World Commission on Environment and Development (1987) defines sustainable development as “meeting the needs of the present without compromising the ability of future generations to meet their own needs”.

This thesis investigates the methods to use cement more efficiently thereby focusing on the sustainability in the concrete construction industry because:

- cement is a finite material therefore using finite elements and resources efficiently improves sustainability
- cement industry contributes 5% of the total global industrial energy consumption (World Energy Council, 1995)
- cement production contributes 5% of total global carbon dioxide (CO_2) emissions as presented in Figure 13 (IEA 2003; Battelle 2002)

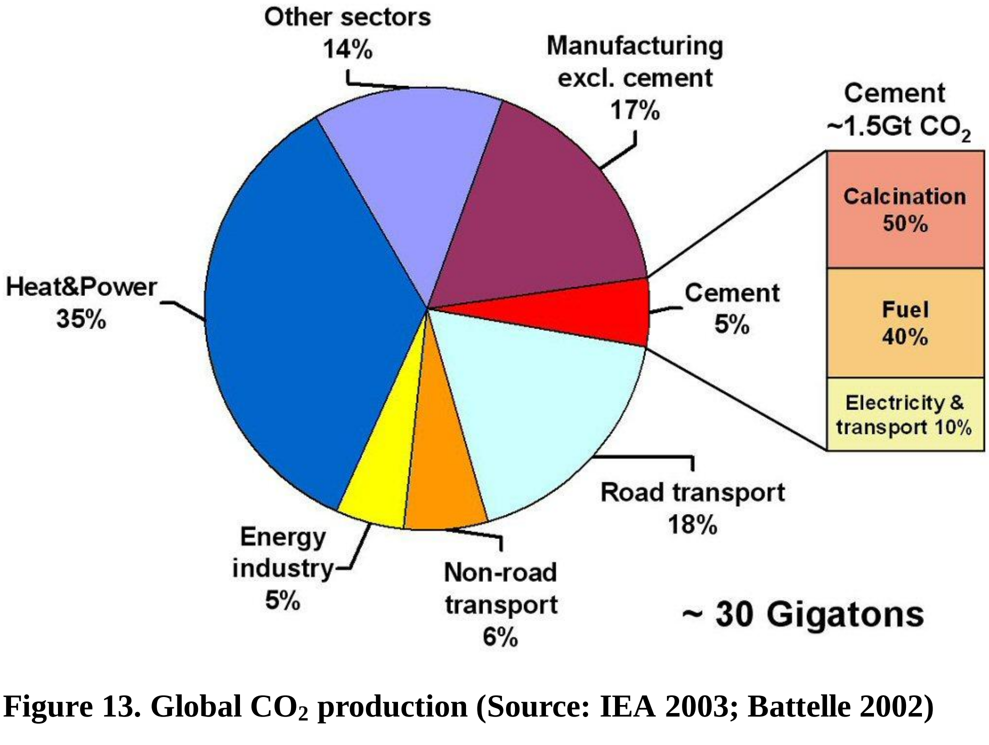


Figure 13. Global CO_2 production (Source: IEA 2003; Battelle 2002)

The easiest sustainable solution for the concrete construction industry is using cement more efficiently. As it is discussed in the previous sections, literature information states that after cement content reaches to its optimum value, using more cement does not contribute to achieve higher strength. In some cases, excessive cement content adversely affect concrete performance and durability by causing shrinkage and crackings.

Therefore, cement can be used more efficiently to improve sustainability and reduce;

- the consumption of finite elements and resources
- the energy consumption
- CO_2 emission

In addition to using cement more efficiently, Hendriks et al. (2004) listed the methods of increasing the sustainability in cement industry as following:

- Improvement of the energy efficiency of the process
- Shifting from wet process to dry process
- Replacement of high carbon fuels by low carbon fuels
- Application of lower clinker/cement ratio
- Application of alternative cements
- Removal of CO_2 from the flue gases

SUMMARY

Information in the literature supports the hypothesis of this research:

- Strength is independent of cement content for a given w/c: increasing cement content does not affect strength (Wassermann et al. 2009; Dhir et al. 2004; Schulze 1999)
- Strength is primarily a function of w/c as long as there is sufficient paste to fill the voids between the aggregate particles and the mixture is adequately consolidated (IMCP 2006; Mindess et al. 2003; Kosmatka et al. 2002; Mehta and Monteiro 1993)
- Increasing cement content may adversely affect durability and performance by increasing shrinkage, chloride penetration, permeability and crackings (Wassermann et al. 2009; Arachchige 2008; Collepardi and Biagini 1989).
- Increasing cement production will increase the energy consumption and CO_2 emission
- Cement is a finite material, therefore using cement efficiently will improve sustainability

In addition to the literature information above, to generalize the recommended cement content for extending its applicability, this study will investigate an appropriate paste volume-to-volume of voids ratio to meet the desired workability, strength and durability requirements.

CHAPTER 3. MATERIALS AND METHODS

This chapter reviews the materials and methods used in this study. The first section describes the overall research design, then materials, test variables, specimen preparation, and finally the experimental work.

RESEARCH DESIGN

The purpose of this experimental project is to identify the minimum cement content associated with an appropriate water-to-cement ratio (w/c) that results in optimum workability, strength and durability requirements at minimum cost for a concrete pavement mixture. High range water reducing agent was added to mixtures when needed to obtain a minimum workability of 3 in. slump.

MATRIX

Variables

To determine the effect of concrete components on overall concrete behavior, cement content and w/c were selected as variables.

Portland Cement Association (PCA) recommends the following components with the specified content to achieve ‘good concrete’:

- A minimum cement content of 6 bags per cubic yard (564 pcy) of concrete
- A maximum water content of 6 gallons per bag of cement (max w/c of 0.53)

The spectrum of these variables was determined including the two extreme sides of the commonly used values (564 pcy of cement content and w/c of 0.40 to 0.45) to monitor the concrete behavior under low, normal and high values of these two variables. Therefore, variables were selected as following:

- 4 cement contents – 400, 500, 600 and 700 pcy
- 4 w/c – 0.35, 0.40, 0.45 and 0.50

In total, 16 mixtures were designed by combining these two variables (4 cement content*4 w/c = 16 mixtures) as presented in Table 3.

Table 3. Variables

Mix No	Cement Content	w/c
1	400	0.35
2	500	
3	600	
4	700	
5	400	0.40
6	500	
7	600	
8	700	
9	400	0.45
10	500	
11	600	
12	700	
13	400	0.50
14	500	
15	600	
16	700	

The slump could not be fixed because both cement content and w/c were controlled. Water reducing admixtures were used in the drier mixtures to improve workability within the range of manufacturers recommended dosages. Slump values were recorded.

Fixed Parameters

According to the sieve analysis test results, the fine aggregate-to-total aggregate ratio was fixed as 0.42 by using the combined aggregate gradation charts. Test methods and selection of the fine aggregate-to-total aggregate ratio will be discussed in detail in the process of mix proportioning section. This was done to remove aggregate grading as a variable from the experimental matrix.

ACI 211 Report (2002)

ACI 211 Report (2002) was followed to determine the appropriateness of the mix component values obtained based on the research mix design.

For each w/c, the amount of cement, coarse aggregates and fine aggregates were calculated by following the standard procedure as shown in Table 4.

Table 4. Mix Proportioning Steps

Step 1	Choice of slump (in.)	3			
Step 2	Choice of maximum size of aggregate (in.)	1			
Step 3a	Estimation of mixing water (lb.) (Table 6.3.3)	325			
Step 3b	Estimation of air content (%)	2			
Step 4	Selection of w/c (Fixed by experimental design)	0.35	0.40	0.45	0.50
Step 5	Calculation of cement content (lb.)	929	813	722	650
Step 6	Estimation of coarse aggregate content (lb.) (Table 6.3.6)	1829	1829	1829	1829
Step 7	Estimation of fine aggregate content (lb.)	908	1004	1079	1139

The observed cement contents in Table 4 requires significantly higher cement contents ranging from 650 pcy to 930 pcy than the designed cement contents ranging between 400 pcy to 700 pcy, for a given w/c.

MATERIALS

To prepare the 16 different concrete mixes, a single batch of each of the following materials was obtained (Table 5).

Table 5. Materials

Material	Type
Cement	ASTM Type I Ordinary Portland Cement
Fine Aggregate	No 4 Nominal Maximum Size Concrete Sand
Coarse Aggregate	1-in. Nominal Maximum Size Crushed Limestone ($CaCO_3$)
Water-reducer	ASTM C494 Type F Polycarboxylate based High Range Water-Reducing Agent (HRWR)
Water	Tap water

The chemical composition of the ASTM Type I portland cement is presented in Table 6. The gradation of the aggregates is discussed in a later section.

Table 6. Cement composition (After ASTM C150, 2002)

Chemical Composition	% by mass
Silicon dioxide (SiO_2)	20.22
Aluminum oxide (Al_2O_3)	4.43
Ferric oxide (Fe_2O_3)	3.19
Manganese (III) oxide	0.48
Calcium oxide (CaO)	62.71
Magnesium oxide (MgO)	3.51
Sulfur trioxide (SO_3)	3.24
Potassium oxide (K_2O)	0.69
Sodium oxide (Na_2O)	0.08
Titanium dioxide (TiO_2)	0.22
Phosphorus pentoxide (P_2O_5)	0.10
Chlorine (Cl)	0.003
Equivalent Alkalies (NaEq)	0.54
Strontium (Sr)	2.65
Argon (Ar)	1.39

MIXTURES

Process of Mix Proportioning

Prior to the mix design, the following laboratory tests were conducted on the aggregates:

- Sieve analysis (ASTM C136) (Figure 14)
- Specific gravity and absorption (ASTM C127 and C128)
- Unit weight and void space (ASTM C29)

Figure 14. Fine aggregate sieve analysis equipment

The sieve analysis of fine aggregate is shown in Table 7.

Table 7. Fine aggregate sieve analysis test results

Sieve Size	**Sieve Size (mm)**	**Retained Weight (g)**	**Individual Retained (%)**	**Cumulative Passing (%)**	**Cumulative Retained (%)**
3/8"	9.5	0	0.0	100.0	0.0
No. 4	4.75	23.9	1.7	98.3	1.7
No. 8	2.36	144.3	10.5	87.8	12.2
No. 16	1.18	214.0	15.5	72.3	27.7
No. 30	0.6	400.2	29.0	43.3	56.7
No. 50	0.3	403.3	29.2	14.1	85.9
No. 100	0.15	185.6	13.4	0.6	99.4
No. 200	0.08	1.5	0.1	0.5	--
Pan	--	4.7	0.3	0.2	--
Total	--	1377.5			283.6
Total Original	--	1380		Fineness Modulus	2.84

Fine aggregate gradation curve is presented in Figure 15.

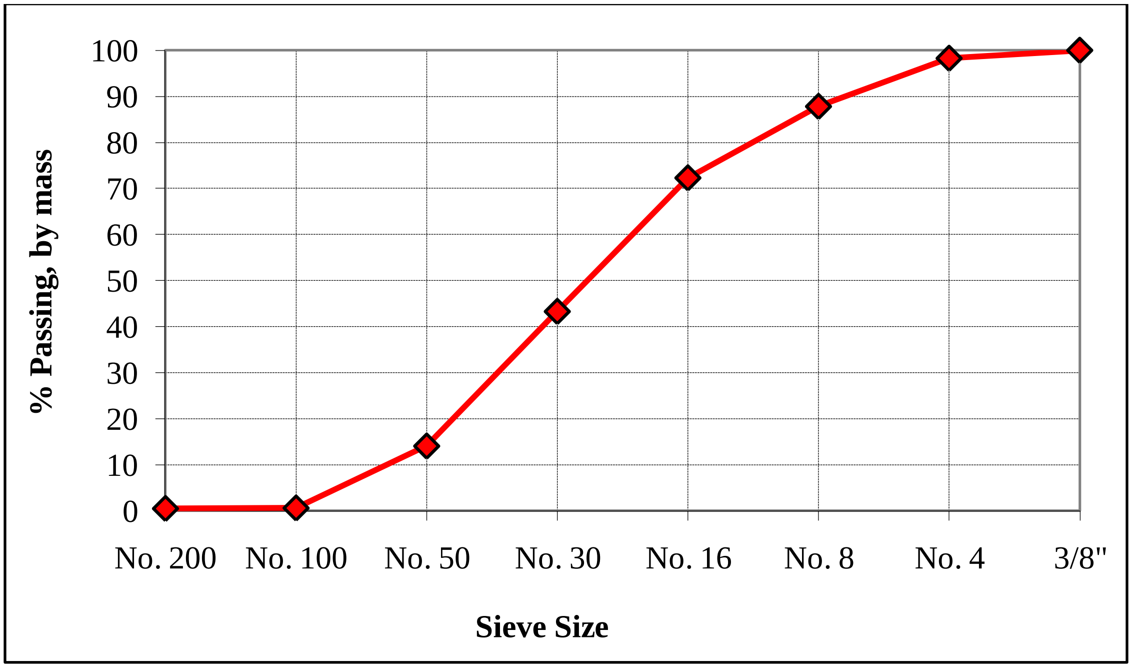


Figure 15. Fine aggregate gradation curve

The sieve analysis of coarse aggregate is shown in Table 8.

Table 8. Coarse aggregate sieve analysis test results

Sieve Size (in.)	Sieve Size (mm)	Retained Weight (g)	Individual Fraction Retained (%)	Cumulative Passing, (%)	Cumulative Retained, (%)
1"	25	24.1	0.24	99.8	0.24
3/4"	19	1949.4	19.47	80.3	19.71
1/2"	12.5	4217	42.11	38.2	61.82
3/8"	9.5	1843.7	18.41	19.8	80.23
No. 4	4.75	1635.3	16.33	3.4	96.56
Pan	--	319.5	3.19	0.0	--
Total	--	9989			741.10
Total Original		10014			

Coarse aggregate gradation curve is presented in Figure 16.

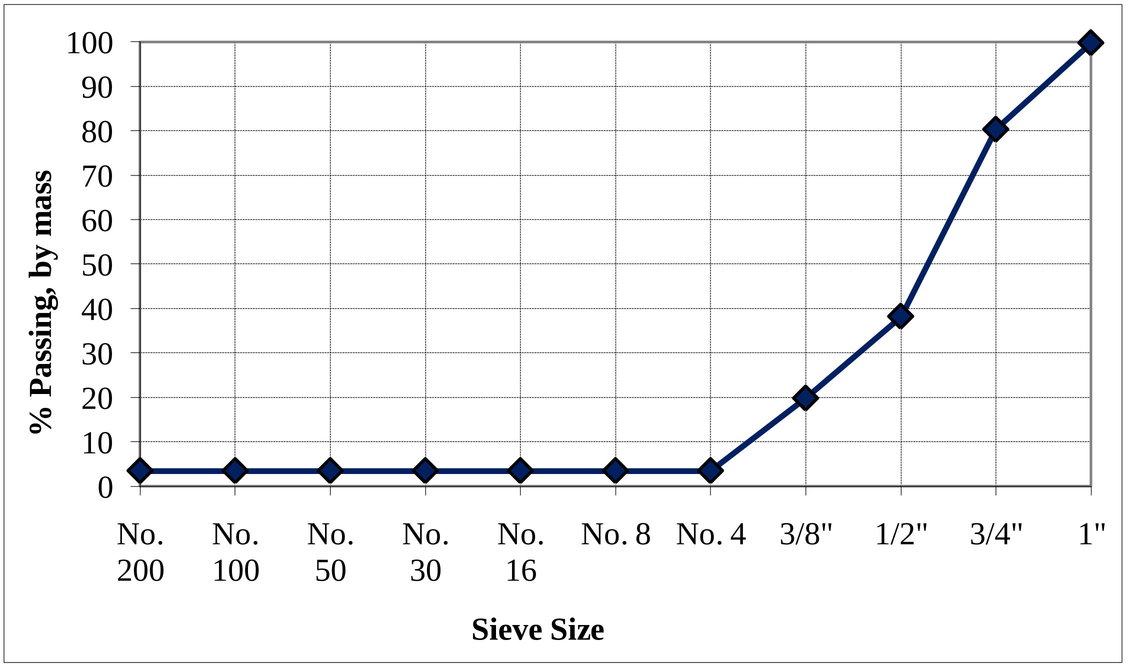


Figure 16. Coarse aggregate gradation curve

Combined Aggregate Gradation

Iowa Department of Transportation (2004) states that “concrete mixtures produced with a well-graded aggregate combination tend to reduce the need for water, provide and maintain adequate workability, require minimal finishing, and consolidate without segregation’. Therefore, well-graded aggregates with maintained void content are important for mix design. To keep the void content of the combined aggregate system constant for all the mixtures, three different gradation charts were compared:

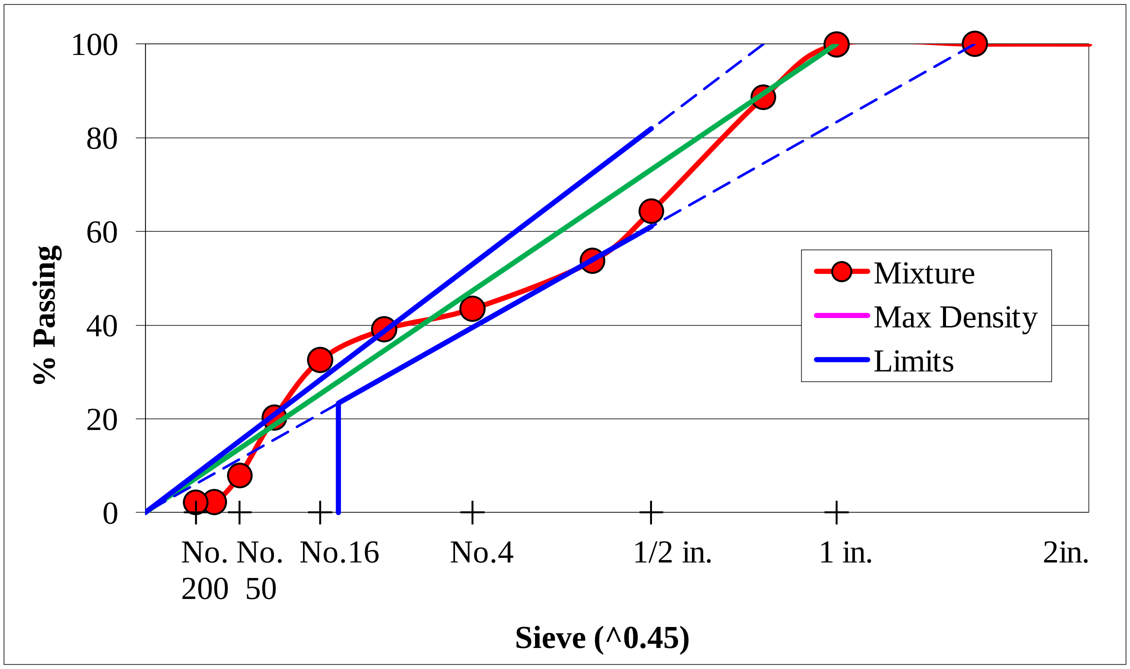
- 0.45 Power curve. The “solver” function on a spreadsheet was used to determine the ratio of fine-to-total aggregate that would provide a gradation as close as possible to the optimum 0.45 plot. Based on this work, the preferred ratio was determined to be 0.45 (Figure 17a).
- Shilstone workability factor chart. Again ratio of fine-to-total aggregate was varied to place the combined system data point within or close to Zone II on the workability factor chart (Figure 17b). Based on this work, the preferred ratio was determined to be 0.42.
- Specific surface approach. The specific surface values of aggregates were used on the 2 in. to #200 sieves to determine the fine-to-total aggregate ratio (Figure 17c). Based on this work, the preferred ratio was determined as 0.39.

Based on the three values determined above, the value of 0.42 was selected because it was the average value that fit all the charts without exceeding their limits. For example, according to the Shilstone workability factor chart, if combined aggregate gradation ratio exceeds Zone II, it may be gap graded (Zone I), sticky (Zone IV) or harsh (Zone V) and having an aggregate system with these properties will adversely affect the concrete performance.

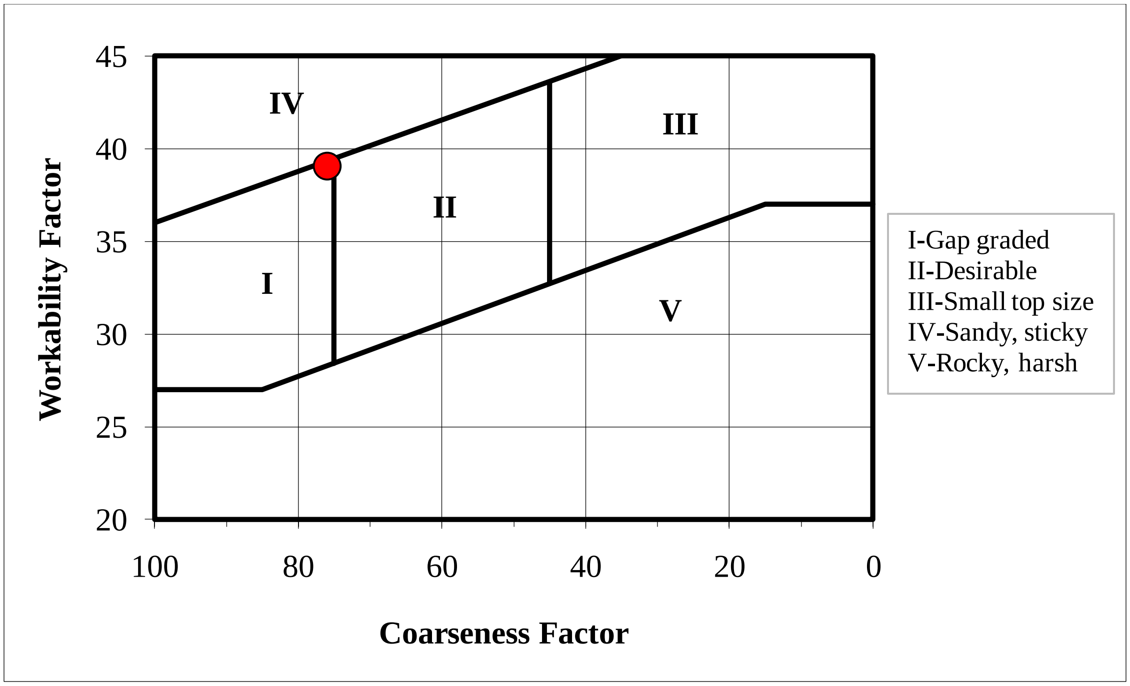
The combined gradations were plotted using:

- ASTM C33 plot (Figure 17d). This plot shows both the individual gradation trends of fine and coarse aggregates, and the combined aggregate system. The combined gradation trend was compared with the ASTM C33 gradation trend to determine the appropriateness of the selected fine-to-coarse aggregate ratio.

