Development of self-consolidating concrete for slip form paving

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Development of self-consolidating concrete for slip form paving

by

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A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Civil Engineering (Civil Engineering Materials)

Program of Study Committee:
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Iowa State University

Ames, Iowa

2005

Graduate College
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Signatures have been redacted for privacy

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ACKNOWLEDGEMENTS

I sincerely thank my advisor Dr. Kejin Wang, for her guidance, suggestions, and continuous support throughout my graduate studies. I greatly appreciate all the support that she has been given to me, both on this thesis and during the entire period in which I have been working for her.

My profound thanks to Dr. R. Bruce Thompson and Dr. Halil Ceylan for serving my thesis committee and for their careful review and valuable comments on my thesis.

My special appreciation goes to my wife, my parents, my sisters and their families, whose love and care have brought me to this level. Their substantial encouragements and support have helped me to succeed in finishing my program here at Iowa State University.

The study presented in this thesis was pool-funded by the Center for Portland Cement Concrete Pavement Technology (PCC Center), Federal Highway Administration (FHWA), 5 state DOTs and Concrete Industry. I would like to acknowledge the PCC Center providing me with a great opportunity to work on this project. A special acknowledgement goes to Mr. Bob Steffes for his help in this study.

ABSTRACT

In this study, a new type of self-consolidating concrete for slip-form paving (SF SCC) was developed. Effects of materials and mix proportions on fresh concrete compactibility, flowability, and shape stability were studied.

Type I cement and class C and F fly ashes were used as cementitious materials. Air-entraining agent (AEA), viscosity modifying admixture (VMA), and superplasticizer were employed as admixtures. Normal river sand and limestone were utilized as aggregate. A total of 46 concrete mixes were studied, and non-rodding slump flow test, modified compaction factor test, IBB rheometer test, and "green" strength tests were performed for the concrete mixtures. In addition, a "mini-paver" was developed to simulate the field SF SCC paving in laboratory.

The study has demonstrated that by engineering concrete materials and mix proportions, it is feasible to develop a new type of SCC for slip form paving application. Concrete mixtures having a compaction factor of approximate 1.0, slump of approximated 8", and spread of approximated 12" displayed not only to be able to self-compact but also to hold its shape right after placement. The test results also indicated that concrete compactibility increased but stability decreased with flowability. There was a nonlinear relationship between slump and spread for the concrete mixtures tested. The interception obtained from the IBB tests (similar to yield stress of the mixtures) had a good relationship with not only slump but also "green" strength of concrete.

CHAPTER 1
INTRODUCTION

1.1 Background

Since its development in the 1940s, slip-form paving has been extensively used by the worldwide paving industry. Slip-form paving combines concrete placement, casting, consolidation, and finishing in one unique process. In this paving process, a concrete mixture with a slump of less than two inches is placed in front of a paver. As the paver moves forward, the mixture is spread, leveled, consolidated by equally-spaced internal vibrators, and then extruded (Figure 1.1). After extrusion, the fresh concrete slab can hold its shape for further surface finishing, texturing, and curing until the concrete sets. However, the low consistency of the mixture requires a great deal of vibration to remove entrapped air and consolidate the concrete.

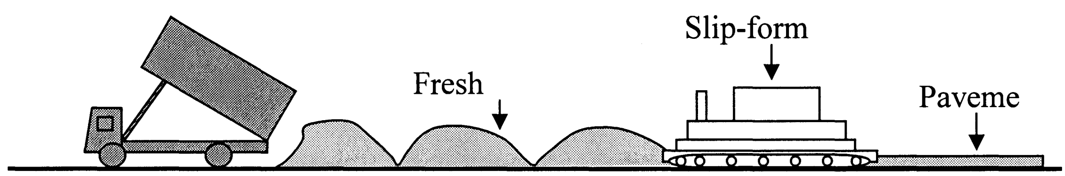


Figure 1.1 Slip-form paving

Consolidation is the process of inducing a closer arrangement of the solid particles in freshly mixed concrete or mortar during placement by reducing the voids, usually through vibration, rodding, and tamping or a combination of these actions. In finished pavements, over-consolidation often occurs, leaving parallel longitudinal vibrator "trails" that contain 3% to 4% less entrained air than that designed or specified for the concrete. This loss significantly reduces the freeze/thaw durability of concrete. In addition, concrete paving crews tend to deposit large piles of stiff concrete in front of the paving machine. Existence of the vibrator trails also impairs pavement smoothness, which is a key factor in determining highway user satisfaction. The Federal Highway Administration has set a performance goal to significantly improve the measured pavement smoothness of the national highway system by 2008. More and more state Departments of Transportation are implementing smoothness and ride ability requirements as pay factors in highway construction contracts. As a result, research is needed to develop more workable concrete that will reduce the tendency of the paver to float and would result in smoother pavements. Also, consolidation is an energy-consuming process that generates significant amounts of noise.

Today's concrete research and practices have shown that material selection and the mix design of concrete can be tailored to provide good compaction without the need for vibration. This approach is based on the principles of self-consolidating concrete (SCC) widely used in precast and cast-in-place construction. SCC, which can be cast and compacted without the need for vibration, has generated tremendous industrial interest since its initial introduction in Japan in 1986. Due to its excellent flowability and stability (segregation resistance), SCC has been used for many different applications, including bridge decks, precast bridge members, and pavement repairs. It increases productivity, reduces environmental impacts (no vibration and noise), improves concrete quality (no vibration to damage the air void structure), and results in fewer defects in casting difficult details and dense reinforcement. If SCC can be applied for slip-form paving, the harmful effects of over-consolidation will be avoided.

SCC is self-compacting due to its weight and is almost completely de-aerated while flowing in the formwork. Flowability is an important characteristic of SCC and makes it self-compacting. The spread (slump flow) of SCC typically ranges from 18 to 32 inches after pulling the flow cone, which means that conventional SCC cannot hold its shape right after casting. The challenge, therefore, is to develop an SCC for slip-form paving that possesses not only excellent self-compactability and stability before extrusion but also sufficient "green" strength right after extrusion while the concrete is still in a plastic state.

Green strength is defined as the ability of an incompletely cured material to undergo both removal from the mold and handling without distortion (CRC Press LLC 1989). Au: We don't need to use a comma to separate words (name of author or publisher) from numbers (year.) It ensures that the fresh concrete can sustain its self-weight, or hold its shape after de-molding, without being supported by any framework. Anti-deformation, or resistance to flow, is a key issue in the green strength of fresh concrete. Studies have determined that the flow and deformation of fresh concrete is controlled by its rheological property-yield stress and that enough yield stress is necessary to resist deformation in fresh concrete (Murata 1984; Rajani and Morgenstern 1991; Christensen 1991; Pashias, et al. 1996; Saak 2000; and Sader and Davidsin 2005). On the other hand, to obtain self-compaction, a concrete mixture needs to overcome the shear strength resulting primarily from particle friction and cohesion (Skarendahl and Petersson 2000). The main goal of this study is to achieve these two conflicting characteristics of concrete at the appropriate times.

Slip-form concrete pavement has a simple rectangular shape and light reinforcement. The typical size of the gap between the dowel bar and top of the sub-base is normally greater than 5 inches. All of these characteristics make the requirement of high flowability for conventional SCC unnecessary in paving technology. The relatively low flowability, which ensures the self-consolidation, enhances the shape stability of fresh concrete. Furthermore, the extrusion process of the paver, although at low pressure, promotes concrete consolidation and green strength by rearranging solid particles for packing. This understanding of paving and concrete materials make it possible to obtain a rational balance between compactability and shape stability of a concrete mixture. The new slip-form SCC will not be as fluid as conventional SCC, but it will (1) be workable enough for machine placement, (2) achieve consolidation without vibration, (3) experience no visible segregation, (4) hold its shape after extrusion from the paver, and (5) possess performance properties (strength and durability) comparable to current pavement concrete.

1.2 Objectives

The goal of this study is to develop a new type of SCC for slip-form paving. The specific objective is to evaluate the effects of materials and mix proportions on concrete compactability, flowability, and shape stability.

1.3 Research Approach

Conventional slip-form pavement concrete has good shape stability (slump value from 1 to 2 inches), but external vibration is required to consolidate and spread it during construction. Conventional SCC has good flowability and self-compactability, but formwork is required after casting. The new slip-form self-consolidating concrete (SF SCC) should have enough flowability to spread and compact itself with its own weight and enough shape stability to hold the shape after paving. These requirements lead to the conclusion that the characteristics of the new SF SCC should fall between conventional pavement concrete and SCC (Figure 1.2).

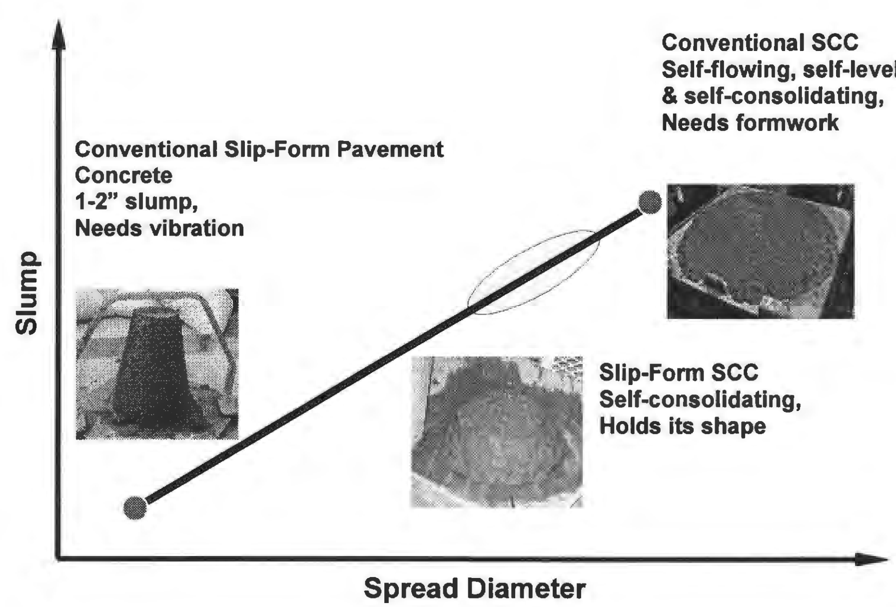


Figure 1.2 Possible SF SCC

To ensure successful SF SCC, the research schematically outlined below (Figure 1.3) was used in the current study.

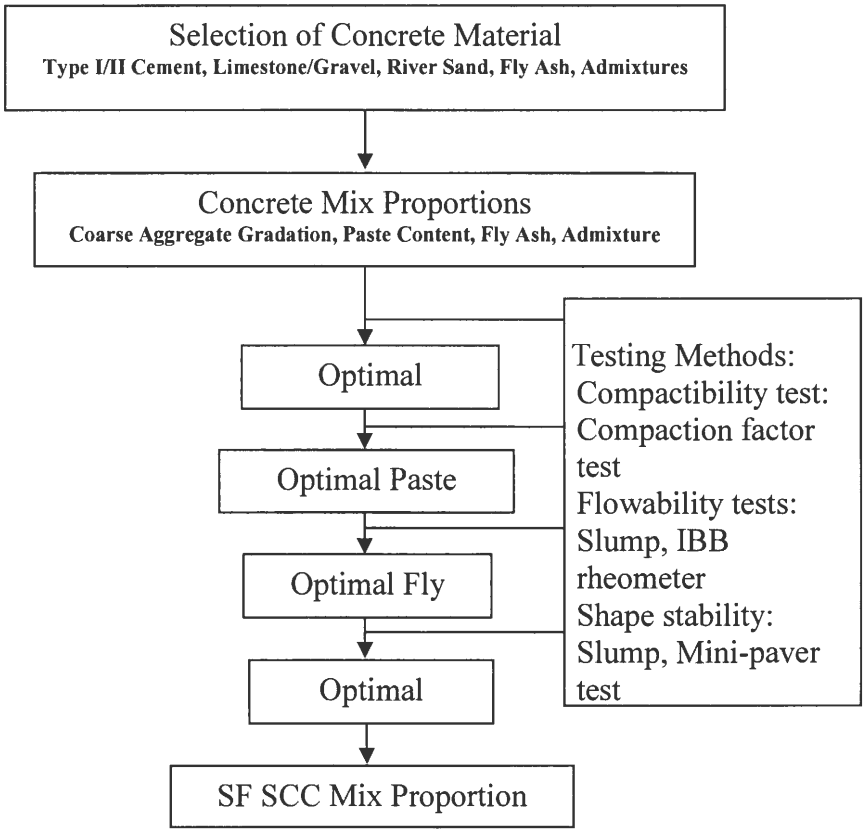


Figure 1.3 Flowchart of development of SF SCC

Different materials were selected for this study based on their properties and potential effects on fresh concrete properties. These materials include Type I/II cement, limestone with different gradations, river sand, fly ash Class C and F, viscosity-modifying admixture (VMA), Acti-Gel, and superplasticizer. To achieve the optimal mix proportion, slump, compactability, and IBB rheometer tests were conducted on each batch of concrete. A selected concrete mixture was tested with a mini-paver and dowel bar box test to evaluate its self-compactability and shape stability.

1.4 Scope of the Thesis

This thesis contains five chapters, including the experimental work and discussion. The experimental studies include compactability, flowability, and shape stability of fresh concrete. The discussion includes the effects of both material and rheology properties on compactability, flowability, and shape stability.

Chapter 2 contains a literature review, which provides the necessary background and terminology about the properties of fresh concrete relevant to this study. The use of different equipment to measure concrete workability, especially the compactability and rheology, is summarized. The effect of material properties on the properties of fresh concrete is also reviewed.

Chapter 3 includes the laboratory work. Lab methods, including the measurement of aggregate properties, concrete compactability, and rheology, are presented. The materials information for each mixture is given in this chapter as well. In total, 46 batches of concrete mix proportions were designed. The complete test procedures are listed, and the experimental program design is explained.

Chapter 4 summarizes the information collected during the experimental work. The analyses and discussions are given in this chapter.

Chapter 5 concludes this thesis with the major findings and the recommendations of the study. The criteria for mix proportions for SF SCC are given at the end of this chapter.

CHAPTER 2
LITERATURE REVIEW

2.1 Mixture Characteristics of Conventional SCC

Pavement concrete is conventional concrete with a slump of 1 to 3 inches (Kosmatka, et al. 2002). In its simplest form, it is a mixture of paste and aggregates. The paste, composed of Portland cement and water, coats the surface of the fine and coarse aggregates. Through a chemical reaction called hydration, the paste hardens and gains strength to form the rock-like mass known as concrete. Mixture proportions for conventional self-consolidating concrete (SCC) differ from those of ordinary pavement concrete; SCC has more powder content and less coarse aggregate (Okamura 1997).

2.1.1 Materials for Conventional SCC

The prototype of SCC was first completed in 1988 using materials already on the market (Okamura 1997). The materials used for conventional SCC are discussed below in two categories: aggregates and admixtures.

Aggregates

Aggregates constitute the bulk of a concrete mixture and give dimensional stability to concrete (Santhanam and Subramanian 2004). Aggregate size, shape, content, and gradation play a critical role in the successful development of an SCC. As with any concrete mix, aggregate size must be limited to that which will pass through rebar openings. In SCC, the top size is often 1/2 to 3/8 inch. Enough attention has not been paid to quantify the effect of the shape, content, and gradation of the aggregate; several references are still available.

By comparing rounded aggregates to angular and semi-rounded ones, Mishima (1999) found that rounded aggregates provide a better flowability and less blocking potential for given water-powder ratio. He also found that self-compactability is achievable at lower fines content when rounded aggregates are used.

O'Flannery and O'Mahony (1999) developed a method for shape characterization of coarse aggregate, which could assist in designing SCC mixtures with suitable aggregates. The purpose of their study was to determine dimensional parameters for the evaluation of any given coarse aggregate.

Chen, et al. (2003) studied SCC mixture proportion using coarse aggregate with gap gradation. In their study, they varied the mixture proportion of gap-graded aggregates and Pozzuolanic materials with different cement paste amounts. By adjusting the amount of paste content, they found that self-compactability is achievable for SCC using gap-graded aggregate.

Sedran and Larrard (1999) presented a more theoretical approach to designing SCC without viscosity-modifying admixture by investigating the packing model instead of the traditional trial-and-error approach. The packing model can be related to aggregate gradation. Their model allows the granular skeleton of concrete to be optimized and the the number of experimental trials to be reduced.

Admixtures

The popularly used chemical admixtures in SCC are high-range water reducer (HRWR), essentially superplasticizer (SP), and viscosity-modifying admixture (VMA). HRWR helps achieve excellent flow at low water contents, and VMA reduces bleeding and improves stability. Because not all types of VMAs have shown satisfying results, research has concentrated on only two types: welan gum and antiwashout admixture.

Whiting (1979) studied four commercially available admixtures used in Type I Portland cement concrete mixes. They represented both melamine- and naphthalene-based formaldehyde condensation products. Hardened properties, such as compressive strength and freeze-thaw resistance, were studied. Whiting found out that HRWR were capable of lowering the net water content of concrete mixtures from 10% to 20% when used in dosages recommended by the manufacturers.

Ozkul and Dogan (1999) studied the effect of a N-vinyl copolymer superplasticizer on the properties of fresh and hardened concrete. The workability of concrete was measured by the slump flow test. The coarse aggregate was crushed stone whose maximum size was 1 inch. By using this chemical admixture, which was slightly different from the conventional ones, the ability of water reduction was increased along with the retention of high workability for a long time.

Roncero, et al. (1999) evaluated the influence of two superplasticizers (conventional melamine-based products and new-generation comb-type polymers) on the shrinkage of concrete exposed to wet and dry conditions. Tests of cylinders with embedded extensometers were used to measure deformations over a period of more than 250 days after casting. It was observed that the incorporation of superplasticizer increased the drying shrinkage of concrete when compared to conventional concrete. The melamine-based product led to slightly higher shrinkage than the comb-type polymer.

Ouchi, et al. (1996) studied the effect of superplasticizer on the balance between flowability and the plastic viscosity of paste in conventional SCC. The ratio of V-funnel speed to flow area of cement paste with a fixed amount of superplasticizer was found to be almost constant and independent of the water-to-cement ratio. A higher amount of superplasticizer results in a lower ratio of V-funnel speed to flow area. The ratio was used as an index of the effect of superplasticizer on cement paste's flowing ability and viscosity with the goal of achieving self-compactability. However, the relationship between HRWR amount and its effect was found to differ depending on the type of cement or chemical admixture.

Khayat and Guizani (1997) studied the fresh properties of conventional SCC using different types of HRWR with VMA. Sari (1999) studied the fresh properties of conventional SCC using different types of HRWR without VMA. Their studies indicate that acrylic copolymers and polycarboxylate ethers are efficient at lower dosages compared to sulfonated condensates of melamine or naphthalene formaldehyde.

Takada, et al. (1999) investigated the influence of welan gum on the water-to-cementitious-material ratio. They found that the VMA raised the value of the ratio due to its tendency to make the mixture viscous. Welan gum increased the viscosity of the free water in the fresh water of fresh concrete because its polymers associate with each other in water. The tests results showed that a slump flow value of 650±30 mm and a V-funnel time of 11±2 seconds were achieved by using 0.01% to 0.02% VMA and 0.025% to 0.035% superplasticizer from the total cementitious materials. These values were considered adequate for a workable SCC.

Dehn, et al. (2000) studied the interaction between superplasticizer and VMA in order to verify the properties of conventional SCC. They discovered that the polymer in the VMA and the polymer in the superplasticizer restrain each other; this phenomena results in a higher segregation resistance. Some larger dosage of superplasticizer and some larger dosage of superplasticizer for a particular deformability.

VMAs have been used for a long time. Based on former studies, Santhanam and Subramanian (2004) theorized that effective addition of VMA in SCC is an application-related issue, and it is more efficient if VMA is added to concrete mixtures after superplasticizer has come in contact with cement particles.

2.1.2 Mixture Proportioning Methods for Conventional SCC

A number of procedures for designing conventional SCC mixtures have been proposed. These procedures can be broadly classified into the following four categories:

1. Empirical methods
2. Rheology-based methods
3. Particle-packing models
4. Statistical methods

Empirical methods

Okamura and Ozawa (1995) first recommended the mix proportions for conventional SCC (Figure 2.1).

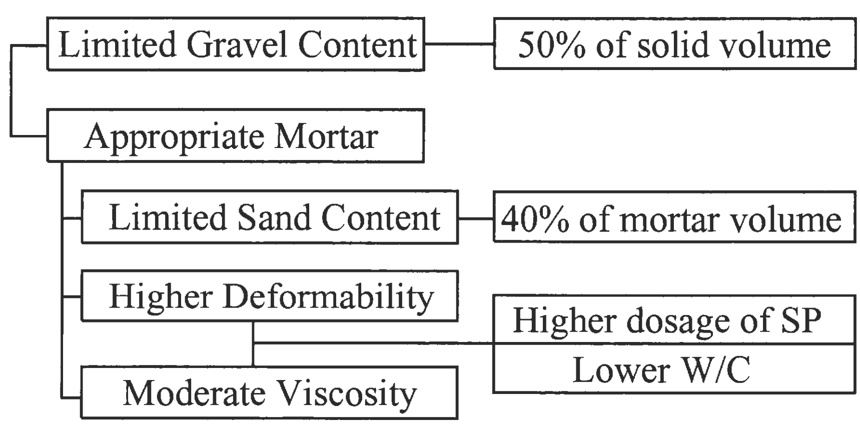


Figure 2.1 Methods for achieving self-compactability (Okamura and Ozawa 1995)

In the method, 50% of solid volume is taken up by coarse aggregate, while 40% of the mortar volume is fine aggregate. Paste composition is then determined using flow tests on mortar. Numerous experiments are required when applying this method.

Edamatsu, et al. (2003) modified Okamura and Ozawa's original method. In Edamatsu's method, the limiting coarse aggregate volume ratio is kept at 0.5. The fine aggregate content is then fixed by using V-funnel tests. Numerous experimental results from funnel tests and mortar flow tests are still required to determine water content and superplasticizer dosage.

EFNARC (2001) also recommended a mixture design procedure based on Okamura and Ozawa's original method. The difference is that a higher amount of coarse aggregate, up to 0.6, is permitted in the case of rounded coarse aggregate. The proportion of sand in the mortar is varied between 40% and 50%. Water content and superplasticizer dosage still need to be determined from mortar slump flow and V-funnel tests.

Rheology-based methods

The rheology-based methods are based on the successful application of the two-parameter Binghan model of concrete flow behavior.

Saak, et al. (2001) proposed a method based on rheological principles to control segregation under both static and dynamic conditions. In his model, a minimum yield stress of paste was used to control the segregation of aggregate in static conditions. Dynamic control of the settling particles can be achieved by minimizing its terminal velocity, which depends on the plastic viscosity. Paste rheology is all that must be adjusted based on experimental results; this can be done using the "self-flow zone" concept. Figure 2.2 shows three zones, one each for plain cement paste, cement paste with silica fume, and cement paste containing silica fume and a cellulose derivative. Only a few experiments will be required to arrive at a suitable paste composition that will fall into one of the self-flow zones.

Other attempts were made to relate the design of conventional SCC to rheology properties. Wallevik (2003) defined a range on yield stress-plastic viscosity diagrams for the development of conventional SCC (Figure 2.3). As they stated, all mixtures with the yield stress and plastic viscosity in the range shown in Figure 2.3 are SCC.

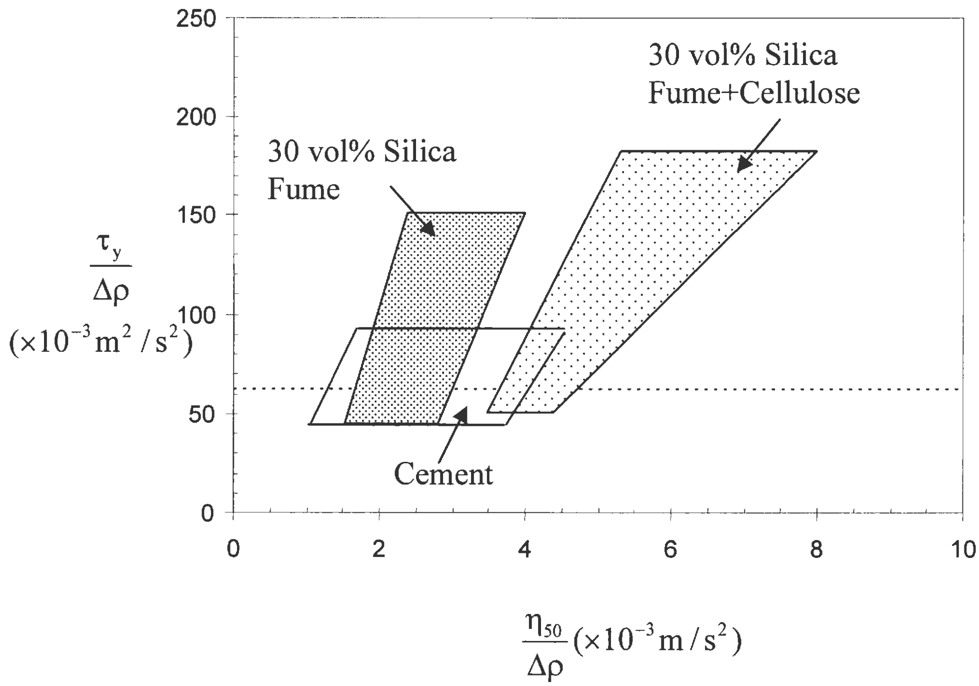
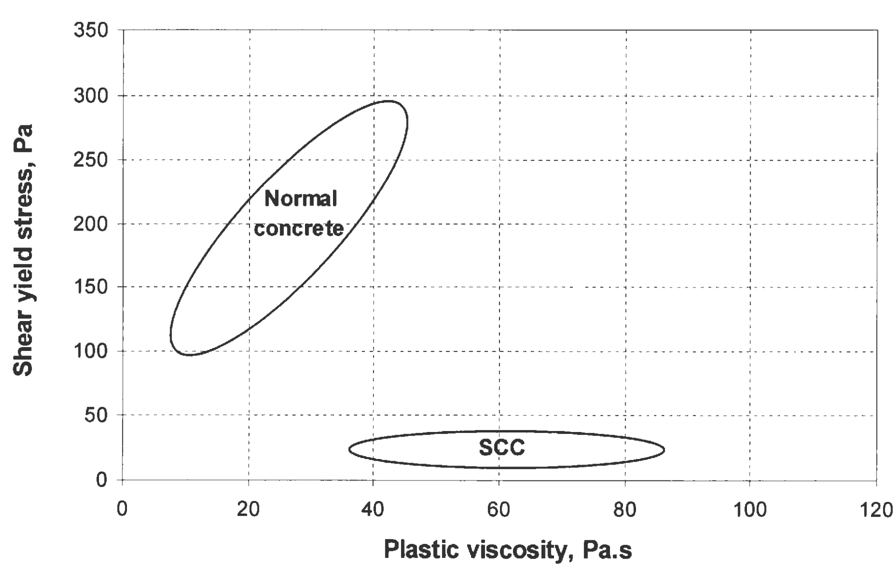


Figure 2.2 Self-flow zones for different pastes (Saak, et al. 2001)



Note : The variable plotted on the x-axis is plastic viscosity

Figure 2.3 Range of rheological properties for normal concrete and SCC (Wallevik 2003)

Wallevik (2002) also related rheological parameters with slump-flow results to define a proposed area for SCC in a yield stress-plastic viscosity diagram (Figure 2.4). If the plastic viscosity is low or below around 40 Pa·s, the SCC should have significant yield value (depending on the viscosity). On the other hand, if the SCC is "viscous," that is, has a plastic viscosity over 70 Pa·s, the yield value has to be about zero. The recommended values are within the inner box in Figure 2.4.

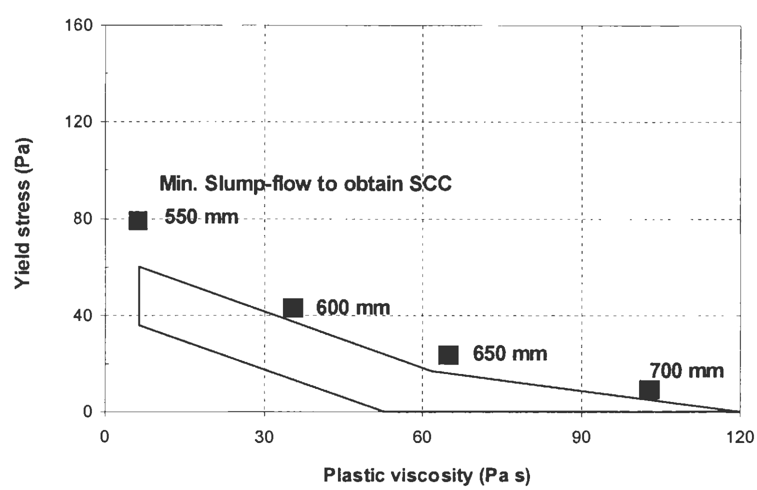


Figure 2.4 Proposed area in yield stress-viscosity diagram for SCC (Wallevik 2002)

Particle-packing methods

Particle packing has been suggested by Andersen and Johansen (1991), and Roy, et al. (1993) as a scientific approach to mixture proportioning of concrete. The principle is to minimize the void content of a dry granular mixture of all ingredients (including cement, fly ash, and silica fume). Two different types of model are available: the discrete model and the continuous model. The discrete model has been used more widely than the continuous one. In this section, the discrete model will be reviewed in detail.

Sedran and Larrard (1999) demonstrated the use of a discrete particle model to design SCC mixtures (without VMA). This model optimized the granular skeleton of concrete and used the results from the rheology measurements of fresh SCC, filling ability (using L box tests), and resistance to segregation. The relationship between these parameters and the packing density of the skeleton were then established. The proportions of fresh SCC were then found by using computer programs that optimized the mixtures with respect to their properties and cost.

Statistical methods

Khayat, et al. (2000) proposed a mixture design procedure based on statistical models using a factorial design of experiments. In Khayat's study, five parameters (cementitious material content, water-to-cementitious-materials ratio, HRWRA concentrations, VMA concentrations, and volume of coarse aggregate) were chosen. The response variables were the slump flow, relative yield stress, and viscosity. The successful application of this model requires a total of 32 SCC mixtures to obtain the required relationship. The advantage of such an approach is that the effects of critical factors can be evaluated using a minimum number of experiments.

2.1.3 Mixture Proportion for Conventional SCC

In workability terms, self-compactability signifies the ability of the concrete to flow after being discharged from the pump hose, a skip, or similar, only through gravity and to fill intended spaces in the formwork to achieve a zero-defect and uniform-quality concrete (Skarendahl and Petersson 2000). As a fresh state property, self-compactability can be characterized in relation to the following functional requirements:

1. Filling ability
2. Resistance to segregation
3. Passing ability

This means the self-compactability requires not only high deformability of paste or mortar but also resistance to segregation between coarse aggregate and mortar when the concrete flows through the confined zone of reinforcing bars.

To achieve good filling ability, the concrete must have small inter-particle friction and the paste must have excellent deformability (Okamura and Ouchi 2003). Reducing the friction between the solid particles, which includes coarse and fine aggregates and all types of powder, is a superior way to make concrete deform well. Currently, popularly accepted methods to decrease the friction of aggregates is to increase the aggregate inter-particle distance. This can be achieved by reducing the aggregate content, or in other words, increasing the paste content.

It is also important for paste to have good flowability (low yield value) and enough resistance to segregation (high yield value and moderate viscosity) to secure the good filling ability of concrete (Saak, et. al. 2001 and Skarendahl and Petersson 2000). The most popular way to increase the deformability of the paste is (1) Using superplasticizer and (2) Balancing the water-to-powder ratio. The effect of superplasticizer on fresh concrete properties will be discussed in detail later.

Segregation of fresh concrete is described by in-homogeneity in the distribution of constituent materials. It can be categorized as the segregation between water and solid (bleeding of water) and aggregate segregation. The former situation can be avoided by reducing the amount of movable water in the mixture. Two methods can be used to achieve this goal: using less water or a lower water-to-powder ratio and using powder materials with a high surface area, such as fly ash (ACI Committee 232, 1996). Aggregate segregation is usually caused by the low yield stress of the paste (Saak, et al. 2001). It can be avoided by increasing both friction and cohesion of paste phase (Skarendahl and Petersson 2000). But increasing cohesion is much more beneficial than increasing friction, because increasing friction also decreases the deformability. To resist segregation, normally aggregates with limited content and reduced maximum size are used together with the viscosity agent and lower water-to-powder ratio.

To satisfy all of these properties, Okamura (1997) developed a method to achieve self-compactability (Figure 2.12), which can also be summarized as follows:

1. Limited aggregate content
2. Low water-to-powder ratio
3. Use of superplasticizer

The mix proportion of SCC is shown in Figure 2.5 compared with roller-compacted concrete and normally used concrete. The aggregate content is smaller than normal concrete that needs external energy to get compacted.

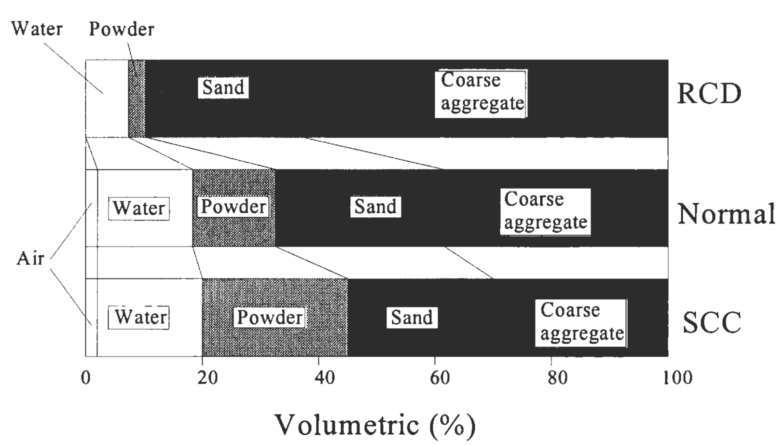


Figure 2.5 Comparison of mix-proportioning of SCC with other types of conventional concrete (Okamura and Ouchi 2003)

2.2 Concrete Rheology

Rheology is defined as the science of deformation and flow of matter. It covers relationships between stress, strain, and time (Banfill 2003). Gjørv (1998) reported that the measurement of rheological parameters could be used to evaluate the flowability and the compactability of fresh concrete. In terms of fresh concrete, the field of rheology is related to the flow properties of concrete or with its mobility before setting takes place. ACI Committee 309 (1993, 1997) defined compactability as an important rheological property of fresh concrete (Figure 2.6). Yen, et al. (1999) found that applying a rheological method could provide more stable results than any other test method in describing the flowability of the fresh concrete. In order to efficiently discuss fresh concrete compactability, flowability and shape stability, it is necessary to review the basic principles of concrete rheology before further discussing compactability, flowability, and shape stability.

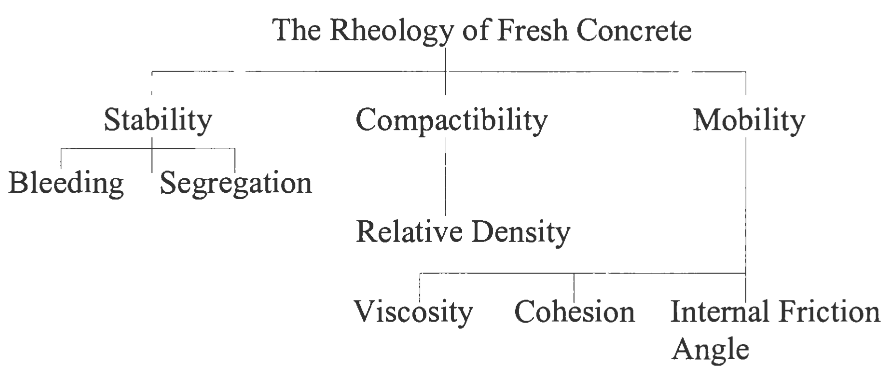


Figure 2.6 Parameters of the rheology of fresh concrete (ACI Committee 309, 1997)

The rheological behavior of fresh concrete is characterized through its yield stress and viscosity. The yield stress is defined as the minimum stress required for a material to start flowing (Schramm 1994). When an external load (such as extrusion and vibration) or an internal load (self weight) is applied, fresh concrete is balanced by its yield stress of shear; it will remain static state and cannot flow but deforms plastically like a solid. If these loads exceed the yield stress, flow will start; this will be a dynamic process. Plastic viscosity is the ability of a material to resist flow. High plastic viscosity is characteristic of a less flowable suspension than low plastic viscosity.

