SELF-COMPACTING CONCRETE WITH HIGH VOLUMES OF FLY ASH

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ABSTRACT

SELF-COMPACTING CONCRETE WITH HIGH VOLUMES OF FLY ASH

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Self-compacting or self-consolidating concrete (SCC) is considered as a concrete that can flow under its own weight to completely fill the formwork and self-consolidate without any mechanical vibration. SCC was initially developed in Japan around mid 1980's to overcome the difficulties of placing concrete in the highly congested reinforced concrete structures. Although SCC is widely used in developed countries, use of SCC in Turkey is very limited. Among its numerous advantages, the most important advantage of SCC over conventional concrete is its perfect flowability; others include: shorter construction period, reduction of the labor cost, better compaction in the structure, especially in confined zones where vibrating compaction is difficult.

Concrete requiring a high slump can easily be achieved by superplasticizer addition to a concrete mixture. However, for such concrete to remain cohesive during handling operations, special attention has to be paid to mixture

proportioning. Previous investigations show that the use of mineral admixtures in SCC reduces the dosage of superplasticizer besides the improvement in its durability.

The objective of this study is to assess the effects of high volumes of high-lime and low-lime fly ash replacements on the fresh and hardened properties of SCCs.

In this investigation, SCCs were prepared by keeping the total mass of cementitious materials (cement and fly ash) constant at 500 kg/m^3, in which 30, 40, 50, 60, and 70% of cement, by weight, was replaced by the high-lime and low-lime fly ash. For comparison, a control SCC mixture without any fly ash was also produced. The fresh properties of the SCCs were observed through, slump flow time and diameter, V-funnel flow time, L-box height ratio, U-box height difference, segregation ratio and the rheological parameters (relative yield stress and relative plastic viscosity). Relations between workability and rheological parameters were sought. Setting times and temperature rise of the SCC were also determined. The hardened properties included the compressive strength, split tensile strength, drying shrinkage and permeation properties (absorption, sorptivity and rapid chloride permeability tests) up to 360 days.

The results obtained indicated that it is possible to produce SCC with a 70% of cement replacement by both types of fly ash. The use of high volumes of fly ash in SCC not only improved the workability and permeability properties but also made it possible to produce concretes between 33-40 MPa compressive strength at 28 days.

Keywords: High Volume Fly Ash, Permeability, Rheology, Self Compacting Concrete.

ÖZ

YÜKSEK HACİMDE UÇUCU KÜL İÇEREN KENDİLİĞİNDEN YERLEŞEN BETON

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Ocak 2006, 109 sayfa

Kendiliğinden yerleşen beton (KYB) veya kendiliğinden sıkışan beton (KSB) kendi ağırlığı altında vibrasyon gerektirmeden yerleşen ve sıkışan beton olarak tanımlanmaktadır. İlk olarak KYB'nin üretiminin 1980'lerin ikinci yarısında Japonya'da geliştirilmesi, yoğun donatılı betonarme elemanlarında sıkıştırma işlemine gerek duyulmadan yerleştirilebilen bir betona olan gereksinimden kaynaklanmıştır. Ancak son yıllarda gelişmiş ülkelerde KYB kullanımının oldukça yaygınlaşmasına rağmen, Türkiye'deki uygulamaları oldukça sınırlıdır. KYB'nin geleneksel betona göre en önemli avantajı mükemmel akıcılığıdır. Bunun yanında, KYB'nin diğer avantajları: yapım süresini kısaltması, işçilik maliyetini düşürmesi ve özellikle yoğun donatılı betonarme elemanlarda betonun kalıba boşluksuz bir şekilde yerleşmesinin sağlanması olarak sıralanabilir.

Betonda yüksek işlenebilirlik süperakışkanlaştırıcı katkıların karışıma ilave edilmesi ile kolayca sağlanabilir. Fakat, bu tür betonlarda, taşıma ve yerleştirme sırasında ayrışmayı engellemek amacıyla karışım tasarımına özen göstermek gereklidir. Daha önceki çalışmalarda, KYB üretiminde mineral katkıların kullanılması, betonun aynı işlenebilirlik seviyesinde, daha az süperakışkanlaştırıcı kullanılmasına yol açtığı ve betonun dayanıklılığını iyileştirdiği gösterilmiştir.

Bu çalışmanın amacı, yüksek hacimde düşük ve yüksek kireçli uçucu külün, KYB'lerin taze ve sertleşmiş özellikleri üzerindeki etkilerini incelemektir.

Bu araştırmada KYB karışımlarındaki toplam bağlayıcı malzeme (çimento ve uçucu kül) miktarı 500 kg /m^3 olarak sabit alınıp, toplam bağlayıcı malzemenin ağırlıkça %30, 40, 50, 60 ve 70'i kadar düşük kireçli ve yüksek kireçli uçucu kül değişimine gidilmiştir. Karşılaştırma amaçlı, sadece çimento ile üretilen kontrol karışımı da hazırlanmıştır. KYB'nin taze özellikleri yayılma süresi ve çapı, V-hunisi akma süresi, L-kutusu yükseklik oranı, U-kutusu yükseklik farkı, segregasyon oranı ve reolojik parametreler (göreli akma dayanımı ve plastik viskosite) üzerinden gözlemlenmiştir. İşlenebilirlik ve reolojik parametreler arasında ilişkiler aranmıştır. Ayrıca, KYB'nin priz zamanları ve sıcaklık artışları da belirlenmiştir. Sertleşmiş betonun özellikleri 360 güne kadar basınç dayanımı, yarmada çekme dayanımı ve kuruma büzülmesi testleriyle ve geçirimlilik özellikleri ise su emme, kılcal geçirimlilik ve hızlı klor geçirimliliği testleriyle değerlendirilmiştir.