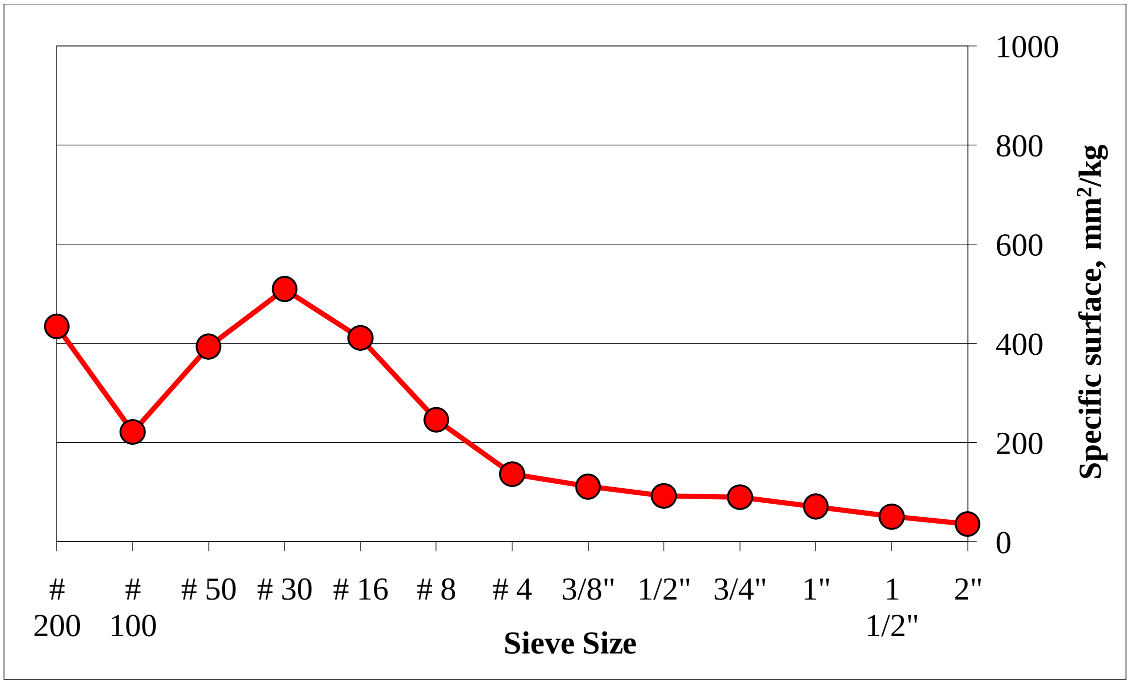
- "Haystack" plot (Figure 17e). This plot shows a shortage of materials on the #8 and #16 sieves. This is not an ideal combination, but was the best combination that could be achieved with the materials available. While not ideal, this type of gradation is common in many construction sites, and is therefore an appropriate combination for this research project.



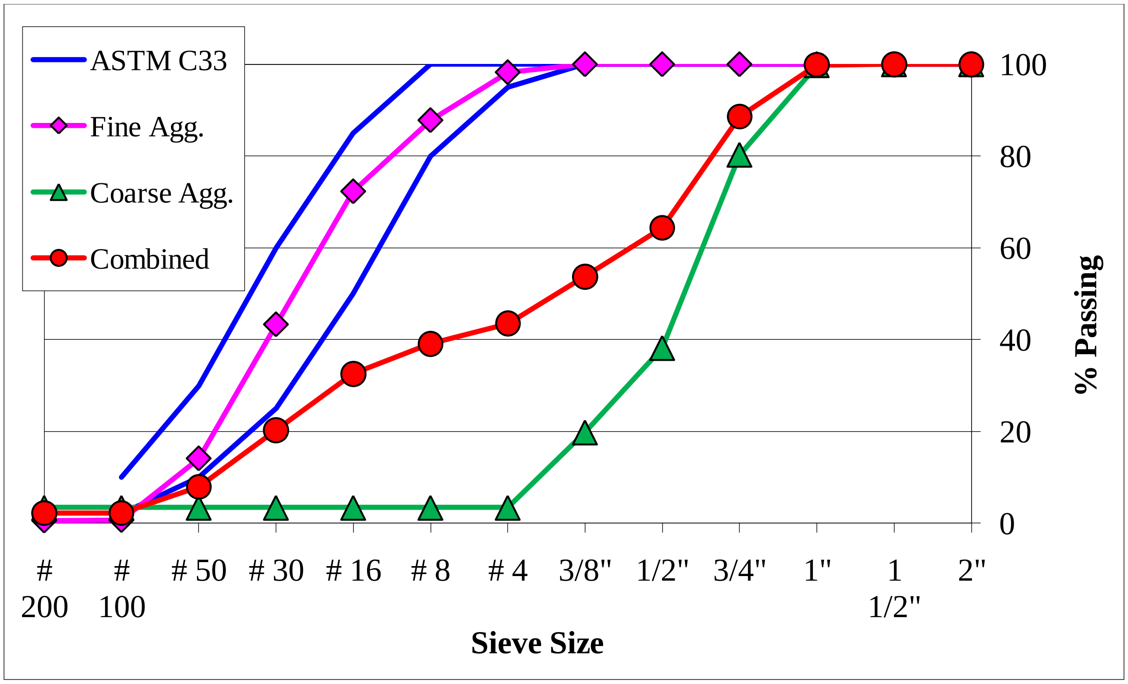
a) Power 45 gradation curve



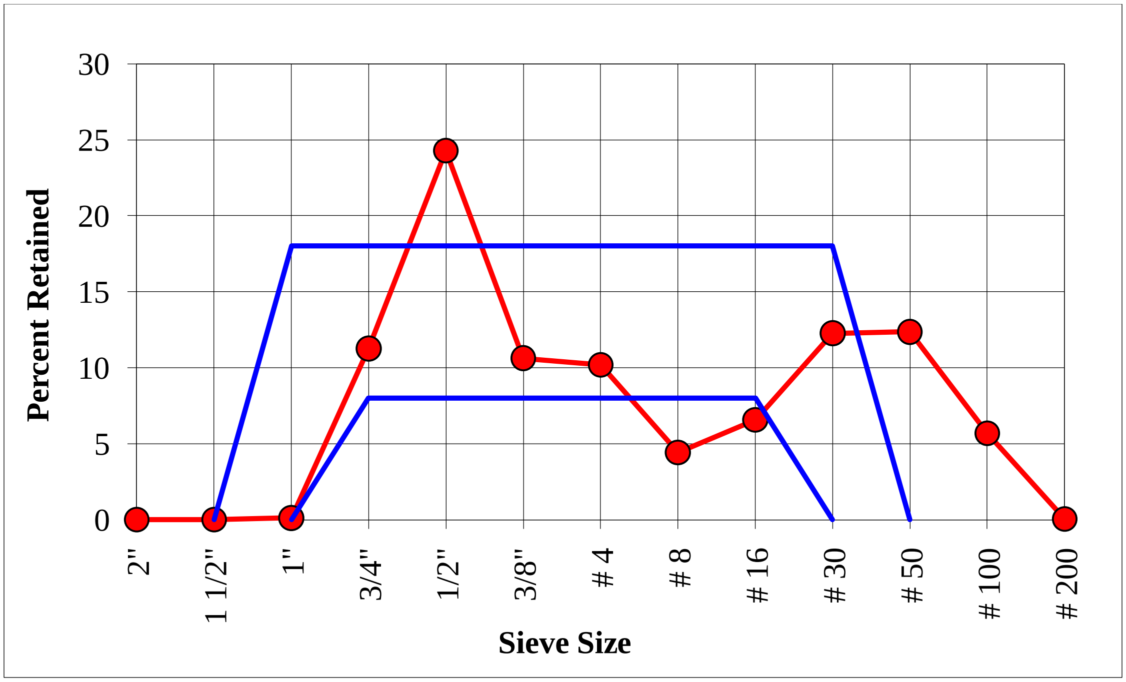
b) Shilstone workability factor chart



c) Specific surface chart



d) ASTM C33 gradation graph



e) 8/18 gradation chart

Figure 17. Combined aggregate gradation curves

Unit Weight and Void Space Test

The bulk density (unit weight) and voids in the combined aggregate were measured by following ASTM C29. This test was conducted 2 times and the overall unit weight of the combined aggregates was observed as 131 lb/ft^3. The void percentage was calculated as 19.8%.

Specific Gravity and Absorption Test

The specific gravity and absorption of the coarse aggregate was determined using ASTM C127. The specific gravity and absorption of the fine aggregate was tested in accordance with ASTM C128. These tests were conducted 5 times to observe accurate results.

The saturated surface dry (SSD) specific gravity and the absorption values of fine aggregate were calculated as 2.62 and 1.1%, respectively. In addition, the SSD specific gravity and the absorption values of coarse aggregate were observed as 2.67 and 1.0%, respectively.

Final Mix Proportions

The final mix proportions were prepared for 16 mixtures with w/c ranging from 0.35 to 0.50; and cement content ranging from 400 to 700 lb/yd^3 (Table 9). The fine aggregate-to-total aggregate ratio was fixed as 0.42. Aggregate content was calculated to achieve a yield of 27 ft^3.

The ratio of paste volume-to-volume of voids in the aggregate was also used to assess the effect of paste content on fresh and hardened concrete properties (Figure 18).

Table 9. Mix proportions

No	Cement (pcy)	Water (pcy)	w/c	WRA[1] (oz/100 lb)	Fine Aggregate (pcy)	Coarse Aggregate (pcy)	V_p/V_V[2] %
1	400	140	0.35	1.86	1,535	2,120	109.8
2	500	175	0.35	1.25	1,461	2,017	140.9
3	600	210	0.35	0.73	1,387	1,915	175.4
4	700	245	0.35	0.43	1,313	1,813	213.8
5	400	160	0.40	1.18	1,513	2,089	118.8
6	500	200	0.40	1.08	1,433	1,979	153.4
7	600	240	0.40	0.31	1,353	1,869	192.2
8	700	280	0.40	0.19	1,274	1,759	235.7
9	400	180	0.45	0.55	1,490	2,058	128.1
10	500	225	0.45	0.37	1,406	1,941	166.4
11	600	270	0.45	-	1,320	1,823	209.7
12	700	315	0.45	-	1,235	1,706	259.0
13	400	200	0.50	0.59	1,469	2,028	137.6
14	500	250	0.50	0.27	1,377	1,902	179.9
15	600	300	0.50	-	1,287	1,777	228.2
16	700	350	0.50	-	1,196	1,652	283.8

---

[1] Water-reducing admixture

[2] The ratio of paste volume-to-volume of voids in the aggregate (%)

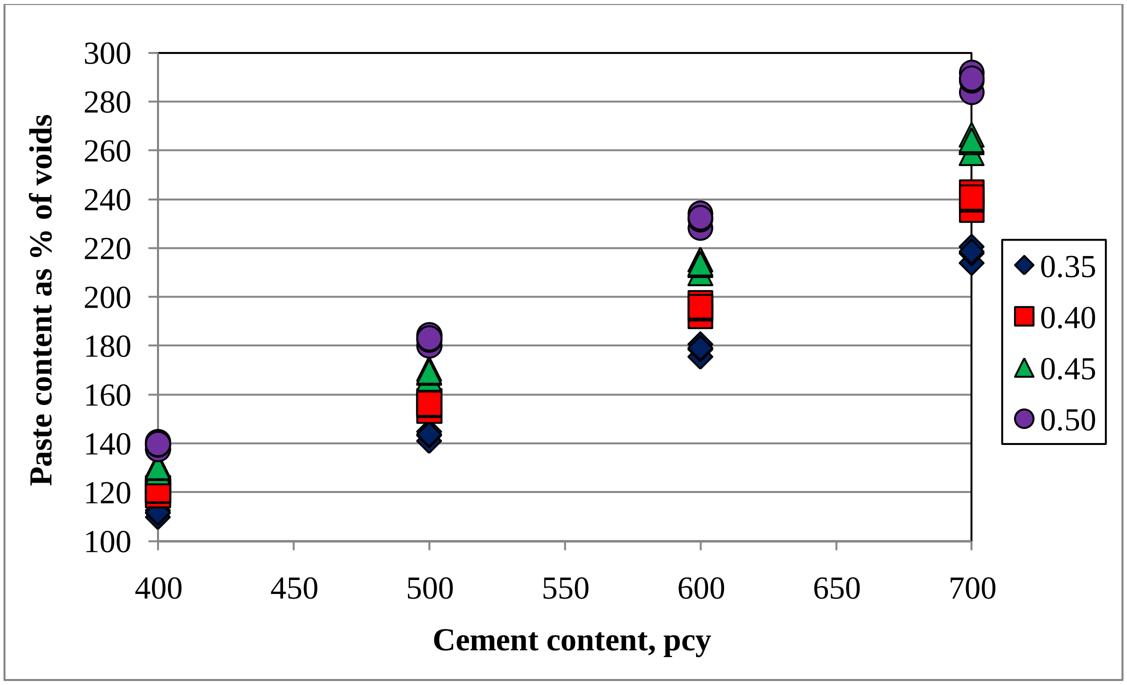


Figure 18. The relationship between paste volume-to-volume of voids ratio and cement content

For each mixture, 15 cylinders were prepared (Table 10). The tests were conducted in duplicate to increase the precision of the test results. However, extra cylinders were cast to test if an extra specimen was needed due to the variations in the test results.

Table 10. Specimens

Test Method	**Specimen Type**	**# Specimens**			**# Total Cylinders**
		1 day	**3 day**	**28 day**	
Compressive Strength	4 in. x 8 in. cylinder	2	2	2	6
Rapid Chloride Penetration	2 in. thick disk			2	6
Air Permeability	1 in. thick disk	2	2	2	

Table 11 presents the tests conducted.

Table 11. Test matrix

Fresh Concrete Property	**Method**	**# Sample**	**Age (days)**
Slump/ Slump flow	ASTM C143/ ASTM C1611	1	NA
Air Content	ASTM C231	1	NA
Setting Time	ASTM C403	1	NA
Hardened Concrete Property			
Compressive Strength	ASTM C39	2 specimens per age	1, 3, 28
Rapid Chloride Penetration	ASTM C1202	2 specimens per age	28
Air Permeability	University of Cape Town Method	2 specimens per age	1, 3, 28

SPECIMEN PREPARATION

The following tests were conducted at the Portland Cement Concrete (PCC) Research Laboratory at Iowa State University.

Mixtures were prepared in accordance with ASTM C 192.

Cylindrical specimens were prepared in accordance with ASTM C31 and stored under plastic sheeting (Figure 19).

The samples were demolded after 24 hours and cured in a fog room in accordance with ASTM C192. Samples were kept in the fog room until tested at the fixed age.

Figure 19. Curing room

EXPERIMENTAL WORK

Although slump, setting time and air content tests were not assessed as control characteristics, they were measured to evaluate the effect of the variables on concrete behavior.

- Slump

The concrete slump was measured by following ASTM C143 (Figure 20). When slump value was more than 8 in., the slump flow was determined in accordance with ASTM C1611.

Figure 20. Slump test

- Air content

Air content of the mixtures was measured with a pressure meter by following ASTM C231 (Figure 21). No air-entraining agent was added to the mixtures.

Figure 21. Air meter

- Setting Time

The concrete setting time was tested based on ASTM C403 (Figure 22).

Figure 22. Penetrometer and penetration needle set

- Strength

Compressive strength tests were conducted on 2 specimens per mixture at 1, 3, and 28 days in accordance with ASTM C39 (Figure 23).

Figure 23. Compressive strength testing machine

Durability was evaluated by conducting rapid chloride penetration and air permeability tests.

- Rapid Chloride Penetration

The rapid chloride penetration test was conducted on 2 samples per mixture using ASTM C1202 to determine their resistance to chloride ion penetration (Figure 24 and Figure 25). This test was not conducted at 1 and 3 days because at early ages the initial mixtures tested showed such high penetrability that the values could not be recorded. Therefore, the rapid chloride penetration test was only conducted at 28 days.

Figure 24. Rapid chloride penetration equipment

Figure 25. Vacuum processing

- Air Permeability

The air permeability test was also conducted on 2 specimens per mixture at 1, 3, and 28 days using the University of Cape Town Air Permeability Method (Alexander et al., 1999) as presented in Figure 26 and Figure 27.

Figure 26. Air permeability equipment

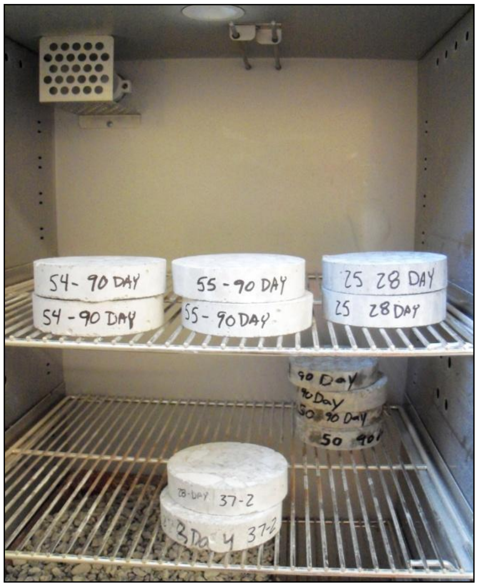


Figure 27. Drying samples in an oven prior to the air permeability test

CHAPTER 4. RESULTS AND DISCUSSION

The purpose of this chapter is to report, analyze, and discuss the laboratory test results for the 16 concrete mixtures considered in this study containing different cement contents and water-to-cement ratios (w/c).

Test results are presented under the following categories:

- workability
- setting time
- strength
- chloride penetration
- air permeability

The experimental data are presented in Table 12 and Table 13.

Table 12. Fresh concrete properties

Materials								Fresh Properties				
								Slump (in)			Set time	
No	Cement (pcy[3])	Water (pcy)	Fine agg.[4] (pcy)	Coarse agg.[5] (pcy)	w/c	WRA[6] (oz/ 100lb)	V_p/V_V %	Slump	Slump flow	Air content (%)	Initial (min)	Final (min)
1	400	140	1,535	2,120	0.35	1.86	109.8	0	-	2.75	290	420
2	500	175	1,461	2,017	0.35	1.25	140.9	0	-	1.50	200	300
3	600	210	1,387	1,915	0.35	0.73	175.4	2.0	-	1.80	205	265
4	700	245	1,313	1,813	0.35	0.43	213.8	1.5	-	1.75	160	240
5	400	160	1,513	2,089	0.40	1.18	118.8	0	-	3.50	210	340
6	500	200	1,433	1,979	0.40	1.08	153.4	0.2	-	2.25	245	335
7	600	240	1,353	1,869	0.40	0.31	192.2	2.5	-	2.00	200	285
8	700	280	1,274	1,759	0.40	0.19	235.7	4.5	-	2.20	205	275
9	400	180	1,490	2,058	0.45	0.55	128.1	0	-	2.60	175	265
10	500	225	1,406	1,941	0.45	0.37	166.4	1.0	-	2.75	190	275
11	600	270	1,320	1,823	0.45	0.00	209.7	4.0	-	3.25	195	260
12	700	315	1,235	1,706	0.45	0.00	259.0	6.0	-	3.50	220	280
13	400	200	1,469	2,028	0.50	0.59	137.6	0.0	-	3.50	225	340
14	500	250	1,377	1,902	0.50	0.27	179.9	3.0	-	3.00	215	305
15	600	300	1,287	1,777	0.50	0.00	228.2	9.0	16.0	0.75	230	295
16	700	350	1,196	1,652	0.50	0.00	283.8	10.5	18.0	0.75	240	320

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[3] Pound per cubic yard
[4] Fine aggregate
[5] Coarse aggregate
[6] Water reducing agent

Table 13. Hardened concrete properties

Materials								Hardened Properties									
No	Cement (pcy)	Water (pcy)	Fine Agg. (pcy)	Coarse Agg. (pcy)	w/c	WRA (oz/ 100 lb)	V_p/V_V %	Strength (psi)			RCP[7] (C[8])	Air Permeability (m/s)					
								1 day	3 day	28 day	28-day	1-day		3-day		28-day	
												Ave. k[9]	API[10]	Ave. k	API	Ave. k	API
1	400	140	1,535	2,120	0.35	1.86	109.8	1,120	2,470	3,920	N/A[11]	N/A	N/A	N/A	N/A	N/A	N/A
2	500	175	1,461	2,017	0.35	1.25	140.9	3,910	6,250	8,210	1,200	0.40	12.39	0.26	12.58	0.13	12.87
3	600	210	1,387	1,915	0.35	0.73	175.4	3,930	5,640	8,165	1,770	0.63	12.20	0.27	12.57	0.15	12.84
4	700	245	1,313	1,813	0.35	0.43	213.8	3,910	5,520	8,140	1,980	0.84	12.07	0.36	12.45	0.19	12.73
5	400	160	1,513	2,089	0.40	1.18	118.8	1,585	2,885	4,315	N/A	N/A	N/A	N/A	N/A	N/A	N/A
6	500	200	1,433	1,979	0.40	1.08	153.4	3,535	5,305	7,950	1,550	0.77	12.11	0.30	12.52	0.16	12.78
7	600	240	1,353	1,869	0.40	0.31	192.2	2,745	4,100	6,495	2,505	1.30	11.90	0.62	12.21	0.33	12.48
8	700	280	1,274	1,759	0.40	0.19	235.7	2,900	4,330	6,675	3,240	2.00	11.71	0.79	12.10	0.46	12.33
9	400	180	1,490	2,058	0.45	0.55	128.1	1,965	3,360	4,795	N/A	N/A	N/A	N/A	N/A	N/A	N/A
10	500	225	1,406	1,941	0.45	0.37	166.4	1,705	3,730	6,520	2,630	1.50	11.82	0.67	12.17	0.38	12.42
11	600	270	1,320	1,823	0.45	0.00	209.7	2,210	3,870	5,960	3,680	2.20	11.66	0.62	12.21	0.33	12.48
12	700	315	1,235	1,706	0.45	0.00	259.0	2,200	3,520	5,695	4,265	2.40	11.63	0.84	12.07	0.39	12.40
13	400	200	1,469	2,028	0.50	0.59	137.6	1,945	3,370	4,875	N/A	N/A	N/A	N/A	N/A	N/A	N/A
14	500	250	1,377	1,902	0.50	0.27	179.9	1,950	3,225	5,830	3,065	1.40	11.86	0.86	12.07	0.40	12.39
15	600	300	1,287	1,777	0.50	0.00	228.2	1,860	2,980	5,475	4,500	4.20	11.37	1.30	11.88	0.50	12.30
16	700	350	1,196	1,652	0.50	0.00	283.8	1,710	2,750	4,915	5,840	N/A	N/A	11.00	10.95	2.00	11.70