Different rheology models are currently available to describe the different rheological behavior of fresh concrete, including normal strength concrete and highly flowable concrete such as conventional SCC (Ferraris, et. al. 2001) (Figure 2.7).

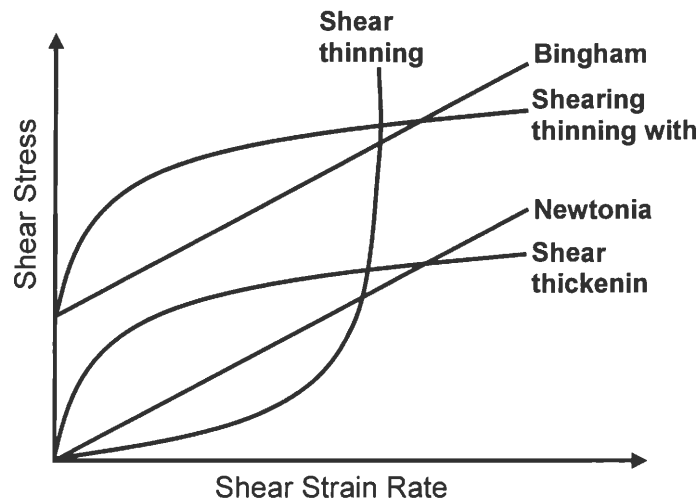


Figure 2.7 Flow curves for concrete (Ferraris, et. al. 2001)

De Larrard (1993) suggested that the Herschley-Buckley model is more suitable than other rheology models for conventional SCC, because the rheological properties of conventional SCC are a low yield stress value together with an adequate plastic viscosity. Ferraris (1998) recommended that for normal-strength concrete, the Bingham model is more suitable. Tattersall (1991) also recommended using the Bingham model to describe fresh concrete rheology behavio, because the flow of most concrete follows this equation well. Two different rheology models for conventional SCC and conventional normal strength concrete are shown in Table 2.1.

Table 2.1 Rheology equations for fresh concrete

Type of concrete	Model	Equation	Reference
Normal-strength concrete	Bingham	$\tau = \tau_0 + \eta\dot{\gamma}$	Ferraris 1999
Conventional SCC	Herschley-Buckley	$\tau = \tau_0 + K\dot{\gamma}^{\eta}$	Ferraris 1999

Variable definitions:
τ =*shear stress* $\dot{\gamma}$ =*shear rate* τ_0 =*yield stress* η =*viscosity*
K=constant

Figure 2.3 shows the typical flow curves according to the Bingham model. Ferraris, et al. (1998) stated that the flow behavior of fresh concrete is controlled by both its yield stress and plastic viscosity. The concrete in Figure 2.8 have the same yield stress but different plastic viscosities. In Figure 2.8 B, they have different yield stresses but the same plastic viscosity. Both yield stress and plastic viscosity are important in describing the flow behavior of fresh concrete.

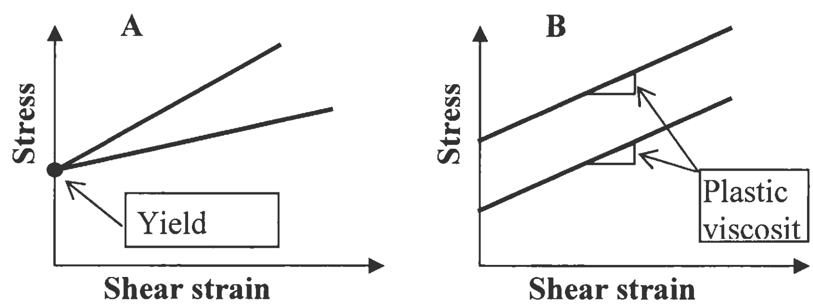


Figure 2.8 Yield stress and plastic viscosity of fresh concrete (Ferraris, et al. 1998)

Gjørv (1998) pointed out that shear stress is rate dependent. As shown in Figure 2.9, the shear stress is different at different shear rates. Mix B has lower shear stress at shear rate γ_1 and thus will be considered to have the better workability. Mix A has lower shear stress at shear rate γ_2 and thus will be considered to have the better flowability. Therefore, to obtain a more general characterization of concrete flowability, it is important to test the flow properties over a certain range of shear rates. By measuring the yield stress and plastic viscosity, a good basis for evaluating both the flowability and the compactability was obtained (Figure 2.10).

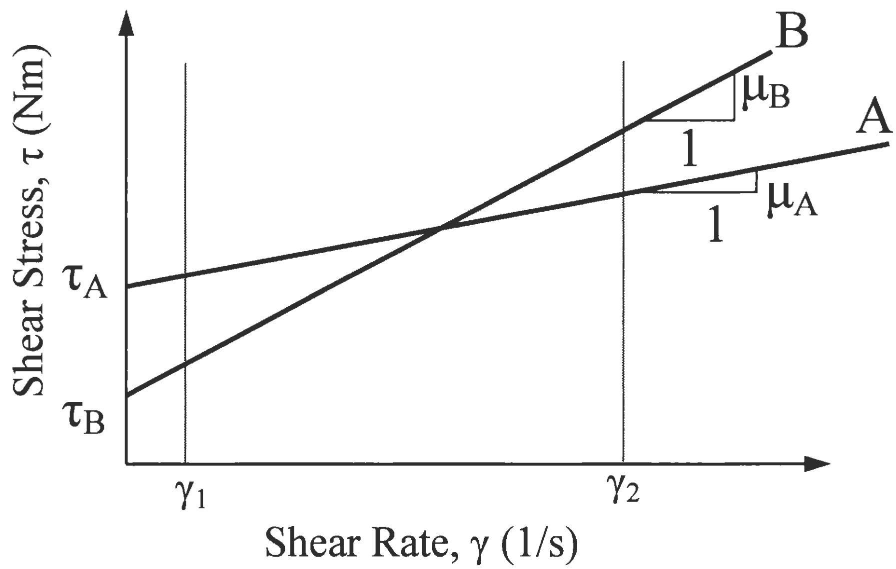


Figure 2.9 Relationship between shear rate and shear stress for two types of concrete A and B (Gjørv 1998)

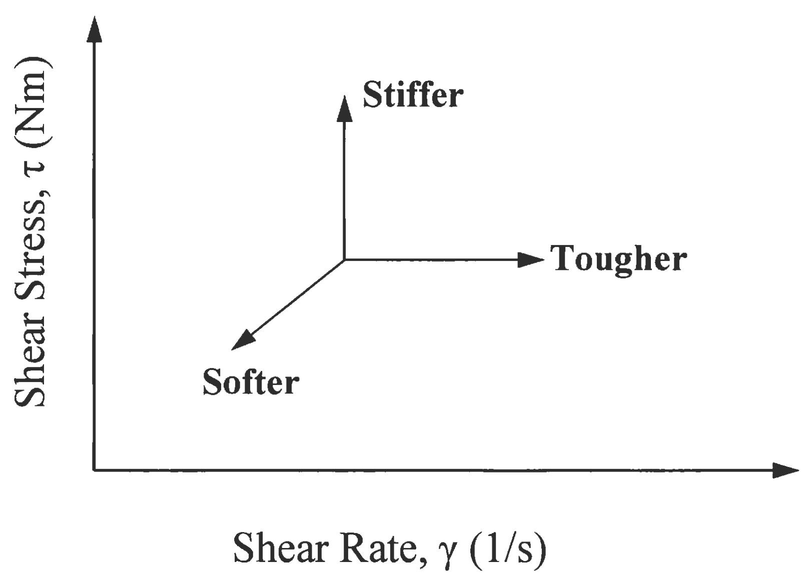


Figure 2.10 Relationship between plastic viscosity and yield stress (Gjørv 1998)

Table 2.2 shows the normal range of rheological parameters for different types of concrete based on the Bingham model. From pavement concrete to conventional SCC, the yield stress decreases. Conventional SCC has plastic viscosity comparable to pavement concrete. However, flowable concrete has lower plastic viscosity.

Table 2.2 Rheological parameters of different types of concrete (Banfill 2003)

Material	Pavement Concrete	Flowable Concrete	SCC
Yield stress (N/m^2)	500-2000	400	50-200
Plastic viscosity (Ns/m^2)	50-100	20	20-100

Fresh concrete rheology is an issue with almost all fresh concrete. Both yield stress and plastic viscosity relate to the properties of fresh concrete. In the current study, three key issues of fresh concrete, compactability, flowability, and shape stability are also directly related to rheology properties. The relationship among rheological properties and the compactability, flowability, and shape stability of fresh concrete will be discussed in detail later.

For more information on fresh concrete rheology, the following references are highly recommended; they cover almost all issues in this field: Ferraris and de Larrard 1998; Ferraris, et al. 2001; de Larrard 1993; and Ferraris, et al. 2005.

2.3 Mix Composition Effects on Fresh Concrete Rheology

Almost all components of concrete and essentially every condition under which concrete is made may affect the fresh concrete rheology properties. These factors can be summarized as follows:

- Water content
- Cement characteristics and content
- Aggregate
- Chemical admixtures
- Supplementary cementitious materials (SCMs)
- Time and environmental conditions
- Vibration

Interactions between constituents complicate the situation because they are not independent of each other in their effects. Only the effects of certain parameters, related specifically to this study, are presented here.

1), Water content

Water content is certainly the most important parameter with respect to the fresh concrete properties. Increase the water content while keeping the proportions of other constituent will decrease yield stress and viscosity of the concrete and increase the possibility of segregation. An increase in water content while keeping the proportions of other constituent produces a reduction in plastic viscosity and the flow resistance as well as the increase in the possibility of segregation. This reduction in both plastic viscosity and the flow resistance is so great that for low W/C, a water reducer or superplasticizer must be used to produce workable concrete (Banfill, 1994).

2), Cement characteristics and content

The workability and rheological properties of concrete are affected by physical and chemical properties of cements. Vom Berg (1979) studied the effect of specific surface area and concentration of solids on the flow behavior of cement paste. He found that the increase of cement fineness or solids concentration will lead an increase in the flow resistance and plastic viscosity of cement paste. The fineness of cement particles controls the balance of attractive and repulsive force between cement particles, which profoundly affects the flow of concrete. At a given water content, low cement content tends to produce harsh mixtures with poor workability, while high cement content produces better cohesiveness.

3), Coarse aggregate effect

The coarse aggregate effect on fresh concrete properties can be classified into different ways, aggregate volume fraction, gradation, shape, and surface texture.

Denis (2002) examined the effect of coarse aggregate on the workability of sandcrete with two different mortar matrix and found that the effect of coarse aggregate concentration can be significant. Geiker (2002) studied concrete yield stress and plastic viscosity and defined the relative yield stress and relative plastic viscosity as the ratio of concrete rheological parameters and mortar ones. He found that the relative yield stress and relative plastic viscosity significantly increased with the increasing of coarse aggregate volume fraction.

Struble (1998) studied the rheology of cement paste as a function of concentration and found that both yield stress and viscosity depend on the amount and grading of the aggregate and properties of cement paste. Jamkar (2004) studied the coarse aggregate particle shape and texture effect on workability, finding that the volume of fine aggregate largely depends on the amount and grading of coarse aggregate and properties of cement paste.

Malhotra (1964) studied the correlation between particle shape and surface texture of fine aggregates and their water requirement. He found that crushed sand tends to have a higher water requirement than natural sand because of the higher angularity and difference in surface texture. Angular fine aggregate particles interlock and reduce the freedom of movement of particles in the fresh concrete.

Kosmatka (2002) also found that workability of fresh concrete and bond between cement paste and a given aggregate is affected by particle shape and surface texture. He found that the water content must be increased to maintain workability if angular aggregate is substituted for round aggregate.

Quiroga (2004) studied the effect of aggregate characteristic on the performance of concrete. He confirmed that aggregate blended with well-shaped, round, and smooth particles requires less paste for a given slump than that blended with flat, elongated, angular, and rough particles.

Summarily, the effect of aggregate on fresh concrete rheology property is related to the amount of paste or mortar. For coarse aggregate, the larger the particles, the fewer the surface areas, which means that a thicker coating is required and it makes particles slide easily. On the other hand, the smaller particles, which have more surface area, require a thinner coating, which leads to the interlocking of smaller particles. In other words, for the same amount of mortar, coarse aggregate with different gradation will show different workability and different engineering properties such as shrinkage.

Particle shape and surface texture also affects the amount of paste needed in the concrete mixture. If the coarse aggregate used in concrete is gravel, which is naturally smooth and round, the lower surface area (compared to the crushed stone) will decrease the amount of paste required to coat each individual particle to achieve certain workability. Meantime, the smooth surface of gravel make particles easy to slid on each other, and then make the concrete highly flowable.

4), Chemical admixtures

Table 2.3 lists the most common types of admixtures and indicates their effect on rheology. For more details on admixtures in general, the papers of Tattersall (1991) or Tattersall and Banfill (1983) are highly recommended.

Because there is only a limited amount of experimental data on the subject, and because of possible interactions between the cement, mineral admixtures or other admixtures, it is very difficult to predict the specific effect of any particular mix without preliminary testing. Experimentation is still the best way to obtain the information. Figure 2.11 shows the usual effect of the addition of water or different admixtures. When more than one admixture is added, the overall effect cannot be predicted, except for the general trend.

Table 2.3 Concrete admixtures (Tattersall and Banfill 1983)

Admixture	Typical material	Effect on rheology
Accelerators	Sodium aluminate Sodium silicate Lime Potassium hydroxide Calcium chloride Calcium format Sodium nitrite	Increased rate of change with time
Retarders	Hydroxycarboxylic acids sugars	Reduced rate of change with time
Water-reducers (WR)	Calcium and sodium lignosulphonate	Low reduction in viscosity high reduction in yield stress
Superplasticizers (SP)	Sulphonated melamine-formaldehyde resin Sulphonated naphthalene-formaldehyde resin Mixture of saccharates and acid amides	Low reduction in viscosity high reduction in yield stress
Air-entraining agents (AEA)	Wood resin Fats lignosulphonates	Significant increase in workability Reduce both yield stress and viscosity
Viscosity-modifying admixtures (VMA)		Increased viscosity with yield stress unchanged

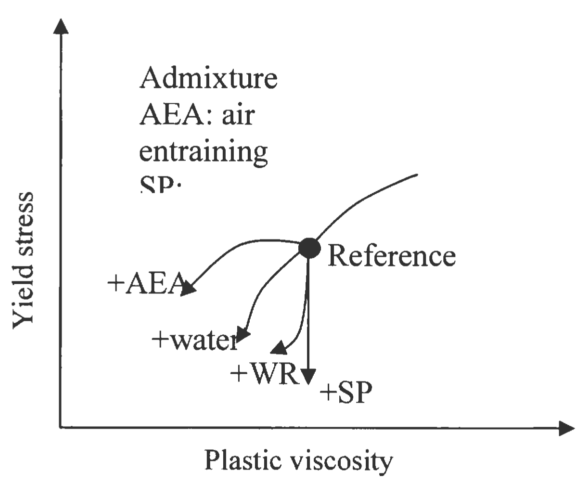


Figure 2.11 Effect of addition of water and different admixtures (Gjørv 1996)

Although water reducers and superplasticizers produce generally similar effect (large reduction of yield stress (flow resistance) and small reduction of plastic viscosity), they are treated differently because the effect of superplasticizers are much greater and also because they are usually used for low W/C concrete and most of times used with Viscosity-modifying admixtures (VMA). As reported by Tattersall (1991), up to a certain dosage (0.15% of cement weight) the addition of lignosulphonate produces a large reduction in yield stress and a significant reduction in plastic viscosity. At higher addition rates, there is no further reduction of yield stress, but a proportional reduction in plastic viscosity.

The increase in the air content produces a rapid decrease in both yield stress and plastic viscosity. For air content higher than 5%, there is no significant reduction in plastic viscosity but the yield stress reduce greatly (Tattersall and Banfill 1983).

5), Fly ash

The absolute volume of cement plus fly ash normally exceeds that of cement in similar concrete mixtures not containing fly ash. This is because the fly ash normally is of lower density and the mass of fly ash used is usually equal to or greater than the reduced mass of cement. While it depends on the proportions used, this increase in paste volume produces a concrete with improved plasticity and better cohesiveness (Lane 1983). In addition, the increase in the volume of fines from fly ash can compensate for deficient aggregate fines.

Fly ash changes the flow behavior of the cement paste (Rudzinski 1984); the generally spherical shape of fly ash particles normally permits the water in the concrete to be reduced for a given workability (Brown 1980). Ravina (1984) reported on a Class F fly ash that reduced the rate of slump loss compared to non-fly ash concrete in hot-weather conditions. Class C fly ash generally has a high proportion of particles finer than 10 μm, which favorably influence concrete workability. Data on the rheology of fresh fly ash-cement-water mixtures was reviewed in detail by Helmuth (1987).

Using fly ash in air-entrained concrete mixtures requires changes in dosage rate of the air-entrained admixture. Some Class C fly ashes can reduce the amount of air-entrained admixture, particularly for those with significant water-soluble alkalies in the fly ash (Pistilli 1983). Required air-entraining admixture dosages may also increase with an increase in the coarse fractions of a fly ash (Lane 1983).

6), Mixing conditions

The mixing conditions, especially mixing sequence and mixer type affect the workability and rheological performance of cementitious materials. The change from the least serve to the most severe mixing procedure can cause both the yield stress and plastic viscosity to decrease by about 60%, at the same time the width of the hystersis loop decreased.

Yang (1995) found that during the first two hours of hydration, mixing methods have strong effect on cement paste rheological properties. Poorly mixed (low mixing energy) cement paste has more rapidly-increasing peak shear stresses than well-mixed cement paste (high mixing energy). Williams (1999) studied the effect of mixing shear rate on yield stress and viscosity of cement paste by using a rheometer with different pre-shear rate. The results showed that well mixed pastes have a lower plastic viscosity and hence improved flowability.

7), Time and environmental conditions

Concrete is a time-dependent material. Freshly mixed concrete loses its flowability with time due to the process of hydration. The reduction in flowability is generally attributed to loss of water by evaporation or absorbed into aggregate, and from chemical reaction with the cementitious materials in early hydration reactions. Further, the rate of water loss increases if the temperatures increased.

The following publications are currently available on the effect of time and environmental conditions on cement paste and concrete rheological properties and flowability: Jiang 1993; Laboutet 1998; Nachbaur 2001; Petit 2005; and Struble 1995.

2.4 Compactability of Fresh Concrete

As defined by ACI Committee 309 (1997), consolidation is the process of inducing a closer arrangement of the solid particles in freshly mixed concrete or mortar during placement by the reduction of voids, usually by vibration, centrifugation, rodding, tamping, or combination of these actions.

Glanville (1938) defined the compactability of fresh concrete as the property of the concrete which determines the amount of useful internal work necessary to produce full compaction. Ritchie (1962) attempted to define the flow of concrete by linking it to compactability by measuring relative density and conducting tri-axial testing of fresh concrete. He found that the fresh concrete's compactability is directly related to its mobility and internal friction. ACI Committee 309 (1997) also defined the compactability as one important property related with fresh concrete workability.

ACI 309 committee (1997) reported the research findings about fresh concrete under the condition of vibrating, which only qualitatively explains the compaction of concrete in terms of material characteristics and mix design. Yamaguchi, et al. (2000) and Nisikawa, et al. (2000) studied the relationship between fresh concrete flowability and compactability. They confirmed that the compactability of fresh concrete is related to its flowability.

Kokubu and Ueno (1996) studied the compactability of extremely dry concrete. Their results can be summarized as follows:

- Compactability increases as the amount of sand increases. The reason they gave is that more sand can increase the distance between coarse aggregate particles, and then decrease the friction between them.
- Water content has significant effect on fresh concrete compactability.
- With constant water content and coarse aggregate content, sand with larger fineness modulus increases the compactability or finer sand reduces compactability.

The only limitation of their research is that it did not go beyond the range of dry concrete. Whether the results are applicable on all kinds of concrete is not confirmed.

Liang, et al. (2003, 2004) studied the compactability of concrete with slump varying from 1 inch to 5 inches using the same idea adopted by Kokubu and Ueno (1996). They studied the effects of different types of coarse aggregate, the variation of sand to total aggregate ratio, water content, and slump loss of concrete on the compaction completion energy of concrete. Their results can be summarized as follows:

- Compactability increases as the water content increases. As the water content increases, slump value also increases. The reason is that the increased water content increases the distance between coarse aggregate particles and then decrease the friction between them.
- Slump value has significant effect on fresh concrete compactability. As slump value increases, the compactability increases.
- Amount of mortar plays an important role in fresh concrete compactability. With the increase of mortar content, the concrete compactability increases.

Although Liang's study was focused on the compactability of fresh concrete with a large range of flowability (slump value from 1 to 5 inches), they only examined the compactability of fresh concrete with external consolidation energy, the self-compactability was not evaluated in their study.

Okamura (1996, 1997) studied workability and promoted a new concept of self-compactability. In workability terms, self-compactability signifies the ability of the concrete to flow after being discharged from the pump hose, a skip or similar, only through gravity and to fill intended spaces in the formwork to achieve a zero-defect and uniform-quality concrete (Skarendahl and Petersson 2000).

Okamura and Ouchi (2003) pointed out that to achieve good filling ability, the concrete must have small inter-particle friction and the paste must have excellent deformability. They found reducing the friction between the solid particles, which includes coarse and fine aggregates and all types of powder, is a superior way to make concrete deform well. Currently, popularly accepted method to decrease the friction of aggregates is to increase the aggregate inter-particle distance. This can be achieved by reducing the aggregate content, or in other words, increasing the paste content.

To achieve self-compactability, Okamura and Ozawa (1995) employed the followingmethods:

1. Limited aggregate content
2. Low water-to-powder ratio
3. Use of superplasticizer

The degree of packing of coarse aggregate in conventional SCC they used is approximately 50% to reduce the interaction between coarse aggregate particles when concrete deforms. The degree of packing of fine aggregate in conventional SCC mortar is approximately 60% to limit shear deformability. The conventional SCC they developed has high flowability as well as ability to resist segregation.

After the first development of conventional SCC in Japan, more significant studies have been done on how to achieve the balance between flowability and ability to resist segregation. Saak, et al. (2001) and Skarendahl and Petersson (2000) pointed out that it is important for paste to have good flowability (low yield value) and meantime have enough resistance to segregation (high yield value and moderate viscosity) to secure the good filling ability of concrete. The most popular way to increase the deformability of the paste is (1) Using superplasticizer and (2) Balancing the water-to-powder ratio.

Segregation of fresh concrete is described by in-homogeneity in the distribution of constituent materials. It can be categorized as the segregation between water and solid (bleeding of water) and aggregate segregation. The former situation can be avoided by reducing the amount of movable water in the mixture. Two methods can be used to achieve this goal, using less water or lower water-to-powder ratio and using powder materials with high surface area, such as fly ash (ACI Committee 232, 1996). Saak, et al. (2001) pointed out that aggregate segregation is usually caused by the low yield stress of the paste. Skarendahl and Petersson (2000) found it can be avoided by increasing both friction and cohesion of paste phase. But increasing cohesion is much more beneficial than increasing friction, because increasing friction also decrease the deformability. In order to resist segregation, aggregates with limited content and reduced maximum size are normally used together with the viscosity agent and lower water-to-powder ratio.

Saak, et al. (2001) found that the segregation of aggregate can be voided by control the rheological properties of paste. In static condition, the minimum yield stress for the paste is required to balance the self-weight of coarse aggregate to make it not segregate. Under dynamic condition, the segregation of coarse aggregate can be eliminated by paste with enough viscosity.

2.5 Flowability of Fresh Concrete

Concrete in its fresh state can be described as a fluid, provided that a certain degree of flow can be achieved and that concrete is homogeneous. Ferraris, et al. (2001) defined this constraint as a slump of at least 4 inches and no segregation. As discussed previously, the flowability of fresh concrete is described as its rheological properties. Almost all items related to the concrete rheology were discussed at the beginning of this chapter; no further discussion will be provided here.

2.6 Shape Stability of Fresh Concrete

Shape stability is defined as the ability that fresh concrete can keep the shape (no deformation) after demodel. Bird, et al. (1983) mentioned that the flow of fresh concrete under its own weight depends critically on both the geometric and material properties. The initial flow of fresh concrete is controlled by its yield stress, which is the stress that must be reached for the material to traverse from solid to fluid-like behavior. For conventional concrete, the collapse of vertical fresh concrete slop is directly related to its yield stress (Dunn, et al. 1980; Anderson and Richards 1987; and Christensen 1991). The two parameters of the Bingham model, yield stress and plastic viscosity, have been investigated using the slump test (Murata 1984; Christensen 1991; Saak, et al. 2004). It is now believed the slump of fresh concrete is a reliable indicator of the shape stability and yield stress.

Christensen (1991) firstly evaluated the slope stability of fresh concrete in order to study the relationship between its slump value and yield stress. In his analysis, the yield value corresponding to failure of the two dimensional slope illustrated in Figure 2.12 was determined using the collapse criterion for soil material presented in Dunn, et al. (1980) as a series of curves relating collapse yield value to the slope angle. It was found that the failure criterion for soil material is not suitable for concrete, but the collapse of fresh concrete slope is directly related to its yield stress.

Murata (1984) published his model relating slump to yield stress based on a simple force balance analysis and the assumption that the slump of fresh concrete is affected by its yield stress and not by its viscosity. In Murata's model, the deformation of the slump cone is considered as the part of the slump cone above the cross section contemplated settling and coming to rest when the maximum shear stress acting on the cross section is gradually decreased, through increase in the cross-sectional area accompanying progress of deformation, to become equal to the yield value (Figure 2. 13). Evidences were given to show that this remarkably simple model of the slump process first proposed by Murata (1984) and corrected by Christensen (1991), is a good predictor of conical slump test results

(Schowalter and Christensen 1997; Saak, et al. 2004). This model can also be applied on cylinder, not only cone (Figure 2.14). Other attempts have been conducted on finite element studies on slump test using different material models relating to the yield stress and plastic viscosity (Davidson, et al. 2000; Sader and Davidson 2004). All of these studies show good prediction on collapse of concrete cylinder. It is further confirmed that the collapse or deformation of concrete cylinder is directly related to its yield stress. In other words, the deformation and the shape after deformation is mainly controlled by yield stress. To study the yield stress is critical in studying the shape stability of fresh concrete. The successful application of Murata's model further confirmed that the deformation/flow is controlled by its yield stress. At any point in the concrete, if the shear stress acting on this point is less than the yield stress, the material cannot deform. For a concrete body with certain geometric properties, it is its yield stress that controls its deformation.

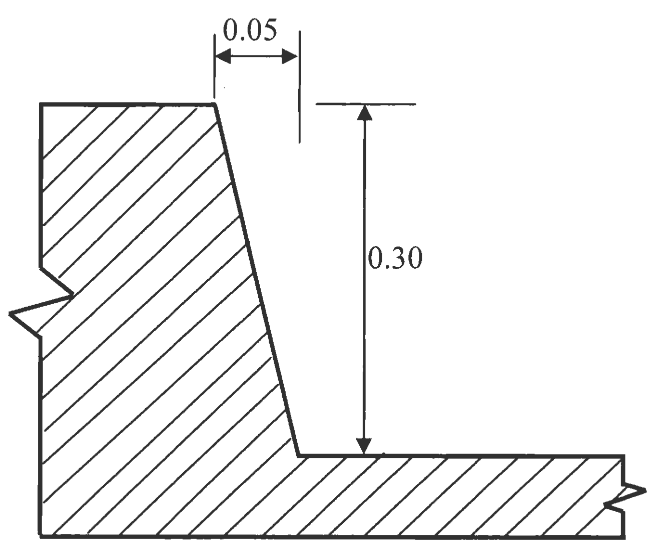


Figure 2.12 Illustration of the slope used in the slop stability calculation (Christensen1991)

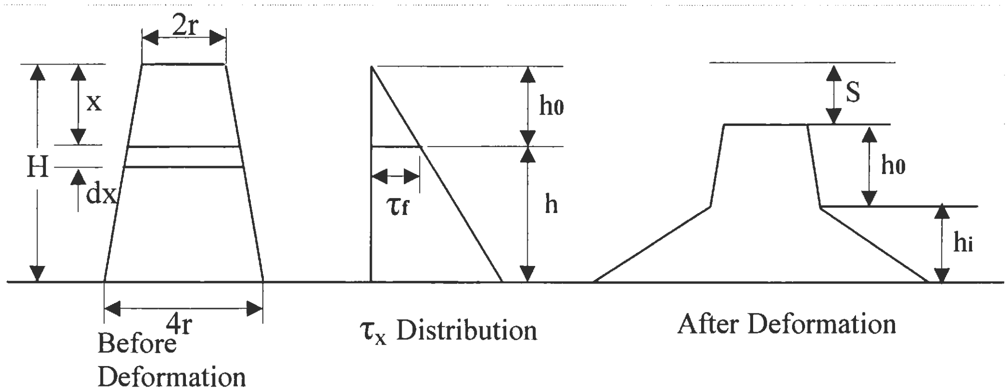


Figure 2.13 Deformation of slump cone (Christensen 1991)

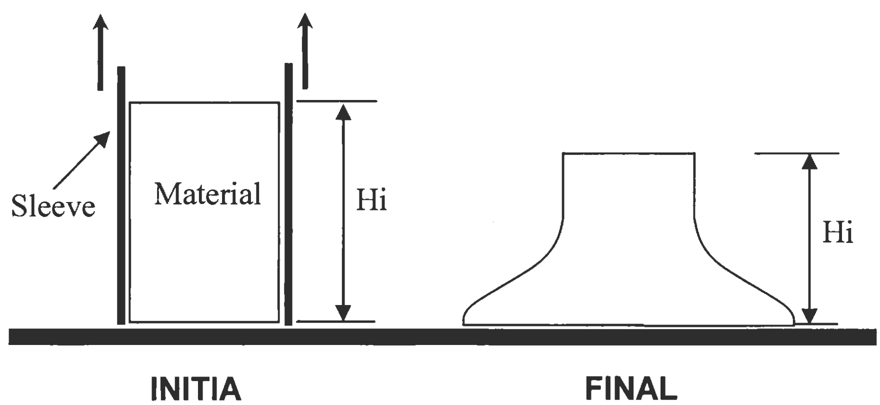


Figure 2.14 Graphical illustration of slump test showing measurement principle and typical deformed final shape (Sader and Davidson 2004)

2.7 Discussion on shape stability and flow ability of fresh concrete

"Green" strength is defined as the ability of an incompletely cured material to undergo removal from the mold and handling without distortion. High green strength means good collapse resistance. The value of green strength depends critically on both the geometric and material properties. Figure 2.15 shows two cylinders with different height and made of same fresh concrete. According to Murata's model (1984), the shear stresses acting on the bottom cross section of the cylinders are different due to different height of cylinders. If the shear stress acting on the bottom of cylinder is less than the yield stress, the cylinder will not deform. Once the shear stress acting on the bottom of cylinder exceeds the yield stress, the deformation will happen. In this case, the green strength of fresh concrete is directly related to its yield stress.

The complexity between flowability and shape stability is that the fresh concrete will deform or flow under certain applied load and then hold a certain shape without any external effect.

To ensure the shape stability of fresh concrete slab for certain height, it is important for it to have the minimum yield stress. This is the criteria for achievement of fresh concrete for pavement. On the other side, the fresh concrete can flow under external load, such as extrusion and vibration or internal effort such as big volume of fresh concrete (Figure 2.16).

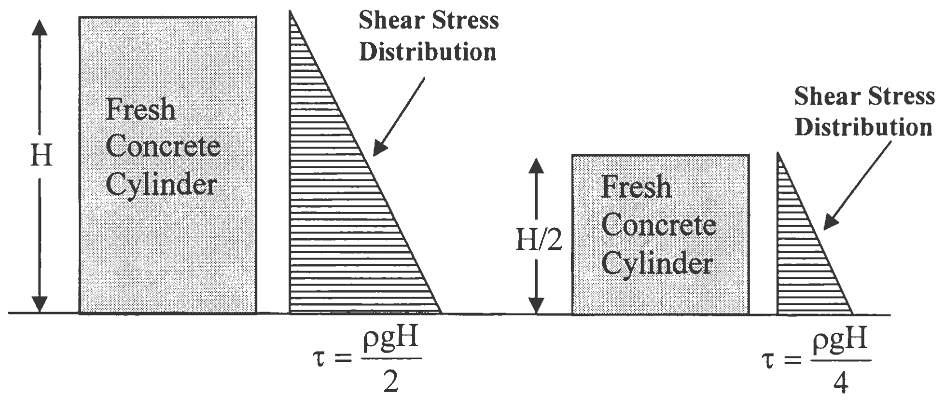


Figure 2.15 Different fresh concrete cylinders

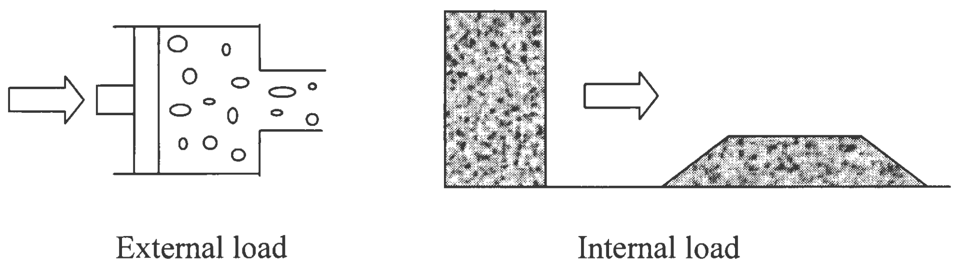


Figure 2.16 Different fresh concrete cylinders

2.8 Test Method Related to Fresh Concrete Compactability, Flowability, and Shape Stability

Since the early 20th century, a large number of testing methods related to fresh concrete compactability, flowability, and shape stability have been developed. Koehler (2003) summarized previously developed equipment; up to 61 different test methods for measuring concrete workability were described in the report. Most of them are empirical and designed for a particular project. In this thesis, only those directly related to the current study are reviewed.

2.8.1 Compactability Measurement

Compacting Factor Test

The compacting factor test was developed in Britain in the late 1940s and has been standardized as the British Standard 1881-103. The apparatus (Figure 2.17) consists of a rigid frame that supports two conical hoppers vertically aligned above each other and mounted above a cylinder. The top cone is filled with well-mixed loose concrete and weighed. It is then allowed to drop to the lower cone and then to the bottom cylinder. The bottom cylinder is smoothed off level, and any surplus concrete on the outside wiped away. The cylinder is then weighed. The difference between the weight of the concrete placed in the top cone and that of the cylinder provides a measure of workability. The higher the weight of the cylinder to the cone, the more workable the concrete, but the difference should not be more than 1.

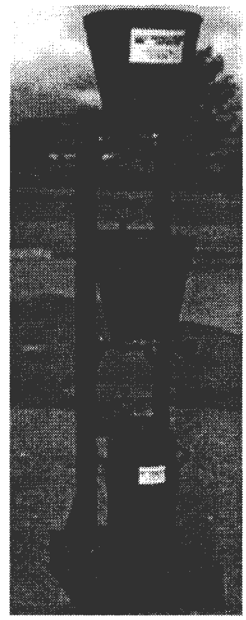


Figure 2.17 Compacting Factor Test apparatus (Koehler, et al. 2003)

This test also measures the workability of concrete in a more precise way than does the slump test. It measures the weight of uncompacted concrete and compares it with the weight of partially compacted concrete.