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[7] Rapid chloride penetration
[8] Coulomb
[9] Average Darcy coefficient of permeability (k) value (10^{-12})
[10] Air permeability index, log scale
[11] Not applicable

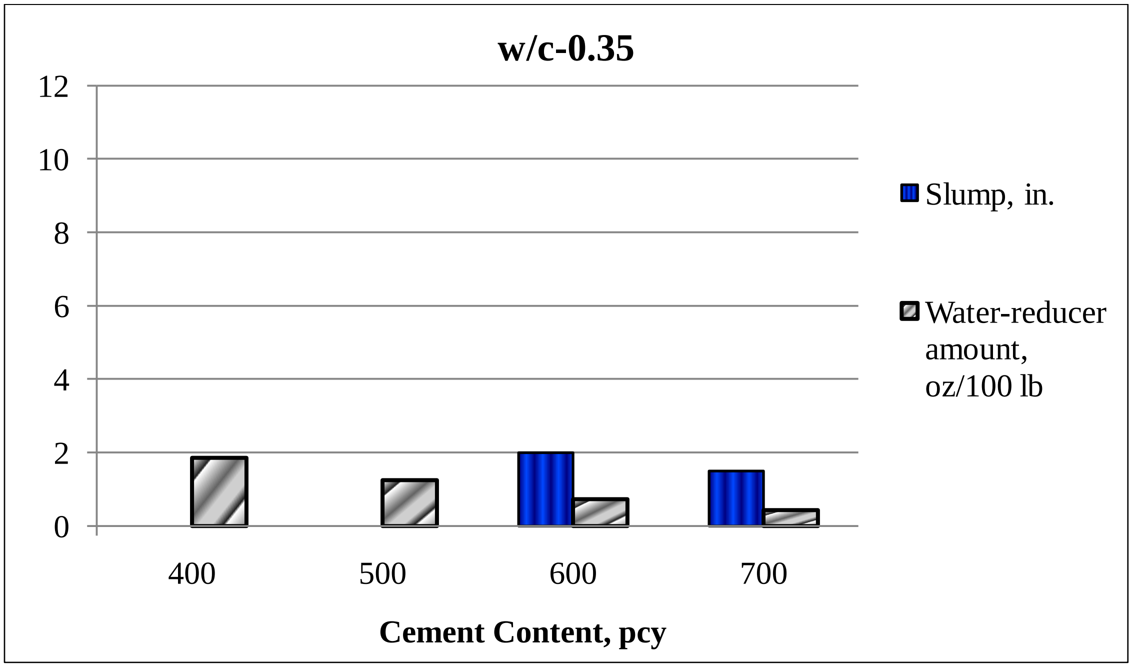
WORKABILITY

The effect of the experimental variables and the dosage of the water-reducing agent on workability are considered in two sections;

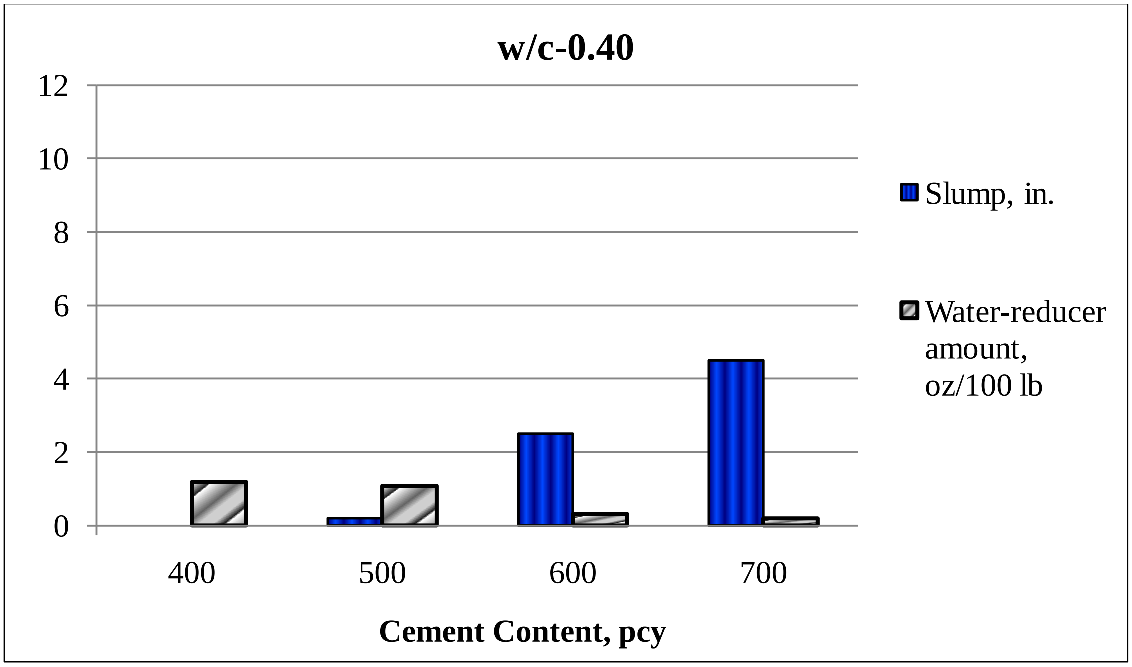
- the effect of cement content on workability, and
- the effect of w/c on workability.

Cement Content

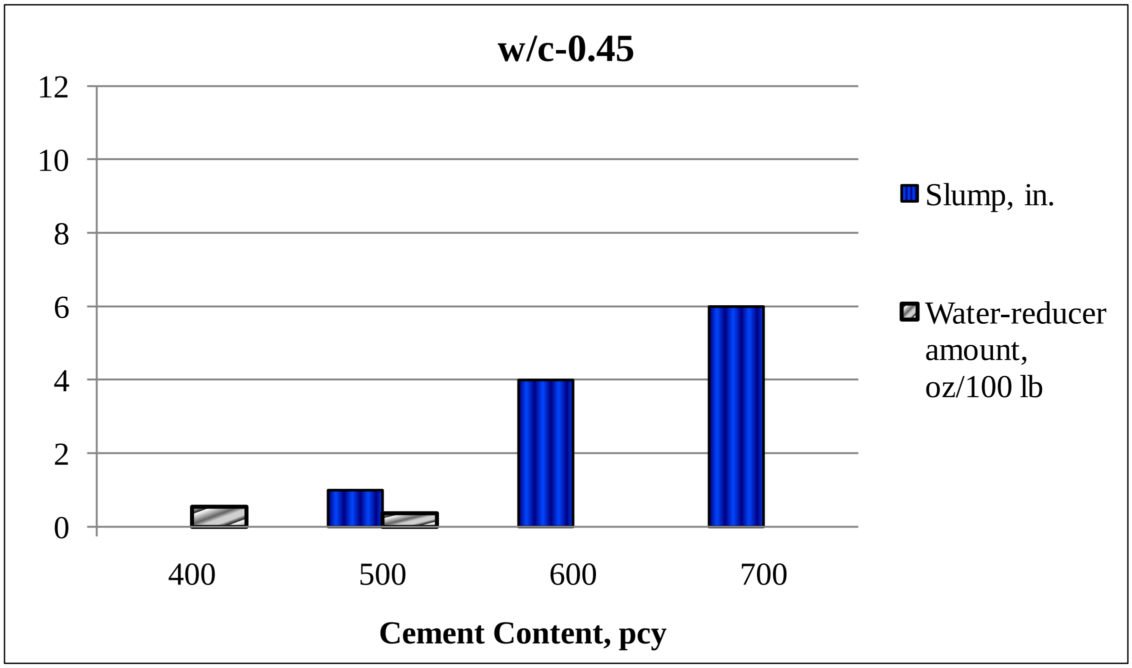
The purpose of this section is to discuss how workability is affected when cement content is increased from 400 pcy to 700 pcy for families of different w/c as presented in Figure 28.



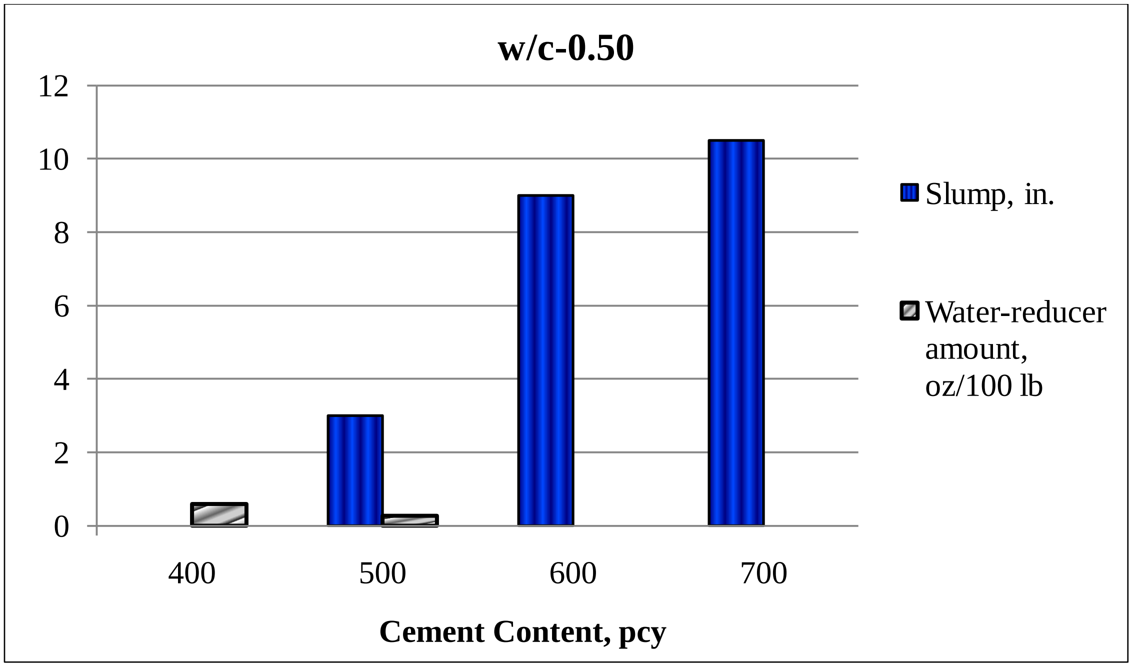
a) w/c of 0.35



b) w/c of 0.40



c) w/c of 0.45



d) w/c of 0.50

Figure 28. The effect of cement content on workability

Figure 28 shows that, for a given w/c, workability decreases as cement content (thus paste content) decreases, likely because there is insufficient paste to lubricate the aggregates. This is more remarkable with the low w/c mixtures that have lower water per unit paste contents. Due to this reduced workability, a high dosage of water-reducing agent was required because mixtures with low paste content were very stiff and had low workability (Figure 29 and Figure 30). This result indicates that adequate paste content is required to achieve a certain degree of workability.

Figure 29. The stiffness of mixture 400 pcy of cement content and w/c of 0.40

However, the addition of water-reducing agent may not help improving the workability of mixtures with low cement content, in every case. For example, despite the increased w/c and the dosage of water-reducing agent, zero slump was measured in the mixtures with 400 pcy of cement content. Moreover, low paste content and high dosage of water-reducing agent adversely affected these mixtures by decreasing their cohesiveness and causing honeycombing.

These findings are consistent with the information contained in the literature (Lamond and Pielert 2006; Kosmatka et al. 2002; Mehta and Monteiro 1993).

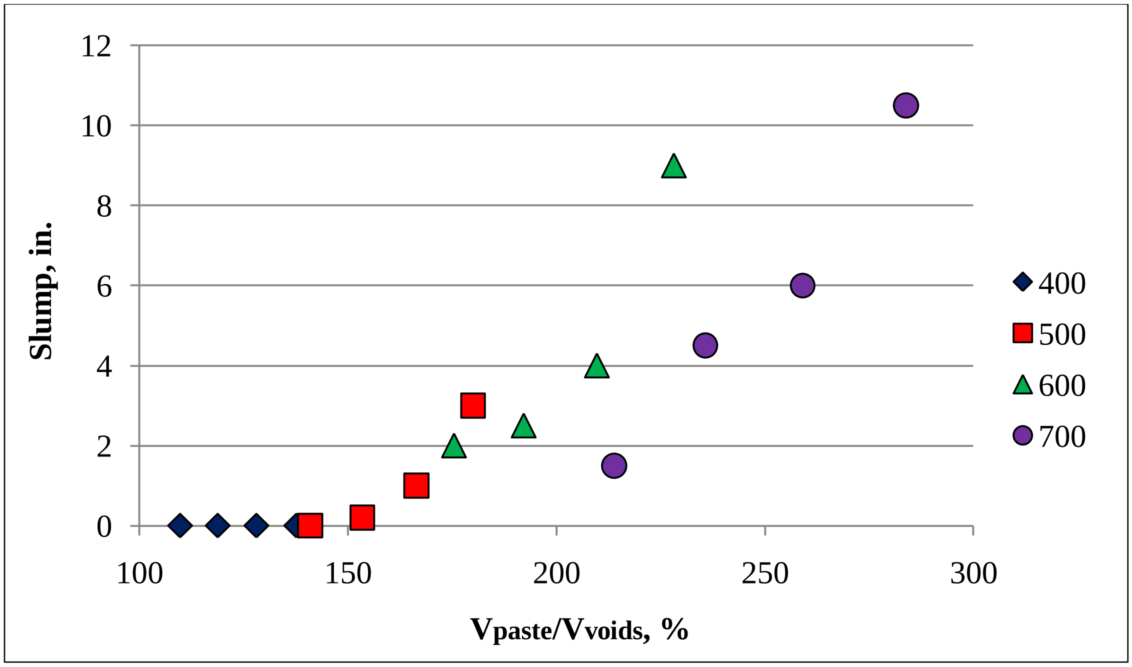


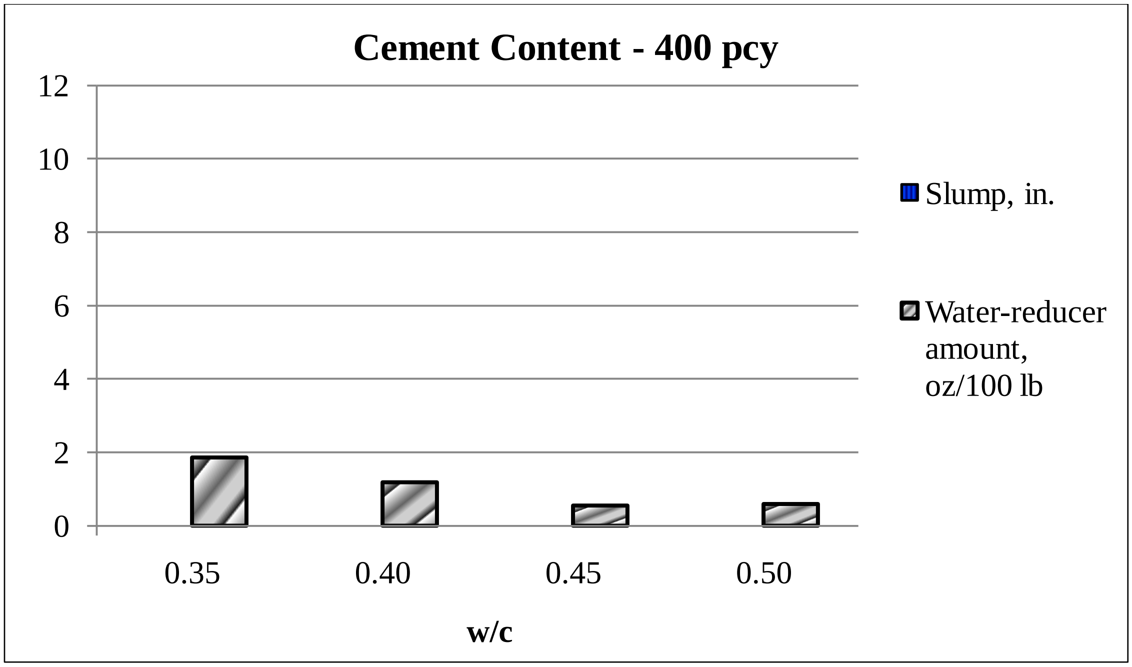
Figure 30. The effect of paste volume-to-volume of voids ratio and cement content on workability

In addition, to eliminate the effect of the selected aggregate system and generalize the findings, the relationship between paste volume and workability is established and presented in Figure 30. This figure does not present the dosage of water-reducing agent; however its effect should be considered whilst evaluating the workability trends as it was added into mixtures with low workability.

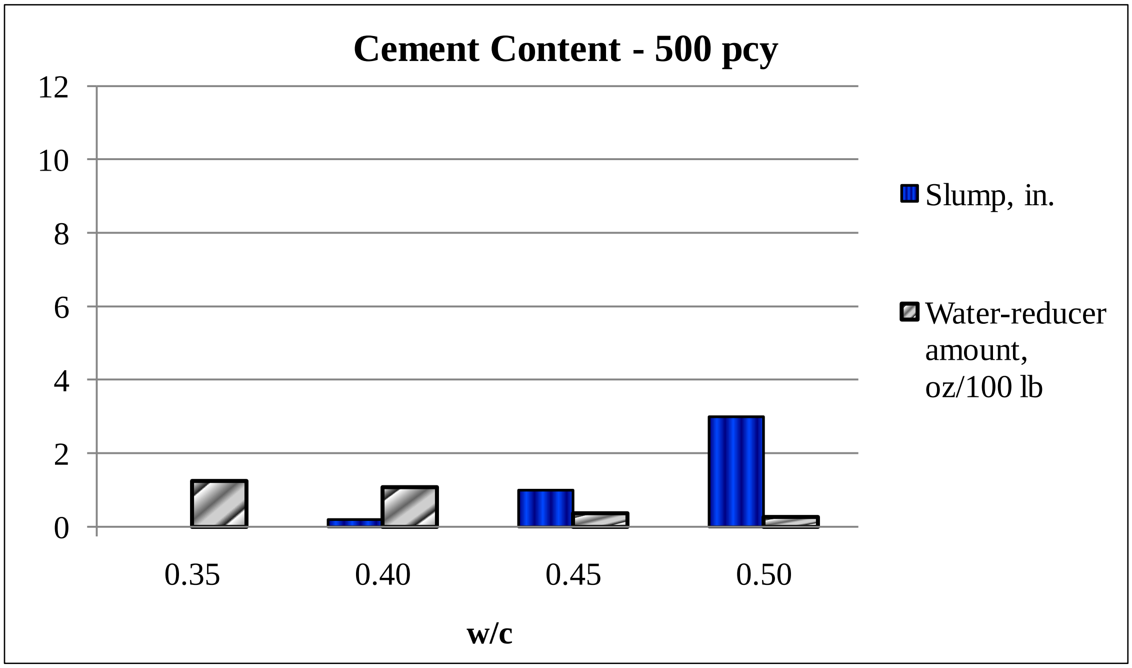
Figure 30 shows that in order to prevent obtaining zero slump, paste volume should be at least 150% of the volume of voids in a concrete mixture.

Water-to-Cement Ratio

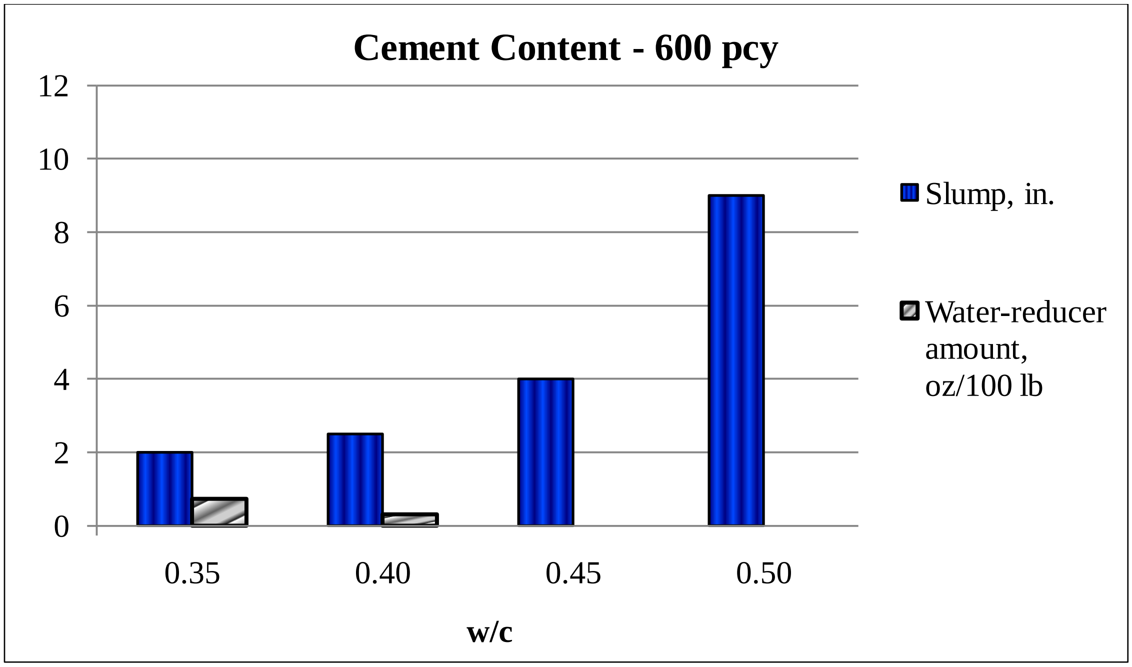
The purpose of this section is to discuss how workability is affected when w/c is increased from 0.35 to 0.50 for families of different cement content.



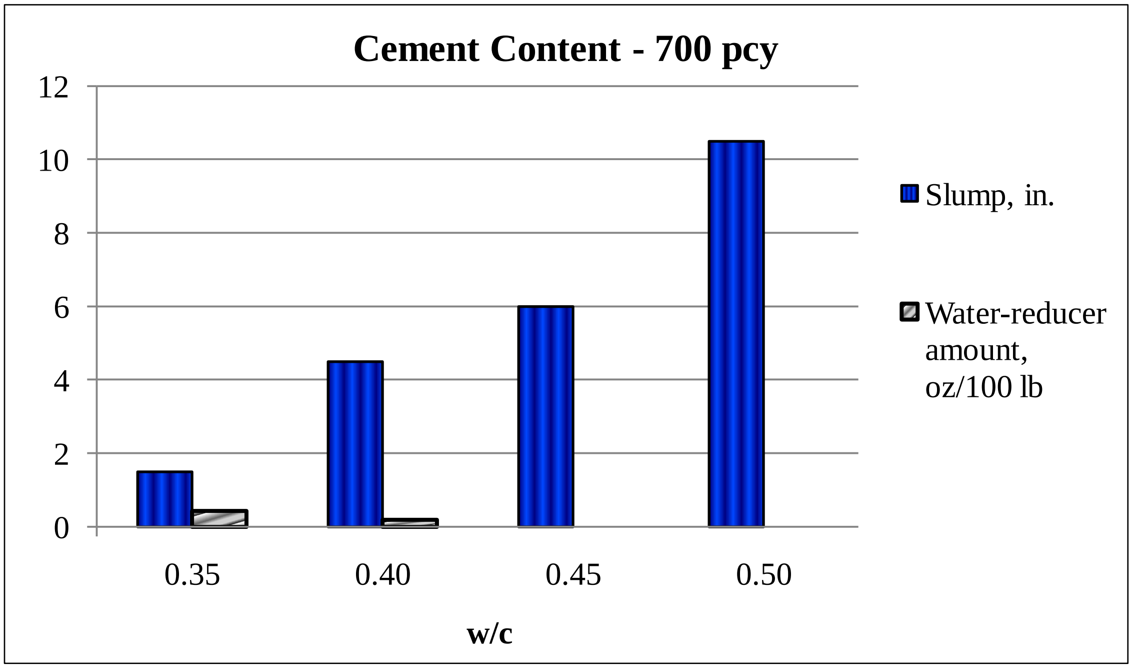
a) cement content of 400 pcy



b) cement content of 500 pcy



c) cement content of 600 pcy



d) cement content of 700 pcy

Figure 31. The effect of w/c on workability

Figure 31 shows that, for a given cement content, increasing w/c improves workability because there is more paste to lubricate the aggregates in mixtures with high w/c where the water content is increased due to the maintaining purpose of the same cement content.

Given the positive effect of increased w/c on workability, when w/c is increased lower dosage of water-reducing agent is needed. In addition, for a given w/c, increasing the paste volume-to-volume of voids ratio requires lower dosage of water-reducing agent (Figure 32). Especially in Figure 31c and d, maximum workability was achieved with mixtures containing high cement content with high w/c although no water-reducing agent was added.

These results are consistent with the information contained in the literature (Lamond and Pielert 2006; Kosmatka et al. 2002; Mehta and Monteiro 1993).

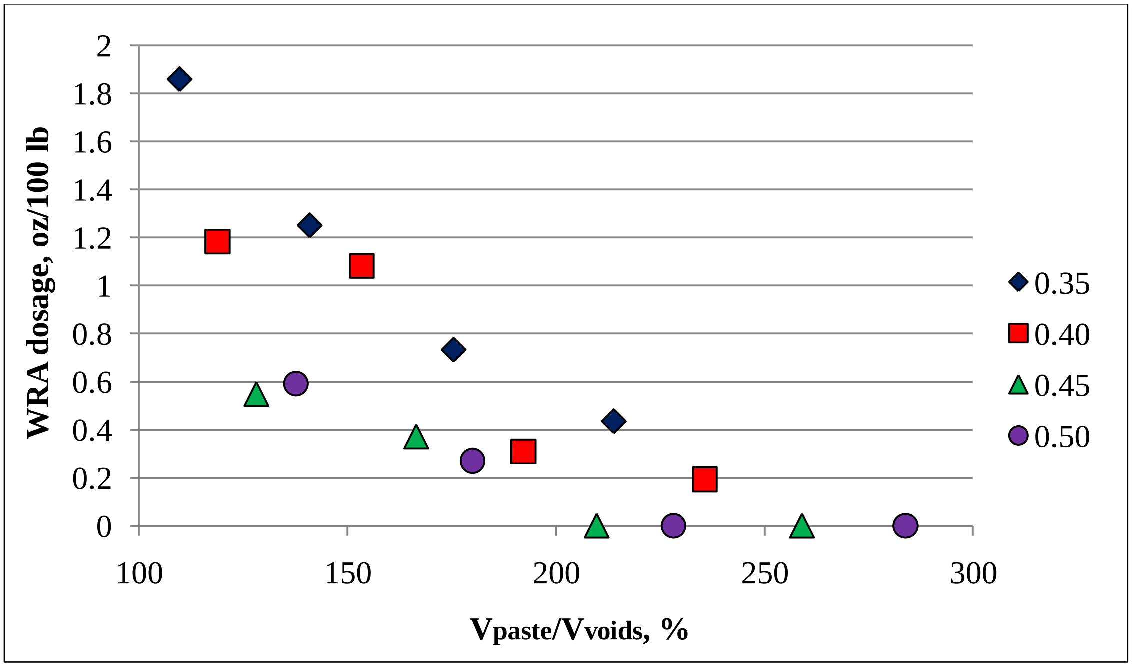


Figure 32. The effect of paste volume-to-volume of voids ratio on the dosage of water-reducing agent

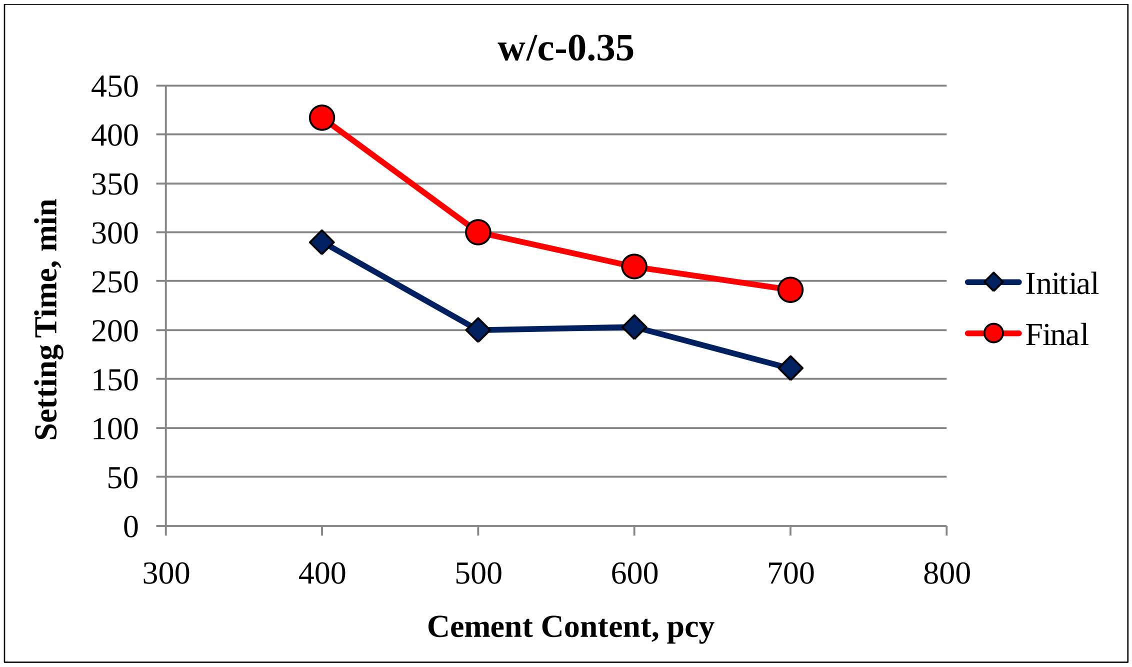
SETTING TIME

The effect of the experimental variables on setting time is considered in two sections;

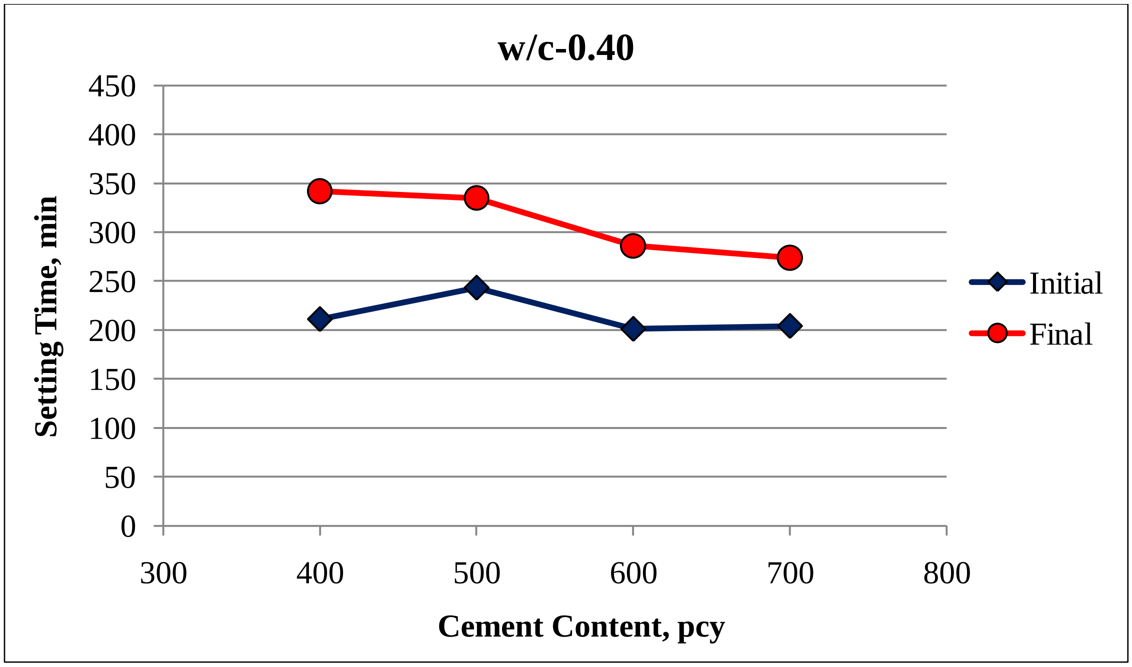
- the effect of cement content on setting time, and
- the effect of w/c on setting time.

Cement Content

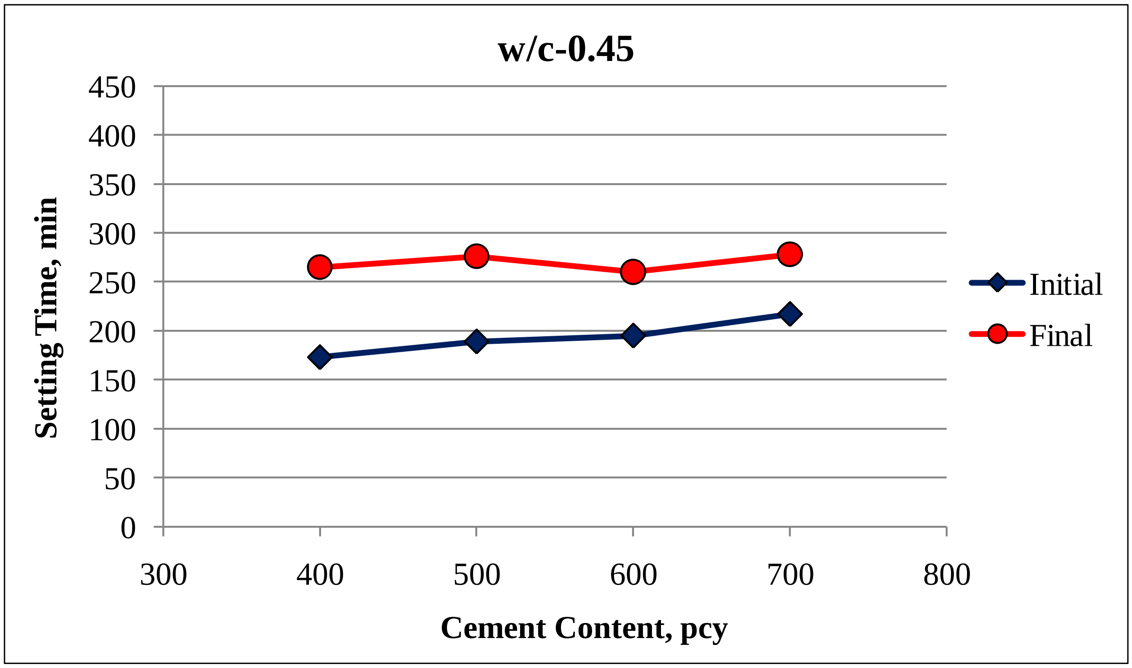
The purpose of this section is to discuss how setting time is affected when cement content is increased from 400 pcy to 700 pcy for families of different w/c as presented in Figure 33.



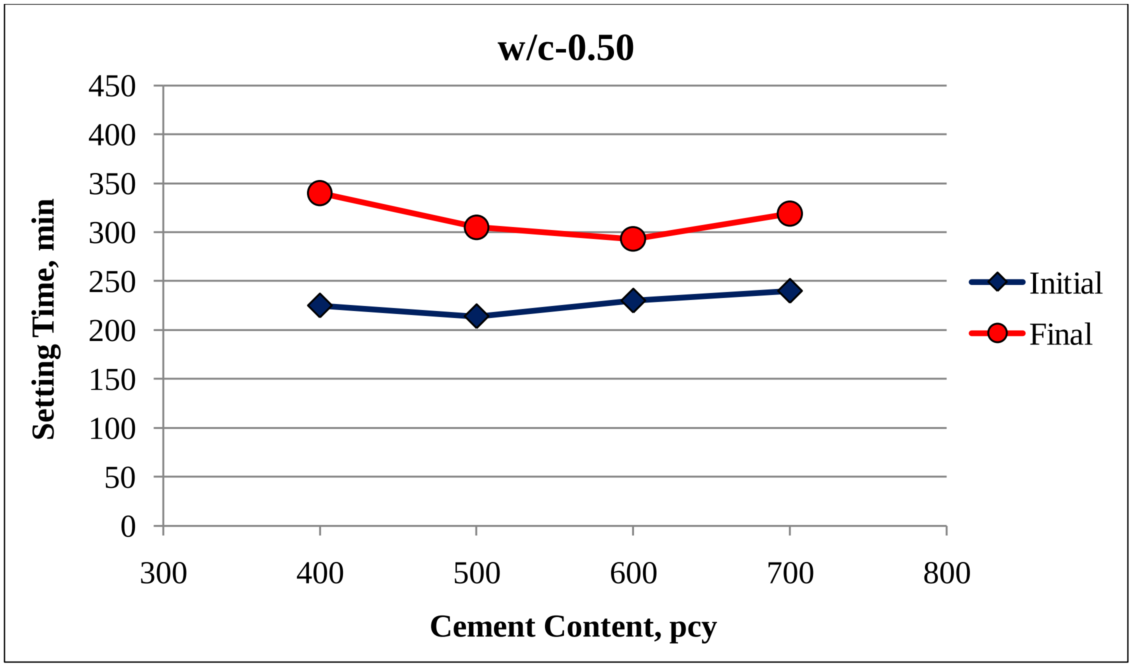
a) w/c of 0.35



b) w/c of 0.40



c) w/c of 0.45



d) w/c of 0.50

Figure 33. The effect of cement content on setting time

Figure 33 shows that, for a given w/c, as cement content decreases, overall setting time increases because of the following reasons:

- In mixtures containing low cement content, there is not sufficient paste to glue together the aggregate particles, thus it takes more time to set and harden.
- The presence of water-reducing agent may also retard the setting time especially mixtures with low w/c. This effect can be observed from Figure 33a which shows a significant reduction trend as different than the other plots. This difference may be due to the addition of high dosage of water-reducing agent into mixtures containing low cement content with a w/c of 0.35 to improve their workability. This result shows that water-reducing agents should be wisely used as it may have a side effect like retardation of setting while improving workability.

In addition, to eliminate the effect of the selected aggregate system and generalize the findings, the relationship between paste volume and setting time is established (Figure 34 and Figure 35). For a given w/c, increasing paste volume decreases both the initial and final setting time due to the same reasons listed above.

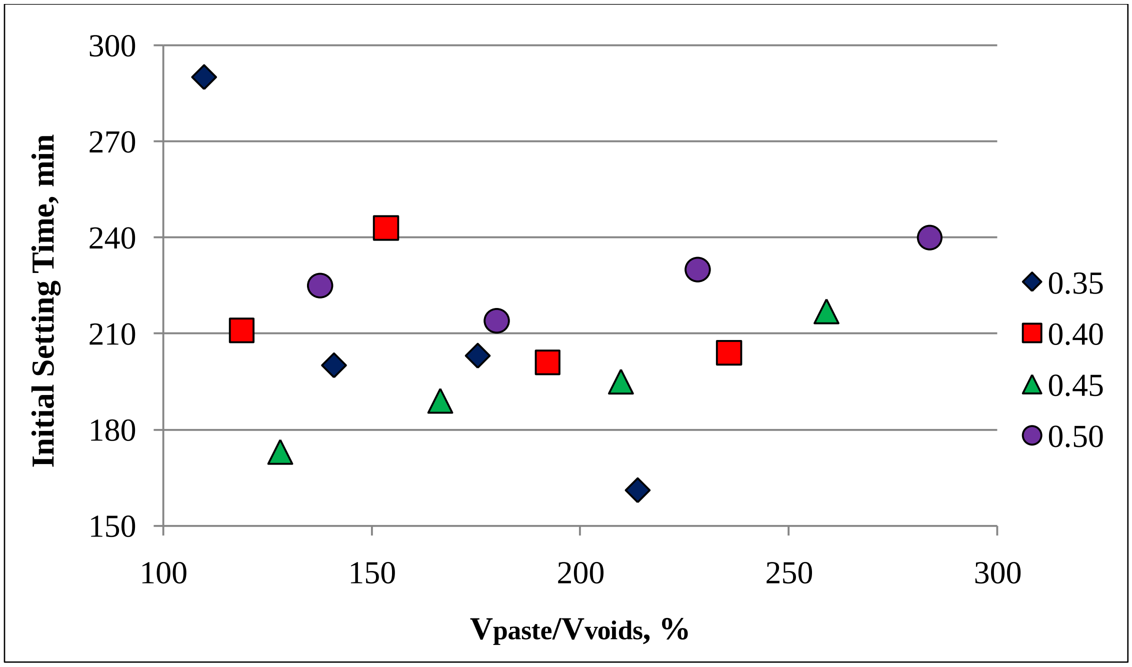


Figure 34. The effect of paste volume-to-volume of voids ratio on initial setting

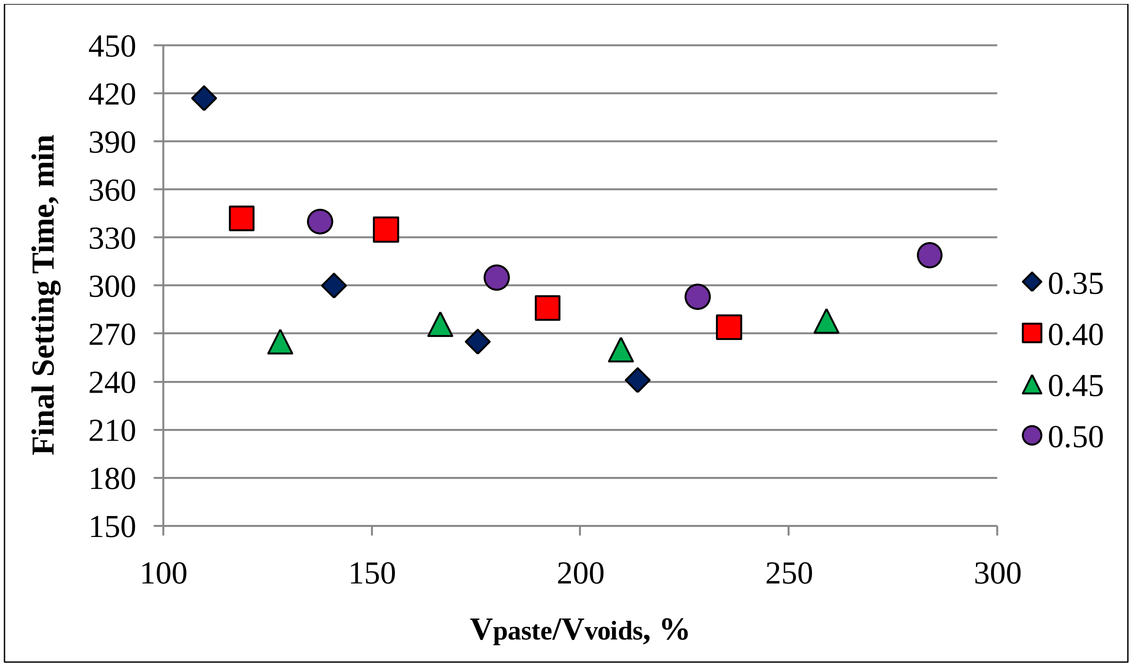
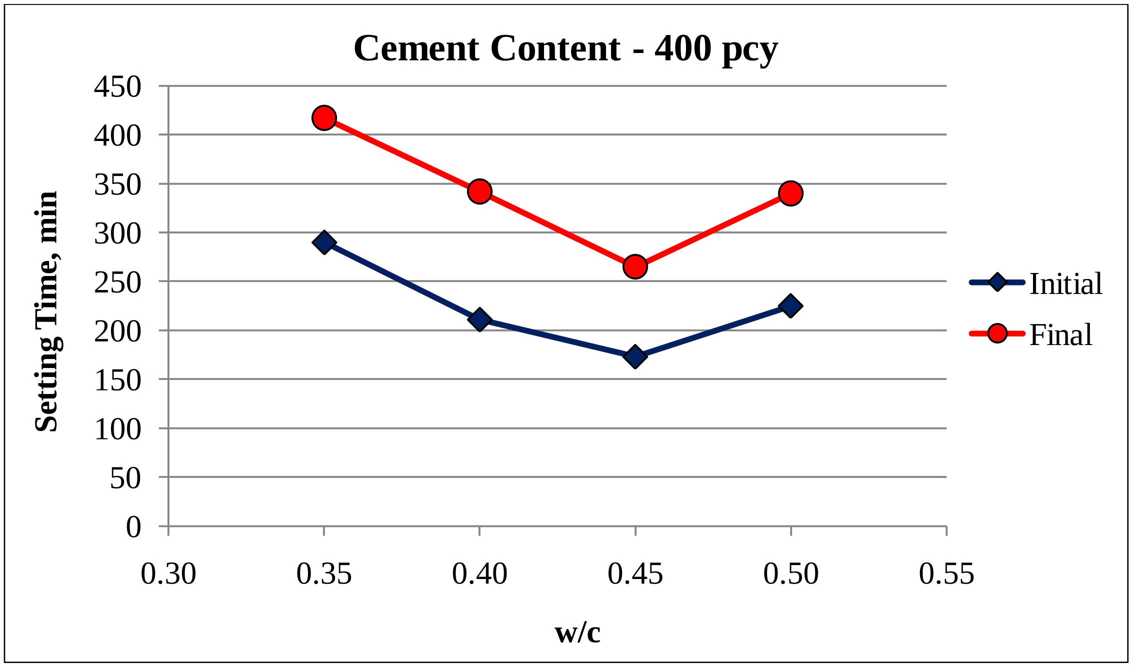