There is a relationship between the results of this test and compactability. In practice, compaction is normally achieved by vibration and not by dropping the concrete from a certain height. In this case, the test is far from representative of the "real world." Also, some energy is lost in friction along the cone surface. This energy loss can be important; currently it is difficult to evaluate this energy, especially for low workability concrete. But for slip-form pavement concrete, since the fresh concrete will be poured into the slip form of the paver from a limited but almost constant height, if the later vibration from vibration bars is not considered, this test is suitable to simulate this progress. To minimize the loss of friction, only one conical hopper can be used; this only means less external energy to compact concrete. This new compacting factor will be discussed later in Chapter 3.

Compaction Test (Walz Test)

This test was developed by Walz in the 1960s and is now a German standard (DIN 1048). This test is applicable for low to high workability concretes. It measures the volume of a concrete sample in a standard container before and after full compaction. The compaction is generally achieved by vibration. It is often referred to as the Compaction Index test.

The apparatus essentially consists of a metallic box 200mm x 200mm x 400mm (Figure 2.18). The container is filled with fresh concrete without compaction. After the top of the filled container has been struck off level, the concrete is compacted by vibrating table or rod tamping. Total compaction should be achieved before measuring the distance from the top of the concrete to the top of the container. The degree of compaction is then calculated as the height of the container divided by the average height of the compacted concrete. Typical values range from 1.02 to 1.05.

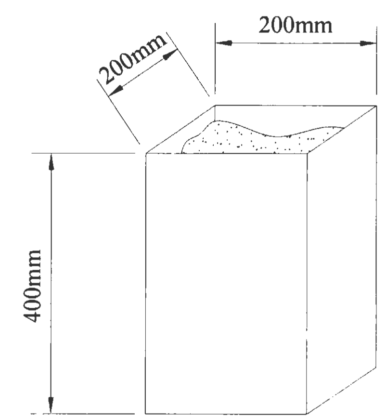


Figure 2.18 Compaction Test apparatus (Koehler, et al. 2003)

Intensive Compaction Test

The intensive compaction test is a gyratory compactor used to measure the workability (mostly the compactability) of concrete mixture with slump less than 0.5 inch.

The test apparatus is a machine that applies compression and shear forces to a concrete specimen in a cylindrical mold while recording the varying density of the specimen (Figure 2.19).

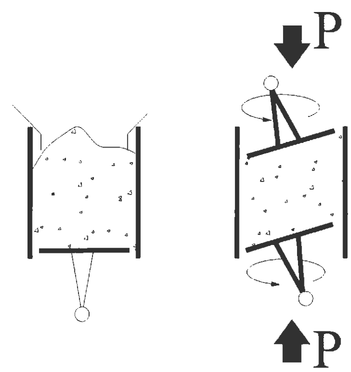


Figure 2.19 Intensive Compaction Test (Koehler, et al. 2003)

To determine the compactability of c concrete mixture, the density of the concrete is plotted versus the number of working cycles of the pistons. Concrete mixes can be compared the density after same number of cycles under same pressure or the number of cycles and pressure to obtain same density. These results show how easy or difficult a concrete mix can get compacted. This is the most accurate measuring method to evaluate the compactability of fresh concrete even though the change in mixture proportions is minor. But it is only applicable to very stiff concrete. For normal concrete or high flowable concrete, it is not applicable because of the loss in weight of concrete due to bleeding. But if a sealed cylindrical mold is used, this problem can be solved, but in the mean time, the shear forces will not be applied. This needs more studies on the pressure and shear forces applied to the concrete specimens.

Compactability Test Used in Japan

This test was first developed by Kokubu (1996) and then modified by Liang (2004). The basic apparatus for this test includes a rigid cylinder container with a vibration table and a data collecting system to measure external energy applied on concrete and volume change of concrete (Figure 2.20). During testing, fresh concrete is poured into the cylinder container, and external effort is applied to compact it. Both compaction energy and volume change of concrete are captured. The external energy to compact concrete can be controlled during testing.

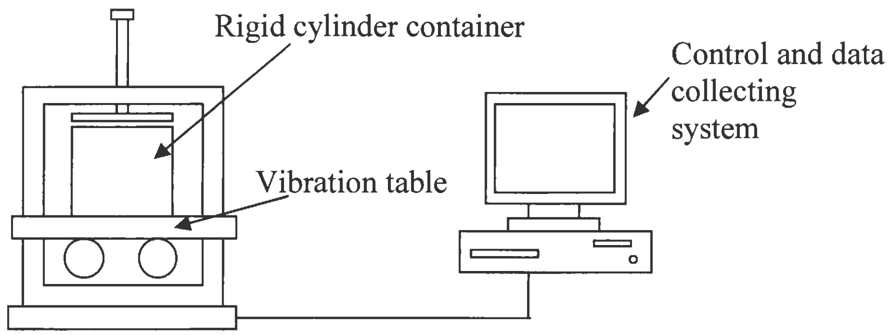


Figure 2.20 Compactability Test apparatus (Kokubu 1996 and Liang 2004)

This testing method is widely used in Japan to evaluate the compactability of fresh concrete. It has been shown to be an efficient method in compactability studies (Kokubu 1996 and Liang 2004).

2.8.2 Flowability and Shape Stability Measurement

Slump Test

The slump test is the most commonly accepted method used to measure the consistency of concrete (ASTM C143). The apparatus consists of a mold in the shape of a frustum of a cone with a base diameter of 8 inches, a top diameter of 4 inches, and a height of 12 inches (Figure 2.21). The slump cone is filled with fresh concrete in three layers, with tamping between each to remove voids. The concrete is leveled off with the top of the cone. On removing the cone, the slump is measured. The higher the slump, the higher the flowability. The slump test can be used with fresh plastic concrete containing coarse aggregate with a maximum size of 1.5 inches.

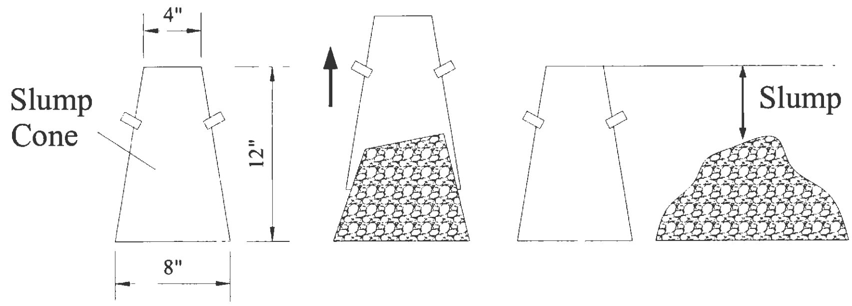


Figure 2.21 Slump Test (Koehler, et al. 2003)

Originally, the slump test was developed to measure the effect of water content on the workability of fresh concrete.

Although the slump test does not directly measure the work needed to compact the concrete, it gives a reasonable indication of the how easily a mix can be placed and is simple to perform. The test is only suitable for reasonably workable, cohesive mixes. Very stiff mixes do not settle enough for useful measurements to be made and uncohesive mixes tend to shear or collapse. The limits of its proper application correspond to slump between 0.5 to 9 inches. In other words, this method does not work well for very stiff or very fluid concrete. Other factors beside the variation in water content may cause variations in slump measurement: Mittelacher (1992) studied operator and other influences. Almost any change in mix composition or in material characteristics will affect the slump. The time history is also important in measuring slump, because concrete is known to lose slump with time. This phenomenon can be very important when superplasticizers are being used (Whiting and Dziedzic 1989)

Murata (1984) developed an analytical expression relating yield stress with slump. His model is based on former work conducted by Tattersall and Banfill (1983), who used coaxial cylinder experiments on fresh concrete and found that it can be interpreted by using the Bingham model. They also concluded that plastic viscosity has little effect on the value of slump obtained but is strongly related to yield stress. Murata related the value of slump to fresh concrete yield value and density. The results he obtained are summarized in Figure 2.22.

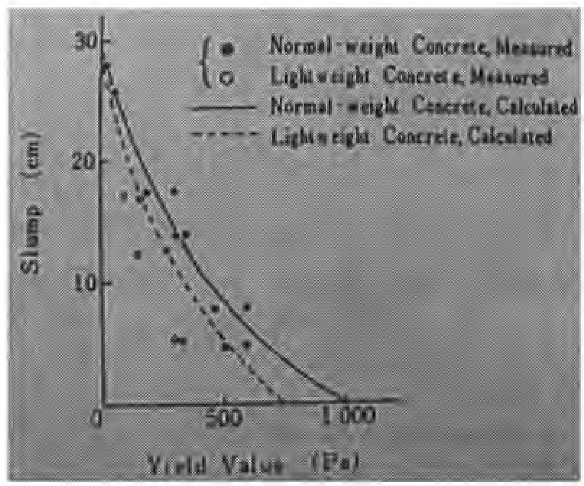


Figure 2.22 Yield value vs. slump (Murata 1984)

Christensen (1991) corrected the integration errors in the original Murata model and converted the units to dimensionless quantities. Christensen's model is independent of the particular material under investigation and the size of the slump cone. However, Christensen did not experimentally confirm the accuracy of the model. The predicting cure based on Christensen's model is shown in Figure 2.23.

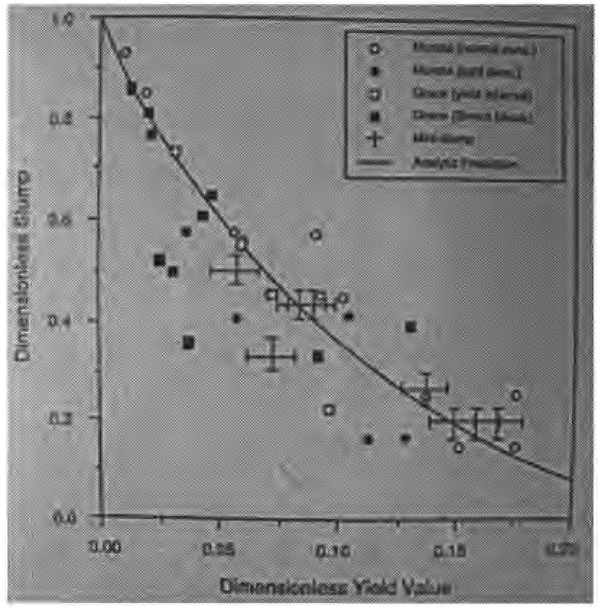


Figure 2.23 Analytic prediction of Christensen's model (Christensen 1991)

During the past twenty years, several researchers revised Murata's analysis works (Rajani and Morgenstern 1991; Pashias and Boger 1996; Schowalter and Christensen 1998; Chamberlain, et al. 2003; and Saak 2004). The simple model of the slump originally developed by Murata has proven to be a good predictor of conical slump test results. Because of the successful application of theoretical rheology models on the slump test, more complicated simulations have been conducted using the finite element method.

Tanigawa, et al. (1986) studied the effect of yield stress and plastic viscosity on slump test results by applying the finite element method to the slump test. The rheological properties were obtained from viscometer and parallel-plates plastometer. Their results are shown in Figure 2.24.

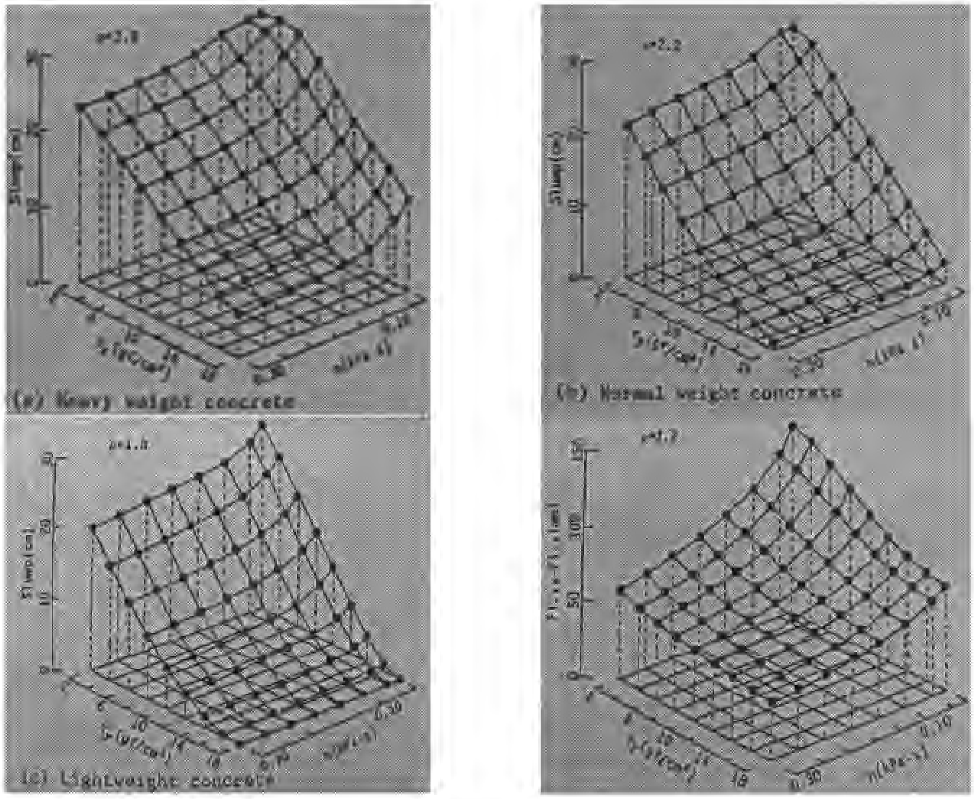


Figure 2.24 Effect of rheological constants on slump and spread (Tanigawa, et al.1986)

Tanigawa, et al. found that slump value is very sensitive to yield stress. The spread value is considerably affected by the rheological constants when the yield stress and the plastic viscosity are both small.

Hu, et al. (1996) developed an expression for yield stress in terms of slump and density based on a finite element model of a slump test (Equation 2.1).

$$\tau_0 = \frac{\rho}{270}(300 - s) \qquad (2.1)$$

where τ_0 is yield stress in Pa, s is slump in mm, and ρ is density in kg/m^3. The finite element calculations were performed for concrete with slumps ranging from 0 to 1 inch. The equation is not applicable for concrete with a plastic viscosity greater than 300 Pa·s. Experimental results from the BTRHEOM rheometer showed agreement between Equation 2.1 and test results.

Modified Slump Test

Tanigawa (1989, 1991) first modified conventional slump tests to study the relationship between slump and time. The experimental setup is shown in Figure 2.25. They used a pair of displacement transformers to measure the time duration for concrete to slump. Their testing procedure was the same one recommended by ASTM (ASTM C143). They found that the slump-time curve could be simulated by finite element analysis of the fresh concrete, assuming it is a Bingham material. The slump-time curve depends on both yield stress and plastic viscosity.

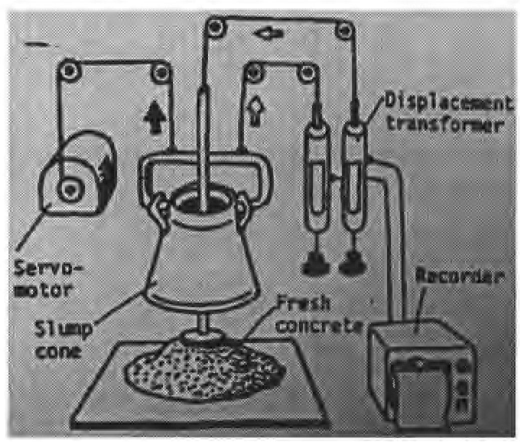


Figure 2.25 Modified slump test of Tanigawa, et al. (1989, 1991)

Ferraris and de Larrard (1998) modified slump tests based on Tanigawa's work. Their slump test setup almost exactly followed Tanigawa's design shown in Figure 2.25. Instead of measuring the whole slump of concrete like Tanigawa, Ferraris and de Larrard measured partial slump (Figure 2.26). Their modified slump test is applicable on concrete with a slump of at least 4 inches. The concrete was placed in the same manner as in the standard slump test (ASTM C143).

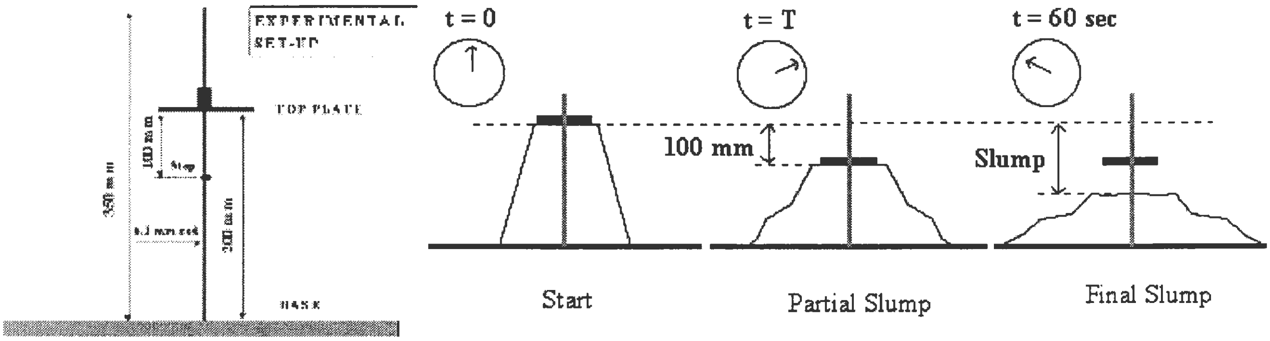


Figure 2.26 Modified slump test of Ferraris and de Larrard (1998)

Based on modified slump test results, an estimation of the fundamental rheological parameters was established. The yield stress of concrete can be calculated from its slump and density by the following empirical equation:

$$\tau_0 = \frac{\rho}{347}(300 - s) + 212 \qquad (2.2)$$

where τ_0 is yield stress of concrete (Pa), ρ is density (kg/m^3), and s is slump (mm).

The plastic viscosity of concrete can be calculated from its density, slump, and slump time by the following equations:

$$\mu = \rho \cdot T \cdot 1.08 \cdot 10^{-3} \cdot (s - 175) \quad \text{for} \quad 200<s<260 \text{ mm} \qquad (2.3)$$

$$\mu = 25 \cdot 10^{-3} \cdot \rho \cdot T \quad \text{for} \quad s<200 \qquad (2.4)$$

Nomographs based on the above equations have been developed that allow quick determination of yield stress and plastic viscosity in the field.

The modified slump test facilitates better quality control of fresh concrete in the field. The final slump combined with the unit mass of the concrete allows an estimation to be made of the yield stress of the concrete in the field for concrete with slump greater than 4 inches. The slump time combined with the preceding measurements can provide an estimate of the plastic viscosity for concrete with a slump between 4.8 to 10.4 inches.

IBB Concrete Rheometer Test

Beaupre and Mindness (1994) developed the IBB rheometer in Canada, based on the two-point device developed by Tattersall (1979). It consists of a cylindrical container holding the concrete, with an H-shaped impeller driven through the concrete in a planetary motion. The speed of the impeller rotation was first increased to maximum rotation rate and then the rotation rate was decreased in six stages, with each stage having at least two complete center shaft revolutions. The torque (N·m) generated by the resistance of the concrete specimen to the impeller rotation was recorded at each stage as well as the impeller rotation rate (revolutions per second) measured by the shaft tachometer. The torque versus the impeller rotation rate can be approximated by a linear function, whose slope is related to the plastic viscosity and intercept, at zero rotation rate, is related to the yield stress. The output of the IBB concrete rheometer can be described in the following equation:

$$T = g + h \cdot N \tag{2.5}$$

where T is torque and N is rotation speed; g is a yield stress related term and h is a plastic viscosity related term.

Because the geometry and flow patterns are too complicated in this rheometer, the values obtained are only proportional to the plastic viscosity and yield stress of the concrete. The units used are N·m and N·m·S for yield stress and viscosity, respectively. The device has been successfully applied to a wide range of concrete workability (Koehler, et. al. 2003)

2.8.3 Test Methods for Conventional SCC

For conventional SCC, workability tests can be broadly split into three categories: filling ability tests, passing ability tests, and segregation resistance tests. Currently, at least eight test methods have been developed for conventional SCC (Koehler, et al. 2003). For current studies, as discussed previously, only slump flow test was discussed below.

Slump Flow Test

The slump flow test is the simplest and most widely used test method for conventional SCC (Koehler, et al. 2003). It is based on the standard slump test. To perform the test, a conventional slump cone is placed on a rigid, non-absorbent plate and filled with concrete without tamping. The plate must be placed on a firm, level surface. The slump cone is lifted and the horizontal spread of the concrete is measured. Additionally, the time required for the concrete to spread to a diameter of 50 cm should be measured to evaluate its flowability.

CHAPTER 3
EXPERIMENTAL WORK

3.1 Materials

ASTM Type I Portland cement (Lafarge) that met the requirements of ASTM C 150 and Class C and Class F fly ash that met the appropriate requirements of ASTM C 618 were used. The chemical and physical properties of the cementitious materials used in this study are summarized in Table 3.1.

Table 3.1 Chemical and physical properties of cementitious materials

Components	Type I Cement	Class C Fly Ash	Class F Fly Ash
CaO	63.01	27.04	1.55
SiO_2	20.62	35.61	46.02
Al_2O_3	4.47	18.90	23.40
Fe_2O_3	3.29	6.03	24.09
MgO	3.10	4.64	0.73
K_2O	0.68	0.38	1.78
Na_2O	0.10	1.73	0.45
SO_3	2.76	1.69	0.37
TiO_2	0.35	1.59	1.07
Mean size (μm)	23.7	13.6	24.1
Specific gravity	3.15	2.66	2.41
Fineness	373	Not measured	Not measured

Limestone with a nominal maximum size of 1 inch was used for all mixes, and gravel with a nominal maximum size of 1 inch was used to replace limestone for selected concrete mixes. The limestone coarse aggregate has a specific gravity of 2.65 and an absorption of 3.0%, while the gravel coarse aggregate has a specific gravity of 2.5 and an absorption of 1.7%. River sand with a specific gravity of 2.70, a fineness modulus of 3.1, and absorption of 1.2% was used as fine aggregate for all of the concrete mixtures. All aggregate was recombined and prepared to reach SSD conditions before concrete casting. The gradation of the aggregates will be provided in the next section. Cold tap water was used for all mixing water. Rheomac VMA 358, Acti-Gel 208, and "W. R. Grace Daracem 19" superplasticizer were used as admixtures. An air-entraining agent (AEA), Daravair 1400, was used in all mixes.

3.2 Mix proportions

A total of 46 concrete mix proportions, listed in Table 3.2, were used in this study. All mix proportions were classified into eight groups. A previous study showed that when the sand-to-aggregate ratio (s/A) was about 45%, a minimum total energy is required to compact fresh concrete (Liang, et al. 2003). The s/A of 44% was thus used in the present study, which is also consistent with Iowa DOT C3 mix design.

Below, an explanation of the various aspects of the mix designations in Table 3.2 is as follows:

- The first letter "P" in Group 2 designates cement paste content. The effect of the cement paste content on concrete properties was evaluated for all mix proportions in this group. The number after the "P" designates the percentage of cement paste content according to the weight of the total concrete.
- The first two letters "FA" in Groups 3 and 4 designate fly ash. The effect of fly ash on concrete properties was evaluated for all mix proportions in these two groups. The third letter in the middle designates the type of fly ash, either Class C or F. The last two-digit number designates the percentage by which fly ash replaced the cement according to weight.
- The first two or three letters--"SP," "VMA," and "AG"--in Groups 5, 6, and 7 designate Superplasticizer, viscosity-modifying admixture, and Acti-Gel, respectively. The last two-digit number designates the dosage of the three above items according to the weight of the cementitious materials.

In Group 8, the letters "L" and "G" designate limestone and gravel, respectively. The last two-digit number designates the ratio of gravel and limestone according to weight.

Table 3.2 Mixture proportions (all in lb/yd^3)

Group	Number	OPC	Fly Ash		Water	Sand	Coarse Agg.	Admixtures			W/C
			Class C	Class F				SP	VMA	AG	
1	series A	810	0	0	311	1269	1620				0.38
	series B	567	243	0	308	1269	1620				0.38
	series C	603	0	0	260	1339	1684				0.43
2	P-23	603	0	0	260	1269	1620				0.43
	P-27	750	0	0	321	1269	1620				0.43
	P-29	810	0	0	350	1269	1620				0.43
	P-30	850	0	0	365	1269	1620				0.43
3	FA-C20	648	162	0	308	1269	1620				0.38
	FA-C30	567	243	0	308	1269	1620				0.38
	FA-C40	486	324	0	308	1269	1620				0.38
	FA-C50	405	405	0	308	1269	1620				0.38
4	FA-F20	648	0	162	308	1269	1620				0.38
	FA-F30	567	0	243	308	1269	1620				0.38
	FA-F40	486	0	324	308	1269	1620				0.38
	FA-F50	405	0	405	308	1269	1620				0.38
5	SP-0.5	810	0	0	308	1269	1620	4.0			0.38
	SP-1.0	810	0	0	308	1269	1620	8.0			0.38
	SP-1.5	810	0	0	308	1269	1620	12.0			0.38
	SP-2.0	810	0	0	308	1269	1620	16.0			0.38
6	VMA-0.2	567	243	0	308	1269	1620		1.35		0.38
	VMA-0.3	567	243	0	308	1269	1620		2.70		0.38
	VMA-0.5	567	243	0	308	1269	1620		4.05		0.38
	VMA-0.67	567	243	0	308	1269	1620		5.40		0.38
7	AG-0.2	567	243	0	308	1269	1620			1.62	0.38
	AG-0.3	567	243	0	308	1269	1620			2.43	0.38
	AG-0.5	567	243	0	308	1269	1620			4.05	0.38
	AG-0.67	567	243	0	308	1269	1620			5.40	0.38
8	G:L=1:3	567	243	0	308	1269	1215L+405G				0.38
	G:L=1:1	567	243	0	308	1269	810L+810G				0.38
	G:L=3:1	567	243	0	308	1269	405L+1215G				0.38
	G:L=1:0	567	243	0	308	1269	1620G				0.38

Notes:

P = Paste
FA-C20 = Fly Ash Class C, 20% replacement of cement
FA-F20 = Fly Ash Class F, 20% replacement of cement
SP = Superplasticizer
VMA = Viscosity-modifying admixture
AG = Acti-Gel
L = Limestone
G = Gravel

All mix proportions in Group 1 were designed to evaluate the effect of coarse aggregate gradation on concrete properties. Six different gradations were used for each mix proportion series in this group (A, B, and C series). The different gradations are shown in Table 3.3. Gradation G1 is the one currently used in the Iowa DOT C3 mix.

G2 and G3 are the lower and upper gradation limits in ASTM C33 (Standard Specification for Concrete Aggregate). G4 is the intermediate gradation of ASTM C33. G5 is an optimum aggregate gradation that meets the 0.45 power gradation curve. G6 is a trial gradation that was designed to limit the amount of large particles (3/4"-1") in G2.

Table 3.3 Aggregate gradation

Sieve Size	Coarse Aggregates % Passing						Sand, % Passing
	G1	G2	G3	G4	G5	G6	
1"	100.0	100.0	100.0	100.0	100.0	100.0	--
3/4"	90.0	55.0	90.0	73.0	77.0	80.0	--
1/2"	50.0	30.0	65.0	46.0	48.0	30.0	--
3/8"	25.0	15.0	35.0	23.0	32.0	15.0	100.0
#4	0.0	0.0	0.0	0.0	0.0	0.0	97.6
#8	0.0	0.0	0.0	0.0	0.0	0.0	91.4
#16	0.0	0.0	0.0	0.0	0.0	0.0	70.0
#30	0.0	0.0	0.0	0.0	0.0	0.0	37.0
#50	0.0	0.0	0.0	0.0	0.0	0.0	14.0
#100	0.0	0.0	0.0	0.0	0.0	0.0	3.0
Pan	0.0	0.0	0.0	0.0	0.0	0.0	0.5

The mix proportion for Series C in Group 1 is currently used in the Iowa DOT C3 mix. Series A and B were designed with the same paste content but with a different flowability. Series A is plain concrete without any admixture. In Series B, 30% cement by weight was replaced by Class C fly ash. In total, 18 batches of concrete were prepared in this group.

Group 2 was designed to evaluate the effect of paste content on concrete properties. The coarse aggregate gradation used in this group was G1 in Table 3.4. The same amount of fine and coarse aggregates were used for all mix proportions in this group. The only component that varied in this group was the amount of paste. The paste content (by weight of concrete) varied from 23% to 30%. The mix proportion P-23 was modified from the C3 used by the Iowa DOT. The amount of total aggregates was reduced by 4.5%, but the s/A was kept as 0.44. The paste content (by weight) was 23% for the P1 mix proportion, 27% for P2, 29% for P3, and 30% for P4. A 30% paste content is normally used for SCC.

Groups 3 and 4 were designed to evaluate the effect of fly ash on concrete properties; Class C fly ash was used for Group 3 mix proportions, and Class F fly ash was used for Group 4 mix proportions. Series A from Group 1 was used as the reference mix proportion. The only variable component in this group was the paste component. Coarse aggregate with gradation G1 was used. The paste content by weight was 28% of total concrete. The ratio of replacement of cement was 20%, 30%, 40% and 50%.

Group 5 was designed to evaluate the Superplasticizer (SP) effect on concrete properties. The reference mix proportion was the same as Groups 3 and 4, and the A series from Group 1. Coarse aggregate gradation G1 was used. The dosage by weight of cement iwa 0.5% for SP-0.5, 1.0% for SP-1.0, 1.5% for SP-1.5, and 2.0% for SP-2.0, respectively. As mentioned previously, the only variable component in this group was the paste component.

Group 6 was designed to evaluate the viscosity-modifying admixture (VMA) effect on concrete properties. The reference mix proportion was FA-C-30 from Group 3; the only variable component in this group was the paste component. Coarse aggregate gradation G1 was used. The dosage by weight of cementitious material was 0.2% for VMA-0.2, 0.3% for VMA-0.3, 0.5% for VMA-0.5, and 0.67% for VMA-0.67, respectively.

Group 7 was designed to evaluate the Acti-Gel (AG) effect on concrete properties. The reference mix proportion was FA-C-30 from Group 3, which was the same as Group 6; the only variable component in this group was the paste component. Coarse aggregate with G1 gradation was used. The dosage (by weight of cementitious material) was 0.2% is for AG-0.2, 0.3% for AG-0.3, 0.5% for AG-0.5, and 0.67% for VMA-0.67, respectively.

Group 8 was designed to evaluate the effect of a combination of limestone and gravel aggregate on concrete properties. The reference mix proportion was FA-C-30 from Group 3, which was the same mix proportion that Groups 6 and 7 used. The ratio by which the gravel replaced the limestone aggregate was 25% for G:L=1:3, 50% for G:L=1:1, 75% for G:L=3:1, and 100% for G:L=1:0, respectively. Both gravel and limestone aggregate has the same gradation as G1.

3.3 Mixing Methods

A Lancaster 30-DH pan concrete mixer (Figure 3.1) was used for concrete mixing. The pan mixer has a flat cylindrical pan to store the concrete. The mixing blades, which are separate from the pan, rotate inside the pan while it is rotating in the opposite direction. A separate blade is fixed against the inside edge of the pan and scrapes the material off of the side, moving it toward the center of pan where the mixing blades are rotating.

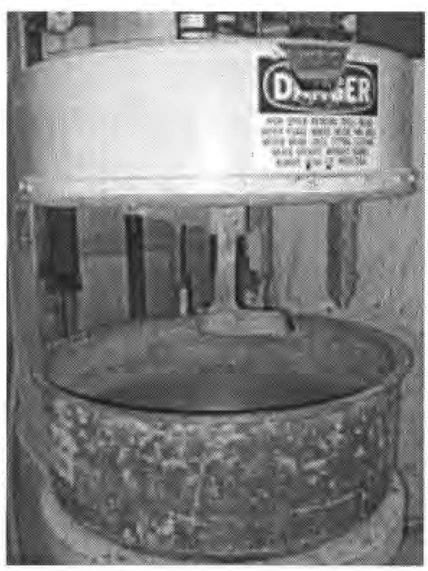


Figure 3.1 Rotating concrete pan mixer

The standard ASTM C192 lab mixing procedure was used as the unique mixing method in this study. This multiple-step mixing procedure is described below:

1. Coarse aggregate and around half of the amount of water with AEA were premixed about 30 seconds,
2. Sand was added to the mixer, followed by cement and the rest of the water. The mixture was then mixed for three minutes.
3. The mixture was allowed to rest for three minutes.
4. The mixture was mixed again for another two minutes.

3.4 Test Methods

Coarse aggregate properties, including specific gravity, friction angle, uncompacted void content and absorption, were measured. Fresh concrete compactability was measured by the modified compaction factor test. Concrete flowability was measured by the IBB rheometer and the slump test. The unit weight of fresh concrete and compressive strength of hardened concrete were measured. Mini-paver and filling ability tests were conducted on selected mix proportions to evaluate their self-compactability, flowability, and shape stability.

3.4.1 Measurement of Coarse Aggregate Properties

The specific gravity and absorption of coarse aggregate were measured in accordance with the specifications in ASTM C127. The loose and compact bulk density and void content of recombined coarse aggregate were measured by filling the measure, that is, by scooping aggregate inside according to ASTM C29 (Figure 3.2).

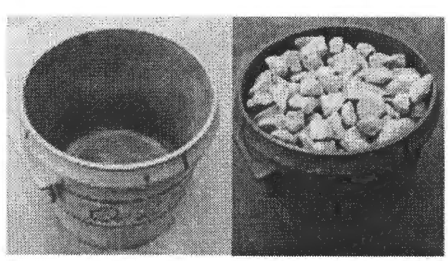


Figure 3.2 Measurement of bulk density and void content of CA

The calculation of void content of coarse aggregate can be shown in the following equation:

$$V_{CA} = \frac{V_{CA} - W_{CA} / G_{SBCA}}{V_{CA}} \times 100\% \qquad (3\text{-}1)$$

In this equation, V_{CA} is the void content (%), V_{CA} is the volume of the measure, W_{FA} is the weight of aggregate in the measure, and G_{SBCA} is the dry specific gravity of the aggregate.

The coarse aggregate friction angle was measured using the stability theory of slopes from geotechnical engineering (Dunn, et al. 1980). According to Lambe and Whitman (1969), the angle of repose for an ore pile of angular pebbles is the internal friction angle of the aggregate (Figure 3.3).

The procedures for coarse aggregate friction angle measurement are described below:

1. Dump aggregate at the center of the circle from a constant distance to the top of the pile. To minimize the impact effect, this constant distance should be as small as possible.
2. Keep dumping until the bottom edge of the pile meets the circle (30” diameter).
3. Measure the height of the pile and then calculate the friction angle of this aggregate (Figure 3.4).

Three measurements were performed for each gradation of aggregate; the average value was used as the friction angle for a given coarse aggregate.