Figure 35. The effect of paste volume-to-volume of voids ratio on final setting

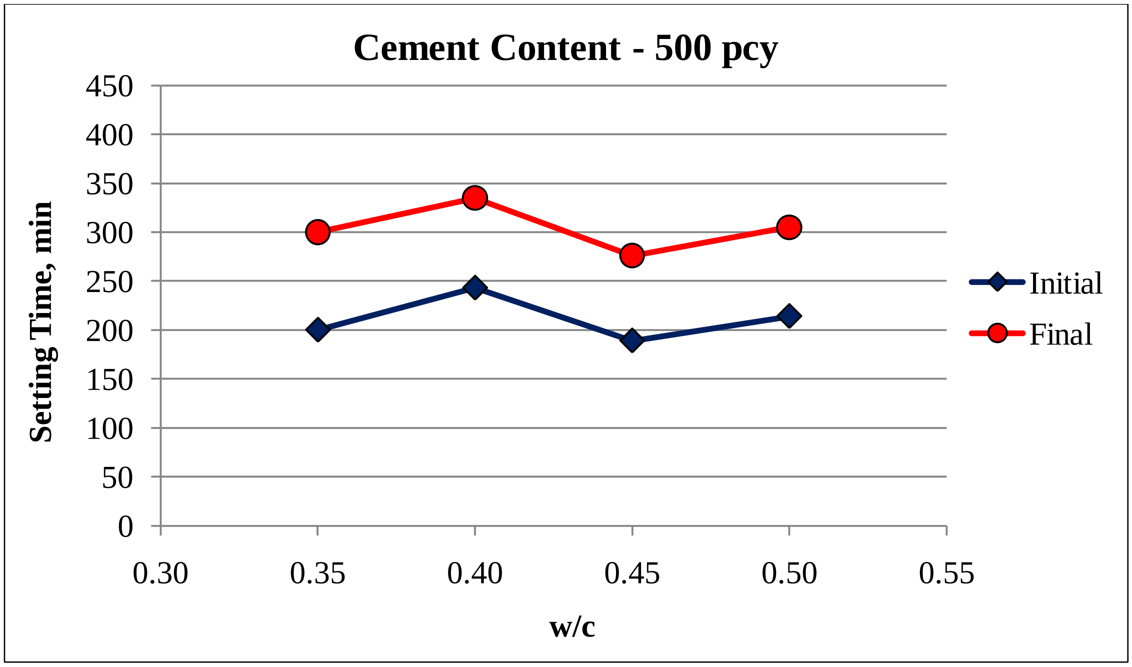
The observed findings are consistent with the literature (IMCP 2006; Mindess et al. 2003; Mehta and Monteiro 1993).

Water-to-Cement Ratio

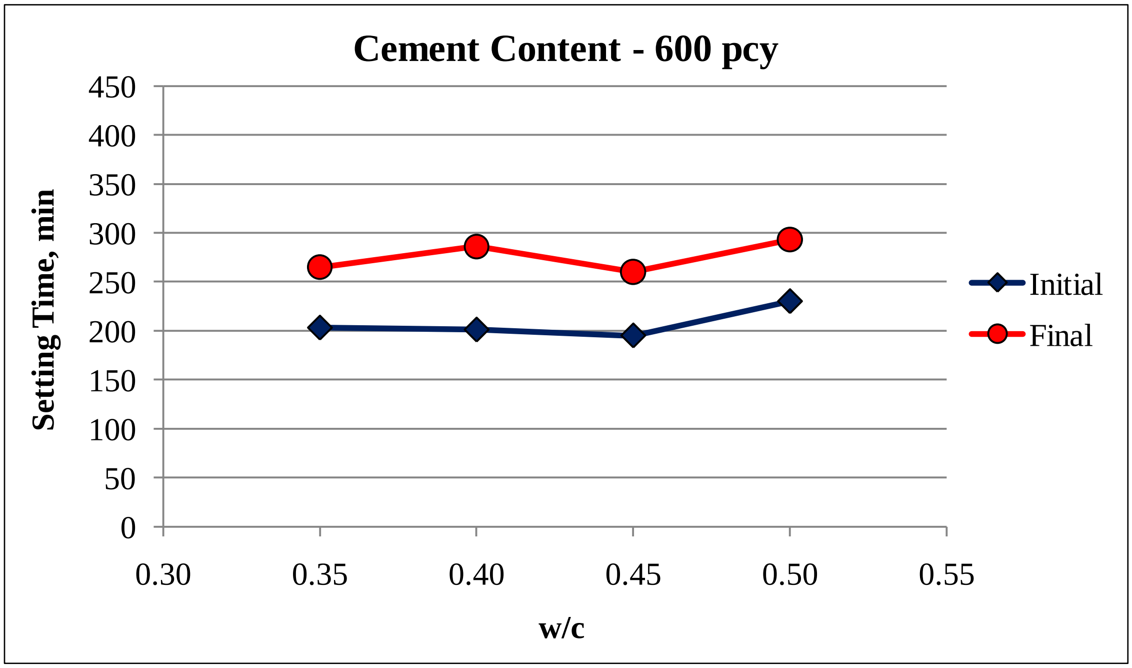
The purpose of this section is to discuss how setting time is affected when w/c is increased from 0.35 to 0.50 for families of different cement content (Figure 36).



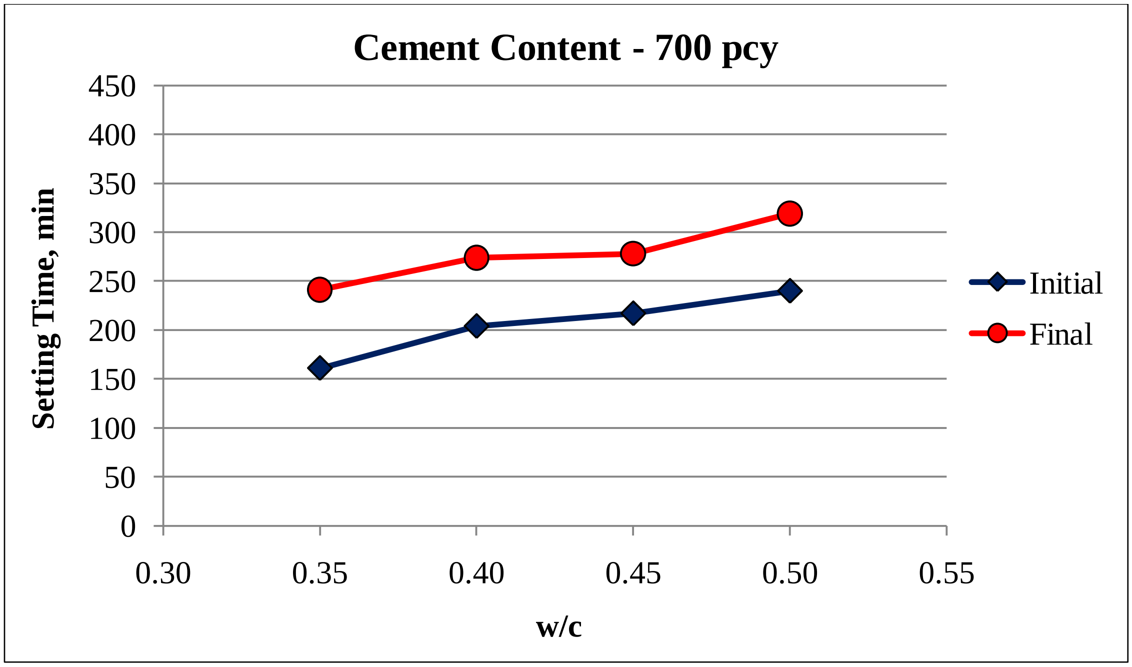
a) cement content of 400 pcy



b) cement content of 500 pcy



c) cement content of 600 pcy



d) cement content of 700 pcy

Figure 36. The effect of w/c on setting time

Figure 36 shows that, for a given cement content, decreasing w/c reduces setting time. This can be explained by the fact that for a given degree of hydration, in mixtures with lower w/c (and lower paste content) cement grains are closer to each other thereby providing a high probability of the hydration products becoming interconnected. This interconnection tends to cause stiffness while reducing the setting time.

The presence of water-reducing agent may also retard the setting time especially on mixtures with low w/c. Figure 36a shows that for a given cement content of 400 pcy, as w/c increases, overall setting time decreases because mixture containing the lowest cement content with a w/c of 0.35 has the highest dosage of water-reducing agent that was added to improve its workability. As w/c increased, the dosage of the admixture was decreased thus the setting time decreased. This result again shows that water-reducing agents should be wisely used as it may have a side effect like retardation of setting while improving workability.

The observed findings are consistent with the literature (IMCP 2006; Mindess et al. 2003; Mehta and Monteiro 1993).

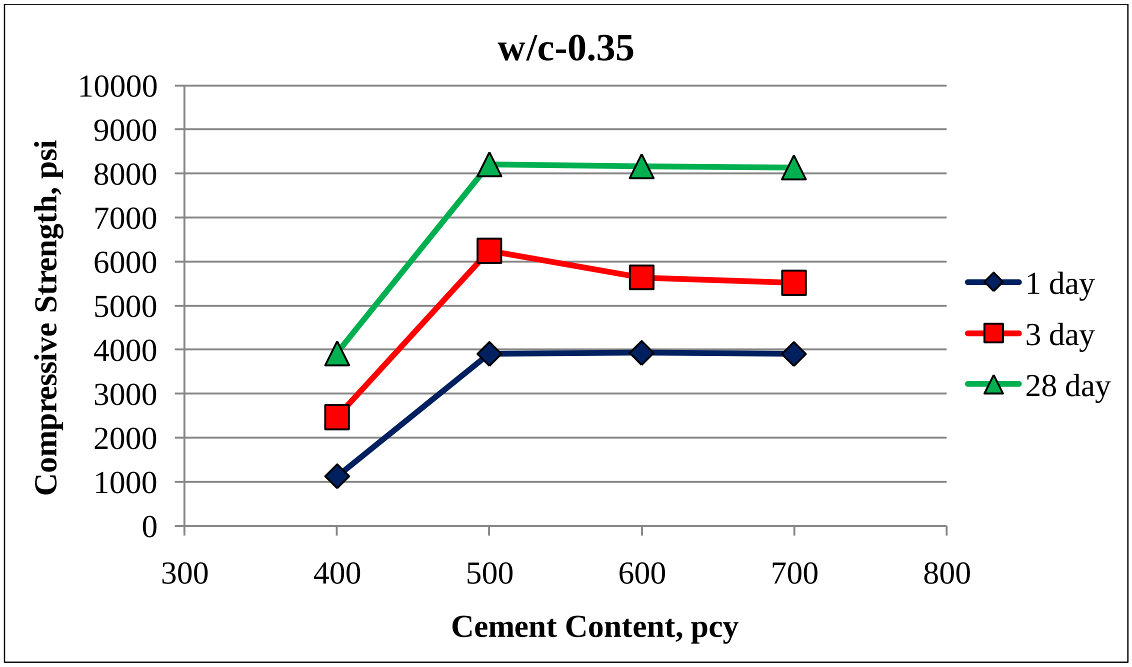
STRENGTH

The effect of the experimental variables on strength is considered in two sections;

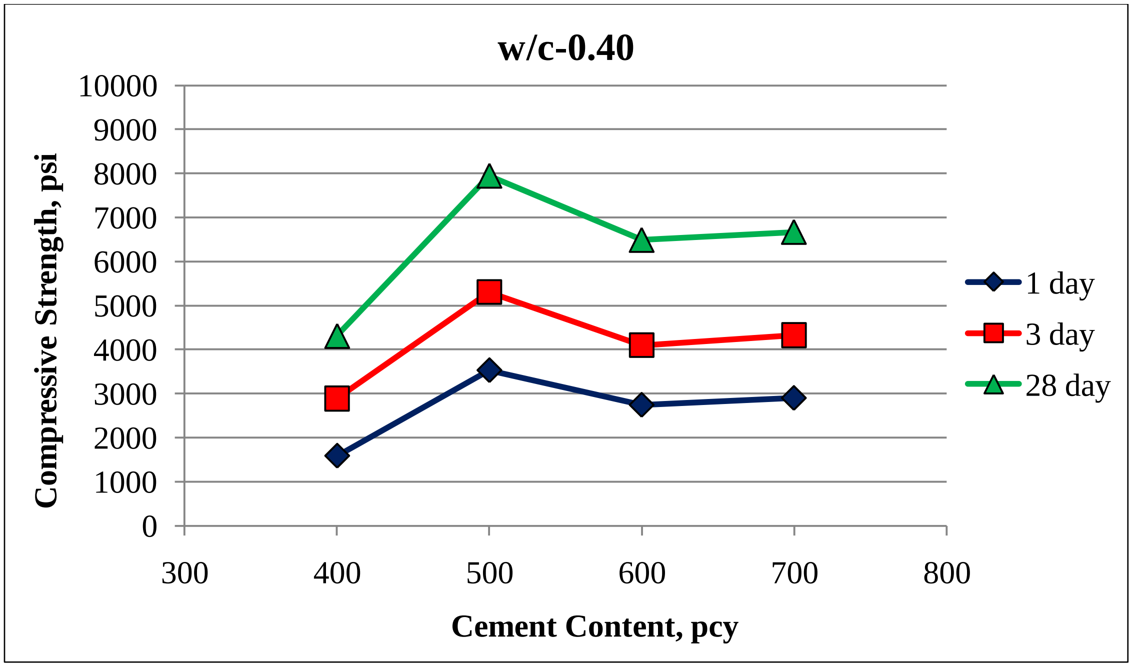
- the effect of cement content on strength, and
- the effect of w/c on strength.

Cement Content

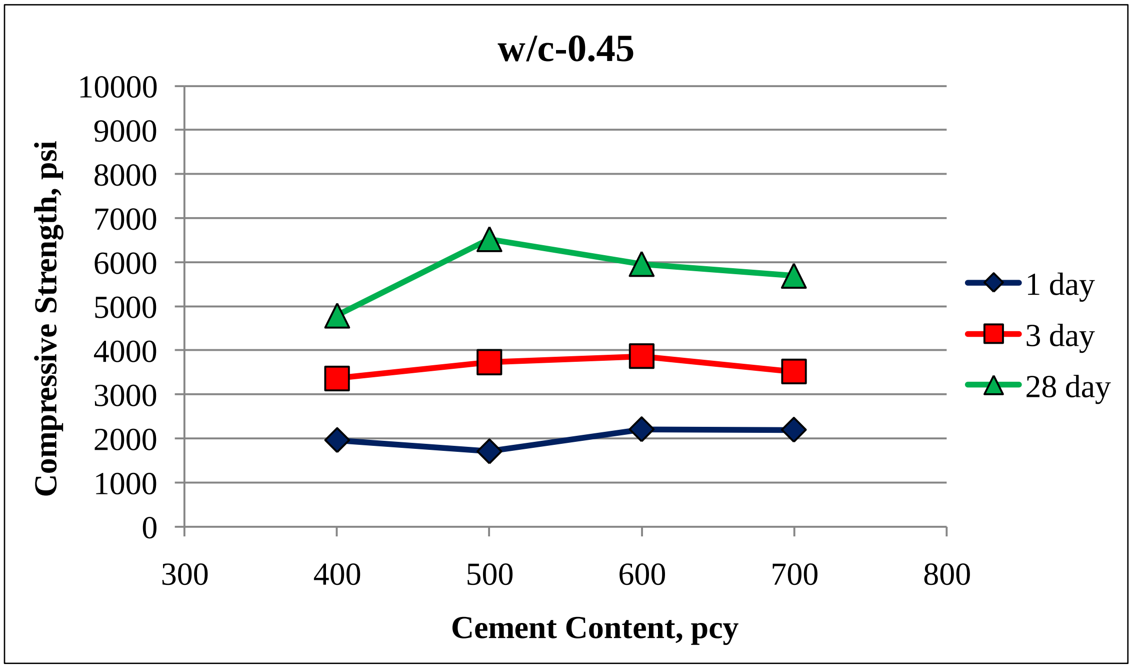
The purpose of this section is to discuss how strength is affected when cement content is increased from 400 pcy to 700 pcy for families of different w/c (Figure 37).



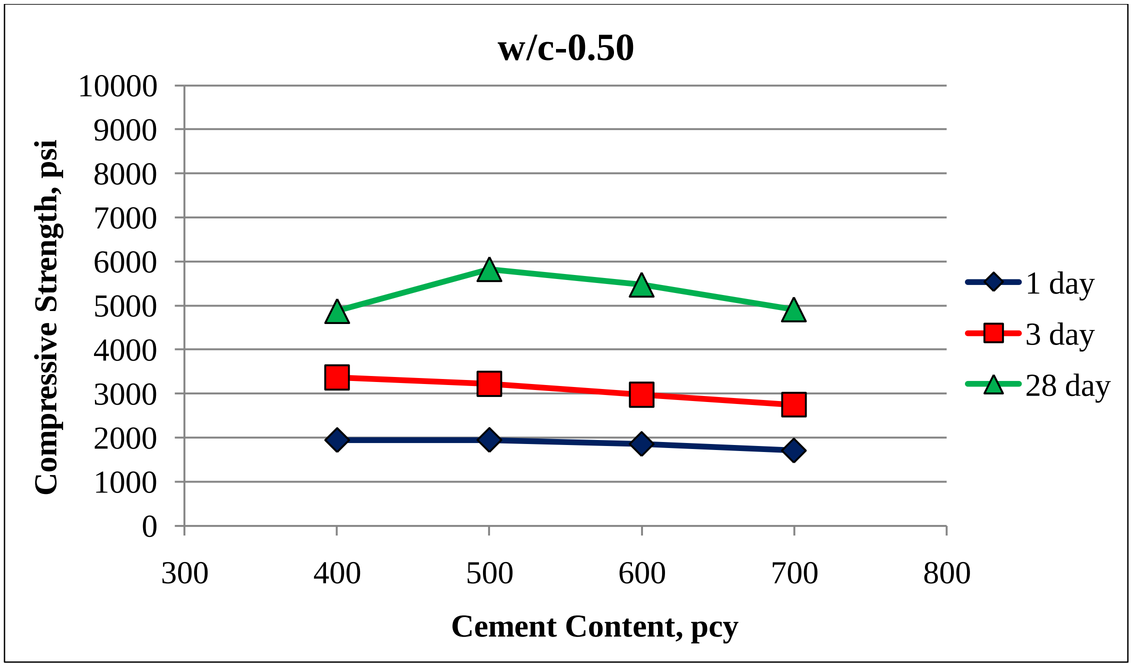
a) w/c of 0.35



b) w/c of 0.40

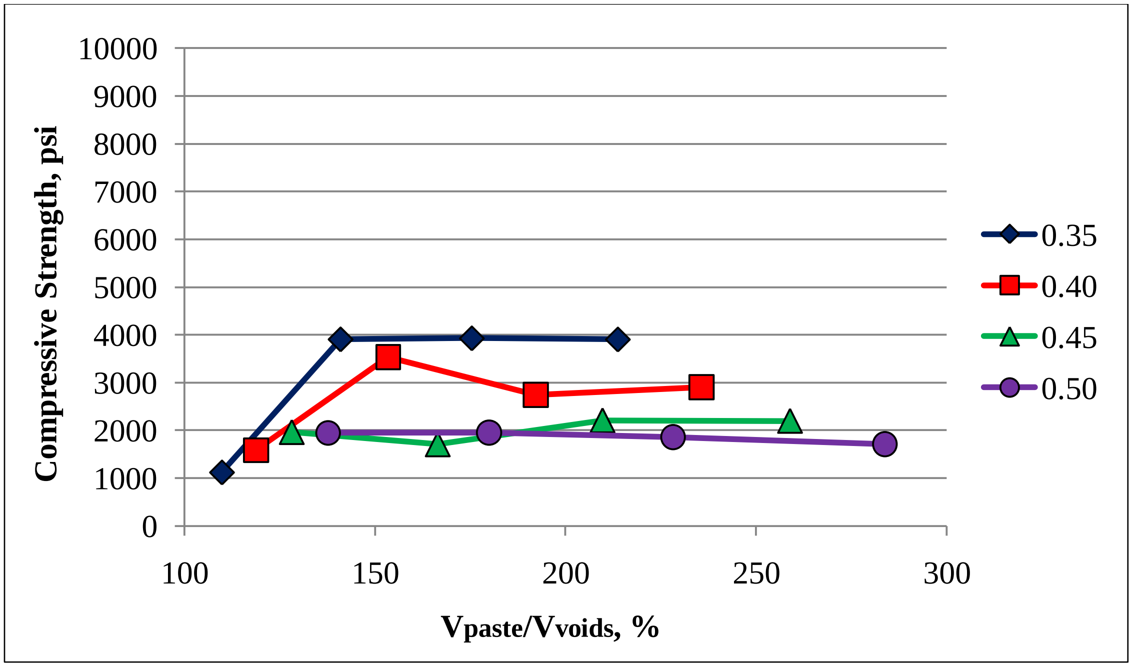


c) w/c of 0.45

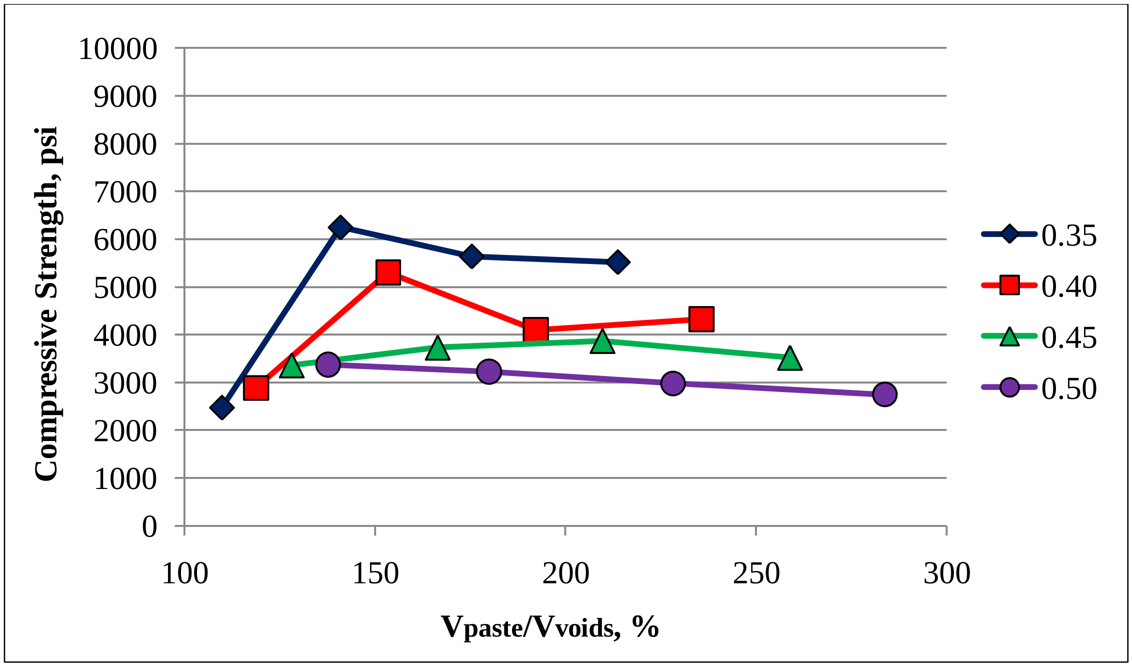


d) w/c of 0.50

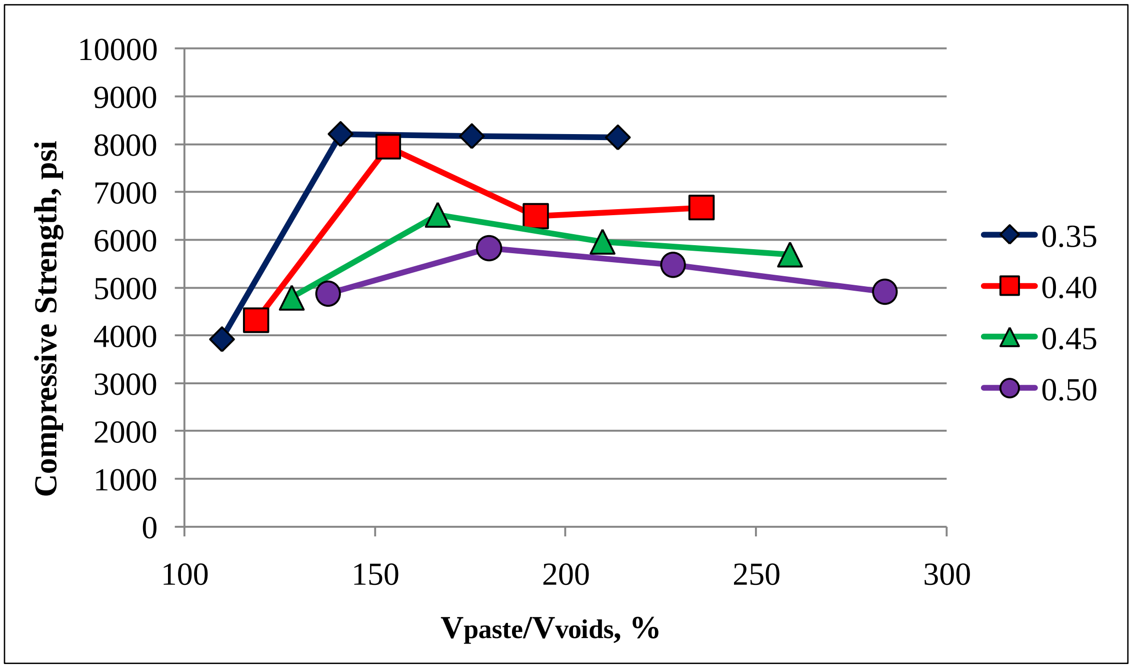
Figure 37. The effect of cement content on compressive strength



a) 1-day compressive strength



b) 3-day compressive strength



c) 28-day compressive strength

Figure 38. The effect of paste volume-to-volume of voids ratio on compressive strength

Figure 37 shows that the overall effect of cement content on strength is similar for mixtures containing different w/c. For given w/c of 0.35, 0.40, 0.45and 0.50, when cement content is increased from 400 pcy to 500 pcy, strength rapidly increases and reaches the maximum value. After that stage, for a w/c of 0.35, increasing cement content does not affect strength. For w/c of 0.45 and 0.50, increasing cement content slightly decreases strength gradually. However, mixtures with a w/c of 0.40 shows a slightly different trend that when cement content is increased from 500 pcy to 600 pcy, strength slightly decreases and then becomes stabilized. This result may be related with the variations of the batch because the standard deviation of strength between mixtures containing 600 pcy and 700 pcy is 4% at every testing age which can be negligible.

In addition, to eliminate the effect of the selected aggregate system and generalize the findings, the relationship between paste volume and compressive strength is also well-established in Figure 38. This figure also supports the findings discussed above by showing that for a given w/c of 0.35, increasing the paste volume-to-volume of voids ratio increases the strength and once the maximum value is reached, strength is not affected much by further increment. However, again mixtures with higher w/c show a slightly different trend after reaching to the maximum strength value, increasing the paste volume-to-volume of voids ratio decreases the compressive strength.

The correlation between early age strength and 28-day strength was also established. The results showed that:

- 1-day strength is 24% to 45% (average of 35%) of the 28-day strength.
- 3-day strength is 52% to 74% (average of 60%) of the 28-day strength.

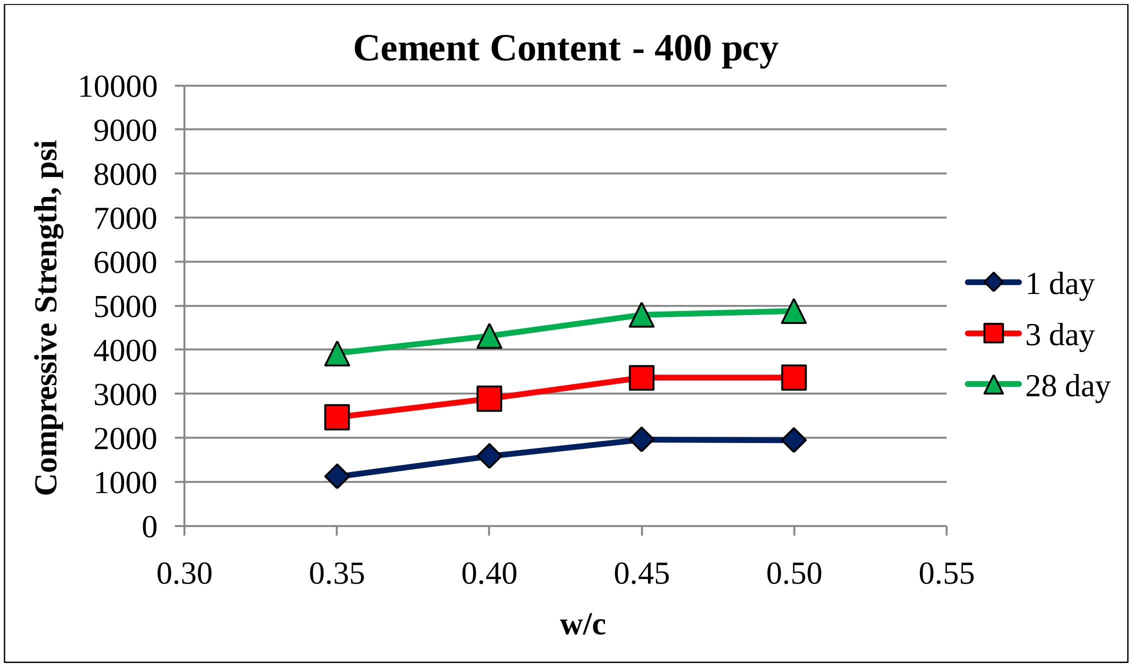
These findings are consistent with the information in the literature (Wassermann et al. 2009; Taylor et al. 2006; Dhir et al. 2004).

The observed findings are very important for this research as they indicate that for a given w/c, after required paste content is reached; increasing paste content does not affect strength. Furthermore, when w/c is constant, for the aggregate system used, 500 pcy is found to be the most appropriate cement content that provides normal 28-day compressive strength ranging from 5,800 psi (with a w/c of 0.50) to 8,200 psi (with a w/c of 0.35). This finding is more remarkable for mixtures containing low w/c (below 0.40). On the other side, in mixtures with high w/c (above 0.40), increasing cement content from 500 pcy to 700 pcy had a negative effect by decreasing 28-day compressive strength approximately 15%.

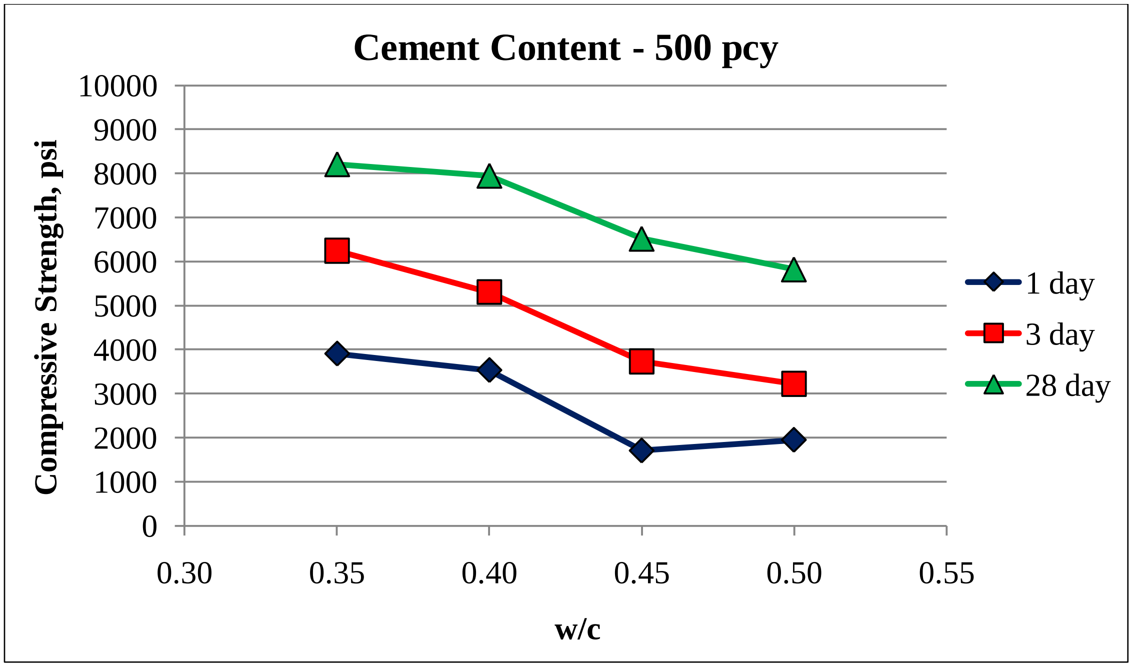
In addition, the paste volume should be within the range of 140% to 170% of the voids volume in a concrete mix to obtain the desired strength. Increasing the paste volume further than this range will not improve the compressive strength.

Water-to-Cement Ratio

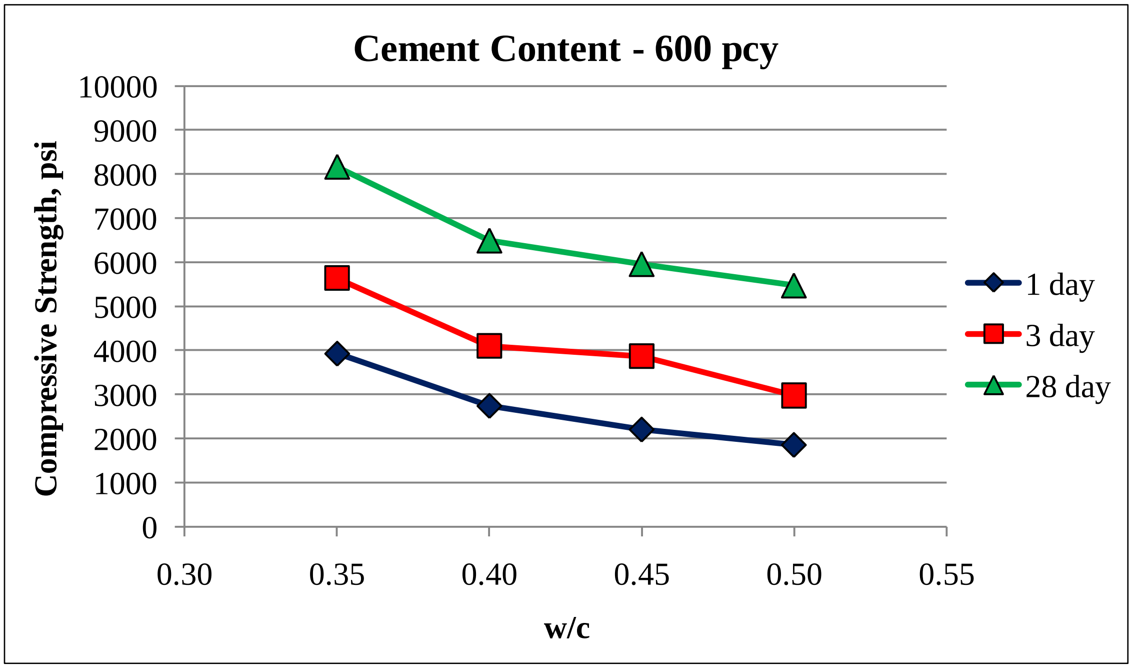
The purpose of this section is to discuss how strength is affected when w/c is increased from 0.35 to 0.50 for families of different cement content (Figure 39).



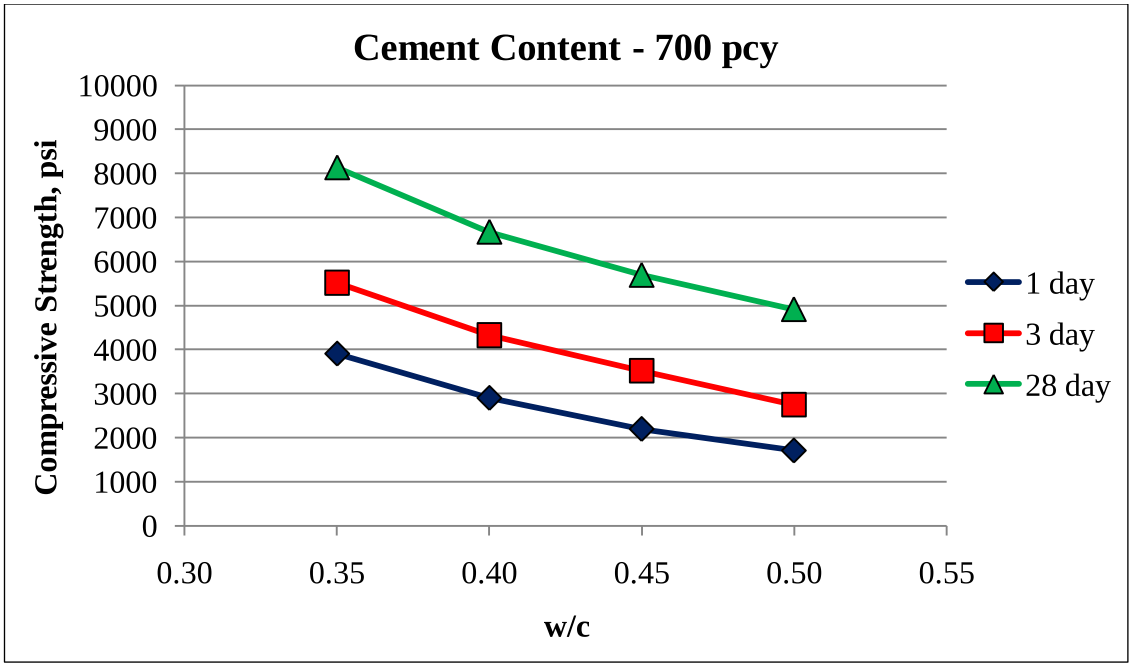
a) cement content of 400 pcy



b) cement content of 500 pcy



c) cement content of 600 pcy



d) cement content of 700 pcy

Figure 39. The effect of w/c on compressive strength

Figure 39 shows that for a given cement content, increase in w/c decreases 1, 3 and 28-day strength. This result is expected and consistent with the literature that strength is a function of w/c and decreases as w/c increases because capillary porosity increases.

However, mixtures with a w/c of 0.35 show a different trend that when w/c is increased from 0.35 to 0.45, strength increases and then becomes stabilized. This result is caused because the cement content of 400 pcy was not sufficient to coat and bind the aggregates as shown in Figure 40.

These findings are consistent with the information in the literature (Wassermann et al. 2009; Taylor et al. 2006; Dhir et al. 2004; Schulze 1999).

From left to right, w/c of 0.35, 0.40, 0.45, and 0.50

Figure 40. The effect of w/c on compactibility, which has been shown to affect compressive strength, for 400 pcy of cement content

RAPID CHLORIDE PENETRATION

The effect of the experimental variables on rapid chloride penetration is considered in two sections;

- the effect of cement content on chloride penetration, and
- the effect of w/c on chloride penetration.

The observed test results were compared with the values in the table below from ASTM C1202.

Table 14. Chloride penetration based on charge passed (ASTM C1202)

Charge Passed (Coulombs)	**Chloride Penetration**
> 4,000	High
2,000 – 4,000	Moderate
1,000 – 2,000	Low
100 – 1,000	Very Low
<100	Negligible

Cement Content

The purpose of this section is to discuss how chloride penetration is affected when cement content is increased from 400 pcy to 700 pcy for families of different w/c (Figure 41).

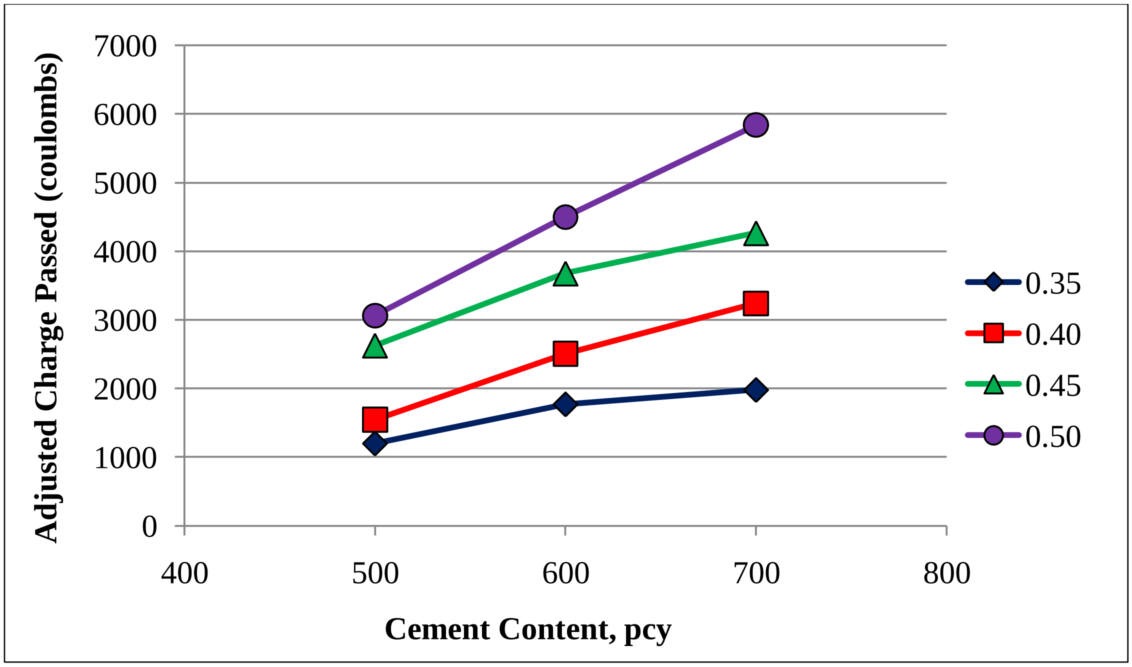


Figure 41. The effect of cement content on rapid chloride penetration

Rapid chloride penetration test failed on mixtures with 400 pcy of cement content as they could not be consolidated properly due to their low paste content (Figure 42).

a)

b)

Figure 42. Porosity of mixture with 400 pcy of cement content and 0.35 of w/c

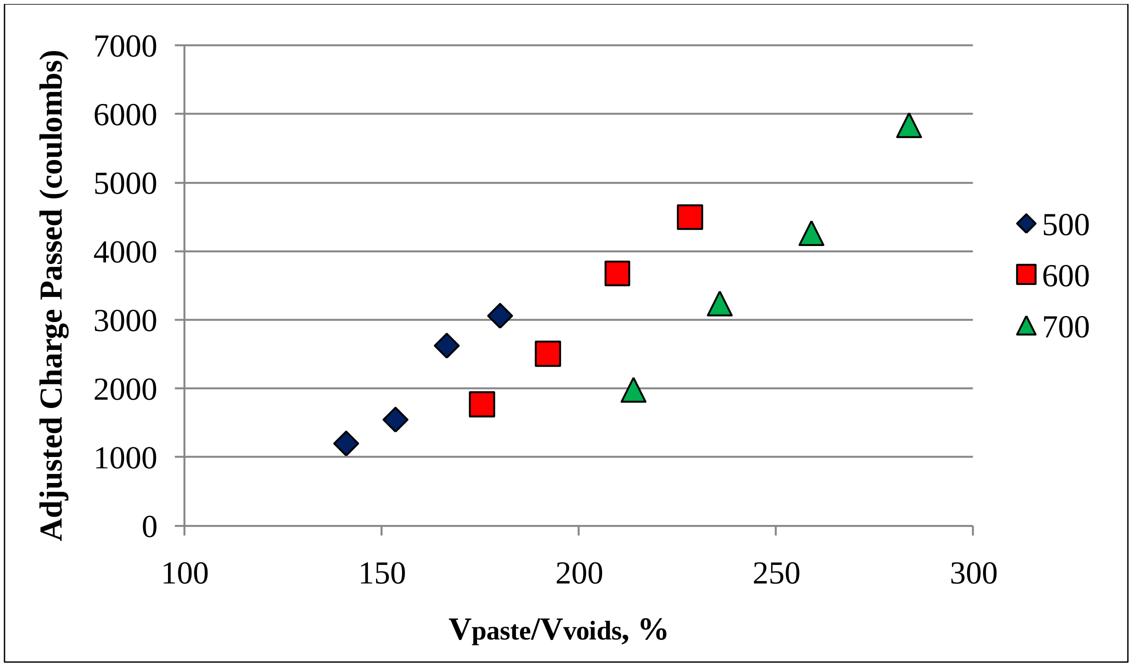


Figure 43. The effect of cement content and paste volume-to-volume of voids ratio on chloride penetration

It is more likely that chlorides penetrate the paste faster than the aggregate. For a given w/c, this increased paste content increases the relative volume of material able to transmit chlorides and chloride penetrability. The paste quality reflected in the w/c also strongly influences chloride penetrability with high w/c allowing larger amounts of chloride penetration (Figure 43). These findings are consistent with the information in the literature (Wassermann et al. 2009; Arachchige 2008; Buenfeld and Okundi 1998; Stanish et al. 1997; Collepardi and Biagini 1989).