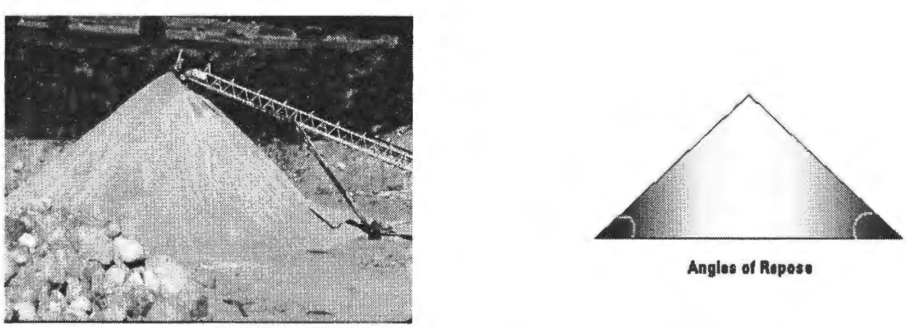


Figure 3.3 Formation of ore pile

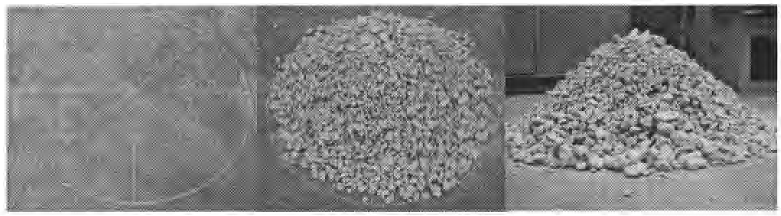


Figure 3.4 Coarse aggregate friction angle measurement

3.4.2 Test Methods for Fresh Concrete Evaluation

The standard tests listed below were used to evaluate fresh concrete properties:

- Unit weight–The unit weight test of fresh concrete was measured in accordance with ASTM C 138.
- Air content–The air content of fresh concrete was measured using a pressure meter in accordance with ASTM C231.

In this study, non-standard tests for fresh concrete include the "non-tamping slump flow" test, "green" strength test, IBB rheometer test, and compaction factor test.

Non-rodding Slump Flow Test

The apparatus and procedures for this test are almost the same as the slump test standard by ASTM. The procedure is described below:

1. The slump cone is placed on a rigid, non-absorbent plate, which is placed on a firm, level surface.
2. Concrete is poured into the slump cone from a constant height without tamping. As Figure 3.5 shows, 30 inches from the base is used here.
3. Concrete is continually poured into the slump cone until it filled the slump cone. After simply smoothing the top surface, the slump cone was lifted up to let the concrete slump.
4. After testing, the slump and spread were measured.

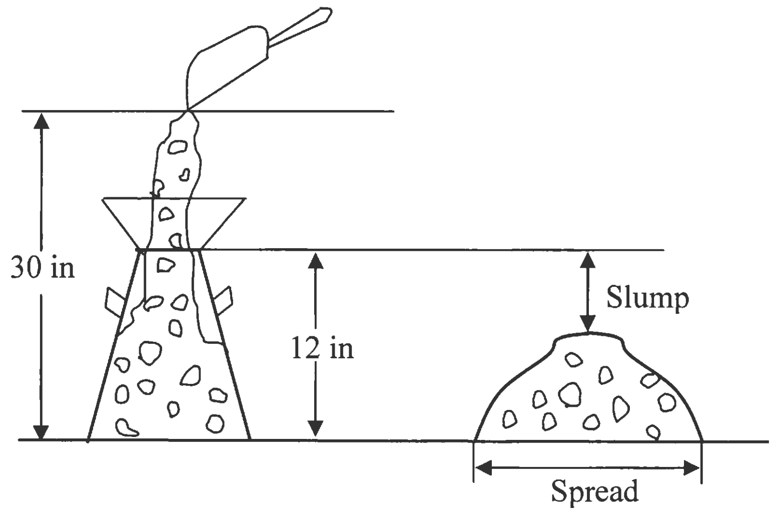


Figure 3.5 Non-rodding slump flow test

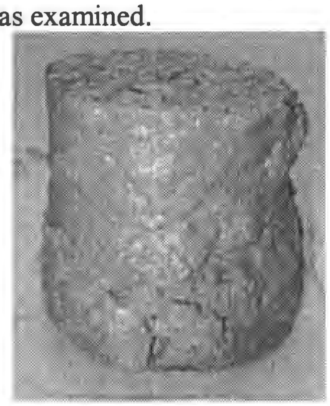
Concrete Green Strength Measurement

A simple test was developed to evaluate the green strength of fresh concrete; a plastic cylinder mold (4" x 8", without a bottom) was used for the concrete casting. During the casting, the concrete mixture was poured into the cylinder mold with standard consolidation (ASTM C192). Right after the cast, the plastic mold was removed and the shape of the concrete sample was examined. If a mixture demonstrated little or no deformation after de-mold, the mixture was considered as having good shape stability. Then the green strength test of the sample was pursued. Hardened concrete slices 4 inches in diameter were slowly placed on top of the fresh concrete sample one by one. The start of deformation was defined as the failure of the fresh concrete. The total weight of the concrete slices applied in the test divided by the loading area of the sample was defined as the green strength of the concrete. Figure 3.6 illustrates the test procedure for concrete green strength measurement.

(a) Casting: The mold was filled with fresh concrete with rodding.

(b) De-molding: After the plastic mold is removed, concrete shape stability was examined.

(c) Loading: Concrete slices are slowly placed on top of the fresh concrete sample one by one.



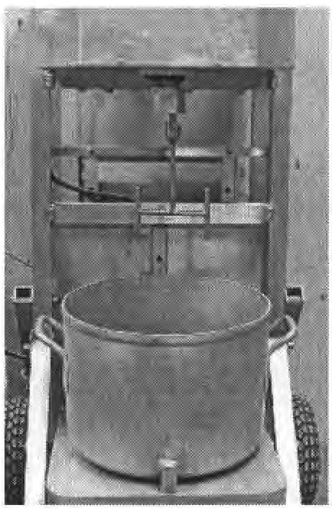
(d) Failure: The start of deformation is defined as concrete failure.

Figure 3.6 Test procedure for concrete green strength measurement

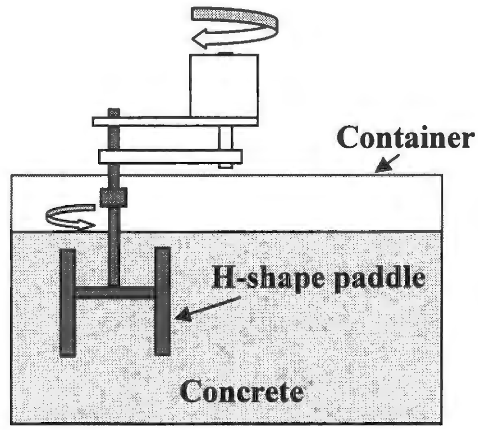
IBB Rheometer Test

In this study, an IBB rheometer was used to evaluate the flowability of fresh concrete. The rheometer was modified from the Tattersall two-point device (Tattersall 1991), which has been successfully applied on concrete from a low slump of 1 inch to self-compacting concrete (Ferraris and Brower 2004). The rotating H-shape impeller of the IBB rheometer was inserted into fresh concrete in a cylindrical container(Figure 3.7). A computer-controlled DC motor turned impeller, which is capable of rotating in a planetary motion. The planetary motion is necessary for low-workability concrete, because a relatively loose portion may be formed if the impeller keeps passing through the original orbit (Tattersall 1991). For each test, the total mass of concrete is kept constant at 90 pounds. The cross-sectional area of the impeller is 6.2 square inches.

The reaction torque from the impeller is measured by a load cell in the IBB rheometer, while the rotation speed of the impeller is measured by a tachometer. A linear relationship was generally found between the torque and speed, which is inconsistent with the Bingham model defined by the slope *H*, which is related to plastic viscosity, and the zero speed intercept *G*, which is related to yield stress (Tattersall and Banfill 1983).



(a) IBB rheometer



(b) Paddle and container

Figure 3.7 IBB concrete rheometer

During the test, the rotation speed of the paddle is controlled by a preset computer program. The test sequences used in this study are shown in Figure 3.8. The concrete specimen was pre-sheared after being placed into the container at a low, constant rate, around 0.2 revolution/s, for 30 seconds. Next the sample was allowed to rest for 30 seconds, and then it was sheared at a constantly increasing rate from 0 to 1 (revolution/s) over a 100-second period. Finally, the sample was sheared at a constantly decreasing rate from 1 (revolution/s) to 0 in 100 seconds.

Figure 3.9 shows a typical result from an IBB concrete rheometer. Interception *G* and slope *H* are obtained from the down curve, because it fits well with the Bingham model. The yield term of *G* is obtained by extending the liner portion of the down curve (1 to $0.04s^{-1}$) to the y axis. As reviewed before, this value represents the minimum stress required for a material to flow or deform; therefore, it can be related to concrete yield stress. The viscosity term H is obtained from the slope of the linear portion of the down curve. This H represents plastic viscosity, which is defined as the ability of a material to resist flow following the initiation of the flow.

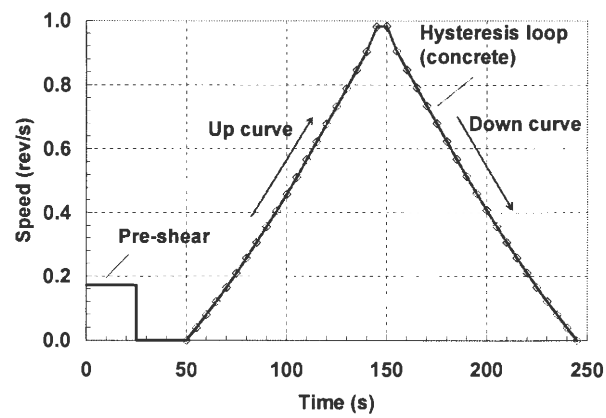


Figure 3.8 IBB concrete rheometer test program

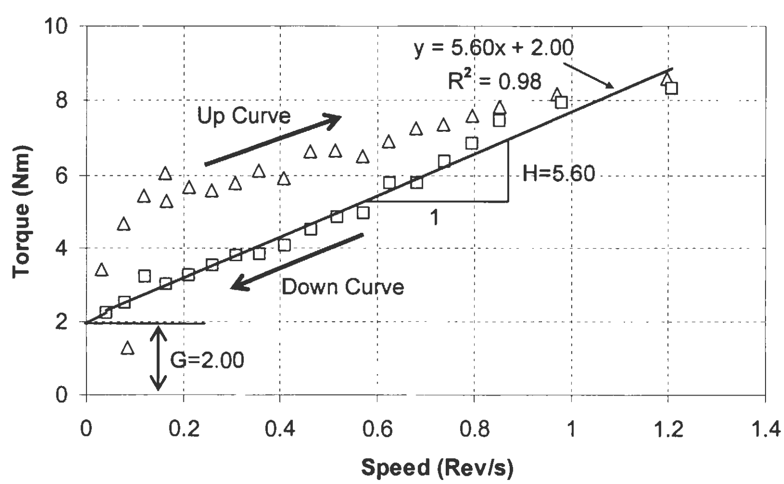


Figure 3.9 Typical IBB concrete rheometer result (FA-C-30)

Modified Compaction Factor Test

This test method was modified from the standard compaction factor test reviewed in Chapter 2. The test apparatus included a measure, slump cone, and rigid frame (Figure 3.10.)

The measure used in this test was a cylindrical container made of steel. In the current study, the nominal maximum size of coarse aggregate was 1 inch. According to ASTM C 138, the capacity of this measure is 0.25 cubic feet. So, the same cylindrical container for the air content test was used here. The distance from the bottom of the measure to the pouring lever of concrete was 30 inches.

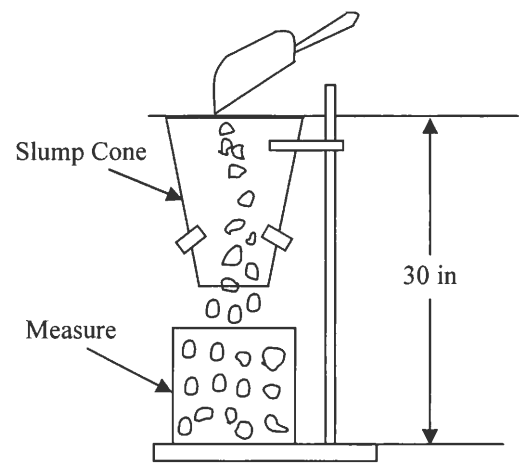


Figure 3.10 Apparatus for compaction factor test

The procedure for the modified compaction factor test is as follows:

1. Pour fresh concrete into the cylindrical container through the slump cone from a constant height (30 inches) until the height of concrete in the container equals that of the container. No rodding or taping was used to compact the concrete in the container.
2. Then simply smooth the top surface (Figure 3.10).
3. Measure the mass of the measure filled with concrete.
4. Calculate the density (unit weight) of concrete in a loose condition.

The compaction factor is defined as follows:

$$\text{Compaction Factor} = \frac{\text{density of concrete in loose condition}}{\text{density of concrete in compacted condition}}$$

The density (unit weight) of concrete in a compacted condition was obtained according to ASTM C 138. This compaction factor is an indicator of the compactability of fresh concrete, and the value is less than 1.

3.4.3 Test Methods for Hardened Concrete Evaluation

In accordance with ASTM C39, compressive strength at 56 days was tested on 4 x 8-inch cylinder samples for all mix proportions. Cylinder specimens were prepared in two different ways: "rodding" and "non-rodding. Concrete cylinder specimens with rodding were obtained according to ASTM C192 standard. The non-rodding concrete cylinder specimens were prepared following the procedures described below:

- Place the slump cone on the top of the cylindrical model upside down.
- Pour fresh concrete into the cylinder mold from a constant height (30 inches was used in this study) until the height of concrete in the mold equals that of the cylinder mold. No rodding or taping was used to compact the concrete in the cylinder mold during casting. Then simply smooth the top surface (Figure 3.11).
- Cure for later testing.
- Conduct compressive test according to ASTM.

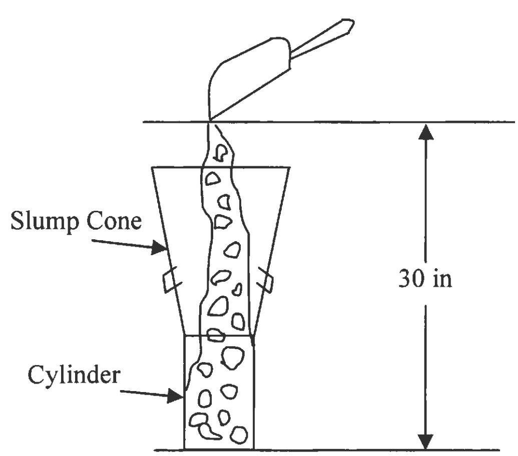


Figure 3.11 Preparing of non-rodding cylinder specimen

In the remainder of this thesis, the compressive strength obtained from cylinder specimens prepared according to ASTM C192 will be identified as rodding; the rest of the specimens will be identified as non-rodding.

3.4.4 Lab Paving Simulation

To find out whether the newly developed SF SCC was applicable to field paving, the research team members at ISU developed a simple mini-paver for paving SF SCC segments in the lab. Recognizing that SF SCC might need a certain pressure to consolidate, the mini-paver was designed on an L box concept. As Figure 3.12 shows, the mini-paver system consists of (1) an L box with a platform on its top, (2) a towing system (a towing cable and a crank), and (3) a working table. The L box had a dimension of 18 inches wide, 24 inches long, 18 inches high, and 3 inches to 6 inches thick. It could pave an 18 inch (width) x 3 inch to 6 inch (thickness) x 48 inch (length) concrete pavement section in the lab, using two cubic feet of concrete mixtures.

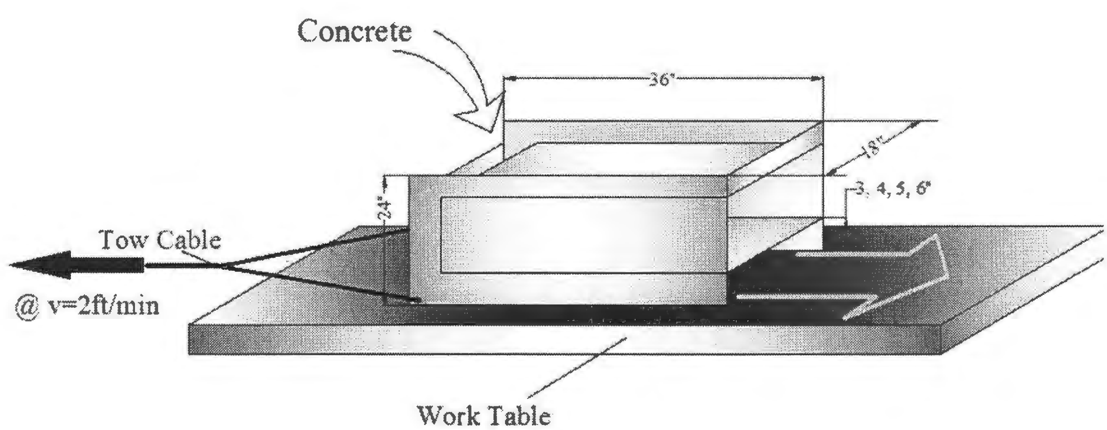


Figure 3.12 Mini-paver

Right before paving, concrete was stored on the platform and approximate 200 pounds of weights were placed on the paver (in a chamber). A stop plate was positioned at the end of the horizontal leg of the L box. To start paving, concrete was pushed from the platform into the vertical leg of the L box up to a certain height, which generates pressure to consolidate the concrete. Then, the stop plate was removed and the crank system was turned at a designated speed (3-5 ft/min), which pulls the mini-paver forward. As the mini-paver moves forward, it extrudes the concrete, or a pavement slab, out of the horizontal leg of the L box.

After paving, the shape stability of the fresh concrete and the surface condition of the pavement were examined. The cross section was examined also to evaluate the distribution of coarse aggregate and air void systems.

CHAPTER 4
RESULTS AND DISCUSSION

In this chapter, the results and discussions of the tests performed in the present study were presented. Effects of coarse aggregate gradation, paste content, class C and F fly ash, viscosity-modifying admixture (VMA), Acti-Gel, superplasticizer, combined coarse aggregate on compactability, flow ability, and shape stability of concrete were studied.

4.1 Aggregate Properties Measurements

The loose and compact bulk density and void content of the recombined limestone coarse aggregate limestone used in this study are presented in Table 4.1. The percentage of difference was defined as the difference between compact and loose bulk density divided by compacted bulk density of the aggregate.

Table 4.1 Dry bulk density of recombined coarse aggregates

No.	Loose		Compacted		Difference	Fineness Modulus	Friction angle (°)
	Bulk Density (lb/ft^3)	Voids (%)	Bulk Density (lb/ft^3)	Voids (%)	(%)		
G1	84.2	44.7	89.5	41.2	5.9	6.85	44.5
G2	83.6	45.4	91.8	40.0	8.9	7.30	45.1
G3	83.2	45.3	92.6	39.2	10.1	6.75	43.1
G4	84.6	44.6	94.5	38.1	10.5	6.91	43.6
G5	85.6	43.8	93.6	38.6	8.5	7.04	43.9
G6	86.5	43.4	89.5	41.3	3.4	7.05	44.1

The percentage of difference indicated the easy of the coarse aggregate particles to be packed without consolidation. The smaller the difference, the easier the aggregate to be compacted.

According to the test results, aggregate G1 and G6 might provide concrete with a better consolidation than aggregate G2 and G5, which might be better than aggregate G3 and G4.

The friction angles of the coarse aggregates are also presented in Table 4.1. As discussed before, the internal friction and interlock of coarse aggregate may affect the flowability and shape stability of fresh concrete in different way.

4.2 Concrete Control Tests Results

The unit weight, air content of fresh concrete and 56-day compressive strength was measured on each batch of concrete. All concrete control tests results are list in Table 4.2.

As described before, the concrete cylinders for compressive strength were prepared with and without rodding. Not all values of compressive strength for concrete specimens prepared without rodding were obtained, as shown in Table 4.2. This is due to the scattering of testing data.

Concrete mixes with fly ash Class C have lower air content than others, to maintain required air content, admixture dosages must be increased. This is consistent with former results by Pistilli (1983) and ACI Committee 232 (1996).

The unit weight of fresh concrete and compressive strength shown in Table 4.2 indicate that no clear pattern of effect of mix design of concrete on these two parameters was observed.

Table 4.2 Concrete control test results

Group	Mix proportion	Air (%)	Unit weight, Rodding, (pcf)	Strength (psi) @ 56-days	
				No Tamping	Tamping
1	A-G1	6.5	143.5	-	8800
	A-G2	6.0	141.8	-	8580
	A-G3	6.4	142.2	-	8750
	A-G4	6.0	142.5	-	8500
	A-G5	6.4	143.8	-	8450
	A-G6	6.6	144.5	-	8648
	B-G1	4.0	141.3	8592	8597
	B-G2	3.8	144.2	8427	8550
	B-G3	4.2	143.0	8234	8314
	B-G4	3.8	143.8	8544	8647
	B-G5	4.0	145.0	8479	8882
	B-G6	4.2	140.0	8560	8670
	C-G1	5.2	144.4	-	8620
	C-G2	4.8	141.6	-	8850
	C-G3	5.0	145.5	-	8375
	C-G4	4.6	140.3	-	8470
	C-G5	4.8	142.4		8230
	C-G6	4.6	139.9	-	8300
2	P23	5.8	141.5	-	8408
	P27	5.4	145.6	-	8500
	P29	4.8	144.7	-	8486
	P30	4.6	140.0	-	8650

3	**FA-C-20**	3.2	144.6	8650	8890
	FA-C-30	3.5	145.2	8950	8967
	FA-C-40	3.3	145.0	8797	9067
	FA-C-50	3.6	145.5	7144	7460
4	**FA-F-20**	4.0	141.5	-	8230
	FA-F-30	4.6	138.9	7250	8400
	FA-F-40	4.2	145.5	7825	8190
	FA-F-50	3.8	144.0	7650	8780
5	**SP-0.5**	6.0	144.2	8760	8900
	SP-1.0	6.1	144.2	8850	9125
	SP-1.5	5.8	145.0	8758	8870
	SP-2.0	6.0	145.2	8970	8990
6	**VMA-0.2**	4.0	141.0	8450	8550
	VMA-0.3	4.6	145.5	7885	8205
	VMA-0.5	5.0	142.6	8350	8565
	VMA-0.67	4.8	144.8	8280	8450
7	**Acti-Gel-0.2**	5.6	141.0	7992	8226
	Acti-Gel-0.3	5.8	142.0	-	8816
	Acti-Gel-0.5	6.0	142.0	-	8970
	Acti-Gel-0.67	6.0	143.5	-	8897
8	**L:G=3:1**	3.1	141.5	8890	8754
	L:G=1:1	3.3	141.5	8775	8665
	L:G=1:3	3.6	143.8	8800	8898
	L:G=0:1	3.5	143.2	8750	8900

Note:
Group 1 : For study of coarse aggregate gradation
Group 2 : For study of paste content
Group 3 & 4 : For study of fly ash
Group 5 : For study of viscosity-modifying admixture (VMA)
Group 6 : For study of Acti-Gel
Group 7 : For study of combined coarse aggregate
Group 8 : For study of superplasticizer

4.3 Concrete Slump Test Results

4.3.1 Effect of Gradation

Concrete slump test results are shown in Table 4.3. The mix proportions in series A have an average slump value of 2.8 inches (standard deviation 0.1882); those in series B have an average slump value of 8.0 inches (standard deviation 0.2787); and 4.0 inches (standard deviation 0.4472) for those in series C.

Figure 4.1 shows the shapes of concrete mixtures after slump tests. All concrete mixes for series A have visible big voids on their surface. Shear collapse were found during test due to the loose structure (big voids inside). This indicates that the concrete mixtures had a poor self-compactability. All concrete mixtures for series B had no visible voids on their surface. Their shape after slump test looked still like a regular cone with top diameter around 8". The side surfaces are smooth for all mixes. Mixes number B-G1, B-G3, B-G5 and B-G6 have smoother top surface than others. Mixtures B-G1, B-G4 and B-G6 showed better shape than mixture B-G3, and B-G5, which swell at the bottom. In mix proportion series C, C-G3 and C-G5 showed better shape after lifting the slump cone. The surface of concretes in this series are smoother than those of concrete in series A and coarser than those of concrete in series B. Furthermore, the visible voids in concrete for series B are more than those in concrete for series A and less in concrete for series B.

Coarse aggregate gradation has effect on concrete slump test. From current results, mixes B-G1 and B-G6 have better shape and surface texture.

Table 4.3 Effect of gradation on concrete slump

Mix proportion	Slump (in)	Spread (in)	Shape*
A-G1	2.50	8.50	C,V,RS
A-G2	2.75	8.75	C, V, RS
A-G3	3.00	8.75	V, RS
A-G4	2.75	8.75	C, V, RS
A-G5	2.75	8.50	V, RS
A-G6	3.00	9.00	V, SS
B-G1	7.90	12.10	SS
B-G2	7.90	12.00	SS
B-G3	8.25	13.75	SS
B-G4	8.00	12.50	SS
B-G5	8.25	13.60	SS
B-G6	7.50	11.60	SS
C-G1	4.25	9.25	V, SS
C-G2	4.75	9.05	V, SS
C-G3	3.50	8.90	V, SS
C-G4	3.75	9.00	V, SS
C-G5	4.00	9.00	SS
C-G6	3.75	9.00	V, SS

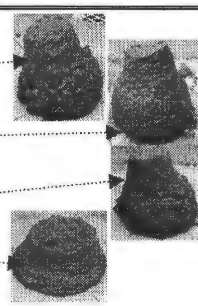
*** Note:**

C: Collapse

V: Visible void

RS: Rough surface

SS: Smooth surface



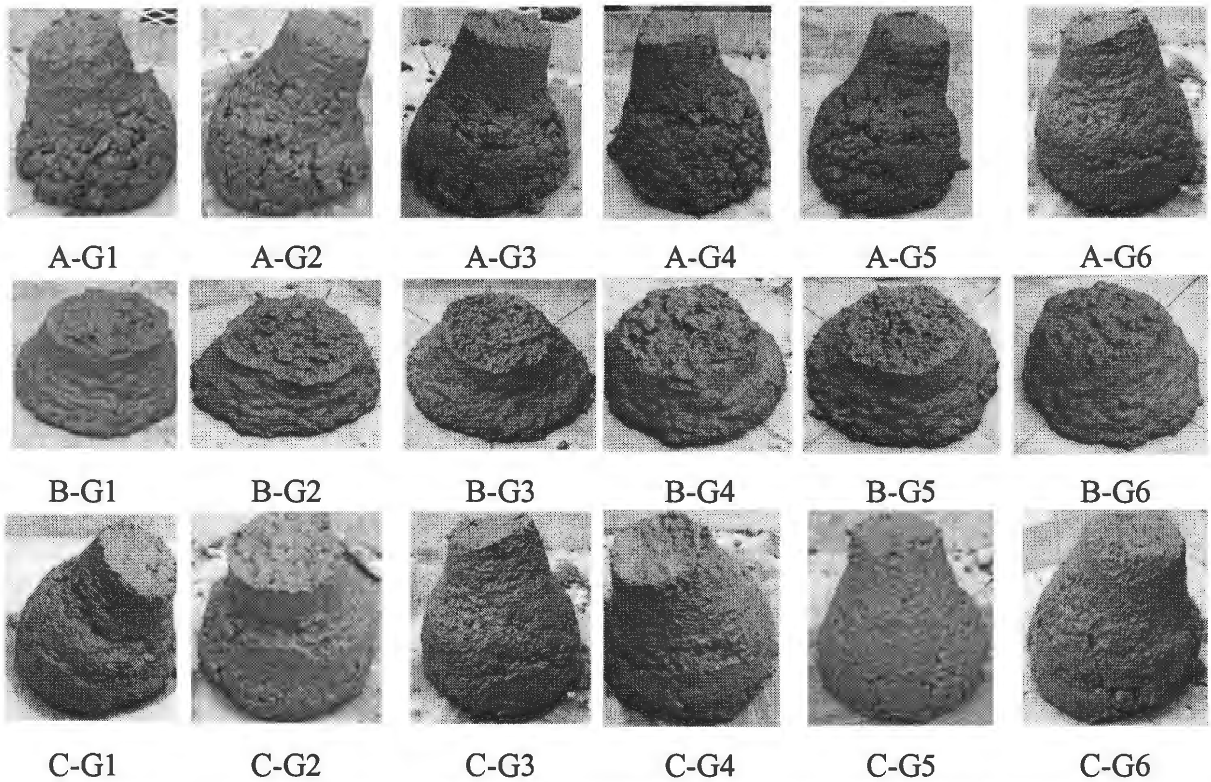


Figure 4.1 Shape of concrete with different graded coarse aggregate after slump test

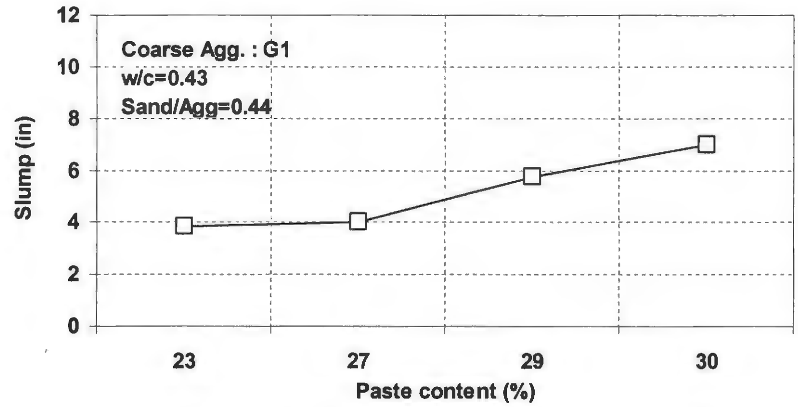
Note:

Series A: OPC, Paste=28%, w/c=0.38;
Series B: OPC+30%FA, Paste=28%, w/c=0.38;
Series C: OPC, Paste=22%, w/c=0.43

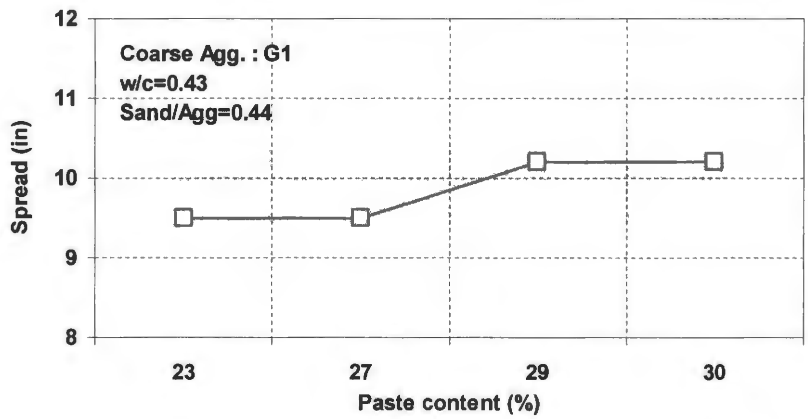
4.3.2 Effect of Paste Content

Slump test results on concrete mixes made with an optimal coarse aggregate gradation (G1) and with different paste content are shown in Figure 4.2. It is clear that as the paste increases, the value of slump and spread increase. As discussed previously, the amount of cement paste which fills up the spaces between aggregate particles and coats the surface of the particles has significant effect on the concrete flowability and shape stability. Generally, the more the paste, the easier the concrete flows.

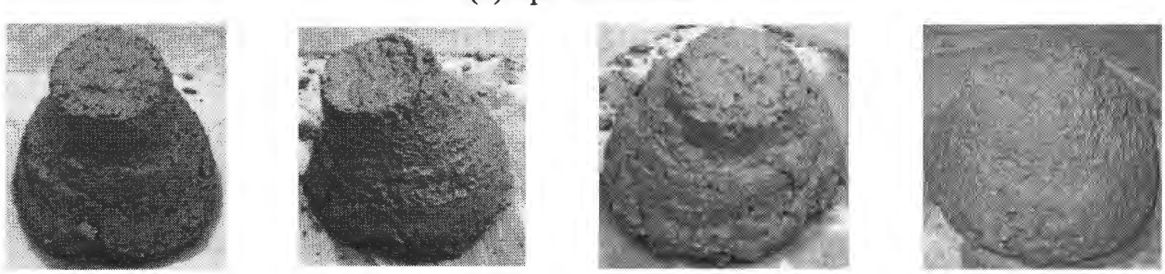
Figure 4.2 (c) shows the remained shape of the concrete after the slump tests. As the paste amount increased, the more regular shape and smoother surface of the slumped concrete were observed. The concrete with 29% and 30% paste had smoother surface than others, with no large voids seen on its top surface. The slumped shape was homogeneous and no collapse was observed during testing.



(a) Slump results



(b) Spread results



P23 P27 P29 P30

(c) Shape of concrete

Figure 4.2 Effect of paste content on slump test results

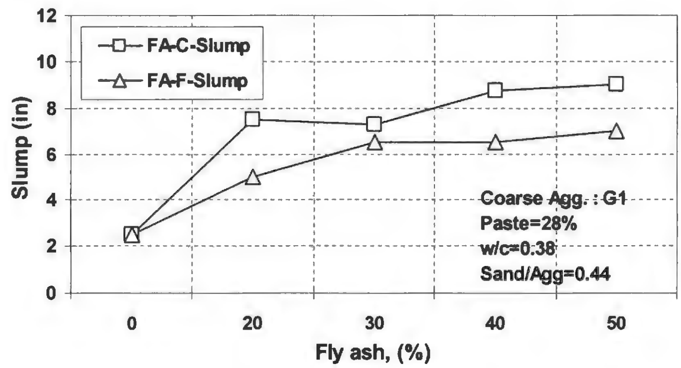
4.3.3 Effect of Fly Ash and Superplasticizer

After the optimal coarse aggregate gradation (G1) and paste content (28%) were selected, slump tests on fresh concrete with the aggregate and paste content but different amount of fly ash were performed and the results are shown in Figure 4.3. Generally, fly ash replacement increased both slump and spread. As shown in Figure 4.3 (c), the concrete with fly ash had a better shape and smoother surface than OPC concrete (FA-C-00). FA-C-20 and FA-C-30 appeared to be the best because no swelling at the bottom of the mixture was found compared with FA-C-40 and FA-C-50 (Figure 4.3 (c)).

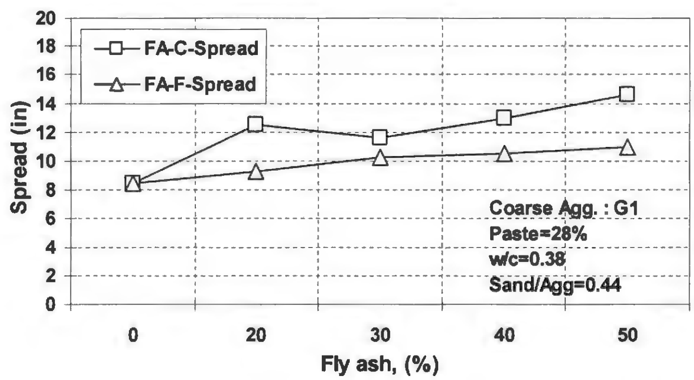
The class F fly ash used in this study did not provide concrete mixtures with good flowability and shape stability until the replacement level reached 50%. Compared with concrete made with class C fly ash =, the mixture of concrete made with 50% class F replacement (FA-F-50) had a less smooth lateral surface, probably due to the slow hydration of the fly ash.

Superplasticizer also increased the flowability of fresh concrete as fly ash did, as shown in Figure 4.4. Concrete with a low dosage (0.5%) of Superplasticizer had a slump of 6.8 inches and a spread of 12.65 inches. It remained a certain shape after the slump test, as shown in Figure 4.4(c). When the superplasticizer dosage further increased from 0.5% to 2.0%, the concrete mixtures had slump more than 10 inches, which indicated that these mixes had no shape stability, formwork is required during casting.

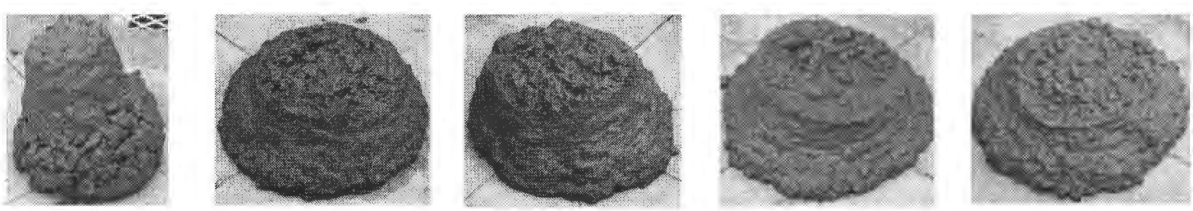
The shape of concrete with 0.5% superplasticizer after slump was similar to FA-C-20 and FA-C-30, as shown in Figure 4.4 (c). But the surface was rough, big voids were observed on the concrete surface. This might be because the absolute paste volume of concrete with fly ash is larger than that of concrete only with OPC and superplasticizer.