When the overall effect of cement content on chloride penetration is evaluated, 400 pcy of cement content is not recommended due to its porosity and honeycombing caused by its low paste content. Furthermore, as increasing cement content increases the chloride penetration, 600 pcy and 700 pcy would not be the best option. Therefore, when w/c is constant, for the aggregate system used, 500 pcy is found to be the most appropriate cement content that provides the lowest chloride penetration.

In addition, to eliminate the effect of the selected aggregate system and generalize the findings, the relationship between paste volume and chloride penetration was established: increasing the paste volume-to-volume of voids ratio increases the chloride penetration (Figure 43). According to Table 14, the charge passed under 2000 coulombs is desirable. Therefore, the paste volume-to-volume of voids ratio should be within the range of 145% to 180% to obtain a mixture with low chloride penetration (less than 2000 coulombs) for the cementitious materials used in this work.

Water-to-Cement Ratio

The purpose of this section is to discuss how chloride penetration is affected when w/c is increased from 0.35 to 0.50 for families of different cement content.

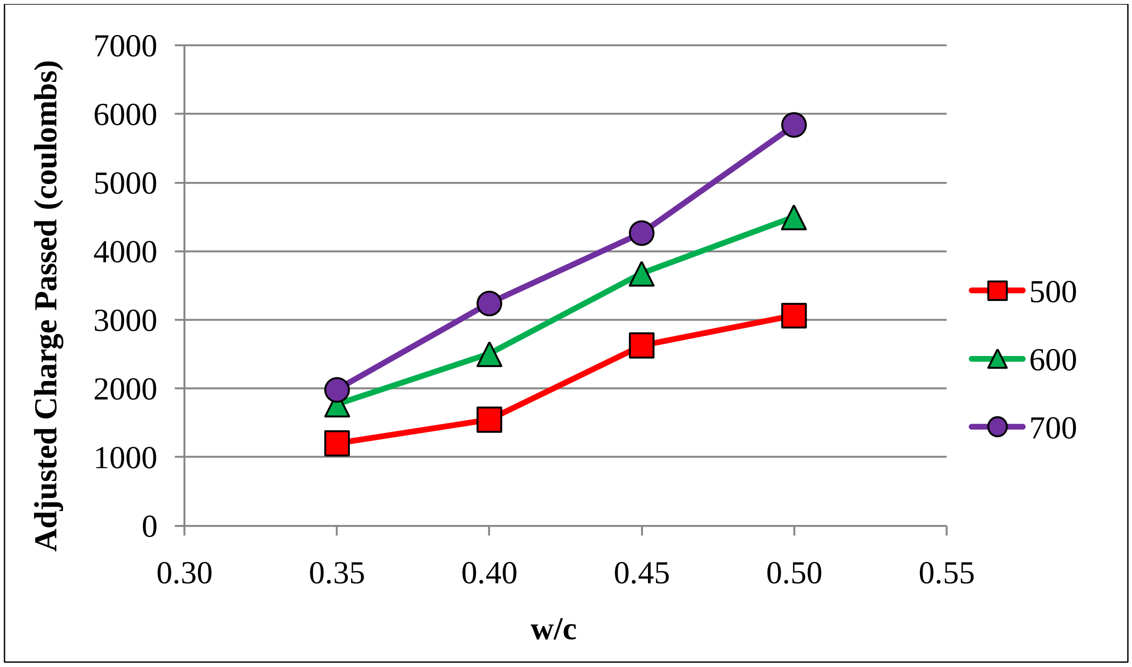


Figure 44. The effect of w/c on rapid chloride penetration

Figure 44 shows that, for a given cement content, chloride penetration increases when w/c increases because the capillary porosity increases and more pores become available for chloride penetration.

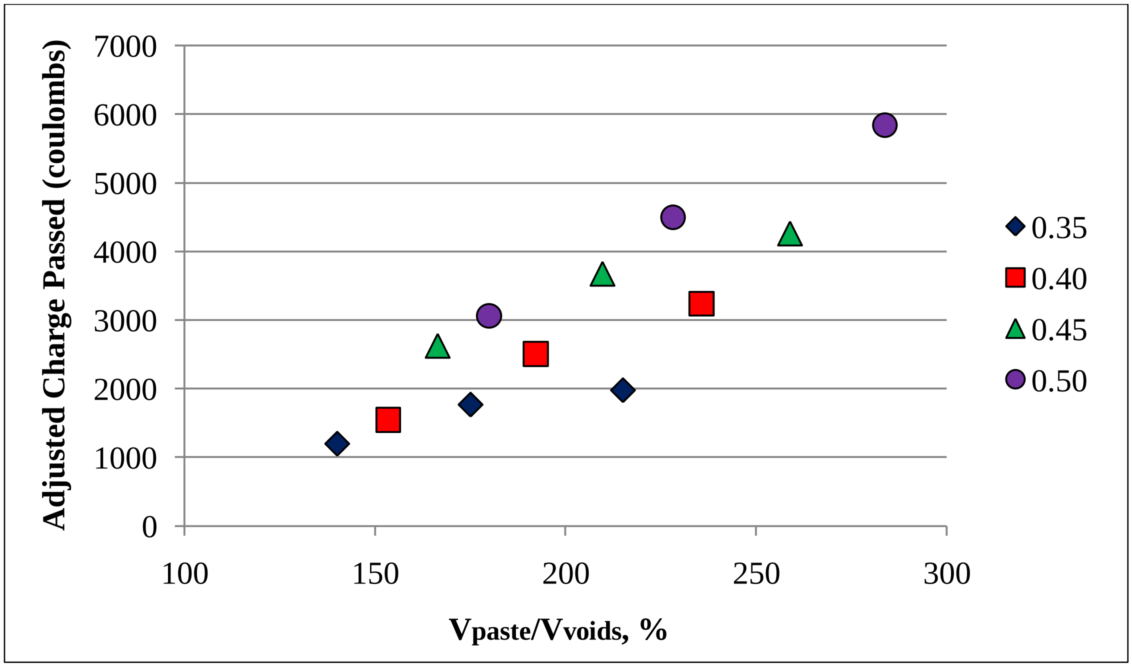


Figure 45. The effect of w/c and paste volume-to-void volume on chloride penetration

In addition, Figure 45 show that increasing the ratio of paste volume-to-the volume of voids also increases the chloride penetration because increased paste content and increased w/c increases the porosity. This result also supports the previous discussion that chloride penetrates the paste rather than the aggregate because chlorides will tend to ingress through the pores rather than penetrating aggregates which are denser.

Based on Figure 45, the paste volume-to-volume of voids ratio should be within the range of 145% to 180% to obtain a mixture with low penetration (less than 2000 coulombs).

These findings are consistent with the information in the literature (Dhir et al. 2004; Mindess et al. 2003; Kosmatka et al. 2002; Stanish et al. 1997; Mehta and Monteiro 1993; Collepardi and Biagini 1989).

AIR PERMEABILITY

Air permeability index is the negative log of the Darcy coefficient of permeability (m/s) and uses a log scale (Buenfeld and Okundi 1998). Therefore, lower air permeability index indicates higher permeability.

The effect of the experimental variables on air permeability is considered in two sections.

Cement Content

The purpose of this section is to discuss how air permeability is affected by changing the cement content, for a given w/c.

Air permeability test could not be conducted on mixtures with 400 pcy of cement content because their low paste content caused high porosity (Figure 46).

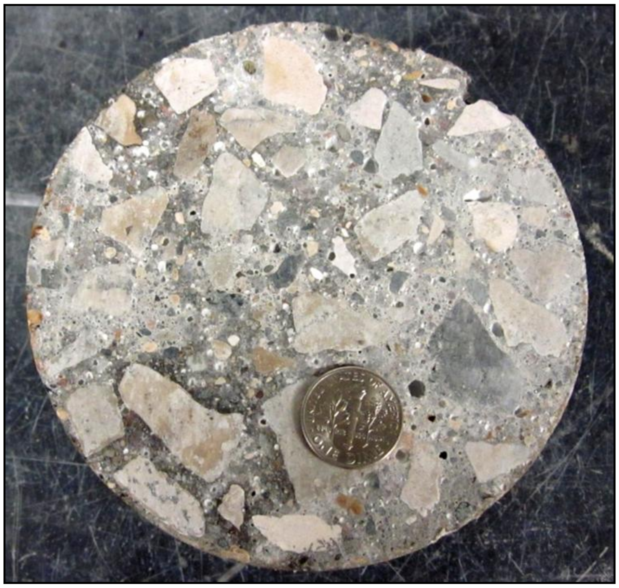


Figure 46. Porosity of mixture with 400 pcy of cement content and 0.40 of w/c

In addition, 1-day air permeability test could not be performed on the mixture with 700 pcy of cement content and a w/c of 0.50 due to its high porosity. High w/c and cement content in concrete caused high cohesiveness in this mixture which hindered the consolidation and caused pores as shown in Figure 47. Therefore, air permeability test failed. This finding is also supported by Buenfeld and Okundi (1998) as they stated that “air permeability measurement reflects more the general state of compaction and macrovoidage in the concrete than the microstructure”.

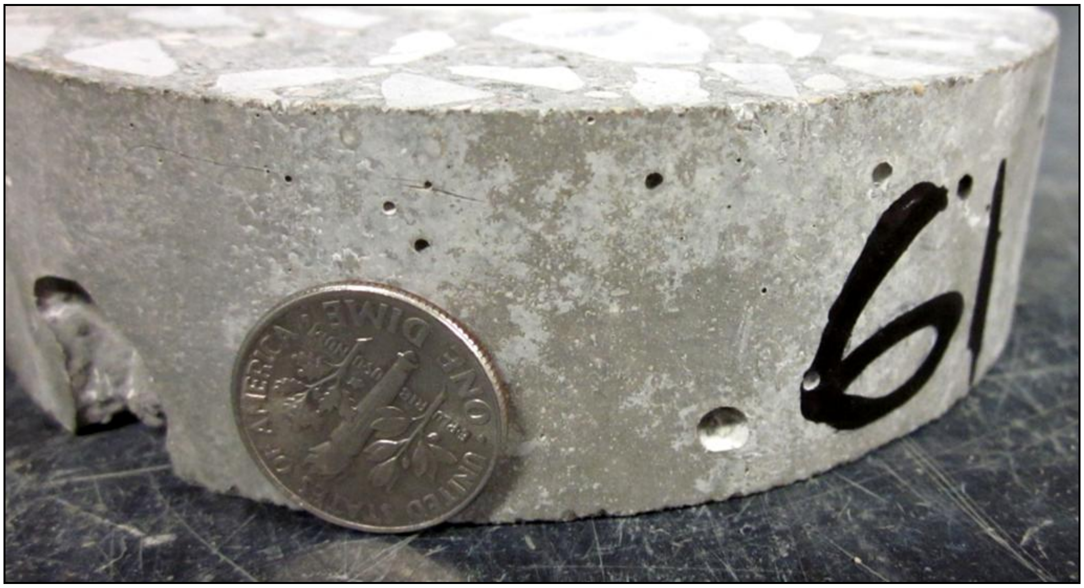
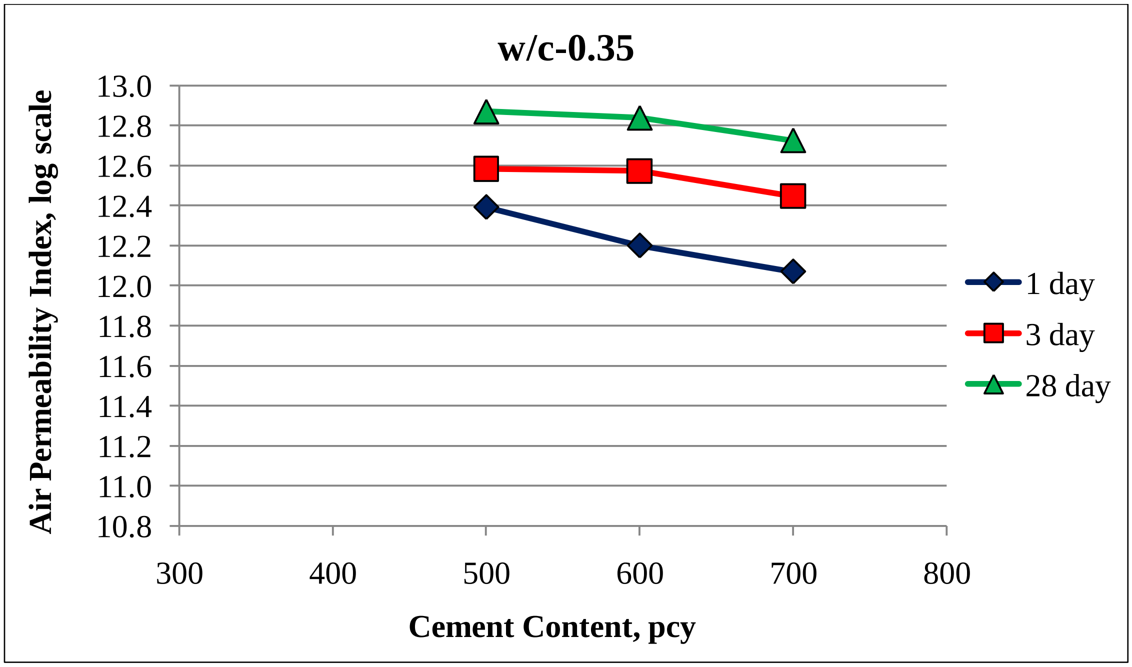
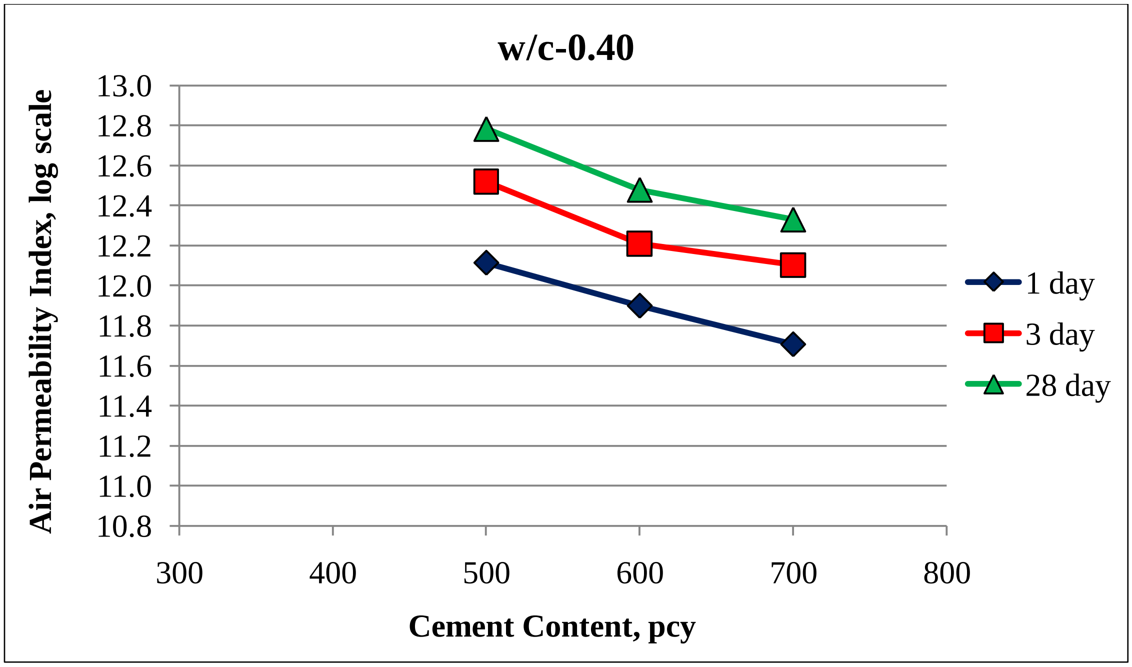


Figure 47. Porosity of mixture with 700 pcy of cement content and 0.50 of w/c

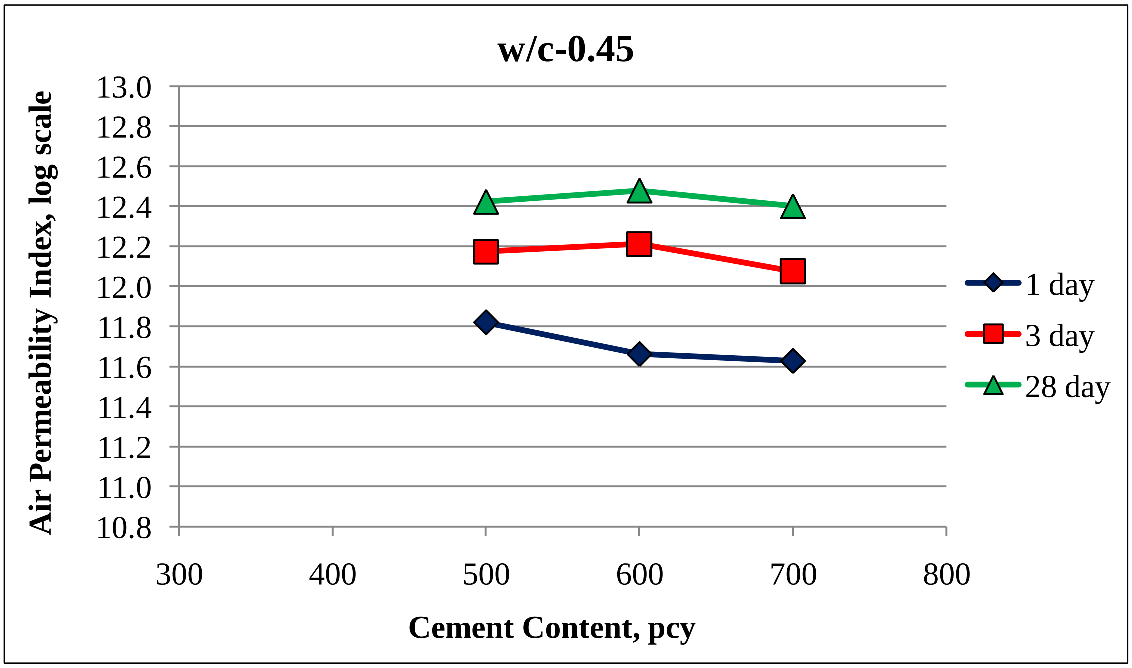
The effect of cement content on air permeability is presented in Figure 48.