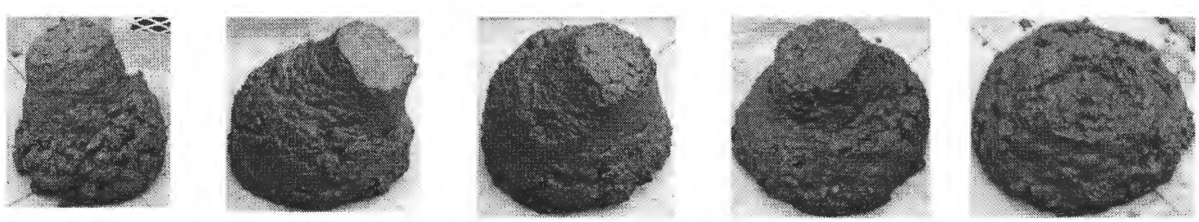
(a) Slump results



(b) Spread results



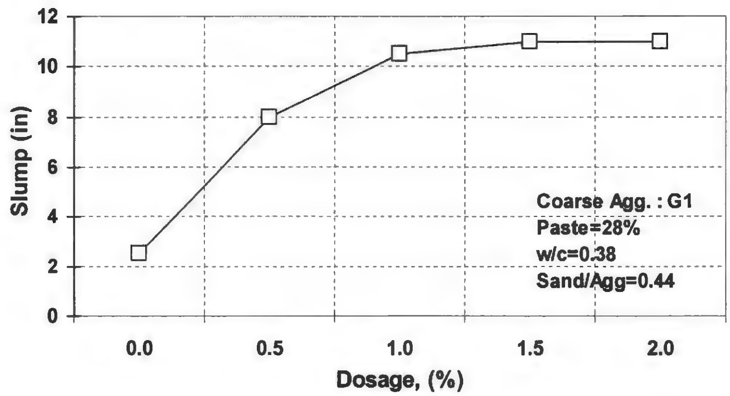
FA-00 FA-C-20 FA-C-30 FA-C-40 FA-C-50



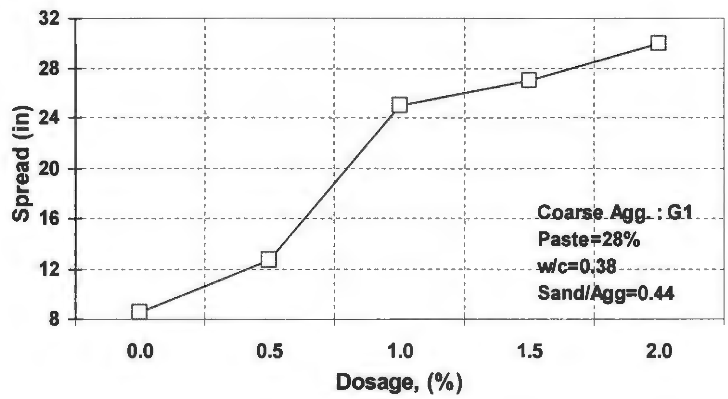
FA-00 FA-F-20 FA-F-30 FA-F-40 FA-F-50

(c) Shape of concrete

Figure 4.3 Effect of fly ash on slump test results

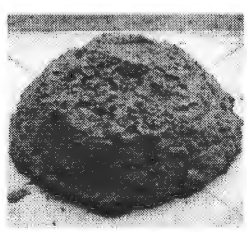


(a) Slump results

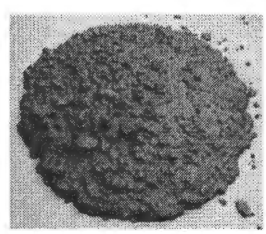


(b) Spread results

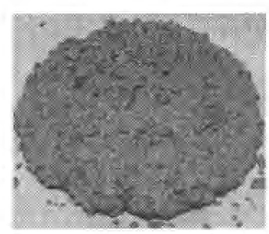
SP dosage 0.0%



SP dosage 0.5%



SP dosage 1.0%



SP dosage 1.5%

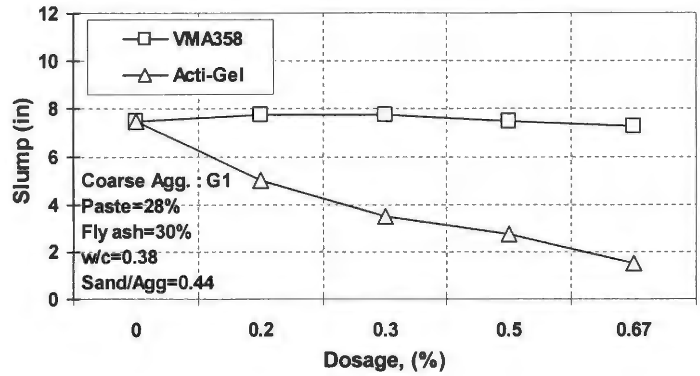
(c) Shape of concrete

Figure 4.4 Effect of superplasticizer on slump test results

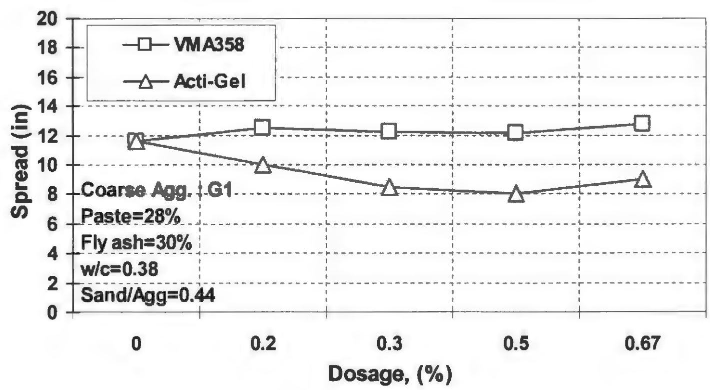
4.3.4 Effect of Admixtures

Slump tests on the concrete mixtures made with the optimal coarse aggregate gradation (G1) and paste content (30%), and fly ash replacement (30% C ash) as well as different type and dosage of admixtures were performed, and the results, shown in Figure 4.5. Two chemicals, VMA358 and Acti-Gel were investigated. Figure 4.5 (a) and (b) show that Acti-Gel addition decreased the slump and spread of fresh concrete. VMA358 addition had no significant effect on slump and spread of fresh concrete.

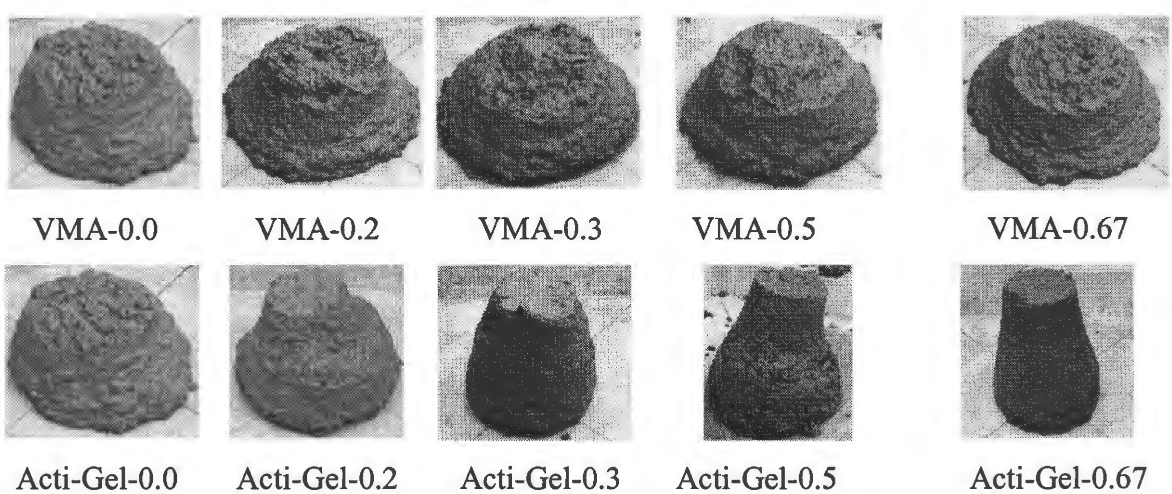
Figure 4.5 (c) shows the shape of concrete with admixtures after slump test. It was observed that VMA358 did not change the shape of concrete after slump test very much. They all have cone shape, smooth surface and flat top surface. But at same amount of addition, Acti-Gel made the concrete mixture stiffer. Concrete mixtures having 0.5 and 0.67% Acti-Gel addition showed honeycomb and large voids on the surface. As a result, the amount of addition for VMA358 could be increased and the amount of addition for Acti-Gel should be limited to less than 0.5% by weight of cement for a self-consolidating concrete without any other admixture.



(a) Slump results



(b) Spread results



(c) Shape of concrete

Figure 4.5 Effect of admixtures on slump test results

Note: Recommended dosage from the manufactory:

VMA358 = 0.13~0.65% weight of cementitious materials; Acti-Gel = 0.25~0.5% weight of concrete

4.4 Compaction Factor Test

4.4.1 Effect of Coarse Aggregate Gradation

The effect of coarse aggregate gradation on fresh concrete compaction factor is illustrated in Table 4.4. All the results were obtained from the modified compaction factor test. As mentioned before, six different coarse aggregate gradations were used in three different mix series. Series A and B were designed with the same paste content but different follow ability. A series is plan concrete without any admixture. Series B had a thirty percent class C fly ash replacement. Mix series C is the Iowa DOT C3 mix with w/c of 0.42. A total of 18 batches of concrete were prepared for the compaction factor study.

Table 4.4 Effect of gradation on concrete compaction factor

Mix proportion	Compaction factor	Mix proportion	Compaction factor	Mix proportion	Compaction factor
A-G1	0.815	**B-G1**	0.994	**C-G1**	0.937
A-G2	0.813	**B-G2**	0.996	**C-G2**	0.916
A-G3	0.806	**B-G3**	0.986	**C-G3**	0.886
A-G4	0.789	**B-G4**	0.989	**C-G4**	0.859
A-G5	0.808	**B-G5**	0.998	**C-G5**	0.920
A-G6	0.829	**B-G6**	0.995	**C-G6**	0.939

Since the difference between loose and compacted coarse aggregate is an indicator of the energy required for coarse aggregate to be well packed, Figure 4.6 is plotted to show the relationship between concrete compaction factor and difference in coarse aggregate bulk density. As expected, the concrete mixture having the coarse aggregate with a smaller difference was self-compacted to a higher density.

Note that concrete mixtures in series B (slump=7-8") all had a compaction factor close to 1.00, the highest as possible. This indicated that concrete with such a slump value could be self-compacted well without a need for additional consolidation. In this series of concretes, the volume of cement paste or mortar appeared sufficient not only to fill the spaces between the coarse aggregate particles with a certain thickness. As a result, coarse aggregate gradation displayed little effect on the compaction factor. The paste or mortar thickness estimation of a given concrete has been studied by Hu (2005). Differently, for concrete mixtures with a middle or low slump (2-4"), effect of coarse aggregate gradation on compaction factor appeared obvious. The better graded aggregate (G6 and G1), the higher compaction factor. Furthermore, the lower concrete slump, the lower the compaction factor the concrete had. The compaction factor less than 1.00 implies a need for an additional consolidation for the concrete mixtures to reach their maximum density.

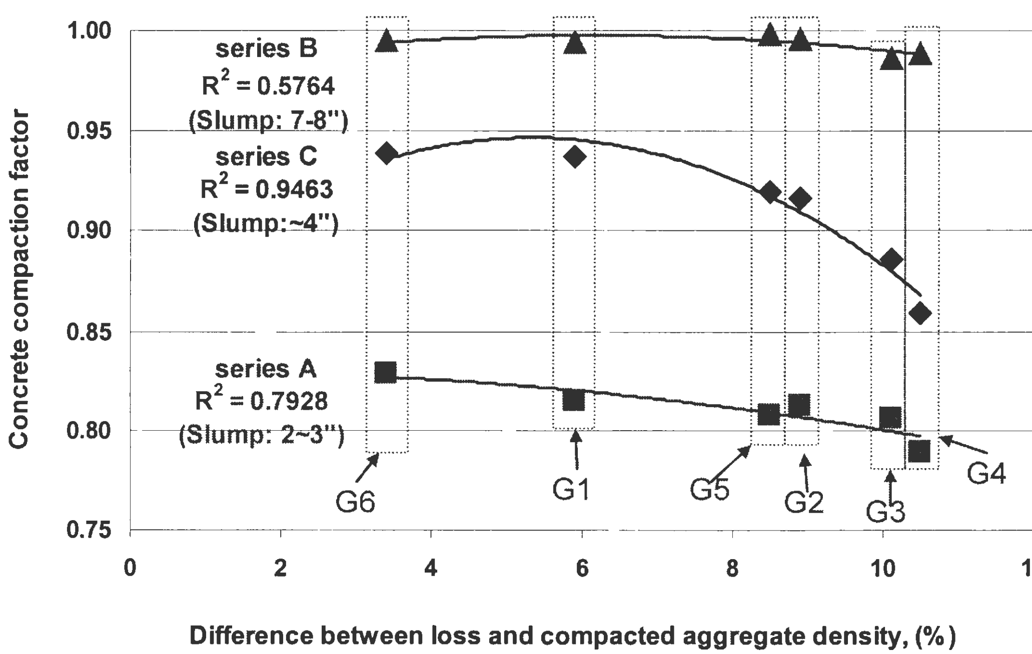


Figure 4.6 Relationship between aggregate and fresh concrete compactibity

Note:

Series A: OPC, Paste=28%, w/c=0.38;
Series B: OPC+30%FA, Paste=28%, w/c=0.38;
Series C: OPC, Paste=22%, w/c=0.43

4.4.2 Effect of Paste Content

Table 4.5 show the compaction factor test results obtained from concrete with different paste content.

Table 4.5 Effect of paste content on concrete compaction factor
(G1, w/c= , sand/Aggregate=0.44)

Mix proportion	P-23	P-27	P-29	P-30
Compaction factor	0.820	0.850	0.930	0.935

As shown in Figure 4.7, the concrete compaction factor increased with paste content. This is mainly due to the excess paste effect. A mixture with an excess of cement paste will be easy to place and will produce a smooth surface; however, the resulting concrete is likely to shrink more and be uneconomical (Oh et al., 1999; and Concrete Basics, 2005). The concrete compaction factor increased significantly from 0.825 to 0.925 if the paste content increased from 23% to 29%. Based on Figure 4.7, for the given concrete materials and mix design parameters, when paste content is approximate 32%, the compaction factor will reach 1.00. This is, further increasing paste content (beyond 32%) is not necessary for self-compactability.

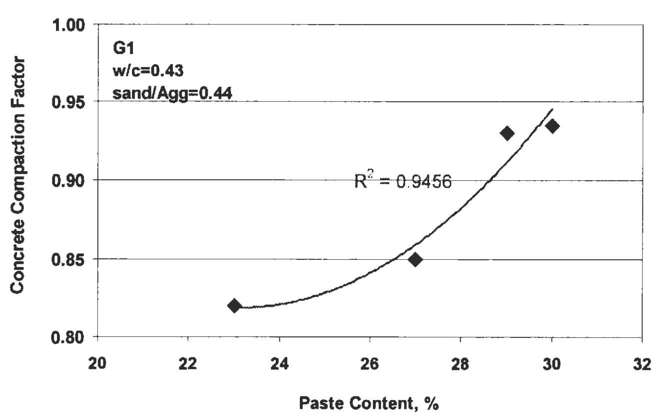


Figure 4.7 Paste content and compaction factor

4.4.3 Effect of Fly Ash and superplasticizer

Figure 4.8 shows fly ash replacement effect on fresh concrete compactability. Fly ash generally has a low specific gravity (2.9 compared with 3.15 for Portland cement). Therefore, fly ash replacement for cement increases paste content of the concrete and provides the concrete with improved plasticity and better cohesiveness (Lane, 1983). In the present study, class C fly ash replacement improved concrete compactability more effectively than class F fly ash. Concrete with class C fly ash had a compaction factor of approximate 1.00 when the class C fly ash content reached 30% or higher. As a result, the optimal fly ash (class C) content is 30-40%. In a consideration that fly ash replacement may reduce concrete early age strength development, 30% class C fly ash was selected in the present study.

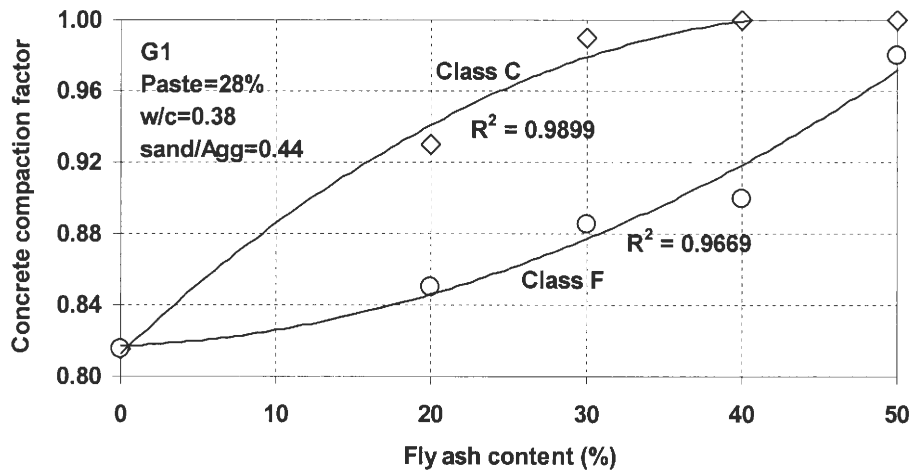


Figure 4.8 Effect of fly ash replacement on compaction factor

Superplasticizer can increase the flowability as well as compactability of fresh concrete greatly. Figure 4.9 shows that at a low dosage (0.5%) superplasticizer increased the concrete compaction factor from 0.80 to 1.00. Further increasing superplasticizer dosage from 0.5% to 2.0% is not necessary for compactability but impairs concrete shape stability.

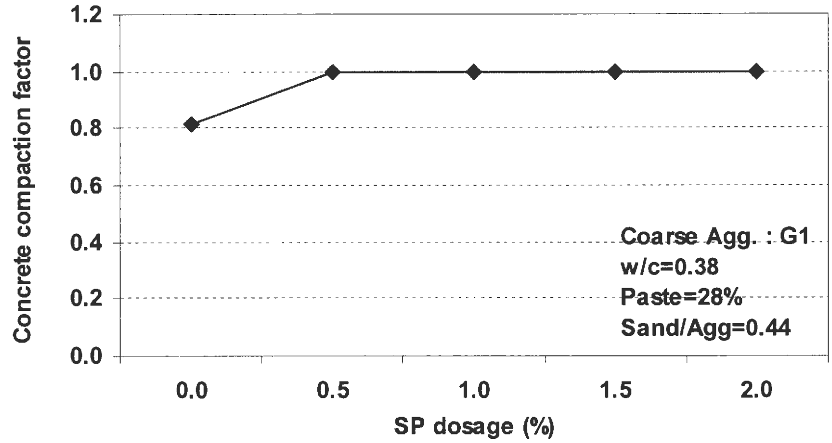


Figure 4.9 Superplasticizer dosage and compaction factor

4.4.4 Effect of Admixtures

Effects of two types of viscosity modifying admixtures, VMA 358 and Acti-Gel on concrete compaction factor, were studied and the results are shown in Figure 4.10. As observed in the figure, addition of VMA358 did not affect the compaction factor of a self-compacting concrete, however, addition of Acti-Gel decreased compaction factor greatly.

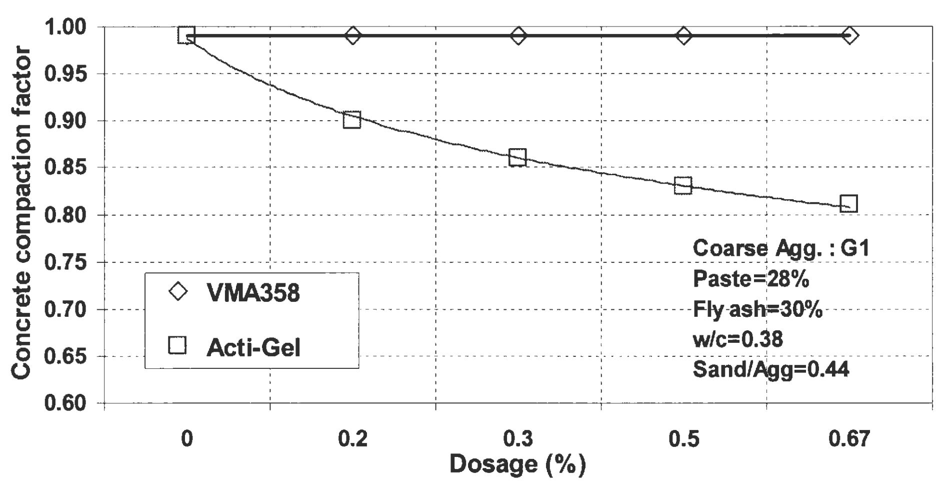


Figure 4.10 Effect of admixtures on compaction factor

4.4.5 Relationship between Slump and Compactability

Although the slump cone test is used extensively in field, it dose not have any theoretical justification as a measure of workability, especially the compactability. In the present study, the slump tests were performed without rodding of concrete mixtures. This method provides a reasonable indication on how easy a mix can be placed.

If the fresh concrete was poured from constant height into slump cone without any rodding, the following results can be observed:

- If concrete is well compacted by its own weight and pour-down energy. The distribution of coarse aggregates is homogenous. There is no or little entrapped air in the mixture. Also, there is no serious structure spoil, such as honeycomb and segregation. After lifting the slump cone, the deformation should be plastically isotropic, see Figure 4.11.
- If concrete is not compacted by its own weight and pour-down energy, the structure of concrete in slump cone is not isotropic. The present of weak parts in concrete mix, which has more entrapped air, honeycombs and voids or has no coarse aggregate but only mortar, will make the deformation anisotropic. The pictures of concrete after slump are shown in Figure 4.12.

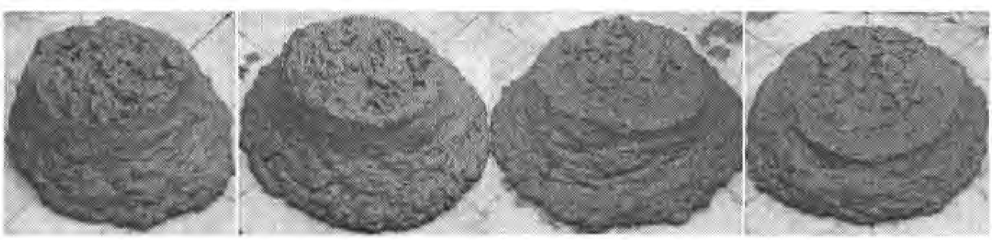


Figure 4.11 Slump test results-well compacted

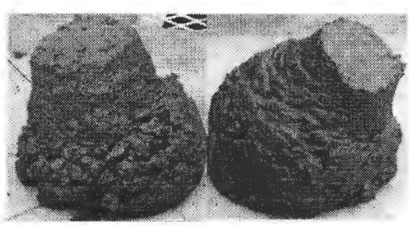


Figure 4.12 Slump test results-poor compacted

4.5 IBB Rheometer Test

A typical flow curve obtained from an IBB rheometer test is shown in Figure 4.13. In the test the torque applied on the paddle was measured as the rotation speed. The relationship between the torque and rotation speed was almost linear, which indicated that the Bingham rheology model might applicable for describing the flow behavior of the concrete. Generally, as the concrete mixtures became stiffer, the applicability of the Bingham model for the mixtures reduced, because the laminar flow assumption might be no longer quite correct as the volume content of solid proportion increase (Nehdi and Mindess, 1996). As observed in the figure, the flow curve also demonstrated a thixotrophy loop and it indicated some material structures were broken down during testing process.

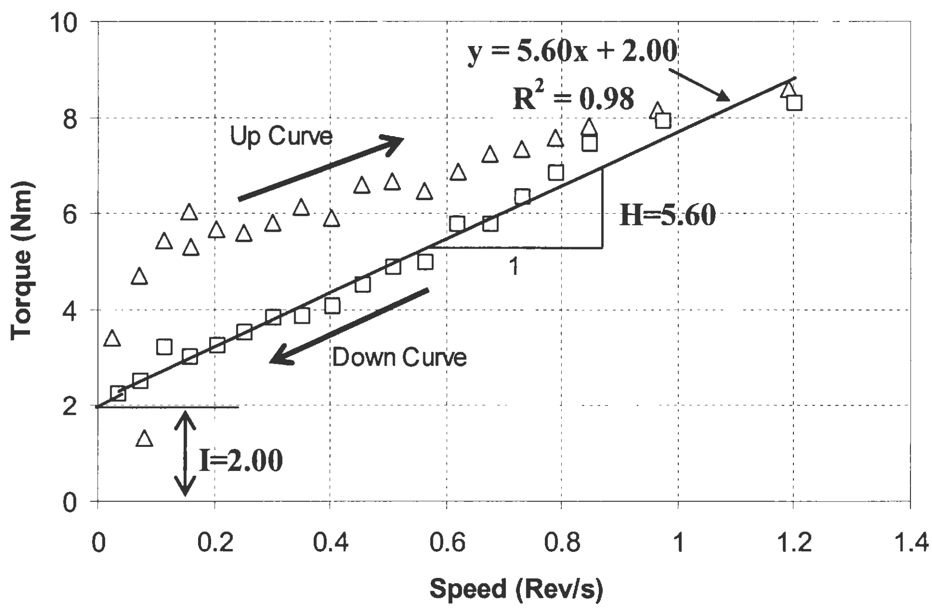


Figure 4.13 Typical flow curve from IBB concrete rheometer test

Interception *I* and slope *H* are calculated from the down curve because it fits well with the Bingham model. The yield term of *I* is obtained by extending the liner portion of the down curve (1 to $0.04s^{-1}$) to the y-axis. As reviewed before, this value represents the minimum stress required for a material to flow or deform, therefore, it can be related to concrete yield stress. The viscosity term *H* is obtained from the slope of the linear portion of the down curve. This *H* represents the plastic viscosity which is defined as the ability of a material to resist flow since it starts.

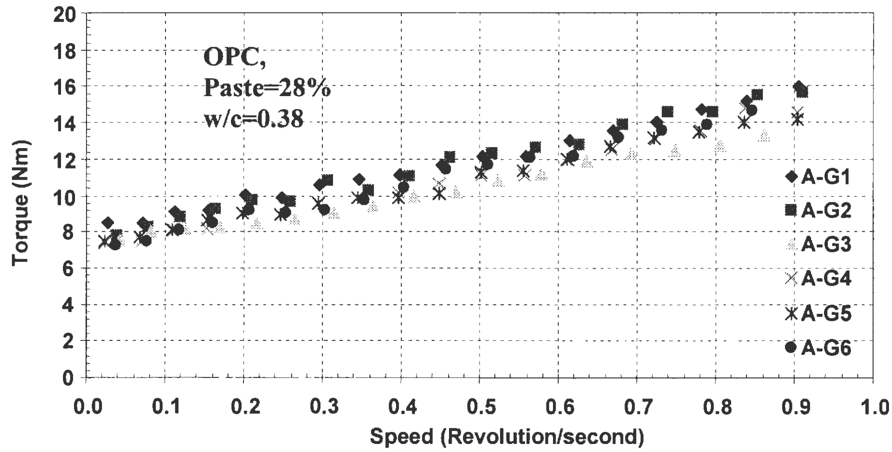
4.5.1 Effect of Coarse Aggregate Gradation

The gradation of coarse aggregate determines the paste required for a concrete with certain workability. It has effect on concrete flowability as well as shape stability. As discussed in Chapter 3, coarse aggregate with gradation G2 has more large size particles than that with gradation G3. When a range of aggregate size is used, the smaller particles can fill up the spaces between the larger particles, thereby decreasing the void space and lowering the amount of paste required for filling the spaces. Thus, excess paste can coat the aggregate surface and improve concrete workability. Result from Figure 4.14 is consistent with this general knowledge.

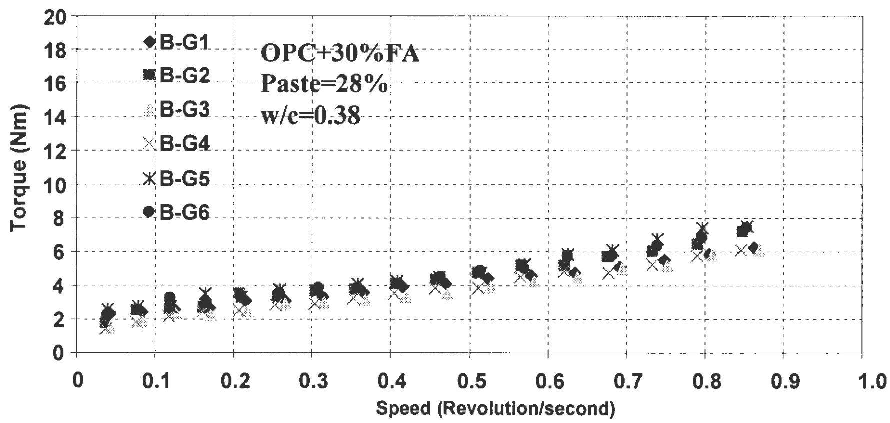
Table 4.6 lists rheological parameters calculated from the down curves obtained from IBB rheometer test on fresh concrete with different graded coarse aggregates and mix proportions.

Table 4.6 Effect of coarse aggregate gradation on concrete rheology properties

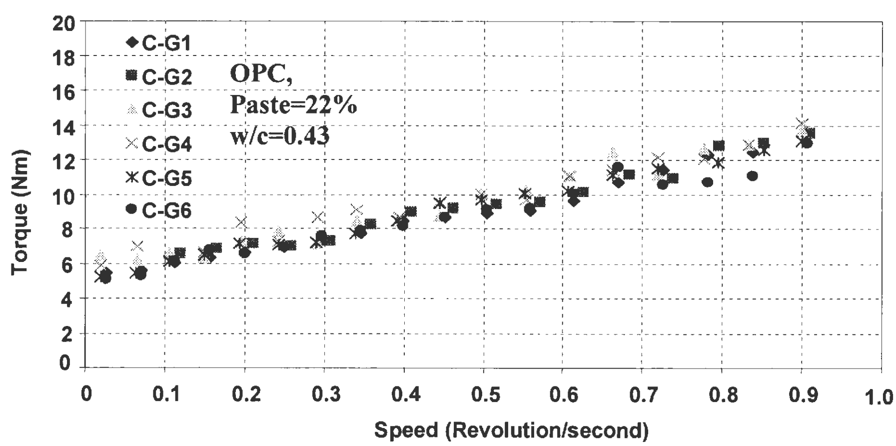
Mix proportion	I (Nm)	H (NmS)	Mix proportion	I (Nm)	H (NmS)	Mix proportion	I (Nm)	H (NmS)
A-G1	8.000	8.400	**B-G1**	1.962	4.660	**C-G1**	4.980	8.400
A-G2	7.760	8.900	**B-G2**	1.845	5.800	**C-G2**	5.450	8.300
A-G3	7.250	7.100	**B-G3**	1.545	4.630	**C-G3**	5.450	8.300
A-G4	7.000	8.500	**B-G4**	1.523	4.930	**C-G4**	5.800	8.300
A-G5	7.150	8.000	**B-G5**	2.067	6.060	**C-G5**	5.050	8.900
A-G6	7.050	8.900	**B-G6**	1.986	5.900	**C-G6**	5.050	8.000



(a)



(b)



(c)

Figure 4.14 Down curve from IBB concrete rheometer test for concrete with different gradations

4.5.2 Effect of Paste Content

Linear regression of the down curves of the IBB rheometer test results of the concretes made with different paste contents are shown in Figure 4.16. It indicated that as the paste content increased, the interception of the fresh concrete mixtures decreased, but the slope of the mixtures had a little change. As discussed before, high paste content might provide the mixtures with excess paste coat the aggregate surface and improved concrete workability. More paste in concrete can increase the distance between aggregate particles, thus reducing the friction between the aggregate particles and increasing the flowability of the fresh concrete.

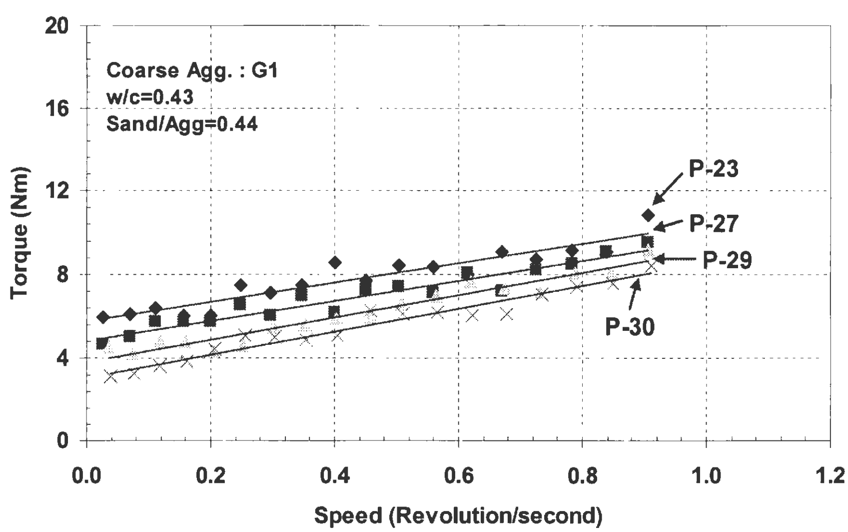
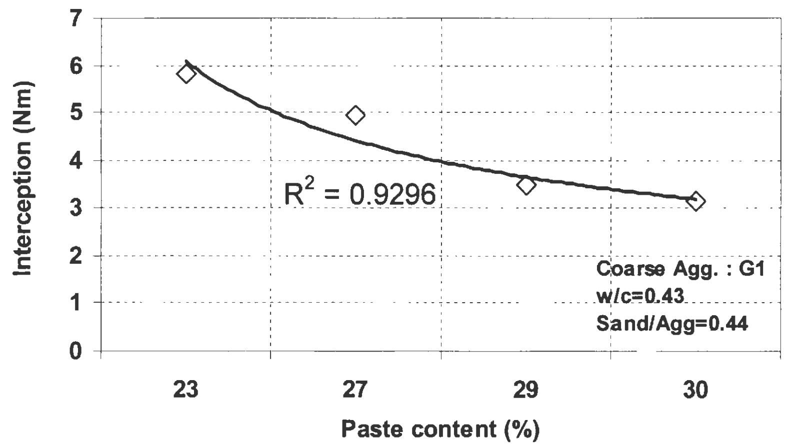
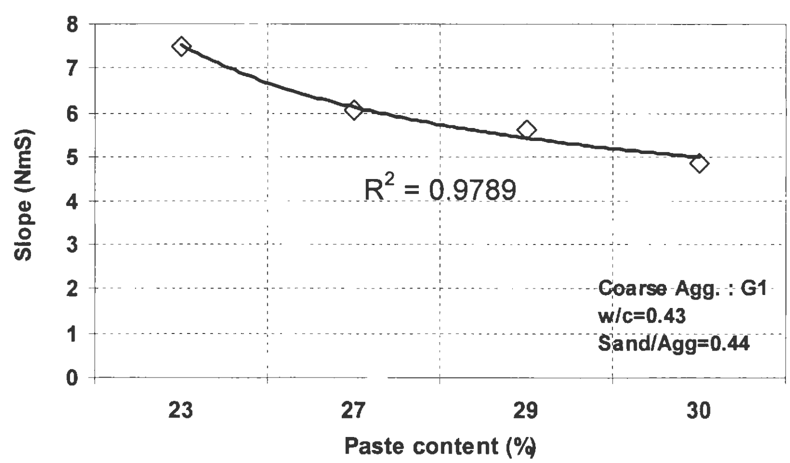


Figure 4.15 Effect of paste content on concrete rheology test results

The slope is related to the viscosity of the concrete mixtures. It is possible that after the excess thickness (or the thickness of the layer of paste coated on the aggregate surface) reaches certain value, the viscosity of the mixtures is mostly controlled by the paste flow properties, rather than aggregate (Oh, et al. 1999a, b). The procedures of calculation of the thickness of excess mortar are shown in Appendix E. Further experimental results are needed to verify the previous findings.



(a) Interception



(b) Slope

Figure 4.16 Effect of paste content on rheological parameters

4.5.3 Effect of Fly Ash Replacement and Superplasticizer

Table 4.8 and Figures 4.17, 4.18 show the results obtained from IBB concrete rheometer tests of the concrete made with different fly ash (class C and F) replacement levels. The deference between concrete with and without fly ash was obvious.

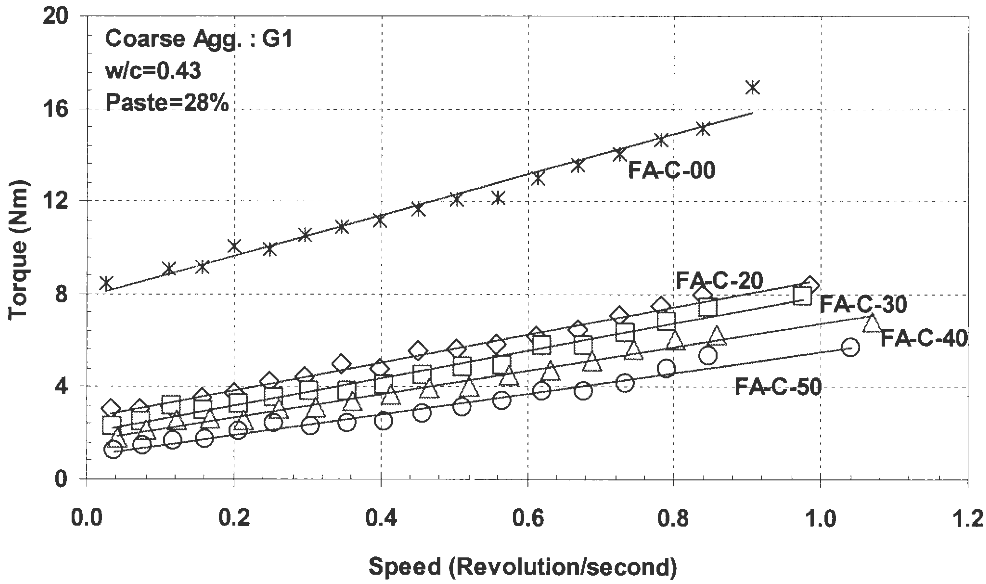
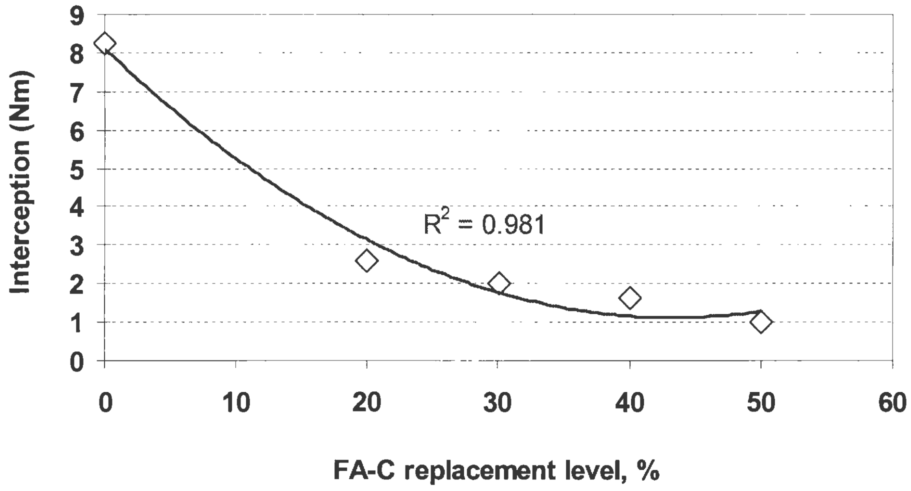
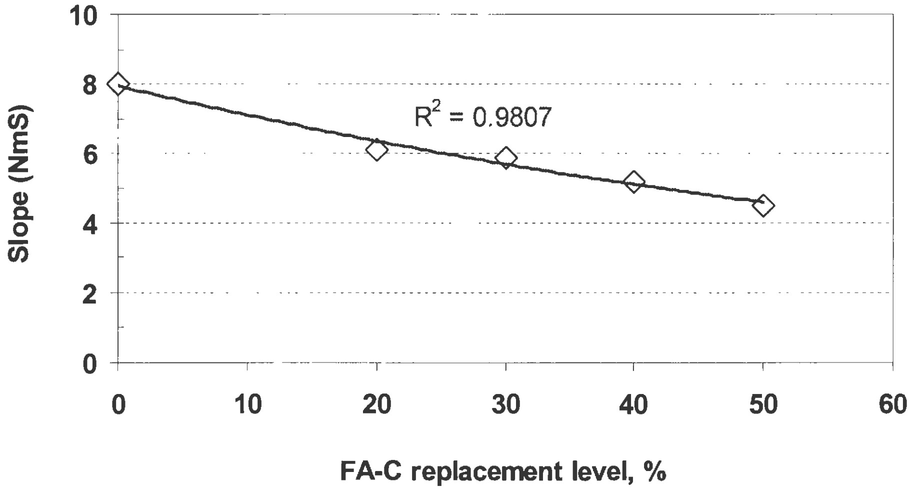


Figure 4.17 Effect of fly ash (class C) on concrete rheology test results

Due to low specific gravity of fly ash, volume of the paste in a given concrete mixture increased with the increased fly ash replacement level. As a result, the excess thickness of the aggregate particles increased and the friction between the aggregate decreased.



(a) Interception



(b) Slope

Figure 4.18 Effect of fly ash (class C) on concrete rheology test results

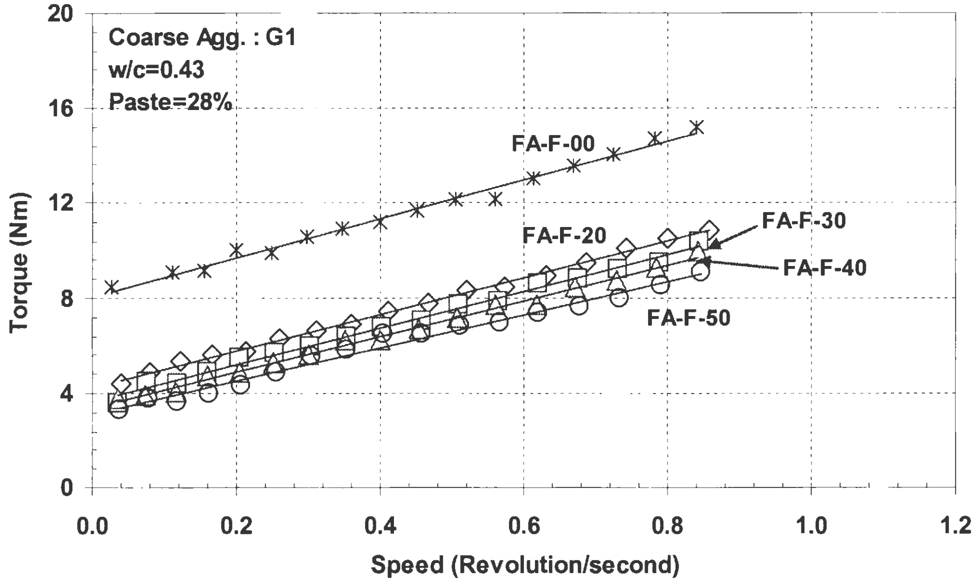
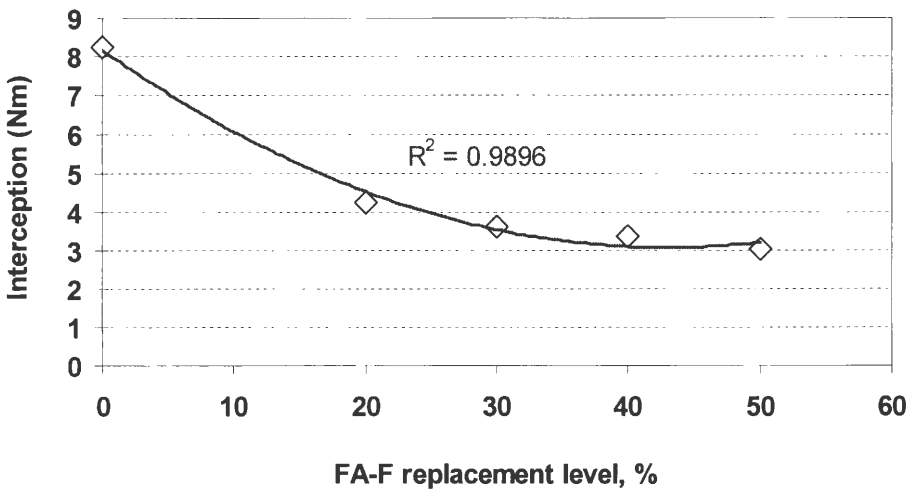
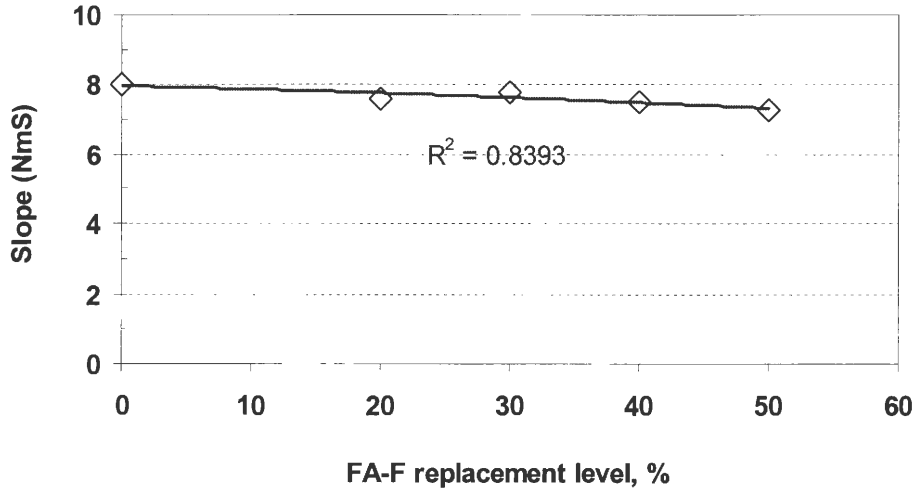


Figure 4.19 Effect of fly ash (class F) on concrete rheology



(a) Interception



(b) Slope

Figure 4.20 Effect of fly ash (class F) on concrete rheology test results

The parameters related to Bingham rheology parameters calculated from down curves in Figure 4.19 were shown in Table 4.7.

Table 4.7 Effect of fly ash on concrete rheology properties

Mix proportion	**G (Nm)**	**H (NmS)**	**Mix proportion**	**G (Nm)**	**H (NmS)**
FA-C-20	2.600	6.100	**FA-F-20**	4.270	7.620
FA-C-30	2.000	5.900	**FA-F-30**	3.620	7.790
FA-C-40	1.620	5.200	**FA-F-40**	3.390	7.500
FA-C-50	1.000	4.500	**FA-F-50**	3.050	7.300

Figures 4.21 shows the flow curves obtained from IBB concrete rheometer tests of concrete with superplasticizer. It was observed that superplasticizer greatly decreased the interception of the fresh concrete, this made concrete have better flowability. The slope did not change too much if the superplasticizer dosage below 1.0, but the interception decreased greatly. Once the superplasticizer dosage beyond 1.0, the slope of concrete increased greatly.

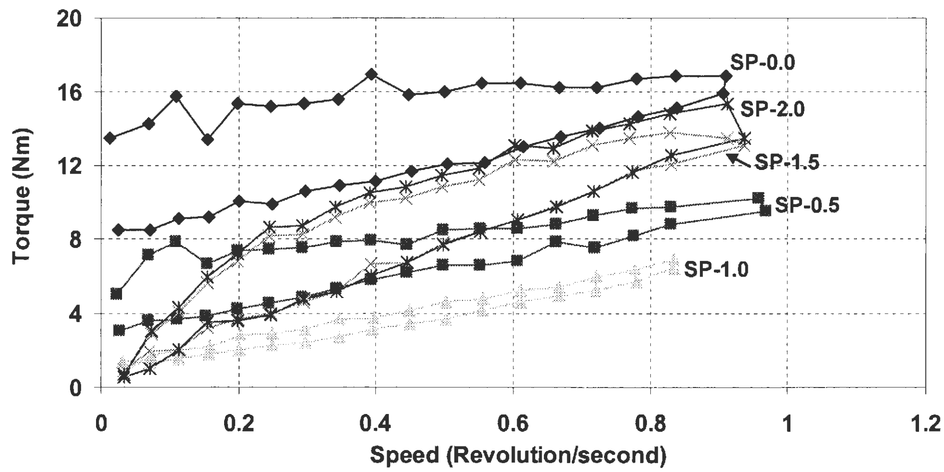


Figure 4.21 Effect of Superplasticizer on concrete rheology

4.5.4 Effect of Admixtures

Figures 4.22 and 4.23 show the flow curves obtained from IBB concrete rheometer tests on concrete with Acti-Gel and VMA358, respectively. The effect of the Acti-Gel dosage on concrete flow behavior appeared more obvious than that of VMA358. Both Acti-Gel and VMA358 increased interception and slope of the concrete flow curve as the admixture dosage increased. However, Acti-Gel affected the concrete flow behavior, especial on the interception, more effectively.

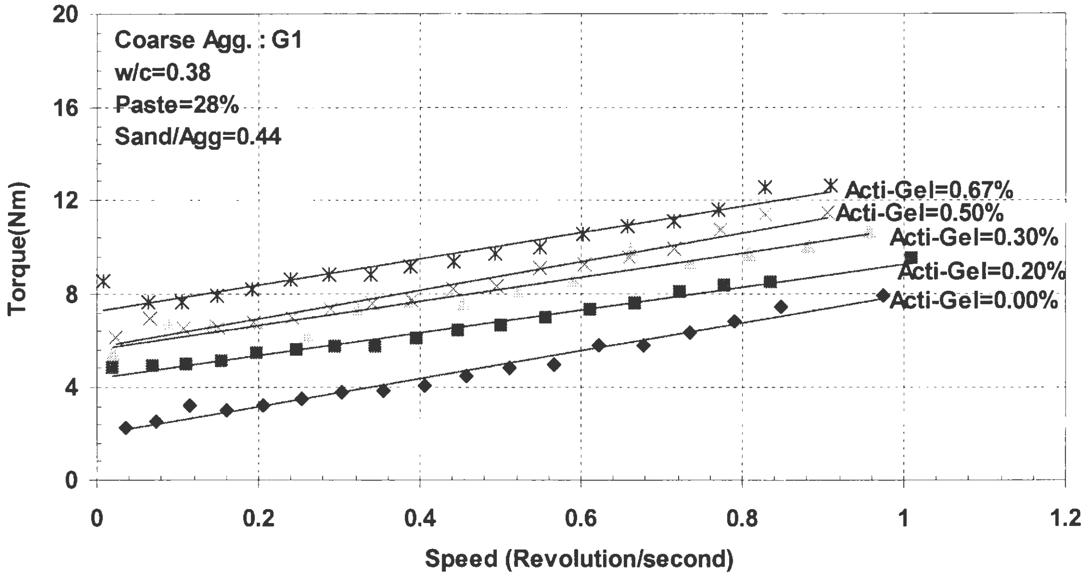


Figure 4.22 Effect of Acti-Gel on concrete rheology test results

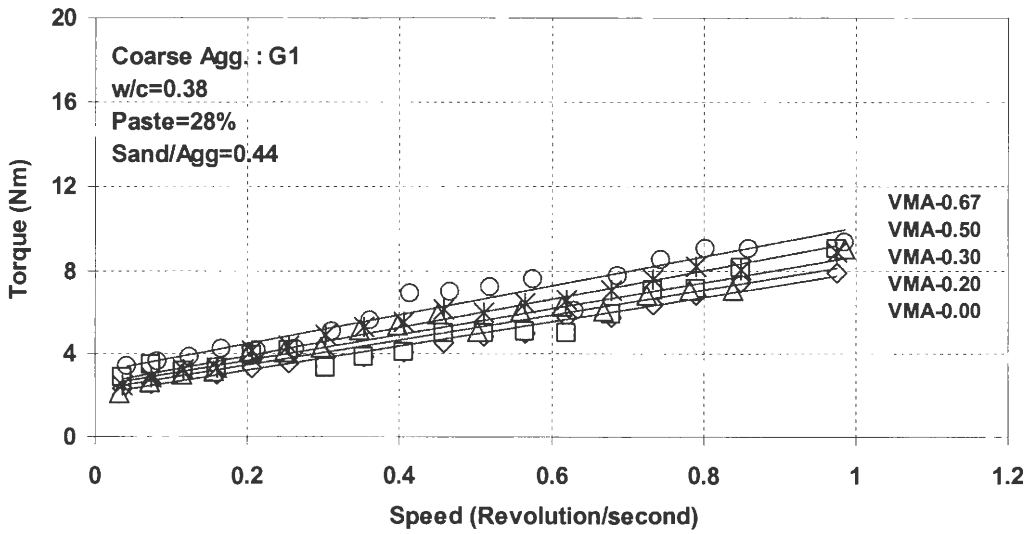
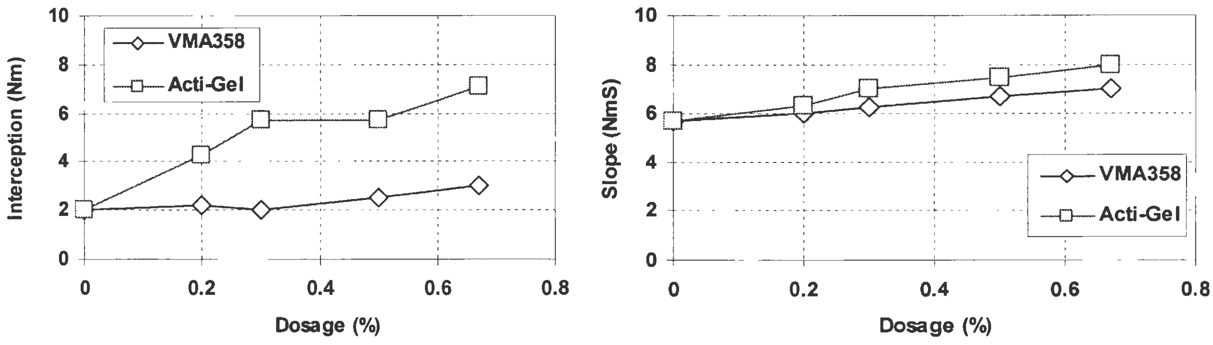


Figure 4.23 Effect of VMA358 on concrete rheology test results



(a) Interception (b) Slope

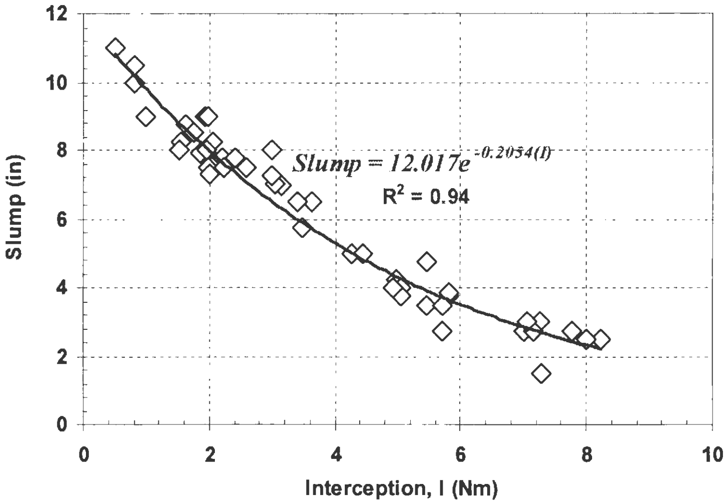
Figure 4.24 VMA358 and Acti-Gel effect on concrete rheology

4.5.5 Relationship between Rheological Properties, Slump and Compaction Factor

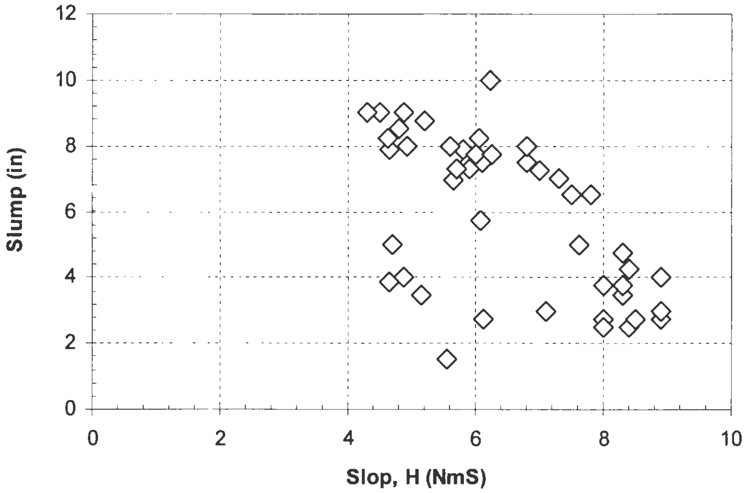
4.5.5.1 Slump Test and Rheological Properties

Figure 4.25 shows the slump values obtained from the present study had a strong correlation with the interception (with a very high R^2 value of 0.93), while the slump values had no clear relationship with slope values. These findings are consistent with previous research, which indicated that the slump value is strongly correlated with yield stress of fresh concrete while largely independent of viscosity (Murata, 1984; Tattersall, 1991; Christensen, 1991; and Saak, 2000). These results support the need to use the rheometer test fully reflect the concrete flowability.

Several research have developed models relating slump measurements and yield stress based on experimental data as well as the results from finite element modeling. Hu and de Larrard (1994) developed a model relating concrete slump to yield stress based on data taken from tests using a BTRHEOM concrete rheometer. Helmuth et al. (1995) developed a slump model based on geometric constraints for the standard ASTM C-143 concrete slump cone, where yield stress was calculated based on Murata's (1984) model.



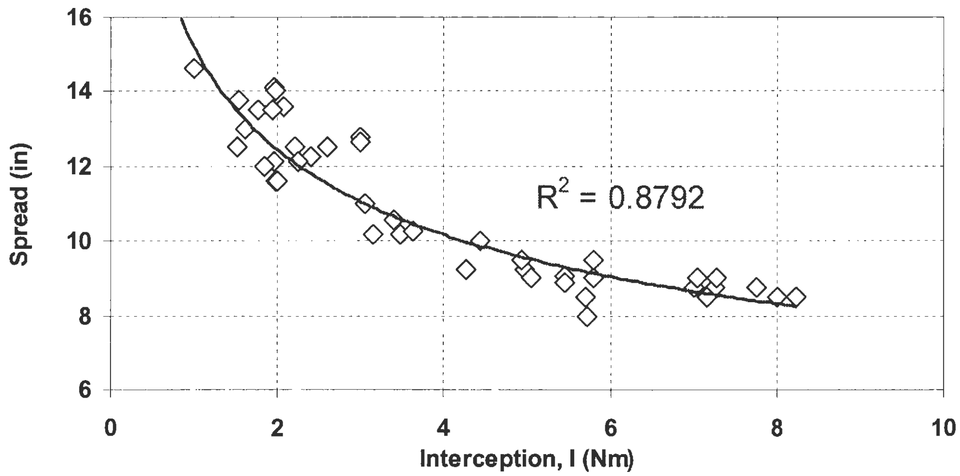
(a) Slump vs. interception



(b) Slump vs. slope

Figure 4.25 Slump and rheology parameters

As shown in Figure 4.26, the spread values were found to have a strong correlation with the interception of IBB test results (Figure 4.26 (a)), and slump values were correlated with the slope of the IBB results, the later of which indicated that the measurement of spread from the slump test partially reflected the flow resistance (or viscosity) of the tested material.



(a) Spread vs. interception

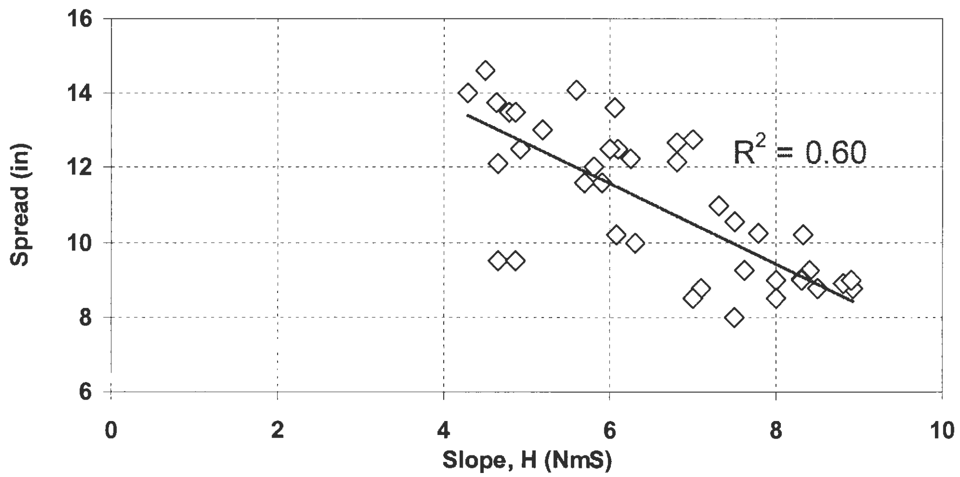


Figure 4.26 Relationship between spread and rheology parameters

Since the interception of the IBB test results showed strong correlations with both slump and spread, there must be a relationship between the slump and spread. The relationship has been actually developed by some previous researchers. Murata (1984) established a simple relationship between slump and yield stress based on simple force balance analysis, Christensen (1991) corrected the integration errors in Murata model, and after that Saak (2000) converted it to a dimensionless quantities and geometry-free application. Helmuth et al. (1995) developed a slump model based on geometric constraints for the standard ASTM C-143 concrete slump cone. Yield stress was calculated based on Murata's model. The radius of the base of the slumped concrete was assumed to be a function of the final slump height as below:

$$r_s = \left(\frac{336}{12 - s} - 3 \right)^{\frac{1}{2}} - 1 \tag{4.1}$$

where "s" is the slump height and "r_s" is the radium of the base of the slumped concrete.

This relationship between slump and spread was shown in Figure 4.27. The present experimental results were also shown in the figure. These results can be divided into three groups.

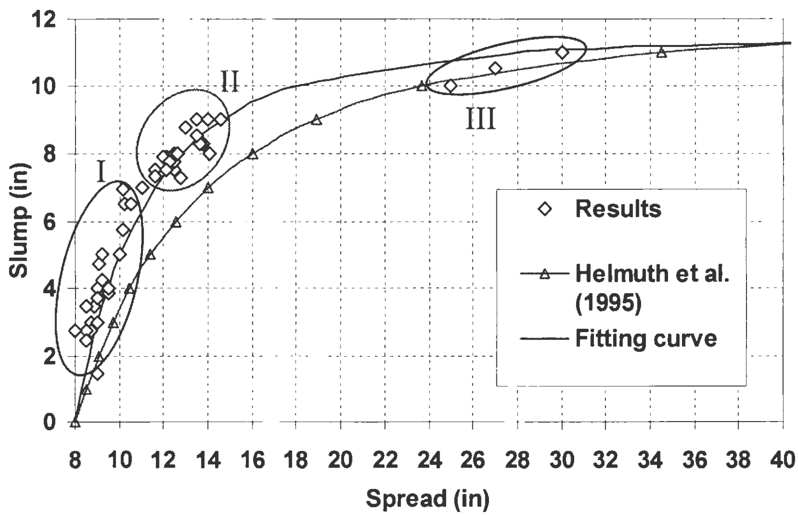


Figure 4.27 Slump and spread

In a range of slump higher than about 9 inches, or spread larger than 24 inches, the calculated and measured values of slump and spread are in good agreement for model developed by Helmuth et al. (1995). But in the range of lower slumps, the calculated values are excessively low. This is mainly due to the non-symmetric slumps due to non-rodding, as shown in Group I Figure 4.28. The structure of concrete in slump cone is not isotropic without compacted.

The present of weak parts in concrete mix, which has more entrapped air, honeycombs and voids or has no coarse aggregate but only mortar, will make the deformation anisotropic.

An empirical function between slump height and the base radium of the slumped concrete based on current experimental results were developed based on the relations shown in Figure 4.25 (a) and Figure 4.26 (a).

$$r_s = 11 \times (11.5 - s)^{-0.415} \quad (4.2)$$

where “s” is the slump height and “r_s” is the radium of the base of the slumped concrete.

Figure 4.28 shows the general ranges of the slump and spread as well as the typical shapes of the concrete mixtures in Group I, II, and III.

As shown in Figure 4.28, Group 1 mixtures behaved just like conventional concrete mixtures. Without rodding and vibration, the mixtures could not hold their shapes due to existence of entrapped air voids. Therefore, rodding or vibration is necessary for them.

Group II mixtures generally had a slump of 7-9” and spread of 12-15”. The mixtures displayed a regular short cone shape because the entire sample deforms horizontally due to viscous forces acting in conjunction with the downward gravitational force, as shown in Figure 4.29. this group of concrete mixtures also had a compaction factor of 1.0. As a result, these mixtures appeared not only able to flow and self-compact but also able to hold it shape after demolding.

Group III mixtures also exhibited excellent flow and self-compactability. However, they had little shape stability, shown by their excessive spread.

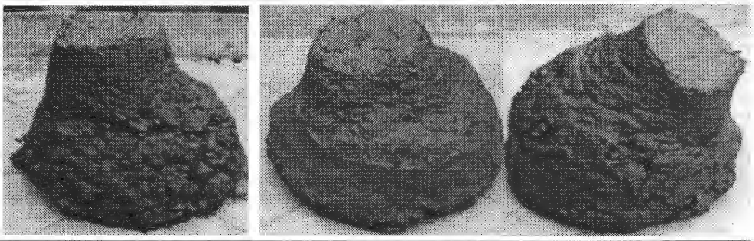
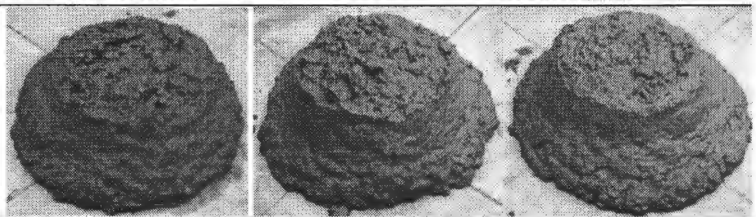
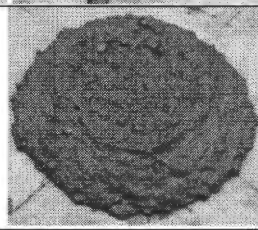
Compaction Factor ≤ 0.8	**Group I** Slump 2-6” Spread 8-11” Shape: irregular cone	
Compaction Factor ≅ 1.0	**Group II** Slump 7-9” Spread 12-15” Shape: regular short cone	
Compaction Factor = 1.0	**Group III** Slump ≥ 10” Spread ≥ 24” Shape: pancake	

Figure 4.28 Cauterizations of concrete mixtures based on slump concretes (without rodding and vibration)

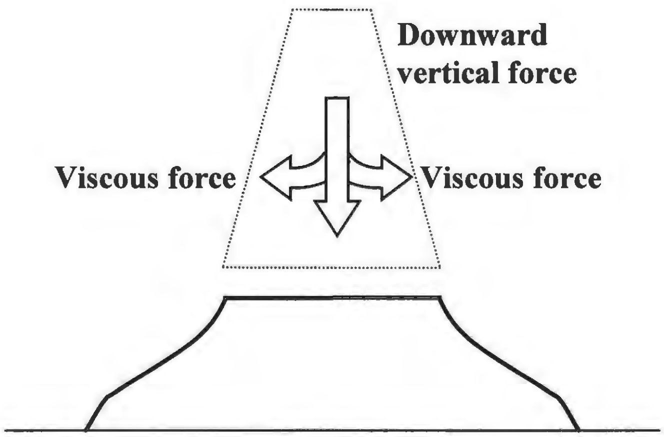


Figure 4.29 Low yield stress slumped concrete

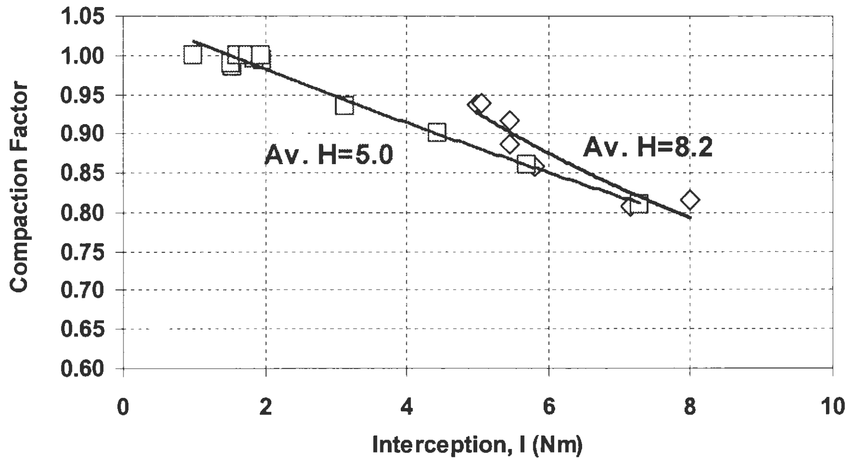
4.5.5.2 Fresh Concrete Compactability and Rheological Properties

The relation between compaction factor and rheology related parameters, interception and slope, were examined. Concrete mixtures with a constant IBB slope (near to 5.0 NmS and 8.2 NmS respectively) were chosen. These mixtures are list in Table 4.8.

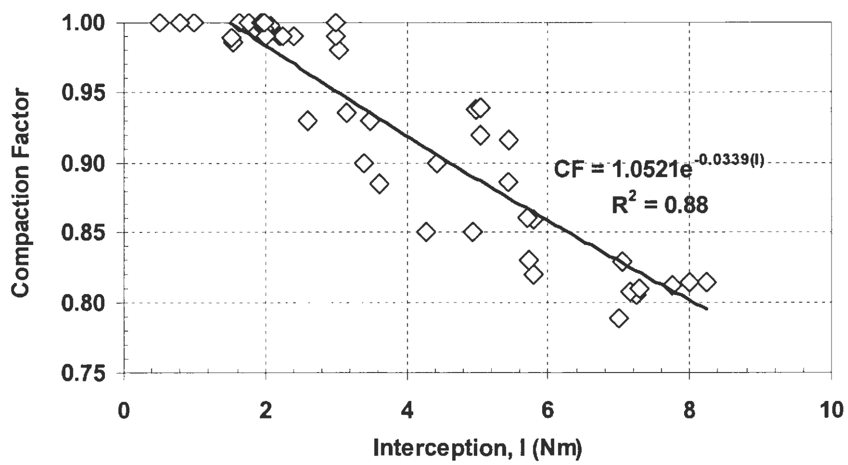
Table 4.8 Mixtures selected for the study of the relationship between interception and concrete compactability

Mix	Compaction Factor	I (Nm)	H (NmS)	Av. H	Standard Deviation
A-G1	0.815	8.000	8.400		
A-G5	0.808	7.150	8.000		
C-G1	0.937	4.980	8.400		
C-G2	0.916	5.450	8.300	8.2	0.172
C-G3	0.886	5.450	8.300		
C-G4	0.859	5.800	8.300		
C-G6	0.939	5.050	8.000		
B-G1	0.994	1.962	4.660		
B-G2	0.996	1.845	5.800		
B-G3	0.986	1.545	4.630		
B-G4	0.989	1.523	4.930		
P-30	0.935	3.140	4.87		
FA-C-40	1.000	1.620	5.200		
FA-C-50	1.000	1.000	4.500	5.0	0.417
AG-0.2	0.900	4.430	4.710		
AG-0.3	0.860	5.700	5.140		
AG-0.67	0.810	7.280	5.560		
G:L=1:1	1.000	1.760	4.790		
G:L=3:1	1.000	1.932	4.870		

As shown in Figure 4.30 (a), for concrete with same slope value, the compaction factor value was found to have a strong correlation with the interception (with very high R^2 values of 0.9138 and 0.9196). With the increase of interception, the compaction factor of fresh concrete decreased. This means that more energy is required to make the fresh concrete mixtures with high interception value well compacted. To achieve the maximum compaction factor of 1, the interception value of a concrete mixture shall be less than 2 Nm, thus, ensuring the fresh concrete is self-compactable.