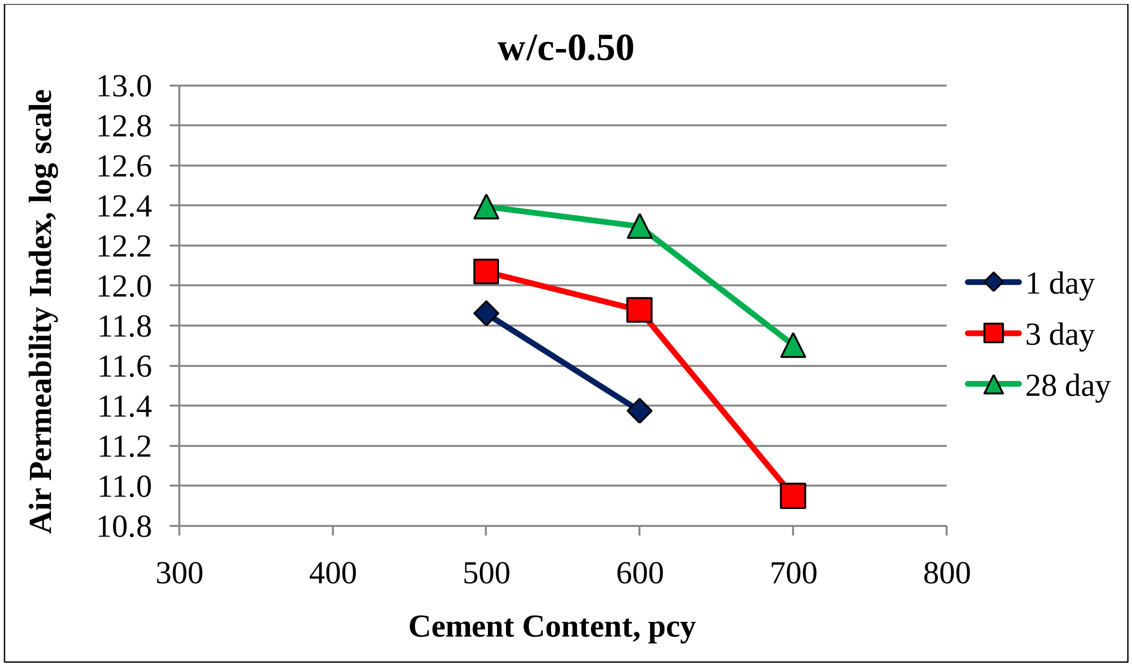
a) w/c of 0.35



b) w/c of 0.40



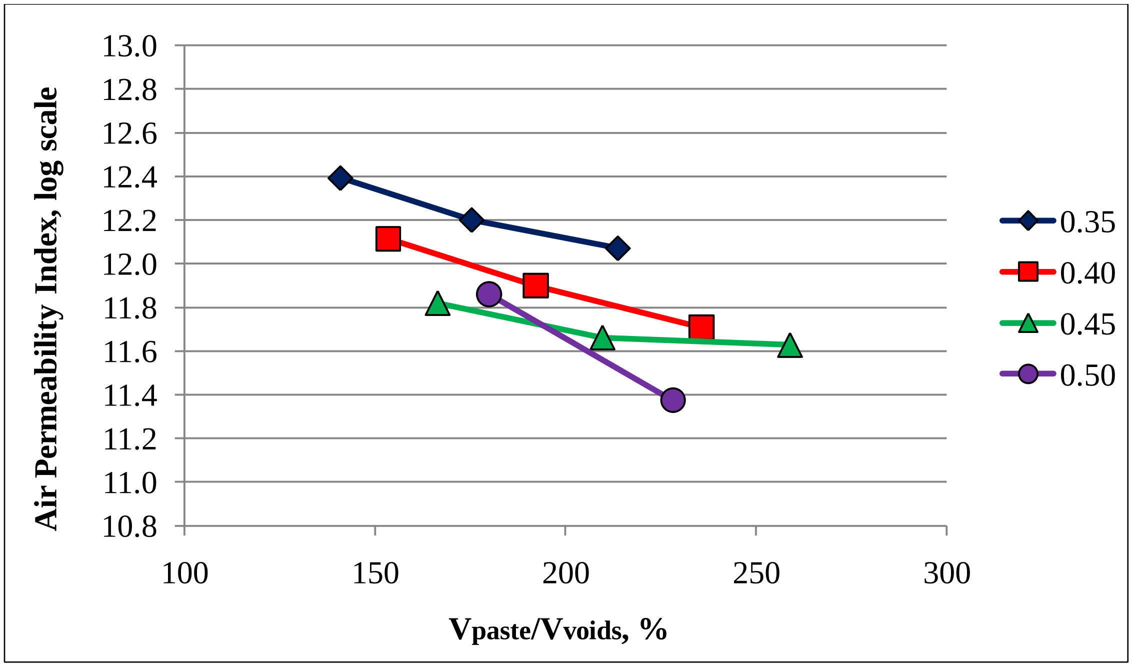
c) w/c of 0.45



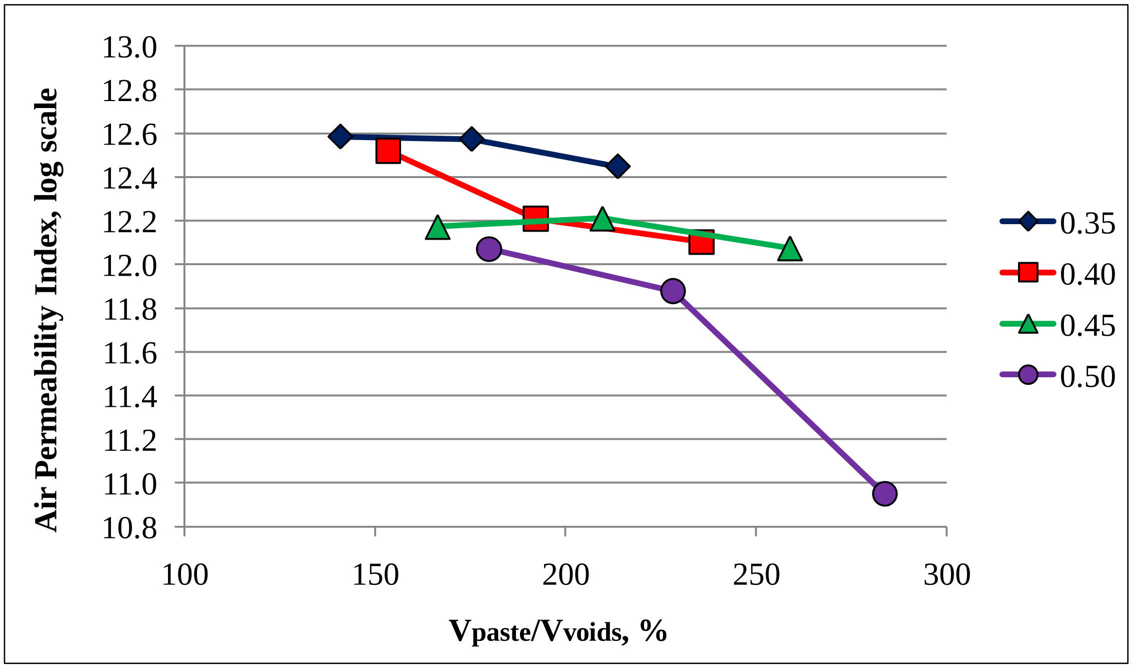
d) w/c of 0.50

Figure 48. The effect of cement content on air permeability

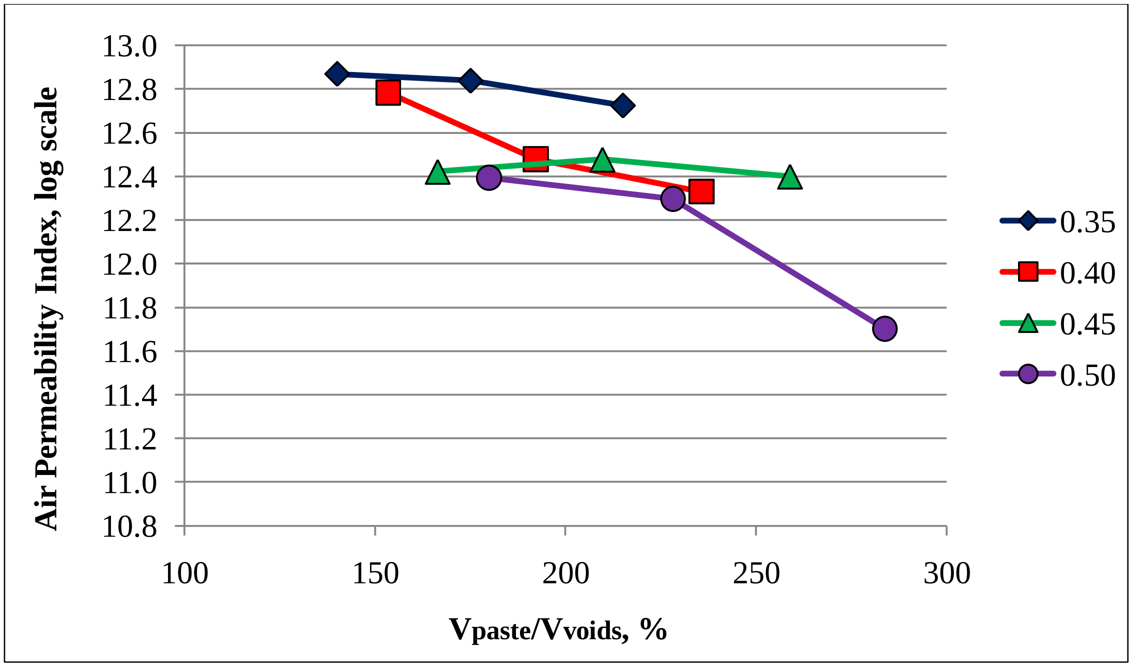
The effect of paste volume-to-volume of voids ratio on air permeability is presented in Figure 49.


Air Permeability Index, log scale
13.0
12.8
12.6
12.4
12.2
12.0
11.8
11.6
11.4
11.2
11.0
10.8
100
150
200
250
300
Vpaste/Vvoids, %
0.35
0.40
0.45
0.50

a) 1-day


Air Permeability Index, log scale
13.0
12.8
12.6
12.4
12.2
12.0
11.8
11.6
11.4
11.2
11.0
10.8
100
150
200
250
300
Vpaste/Vvoids, %
0.35
0.40
0.45
0.50

b) 3-day



c) 28-day

Figure 49. The effect of paste volume-to-volume of voids ratio on air permeability

Figure 48 shows that, for a given w/c, increasing cement content increases the air permeability because as similar case with the chloride penetration, air tends to penetrate through the less dense system.

In addition, to the make the findings independent of the aggregate system used in this study, the effect of paste volume on air permeability is also presented in Figure 49 which shows that, increasing the paste volume-to-volume of voids ratio increases the air permeability. For a fixed paste volume-to-volume of voids ratio, increasing w/c will also increase the permeability due to the increased porosity in cement paste.

This can also be explained by the fact that increasing paste content will decrease the coarse aggregate content thus increase the porosity of paste. In addition, when the testing age is increased from 1-day to 28-day, air permeability decreases. This result is expected because cement hydration continues within time and as hydration continues the pore sizes get smaller and concrete becomes more impermeable. The observed results are consistent with the information in the literature (Alexander et al. 2007; Dinku et al. 1997):

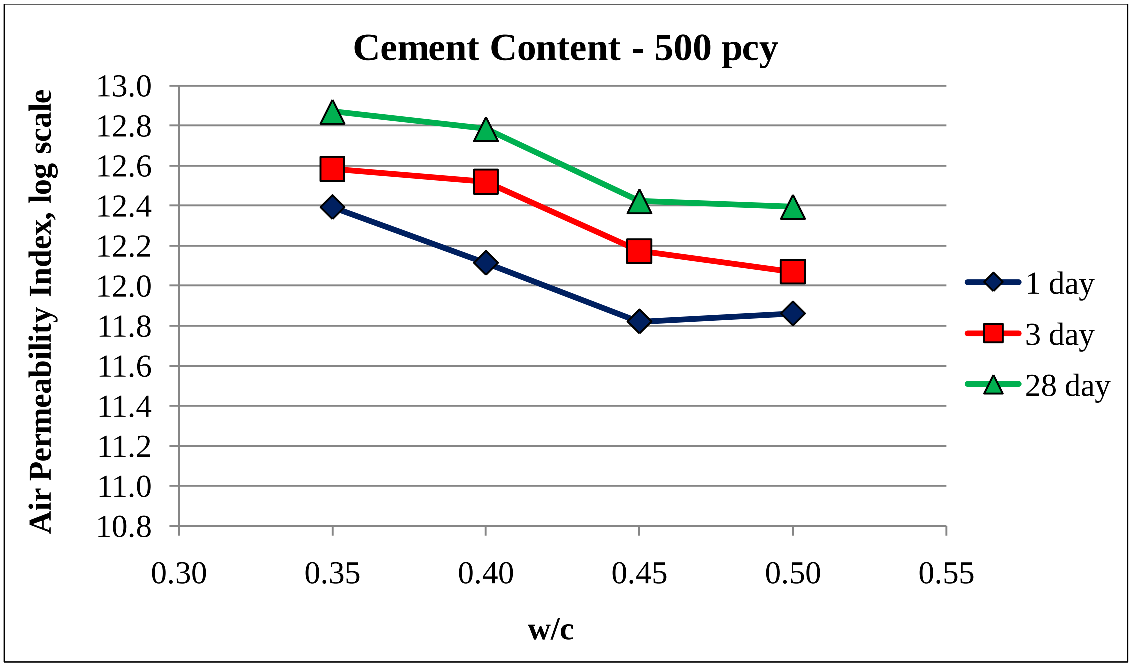
When the overall effect of cement content on air permeability is evaluated, 400 pcy of cement content is not recommended due to its porosity caused by its low paste content.

Furthermore, as increasing cement content increases the air permeability, 600 pcy and 700 pcy would also not be the best option. Therefore, when w/c is constant, for the aggregate system used, 500 pcy is found to be the most appropriate cement content that provides the lowest air permeability.

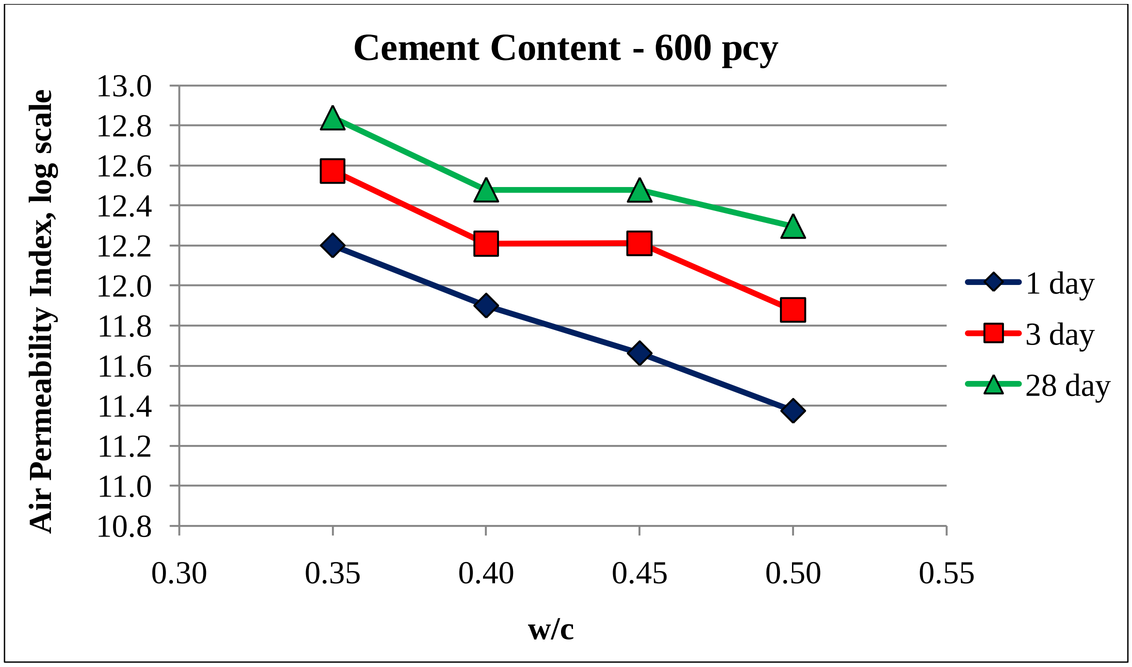
In addition, the paste volume-to-volume of voids ratio should be within the range of 145% to 180% to observe a mixture with low air permeability. Exceeding this range will further increase the air permeability.

Water-to-Cement Ratio

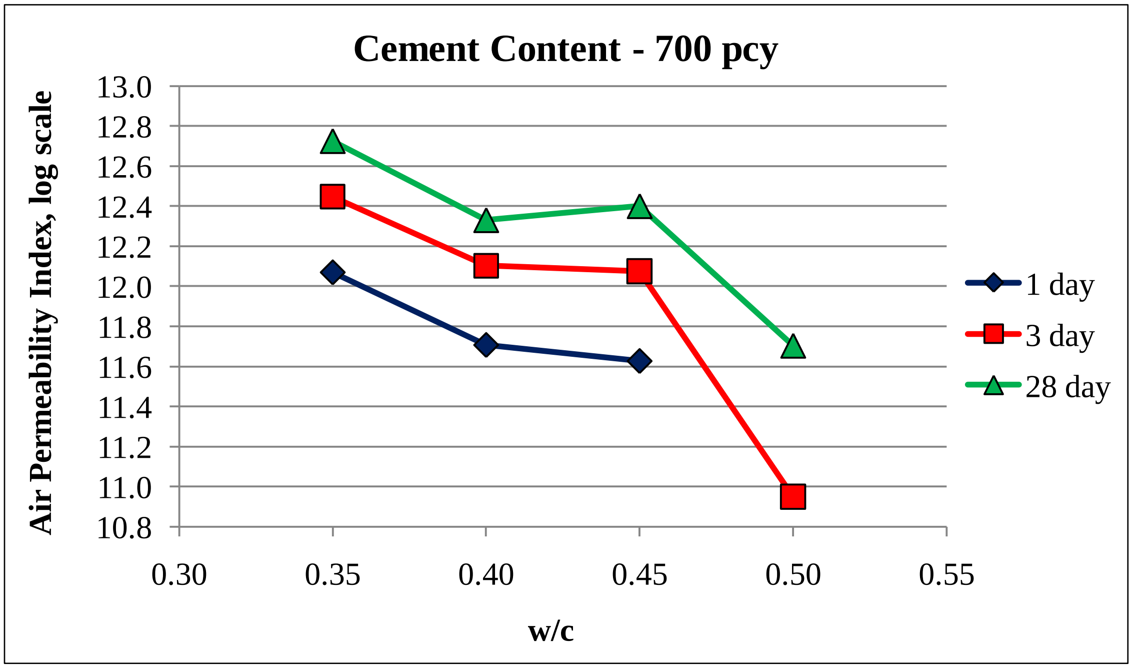
The purpose of this section is to discuss how air permeability is affected by changing the w/c, for a given cement content (Figure 50).



a) cement content of 500 pcy



b) cement content of 600 pcy



c) cement content of 700 pcy

Figure 50. The effect of w/c on air permeability

Figure 50 shows that, for a given cement content, increasing w/c increases the air permeability as a result of increased capillary porosity. In addition, when the testing age is increased from 1-day to 28-day, air permeability decreases because of the hydration of cement continues within time.

Test results showed that air penetrates through the paste and increasing w/c will increase the paste content therefore more air will be able to penetrate. The behavior of the mixture containing high cement content and w/c is also caused by the same principle. When cement content was increased to 700 pcy with a w/c of 0.50, paste content was significantly increased and caused more porosity for air to penetrate. In addition, the inconsistency of the data shown in Figure 50a is also related with the high cohesiveness. Although high cement content increases the cohesiveness (thus workability), it adversely affects the consolidation and air permeability. Therefore, the observed results are expected and consistent with the information in the literature (Alexander et al. 2007; Buenfeld and Okundi 1998; Dinku et al. 1997).

CHAPTER 5. CONCLUSIONS

The purpose of this chapter is to present a summary of the conclusions based on the observed test results.

The ultimate goal of this study was to investigate the minimum cement content required with an appropriate water-to-cement ratio (w/c) to meet given workability, strength, and durability requirements in a concrete pavement; and in turn to reduce carbon dioxide emissions, energy consumption, and costs.

The hypothesis that guided this study was, when other parameters are kept constant, after a required cement content is reached, concrete properties such as strength, chloride penetration, and air permeability will not be affected by adding additional cement. Although compressive strength test results verified the hypothesis; results showed that increasing cement content further increases the chloride penetration and air permeability.

Based on the findings of this study, for the aggregate system used in this work, it is possible to reduce the cement content without sacrificing the desired workability, strength and durability for a given w/c. When the overall effect of cement content on concrete properties is evaluated, 400 pcy of cement content is not recommended due to its high porosity caused by its low paste content. Furthermore, 700 pcy would also not be appropriate as increasing cement content does not improve the strength, after the required content is reached; and may decrease durability as high cement content both increases air permeability and chloride penetration. Moreover, for a w/c higher than 0.35, cement content of more than 500 pcy adversely affects the concrete performance by decreasing strength (increasing cement content from 500 pcy to 700 pcy approximately reduced the 28-day compressive strength by 15%) and may cause shrinkage related cracking problems.

Therefore, for a given w/c and for the aggregate system used in this study, the range of 500 pcy to 600 pcy is found to be the most appropriate cement content range that provides the desired workability, strength, chloride penetration and air permeability. Although mixtures with 500 pcy of cement content did not have a high workability (ranging from 0 in. to 3 in. depending on the w/c), it may be improved by the addition of supplementary cementitious materials, water-reducing agents, or using a different aggregate gradation system.

The given cement content range was compared with the values obtained in accordance with the ACI 211 Report (2002): considering the high cement content range of 650 pcy to 930 pcy provided by the ACI 211 Report (2002) for the same given conditions, the recommended cement content range of 500 pcy to 600 pcy will have significant effects and benefits on the concrete construction industry with respect to the reduction of cement content.

In addition, to make the findings independent of the selected aggregate system, the relationship between paste volume and concrete properties was established. In order to meet the desired workability, strength and durability requirements; the paste volume should be within the range of 160% to 170% of the volume of voids. Exceeding this range will adversely affect the concrete performance by decreasing strength, chloride penetration and air permeability.

The effect of the experimental variables on overall fresh and hardened concrete behaviors was investigated and the following conclusions are made;

- For a given w/c, workability decreases as cement content (thus paste content) decreases, because of having insufficient paste to lubricate the aggregates. This is more pronounced for mixtures with low w/c mixtures that have lower water per unit paste contents.
- For a given cement content, increasing w/c improves workability because there is more paste to lubricate the aggregates in mixtures.
- For a given w/c, as cement content decreases, overall setting time increases because in mixtures containing low cement content, there is not sufficient paste to glue together the aggregate particles.
- For a given cement content, decreasing w/c reduces setting time because in mixtures with lower w/c (and lower paste content) cement grains are closer to each other thereby providing a high probability of the hydration products becoming interconnected. This interconnection tends to cause stiffness while reducing the setting time.

- 28-day data can be predicted based on the observed 1 and 3-day strength data. 1-day strength is found to be around 35% of the 28-day strength. In addition, 3-day strength is approximately 60% of the 28-day strength.
- Strength is a function of w/c and decreases as w/c increases because capillary porosity increases.
- For a given w/c, increasing paste content increases the chloride penetrability. In addition, for a given cement content, chloride penetration increases when w/c increases because the capillary porosity increases and more pores become available for chloride penetration.
- For a given w/c, increasing cement content increases the air permeability because air tends to penetrate through the less dense system. In addition, for a given cement content, increasing w/c increases the air permeability as a result of increased capillary porosity.

The state of the art contributions to the literature include:

- Presenting proof that increasing cement content does not improve concrete performance.
- Providing a range of the paste volume-to-volume of voids ratio that meets the desired workability, strength and durability requirements for a plain portland cement mixture. This information will be beneficial for the concrete construction industry because it is independent of the aggregate system used.

CHAPTER 6. RECOMMENDATIONS

This chapter presents recommendations that can be provided according to the observed test results.

Reducing cement content (thus paste content) is recommended based on the observed test results. Using the right amount of cement content in concrete will have an immediate impact on concrete performance because low cement content causes high porosity and honeycombing whereas high cement content adversely affects the durability and the consequent risk of cracking. In addition, using less cement will also be a sustainable method for concrete construction.

Further investigation should be carried out to quantify the effect of:

- cement content and w/c on the long-term strength development and durability
- supplementary cementitious materials (e.g. Class C fly ash, slag, silica fume) on concrete properties
- different aggregate gradation systems on concrete performance
- conducting additional tests such as shrinkage, freeze-thaw, and carbonation tests
- performing more tests/trials (with additional cement contents and w/c) to increase the number of data points and assess the repeatability

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