(a) Constant H



(b) Different H

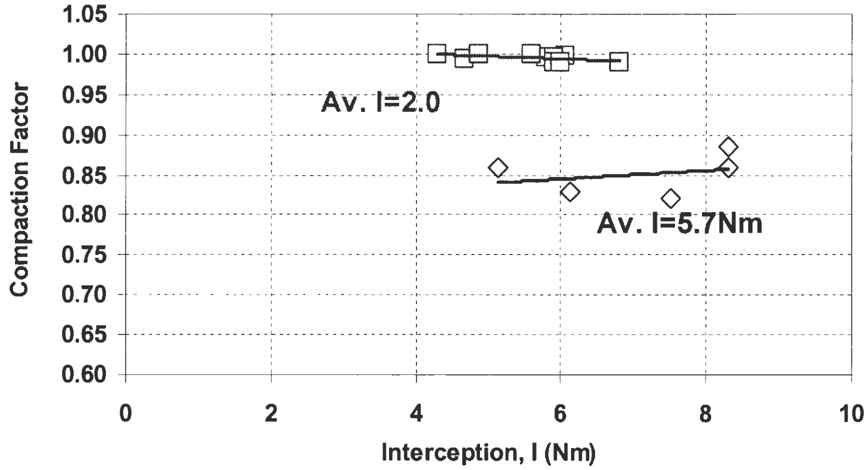
Figure 4.30 Relationship between concrete compactability and interception

Figure 4.32(b) demonstrates that the relationship still exists for different H values. Similarly, in the study of the relationship between concrete compactability and the IBB slope values, concrete mixtures with a constant interception (near 2.0 Nm and 5.7 Nm) were selected. These mixtures were list in Table 4.12.

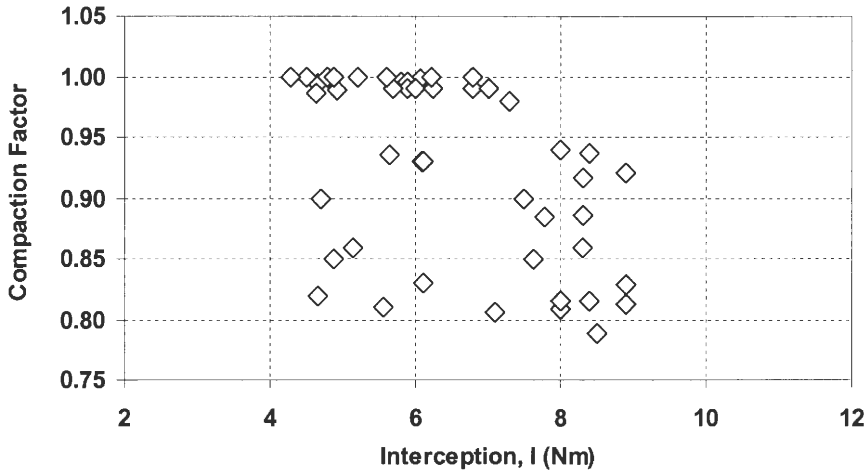
Table 4.9 Mixtures selected for the study of the relationship between slope and concrete compactability

Mix	Compaction Factor	I (Nm)	H (NmS)	Av. I (Nm)	Standard Deviation
B-G1	0.994	1.962	4.660		
B-G2	0.996	1.845	5.800		
B-G5	0.998	2.067	6.060		
B-G6	0.995	1.986	5.900		
FA-C-30	0.990	2.000	5.900	2.0	0.121
VMA-0.2	0.990	2.200	6.000		
VMA-0.5	0.990	2.240	6.800		
L:G=3:1	1.000	1.960	5.600		
L:G=1:3	1.000	1.932	4.870		
L:G=0:1	1.000	1.975	4.290		
C-G3	0.886	5.450	8.300		
C-G4	0.859	5.800	8.300		
P-23	0.820	5.800	7.500	5.7	0.042
AG-0.2	0.860	5.700	5.140		
AG-0.5	0.830	5.720	6.120		

Figure 4.31 shows that for concrete mixtures with a given interception value, the compaction factor values appeared independent upon the slope values from the IBB tests. When the slope increased, the compaction factor of fresh concrete did not vary significantly. For a given slope value for example, 5, both low and high compaction factors (0.85 and 1.00) were achieved.



(a) Constant G values



(b) Different G values

Figure 4.31 Relationship between concrete compactability and slope

The experimental results of fresh concrete compaction factor and rheological parameters are shown in Figure 4.32. All experimental data were divided into two groups according to their compaction factor values, less than 0.99 and more than it. Results show that no clear correlation between interception and slope. But fresh concrete compactability is found an interception controlled property. All concrete mixtures with compaction factor more than 0.99 are in the area shown in Figure 4.32. Meantime, the maximum interception value of 3 is required to obtain self-compactability. Further increase the interception will decrease the self-compactability of fresh concrete. This should be a design critical for self-consolidating concrete.

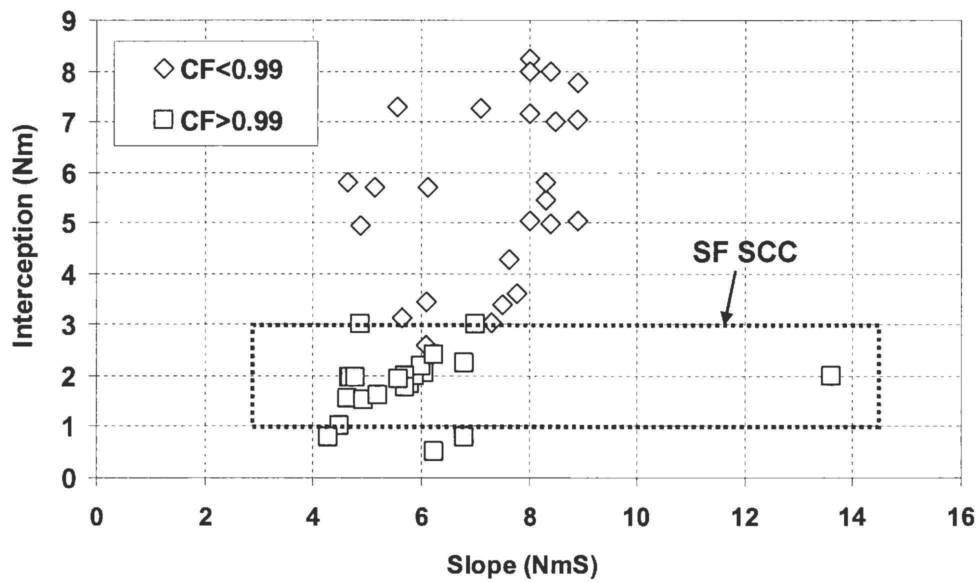


Figure 4.32 Interception vs. slope

4.6 Green Strength Test

Green strength was tested for selected concrete mixtures. These mixtures had different rheological properties. Table 4.10 lists all mix proportions, slump test results and rheological properties used in this study. The start of any deformation of the concrete specimen is defined as the failure.

Figure 4.33 shows pictures of the fresh 4x8 inch concrete cylinders right after demolding. Two specimens, FA-C-30 and FA-F-30, slumped after demolding. These two mixtures had lower interception values than others. For FA-C-30, no "green" strength was able to be measured on a 4x8 inch cylinder because the whole concrete cylinder slumped. Instead, a 4x4 inch cylinder was used in the green strength test. For FA-F-30, green strength was still measured on 4x8 inch cylinder, although the concrete cylinder partly deformed at the bottom, as shown in Figure 4.36. Another 4x4 inch cylinder was also tested.

Table 4.10 Concrete mixes selected for green strength test

Number	Slump (in)	Spread (in)	I (Nm)	H (NmS)
A-G1	2.50	8.50	8.23	8.00
C-G1	4.25	9.25	4.90	8.60
FA-C-30	7.30	11.60	2.00	5.90
FA-F-30	6.50	10.25	3.63	7.79
ActiGel0.5	2.75	8.00	5.75	7.50
ActiGel0.67	1.50	9.00	7.10	8.00

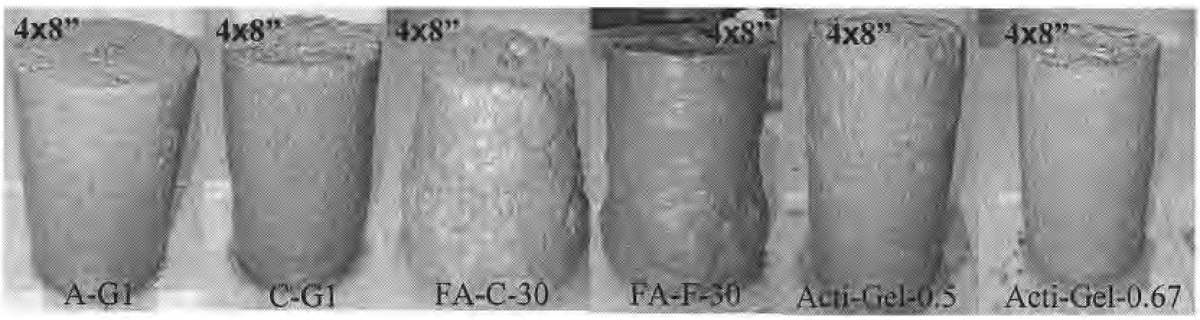


Figure 4.33 Shape of concrete after demolding

In Figure 4.34, pictures taken after the concrete cylinders' failure are shown. For fresh concrete cylinders A-G1, C-G1, Acti-Gel-0.5 and Acti-Gel-0.67, a failure surface was observed. For fresh concrete cylinders FA-C-30 and FA-F-30, the failure is plastic deformation start from the bottom of the cylinder.

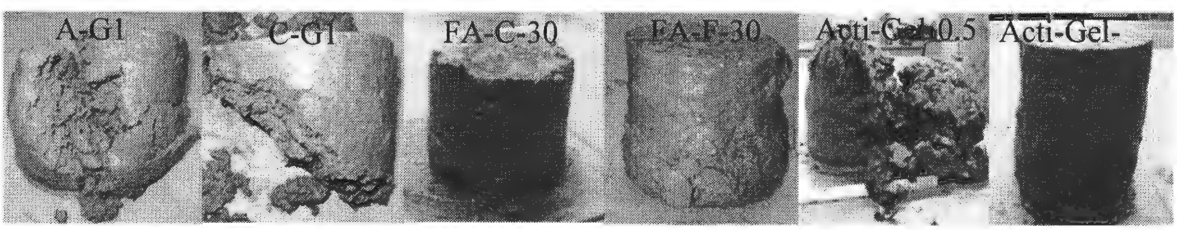


Figure 4.34 Shape of concrete after failure

Table 4.11 Green strength results

	I (Nm)	Green strength (psi)	
		4x4"	4x8"
A-G1	8.00	2.74	2.40
C-G1	4.98	1.44	1.10
FA-C-30	2.00	0.92	N/A
FA-F-30	3.62	1.35	0.91*
AG-0.5	5.72	1.69	1.35
AG-0.67	7.28	2.06	1.72

Note:
*: Concrete cylinder has already partly deformed before measuring the green strength.

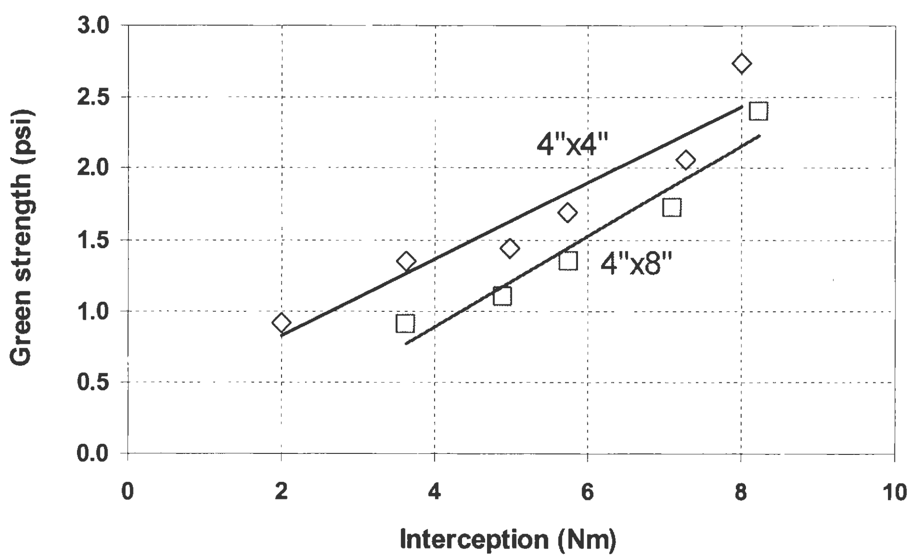


Figure 4.35 Relationship between fresh concrete green strength and interception G

It is clear that the fresh concrete's green strength is strong correlate with its yield term rheological parameter, as discussed in literature review.

4.7 "Mini-paver" and Filling Ability Test

One concrete mixture (FA-C-30) having the compaction factor values of 1.0, was selected for a mini-paver test to further evaluate its compactability, flowability and shape stability. The thickness of the mini-paver pavement section was set as 4 inches.

Table 4.12 Concrete mix for mini-paver test

Number	OPC	Fly Ash-C	Water	Sand	Coarse Agg.
FA-C-30	567	243	308	1269	1620

As shown in Fig. 4.36, the mini-paver test demonstrated that well-designed SF SCC mixtures could not only self-consolidate but also hold its shape very well after coming out from the paver. The top surface of the final pavement section was smooth, and little or no edge slump was observed.

Figure 4.36 Mini-paver test section for SF SCC

After the concrete was hardened, the mini-paver test section was cut into smaller sections. Three 50 mm (2") and 100 mm (4")-diameter cores were taken at the age of 9 days for compressive and split tensile strength tests, respectively. The average concrete compression strength was 4900 psi, and the average split tensile strength was 420 psi. Cross section of the SF-SCC section showed no visible honeycomb and segregation, and the aggregate distribution was as well as that in conventional pavement concrete (Figure 4.37).

Figure 4.37 Cross section of pavement slab

CHAPTER 5
CONCLUSION AND RECOMMENDATIONS

5.1 Summary

In this study, a new type of self-consolidating concrete for slip-form paving (SF SCC) was developed. Effects of materials and mix proportions on fresh concrete compactibility, flowability, and shape stability were studied.

Type I cement and class C and F fly ash were used as cementitious materials. Air-entraining agent (AEA), viscosity modifying admixture (VMA), and superplasticizer were used as admixtures. Normal river sand and limestone were used as aggregate. A total of 46 different mix proportions were evaluated. Nun-rodding slump flow test, modified compaction factor test, IBB rheometer test and "green" strength tests were performed to evaluate the concrete compactibility, flowability, and shape stability. In addition, a "mini-paver" was developed to simulate the field SF SCC paving in laboratory.

This research has demonstrated that by engineering concrete materials and mix proportions, it is feasible to develop a new type of SCC for slip form paving application. A new type of self-consolidating concrete for slip-form paving was developed, as well as a new test method for evaluation of fresh concrete compactibility and a new test method for lab simulation of paving.

5.2 Conclusions

The following conclusions can be drawn from the present study:

1) Difference between compacted and uncompacted coarse aggregate void content has a significant influence on concrete compactability. The less the difference between compacted and uncompacted coarse aggregate void content (generally presented by

well graded aggregate), the higher the concrete compactability. Increasing the paste content results in higher concrete compactability. Fly ash (both class C and F) replacement for Portland cement can further improve concrete compactability. Low aggregate content, or high paste content, generally provides concrete with improved flowability.

2) VMA can enhance concrete shape stability via increased plastic viscosity but with no significant change in yield stress of the concrete. Differently, Acti-Gel improves concrete shape stability via increases in both concrete yield stress and plastic viscousity. Acti-Gel has significant effect on fresh concrete rheology properties even at very small amount. Superplasticizer greatly improves the flowability by decreasing the yield stress. Therefore, optimal combination of fly ash, VMA, Acti-Gel, and/or Superplasticizer is necessary to obtain a good balance between flowability and shape stability of concrete.
3) For the concrete mixtures used in the present study, concrete compactibility increased but stability decreased with flowability. There was a nonlinear relationship between slump and spread for the concrete mixtures tested. The interception obtained from the IBB tests (similar to yield stress of the mixtures) had a good relationship with not only slump but also "green" strength of concrete.

5.3 Recommendations

Based on the present test results, the following performance criteria are recommended for the future SF SCC mix design:

- Slump: 7-8".
- Spread: 11-14".
- Shape of concrete after slump test: Cone with the flat top surface with the same diameter as the bottom diameter of slump cone.

A potential SF SCC may contain:

- The paste content should be at least 28% of the total weight of concrete.
- Sand to total aggregate ratio is around 0.44.
- Around 30% of cement should be replaced by class C fly ash.
- With or without viscosity-modifying admixture (VMA) and superplasticizer.

Further study is needed to improve SF SCC performance for field applications:

- To further study aggregate particle packing and its relationship with concrete flowability, compactability and shape stability.
- To investigate effect of hydraulic pressure on shape stability of concrete.
- To refine concrete mix design for its application to various field construction and environmental conditions
- To study durability of SF SCC for a better service life.

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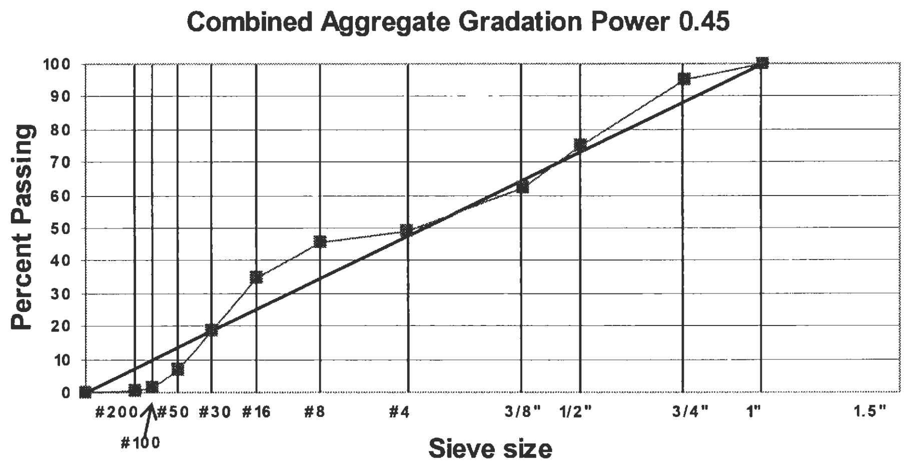
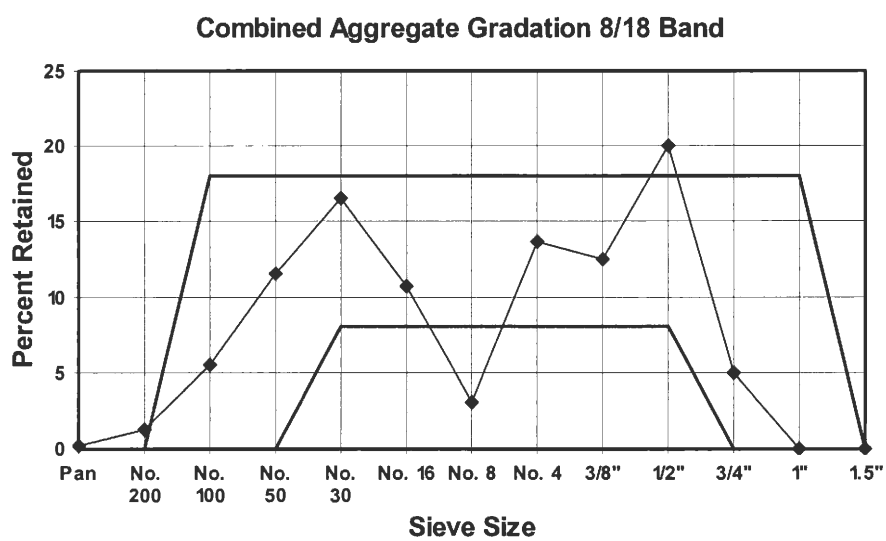
APPENDIX A

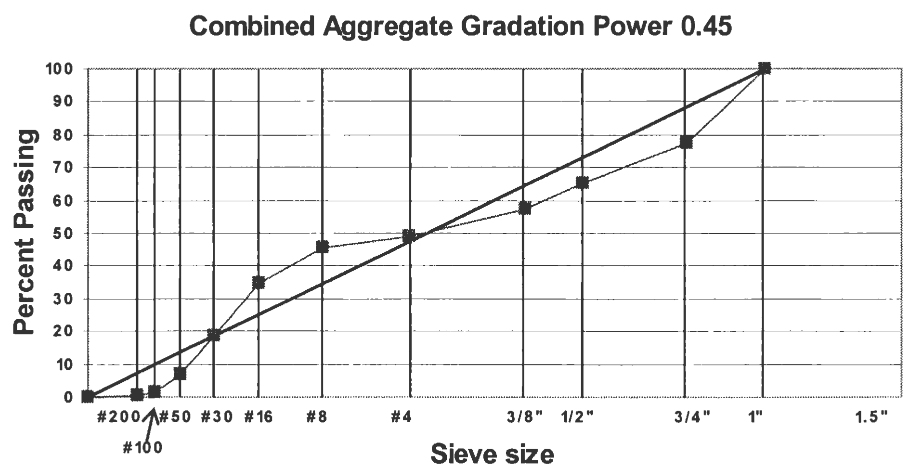
COARSE AGGREGATE GRADATION

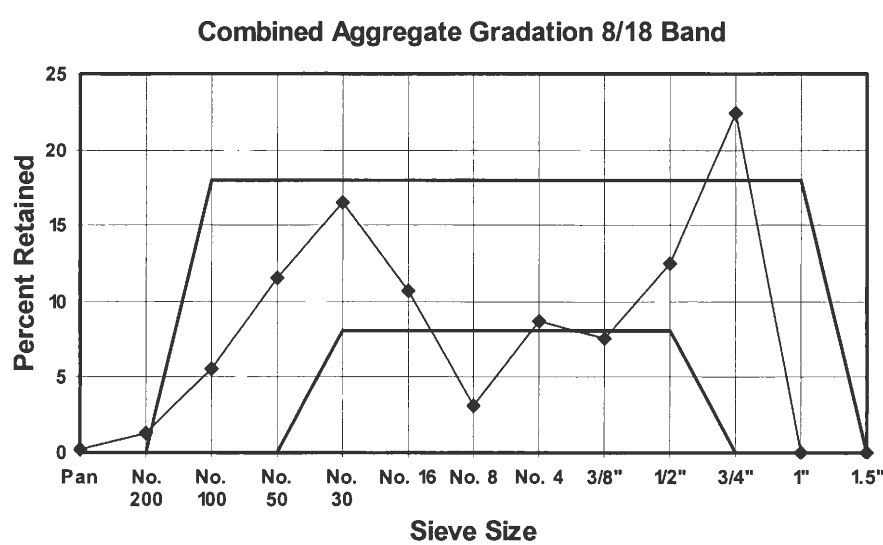
Gradation curves for different aggregate gradations used in this study are presented below.



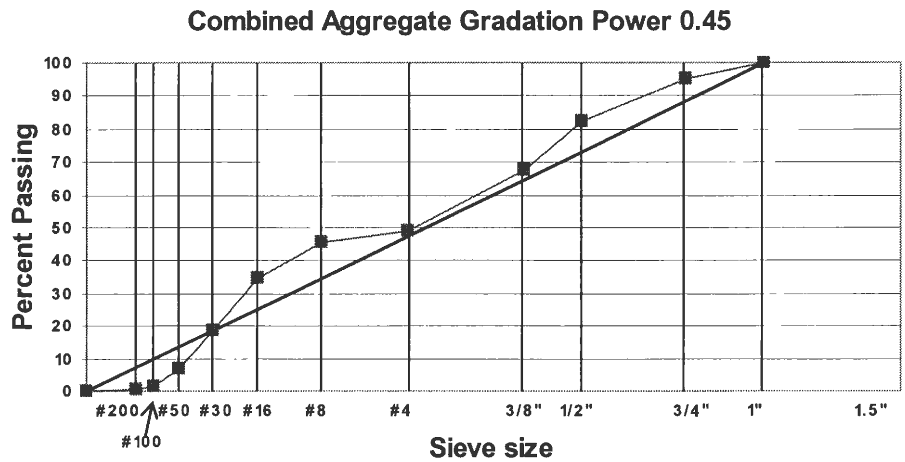


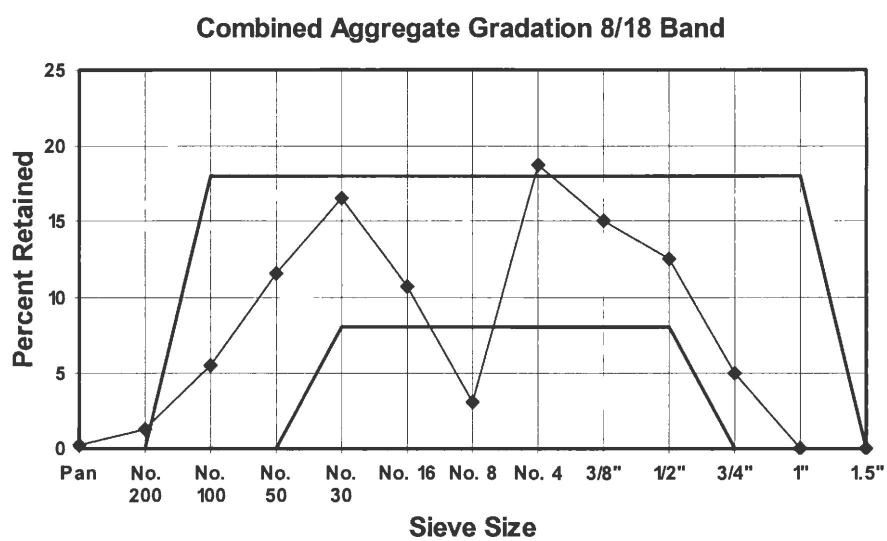
Gradation - G1





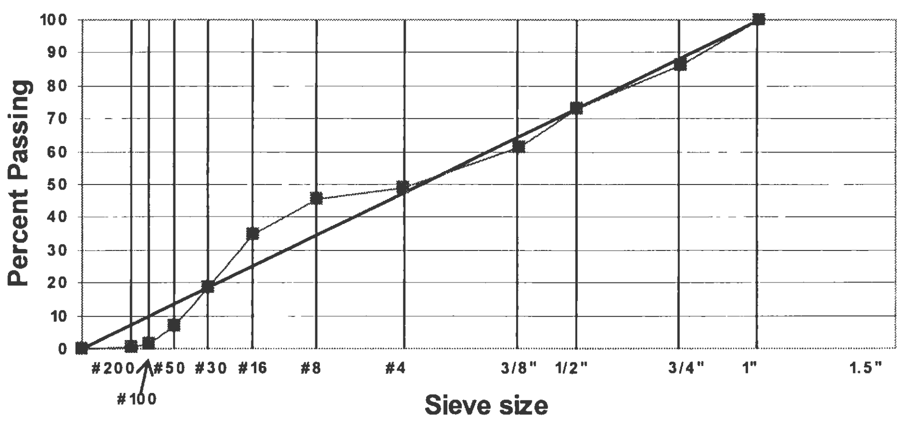
Gradation – G2



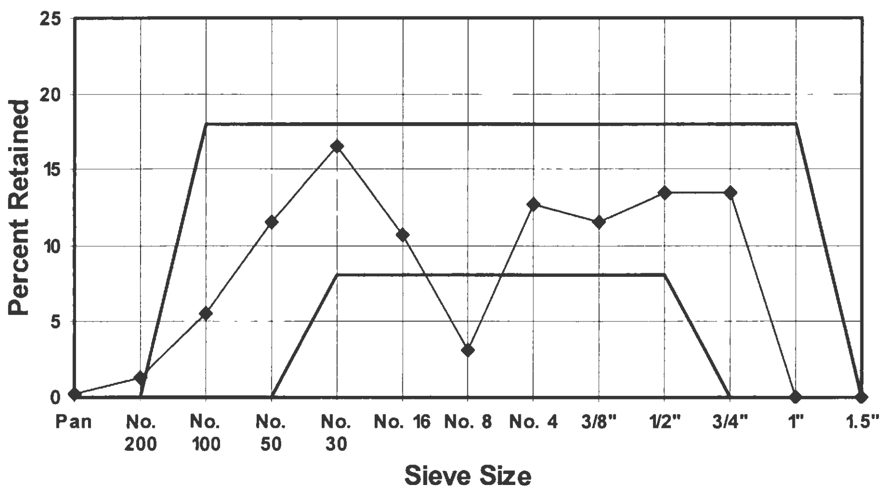


Gradation – G3

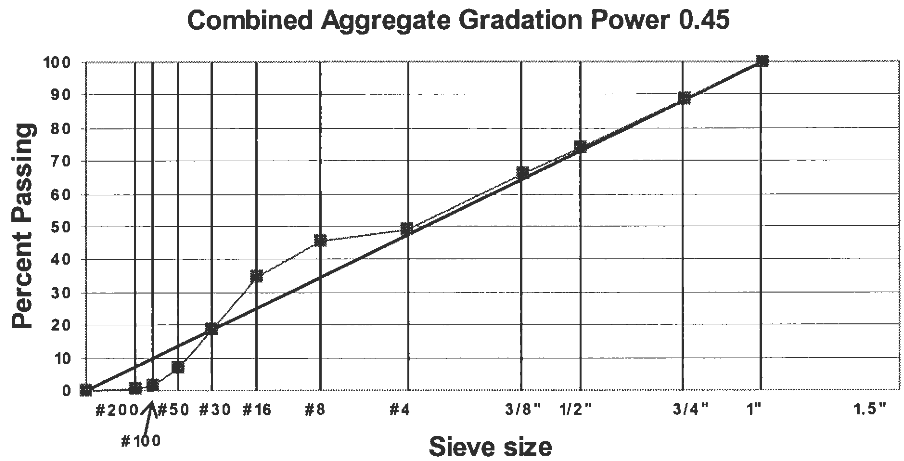
Combined Aggregate Gradation Power 0.45

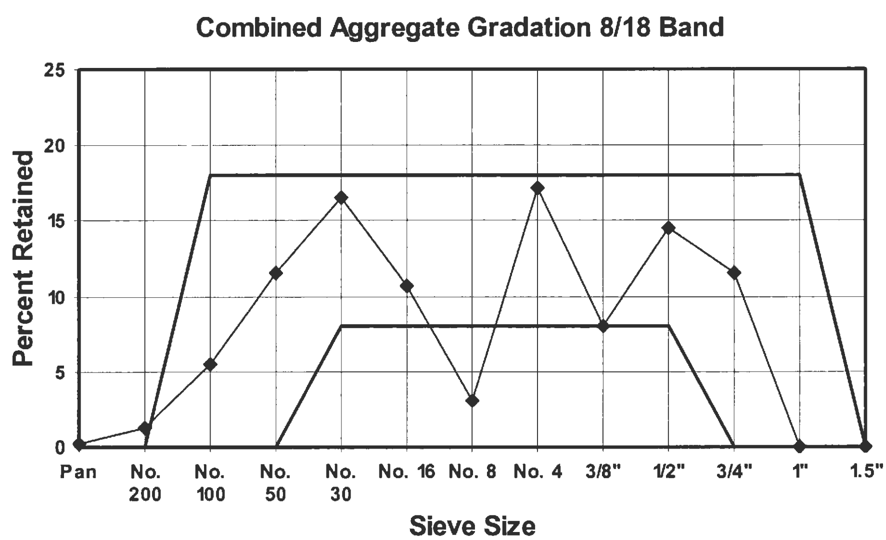


Combined Aggregate Gradation 8/18 Band

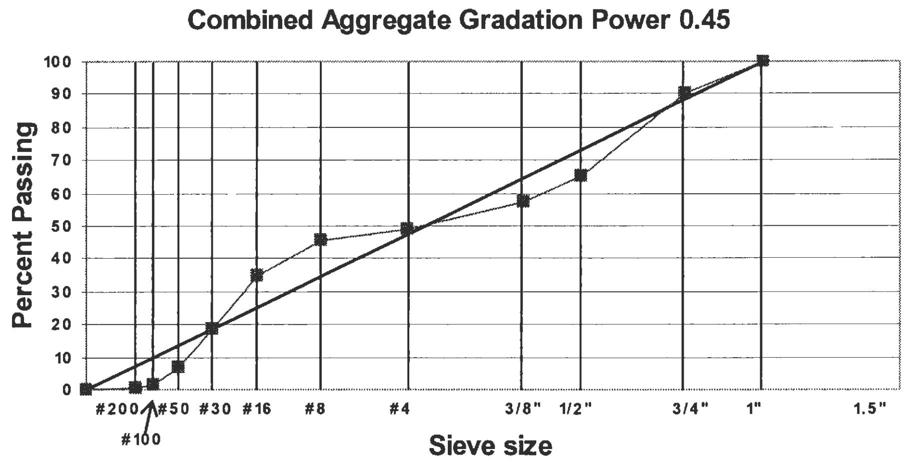


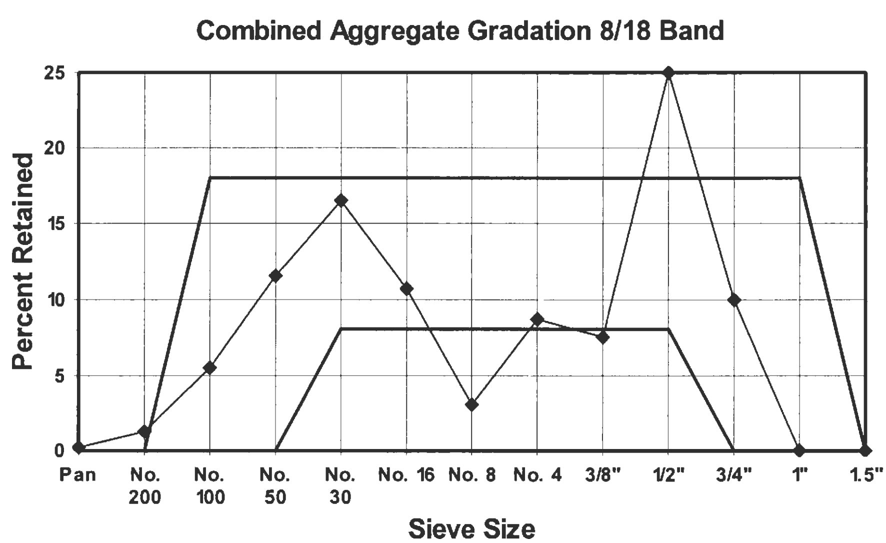
Gradation – G4





Gradation – G5



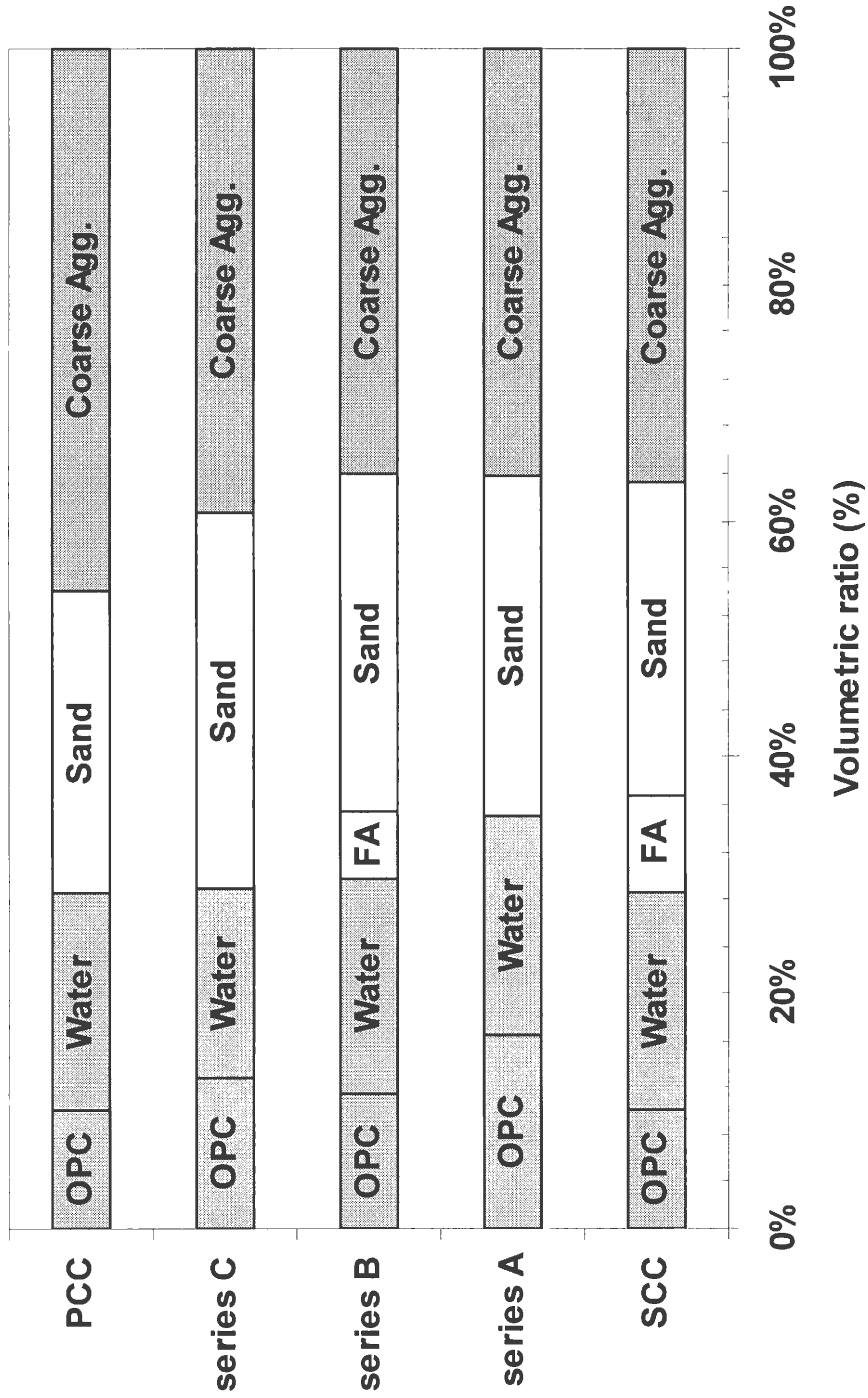


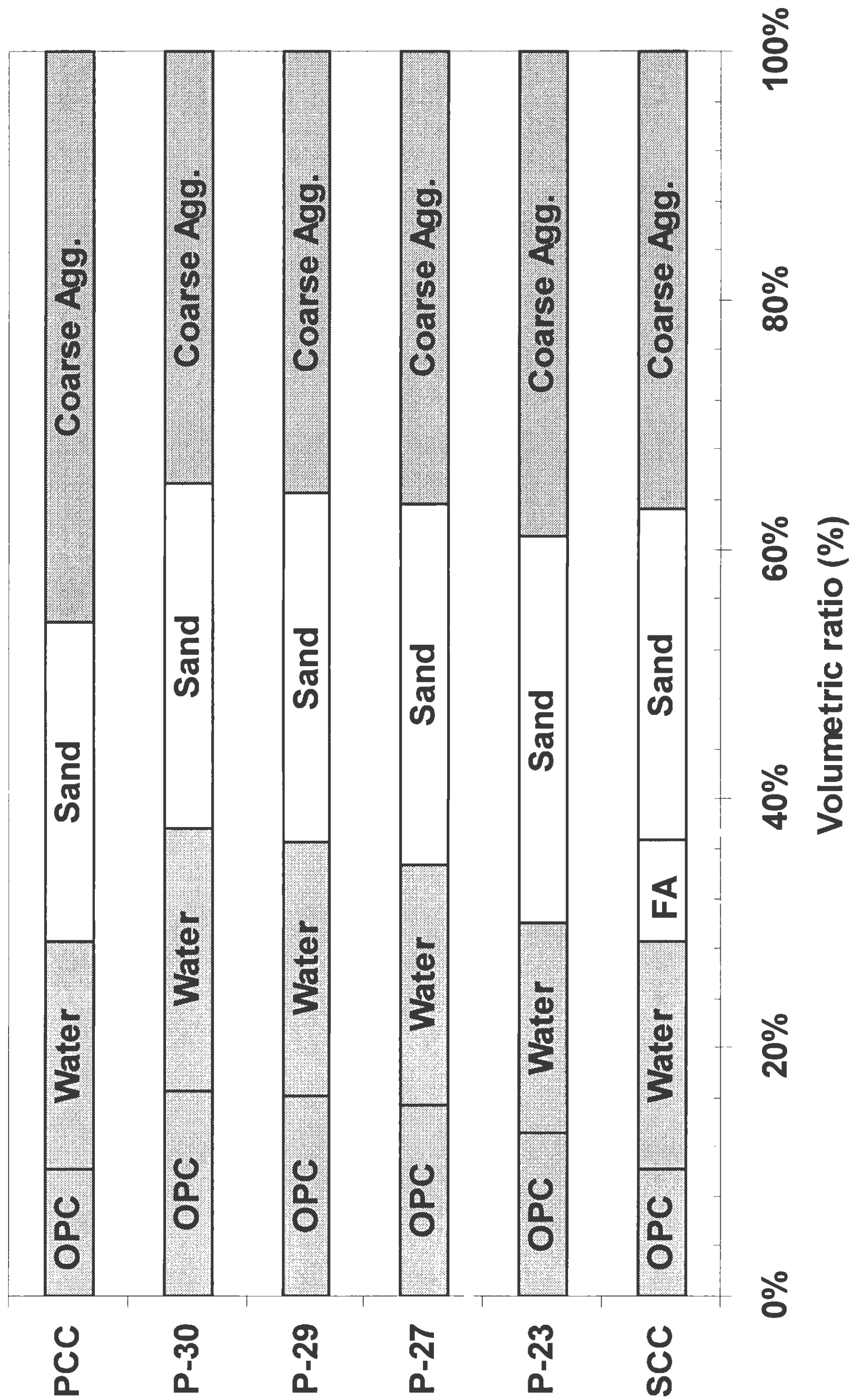
Gradation – G6

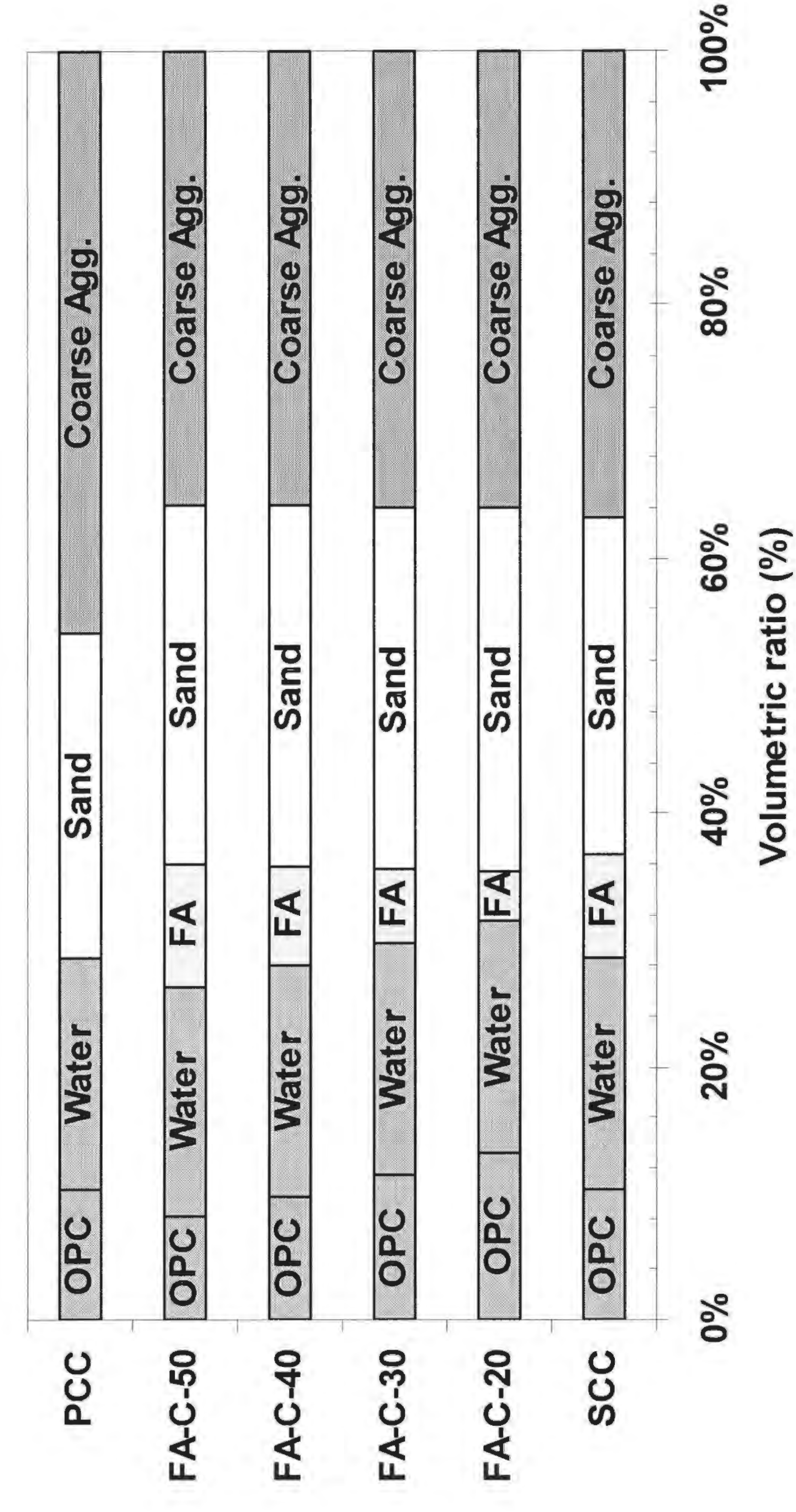
APPENDIX B
COMPARISON OF MIX PROPORTIONS

Typical mix proportions for conventional SCC (Kosmatka, et al. 2002) and pavement concrete (IOWA DOT C3 mix) are shown in this part comparing with the mix proportions used in this study.

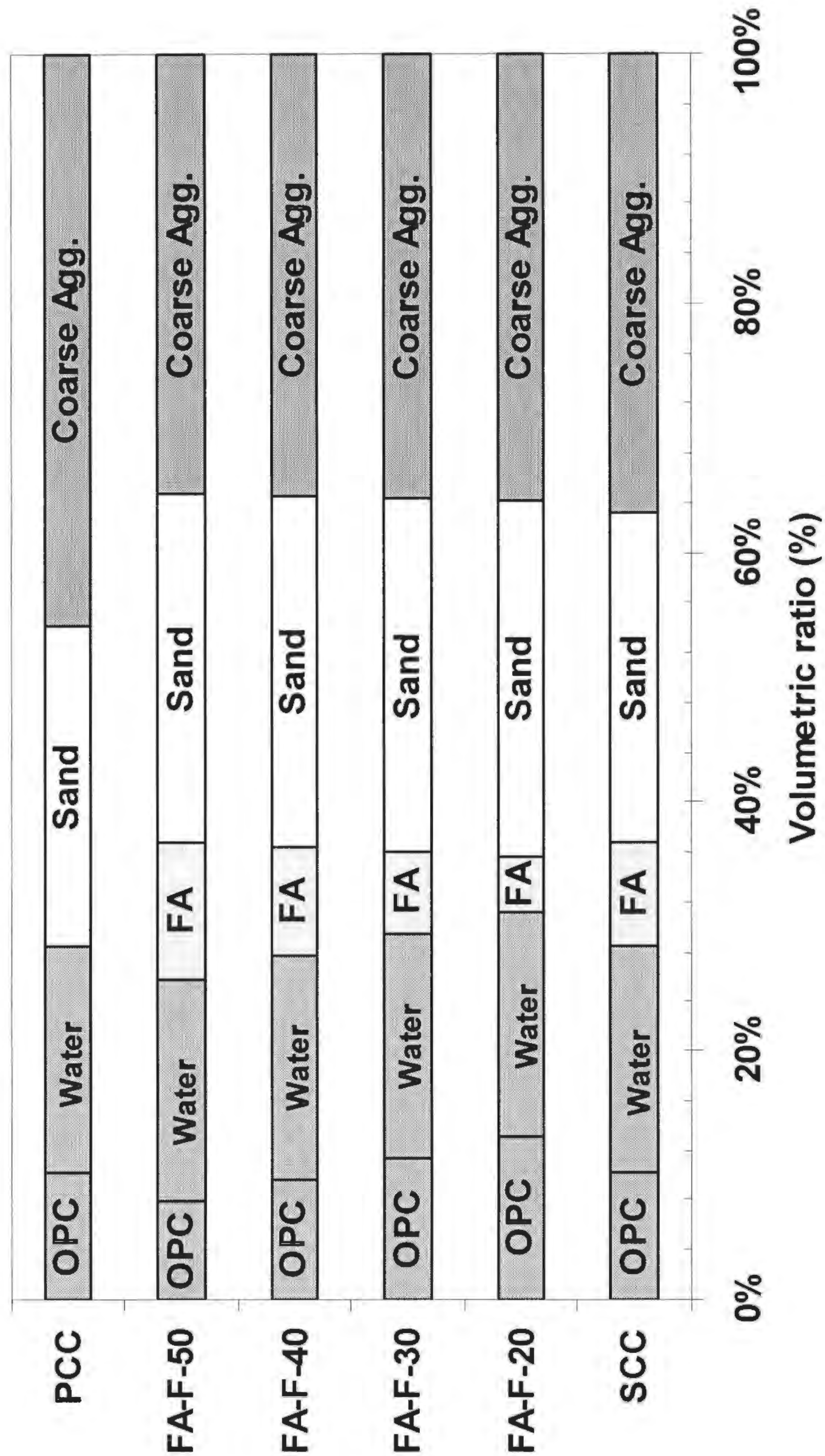
It is clear that all mix proportions used in this study is between the conventional pavement concrete and SCC. For conventional SCC, great deal of superplasticizer is normally used to improve its flowability. But in current study, it is not very necessary to do so since the fresh concrete do need desired shape stability. Flowability and segregation resistance for SF SCC are not as important as for conventional SCC.


PCC
series C
series B
series A
SCC
OPC
Water
FA
Sand
Coarse Agg.
0%
20%
40%
60%
80%
100%
Volumetric ratio (%)


PCC
P-30
P-29
P-27
P-23
SCC
OPC
Water
FA
Sand
Coarse Agg.
0%
20%
40%
60%
80%
100%
Volumetric ratio (%)



PCC
FA-C-50
FA-C-40
FA-C-30
FA-C-20
SCC
OPC
Water
FA
Sand
Coarse Agg.
0%
20%
40%
60%
80%
100%
Volumetric ratio (%)


PCC
FA-F-50
FA-F-40
FA-F-30
FA-F-20
SCC
OPC
Water
FA
Sand
Coarse Agg.
0%
20%
40%
60%
80%
100%
Volumetric ratio (%)

APPENDIX C
FRICTION ANGLE OF GRADED LIMESTONE AGGREGATE

Figure C.1 shows fresh concrete compactibility vs. coarse aggregate friction angle. No clear relation can be found. Based on current test results, the friction angle of coarse aggregate has no significant effect on concrete compactibility. Concrete slump values and coarse aggregate friction angles are shown in Figure C.2. Again no clear relation can be found clearly. This is mainly because the difference between friction angles of graded coarse aggregate is too small to show difference clearly. But in Figure C.2, slight decrease in slump can be found with increase of coarse aggregate friction angle.

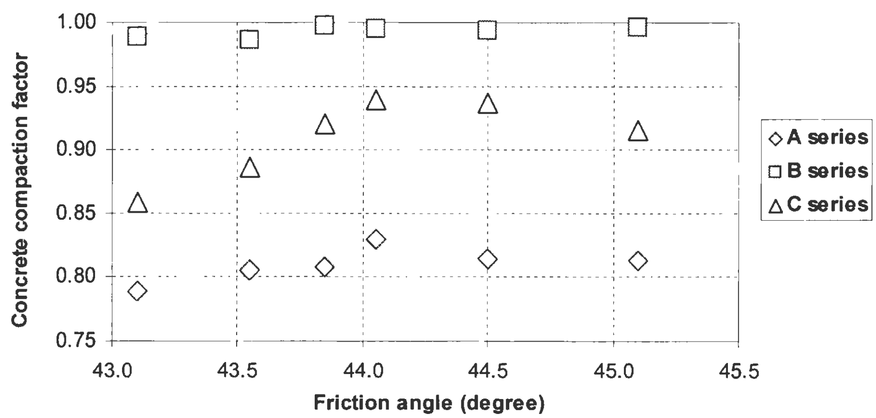


Figure C.1 Coarse aggregate friction angle vs. concrete compaction factor

No clear relation can be found from Figure C.3 between spread and coarse aggregate friction angle. This is mainly because the flowability of concrete in this study is low. The mortar plays a main and important role in flowability of fresh concrete.

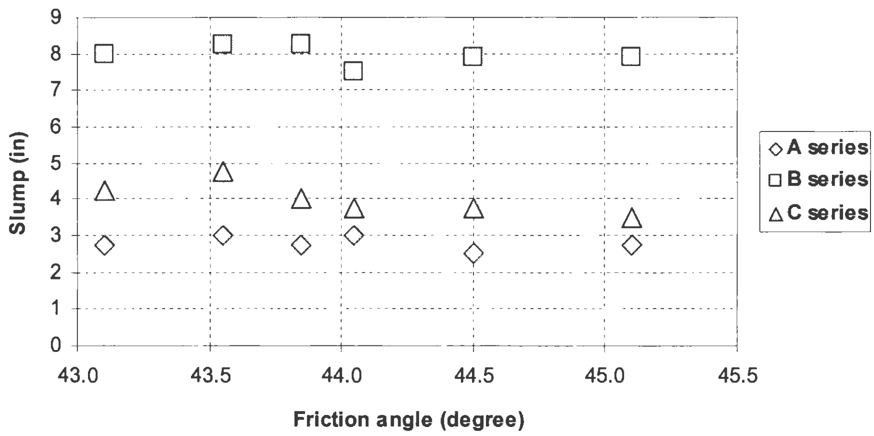


Figure C.2 Coarse aggregate friction angle vs. concrete compaction factor

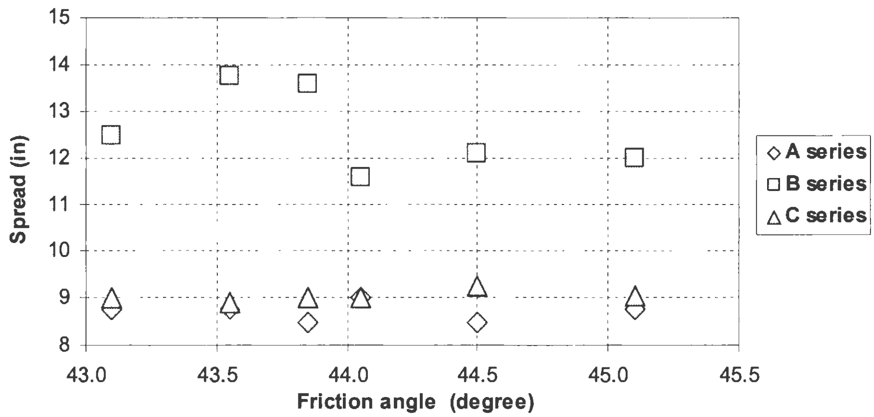


Figure C.3 Coarse aggregate friction angle vs. concrete compaction factor

APPENDIX D

IBB CONCRETE RHEOMETER TEST RESULTS

Table D.1 Concrete test results

Group	Mix proportion	Compaction Factor	I (Nm)	H (NmS)	Slump (in)	Spread (in)
1	A-G1	0.815	8.000	8.40	2.50	8.50
	A-G2	0.813	7.760	8.90	2.75	8.75
	A-G3	0.806	7.250	7.10	3.00	8.75
	A-G4	0.789	7.000	8.50	2.75	8.75
	A-G5	0.808	7.150	8.00	2.75	8.50
	A-G6	0.829	7.050	8.90	3.00	9.00
	B-G1	0.994	1.962	4.66	7.90	12.10
	B-G2	0.996	1.845	5.80	7.90	12.00
	B-G3	0.986	1.545	4.63	8.25	13.75
	B-G4	0.989	1.523	4.93	8.00	12.50
	B-G5	0.998	2.067	6.06	8.25	13.60
	B-G6	0.995	1.986	5.90	7.50	11.60
	C-G1	0.937	4.980	8.40	4.25	9.25
	C-G2	0.916	5.450	8.30	4.75	9.05
	C-G3	0.886	5.450	8.30	3.50	8.90
	C-G4	0.859	5.800	8.30	3.75	9.00
	C-G5	0.920	5.050	8.90	4.00	9.00
	C-G6	0.939	5.050	8.00	3.75	9.00
2	P-23	0.820	5.800	7.50	3.85	9.50
	P-27	0.850	4.930	6.08	4.00	9.50
	P-29	0.930	3.470	5.64	5.75	10.20
	P-30	0.935	3.140	4.87	6.95	10.20
3	FA-C-20	0.930	2.600	6.10	7.50	12.50
	FA-C-30	0.990	2.000	5.90	7.30	11.60
	FA-C-40	1.000	1.620	5.20	8.75	13.00
	FA-C-50	1.000	1.000	4.50	9.00	14.60
4	FA-F-20	0.850	4.270	7.62	5.00	9.250
	FA-F-30	0.885	3.620	7.79	6.50	10.25
	FA-F-40	0.900	3.390	7.50	6.50	10.56
	FA-F-50	0.980	3.050	7.30	7.00	11.00
5	SP-0.5	1.000	3.000	6.80	8.00	12.65
	SP-1.0	1.000	0.800	6.23	10.00	25.00
	SP-1.5	1.000	0.800	13.6	10.50	27.00
	SP-2.0	1.000	0.500	14.2	11.00	30.00

6	**VMA-0.2**	0.990	2.200	6.00	7.75	12.50
	VMA-0.3	0.990	2.400	6.25	7.75	12.25
	VMA-0.5	0.990	2.240	6.80	7.50	12.13
	VMA-0.67	0.990	3.000	7.00	7.25	12.75
7	**AG-0.2**	0.900	4.430	4.71	5.00	10.00
	AG-0.3	0.860	5.700	5.14	3.50	8.50
	AG-0.5	0.830	5.720	6.12	2.75	8.00
	AG-0.67	0.810	7.280	5.56	1.50	9.00
8	**G:L=1:3**	1.000	1.960	5.60	8.00	14.10
	G:L=1:1	1.000	1.760	4.79	8.50	13.50
	G:L=3:1	1.000	1.932	4.87	9.00	13.50
	G:L=1:0	1.000	1.975	4.29	9.00	14.00

Note:
H=Slope
I=Interception

APPENDIX E
EXCESS MORTAR AND ITS THICKNESS

The computation method for excess paste is based on the assumption of the two-phase flow theory (Oh et al., 1999a,b). The same concept can be applied on the calculation of excess mortar in concrete just simply replace the paste phase with mortar in Figure E.1 and E.2.

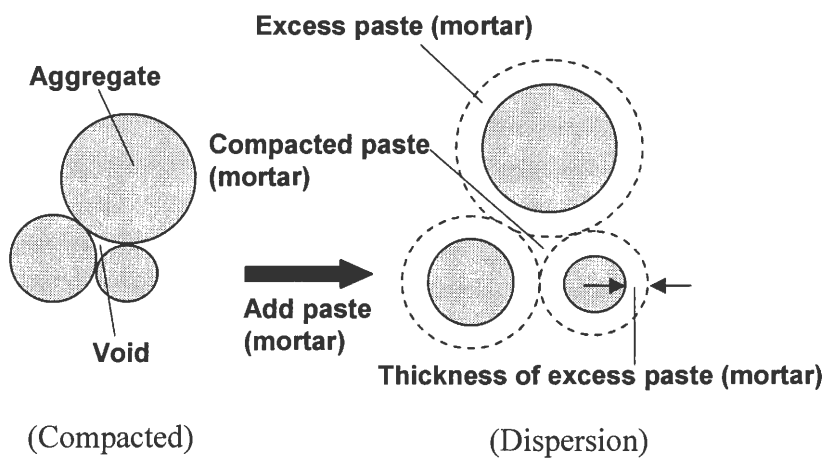


Figure E.1 Excess paste theory (Oh et al., 1999b)

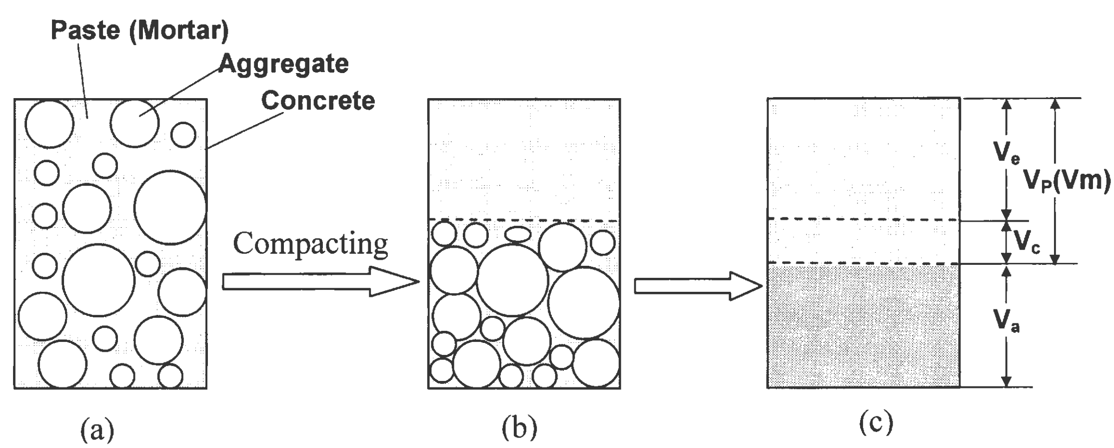


Figure E.2 Excess paste theory (Oh et al., 1999b)

The volume of the excess mortar can be obtained from total mortar volume and "compact" mortar volume

$$V_e = V_m - V_c \tag{E.1}$$

where V_e is excess mortar volume; V_m is total mortar volume; and V_c is "compact" mortar volume.

The total mortar volume (V_m) can be calculated from the weight of mortar based on the mix proportion.

$$V_m = W_m / \gamma_m \tag{E.2}$$

where γ_m is the density of mortar. It can be obtained from test or assumed to be a constant value of 2500kg/m^3 (Mindess et al., 2003).

The "compact" mortar volume (V_c) can be calculated from the compacted voids (ν_c) of coarse aggregates.

$$V_c = \frac{W_{CA}}{D_{CA}} \cdot \nu_C \tag{E.3}$$

where W_{CA} is weight of coarse aggregates, D_{CA} is compacted bulk density of coarse aggregates, as shown in Table 4.1.

In order to calculate the total surface area of coarse aggregate of graded coarse aggregates, one simplification was employed here to calculate the mean diameter of coarse aggregate particles for each sieve in ASTM C 33. The average of minimum and maximum sieve size was defined as the "mean diameter" for coarse aggregate particles in this sieve group, as shown in Table E.1.

Table E.1 Mean diameter for coarse aggregate particles

Nominal size, sieves with square openings (mm)	Mean diameter, D_{Mi} (mm)
19.00 ~ 25.00	$D_{Mi} = \frac{19.00 + 25.00}{2} = 22.000$
12.50 ~ 19.00	$D_{Mi} = \frac{19.00 + 12.50}{2} = 15.750$
9.50 ~ 12.50	$D_{Mi} = \frac{9.50 + 12.50}{2} = 11.000$
4.75 ~ 9.50	$D_{Mi} = \frac{9.50 + 4.75}{2} = 7.125$

Then the volume of each coarse aggregate particle for each sieve group can be simplified as the volume of a sphere with diameter value of D_M.

$$V_i = \frac{4}{3}\pi\left(\frac{D_M}{2}\right)^3 \tag{E.4}$$

The volume of coarse aggregate can be calculated from its weight and density.

$$V_{CAi} = \frac{W_{CAi}}{\gamma_{CA}} \tag{E.5}$$

where W_{CAi} is the weight of coarse aggregate, γ_{CA} is the density of coarse aggregate.

The number of coarse aggregate particles can be calculated from:

$$N_i = \frac{V_{CAi}}{V_i} \tag{E.6}$$

Then, the total particle number for graded coarse aggregate is:

$$N_{CA} = \sum_i N_i \tag{E.7}$$

The surface area for each spherical coarse aggregate particle with diameter of D_{Mi} is:

$$S_i = 4\pi\left(\frac{D_{Mi}}{2}\right)^2 \tag{E.8}$$

The total surface area of coarse aggregate particles is:

$$S_{all} = \sum_i S_i \times N_i \tag{E.9}$$

The thickness of excess mortar (t_p) can be calculated by dividing the volume of excess mortar (V_e) by the total surface area of the coarse aggregates (S_{all}).

$$t_p = \frac{V_e}{S_{all}} \tag{E.10}$$

The nominal Diameter (D_A) of the whole coarse aggregate particles can be obtained from:

$$V_{CA} = \sum_i V_{CAi} = \frac{4}{3}\pi\left(\frac{D_A}{2}\right)^3 \times N_{CA} \tag{E.11}$$

where V_{CA} is the total volume of coarse aggregates, N_{CA} is the total particle number for graded coarse aggregate.

Then,

$$D_A = 2 \times \left[\frac{\sum_i V_{CAi}}{\left(\frac{4}{3}\cdot\pi\right)\cdot\sum_i N_i} \right]^{1/3} \tag{E.12}$$

Then the relative thickness of excess mortar is

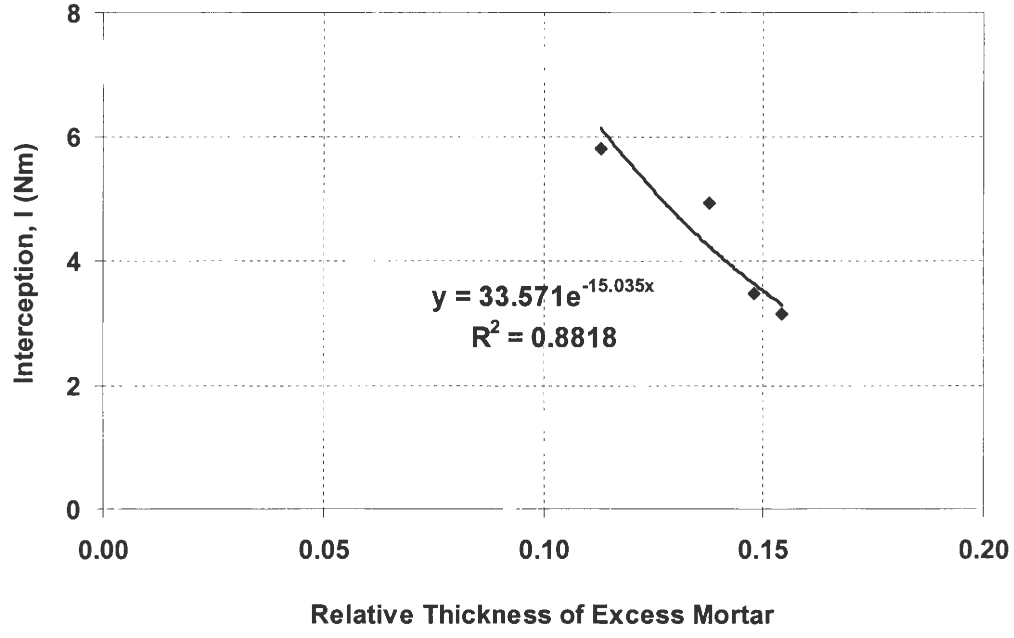
$$\Gamma = \frac{t_p}{D_A} \tag{E.13}$$

The results of the thickness and relative thickness of excess paste for this study is shown in Table E.2.

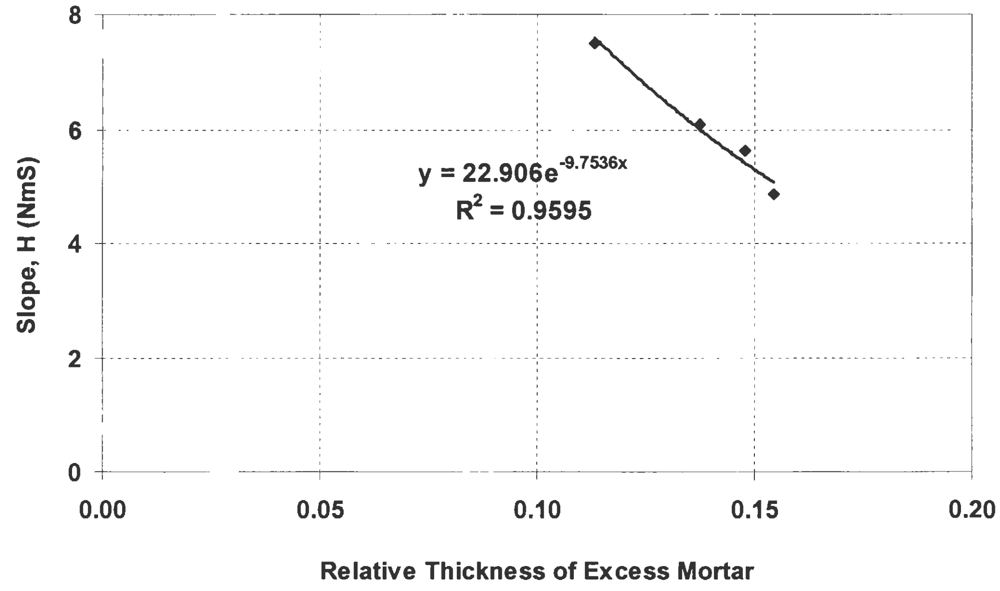
Table E.2 Mean diameter for coarse aggregate particles

Number	**Excess paste thickness, t_p (mm)**	**Relative thickness, Γ**
P-23	1.135	0.1132
P-27	1.379	0.1375
P-29	1.483	0.1479
P-30	1.548	0.1543

The relationship between relative thickness of excess mortar and rheology parameters were shown in Figure E.3.



(a) Γ vs. interception



(b) Γ vs. slope

Figure E.3 Relative thickness of excess mortar and rheology properties