Elde edilen sonuçlar ışığında, %70 uçucu kül (düşük kireçli ve yüksek kireçli) değişimi ile KYB üretiminin mümkün olduğu görülmüştür. KYB üretiminde yüksek hacimde uçucu kül kullanılması sonucunda, 28 gün sonunda normal dayanıma sahip (33-40 MPa), taze halde işlenebilirliğin (özellikle düşük kireçli

uçucu kül ile) sertleşmiş halde ise geçirgenliğin kontrol karışımına göre daha iyi değerlere ulaştığı sonucuna varılmıştır.

Anahtar Kelimeler: Yüksek Hacimde Uçucu Kül, Geçirgenlik, Reoloji, Kendiliğinden Yerleşen Beton.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ASTM	: American Society for Testing and Materials
CANMET	: Canada Center for Mineral and Energy Technology
CSA	: Canadian Standards Association
EFNARC	: European Federation of National Trade Association
FA	: Fly Ash
FA_H	: High-Lime Fly Ash
FA_L	: Low-Lime Fly Ash
HVFA	: High-Volume Fly Ash
LFA	: Lignite Fly Ash
LP	: Limestone Powder
MAS	: Maximum Aggregate Size
NIST	: National Institute of Standards and Technology
PC	: Portland Cement
RCPT	: Rapid Chloride Permeability Test
SCC	: Self Compacting Concrete
SEM	: Scanning Electron Microscope
SP	: Superplasticizer
VMA	: Viscosity Modifying Admixture
W/CM	: Water-Cementitious Material Ratio
W/P	: Water-Powder Ratio
UFFA	: Ultra Fine Fly Ash
UPV	: Ultrasonic Pulse Velocity
XRD	: X-Ray Diffraction

CHAPTER 1

INTRODUCTION

1.1 General

Self compacting concrete (SCC) is a concrete which has little resistance to flow so that it can be placed and compacted under its own weight with little or no vibration effort, yet possesses enough viscosity to be handled without segregation or bleeding [Şahmaran et. al., 2005]. The most important advantage of SCC over conventional concrete is its perfect flowability. There are also many other advantages of using SCC. These include: shorter construction periods, reduction in the labor cost, and better compaction in the structure especially in confined zones where compaction is difficult. SCC is one of the latest achievements of concrete technology, and it has been first introduced by Japanese researchers with an intend to increase the durability of reinforced concrete structures. However, its superior workability properties were soon realized and started to be called as a high performance concrete, in the concrete technology literature. After its first introduction in the second half of 1980's, it has been used satisfactorily in bridges, silos, tunnels, pre-cast concrete production and etc., all around the world [Ouchi, 2001; Bennenk 2001].

The common practice to obtain self-compactibility in SCC is to use new generation superplasticizers, to limit the maximum coarse aggregate size and content, and to use low water-powder ratios or use viscosity modifying admixtures. Therefore, one of the disadvantages of SCC is its cost, associated with the use of chemical admixtures and use of high volumes of portland cement. One solution to reduce the cost of SCC is the use of mineral admixtures such as limestone powder, natural pozzolans, and fly ash (FA). Among these mineral admixtures, FA is a finely divided residue of the very fine ash resulting as a by-product from the combustion of powdered coal in power plants. Previous investigations show that the use of FA in concrete reduces the dosage of superplasticizer and improves the mechanical properties and durability of concrete [Bilodeau, 1994]. In several studies, portland cement is partially replaced with FA usually in the range of 20 to 40% to produce economical SCC [Bouzoubaa and Lachemi 2001; Yahia et. al., 1999; Kurita and Nomura, 1998; Kim et. al., 1996; Leemann and Hoffmann, 2005].

The amount of fly ash in concrete for structural use is generally limited to 15 to 25% of the total cementitious materials. Concretes having large amounts of FA (usually above 50%) are termed as high-volume fly ash (HVFA) concrete. HVFA concrete was initially developed for mass concrete applications to reduce the heat of hydration [Bilodeau and Malhotra, 2000]. Canada Centre for Mineral and Energy Technology (CANMET) first developed high volume fly ash concrete for structural use by the late 1980's [Malhotra, 1986]. In a study undertaken by Bouzoubaâ and Lachemi, it was shown that it was possible to design SCC with high volumes of fly ash by replacing up to 60% of cement with Class F fly ash [Bouzoubaa and Lachemi, 2001]. Moreover, Nehdi et. al. also studied the durability of SCC with high volume replacement materials (fly ash and ground granulated blast furnace slag), and concluded that SCC with 50% replacement with portland cement of fly ash and slag can improve the workability and durability [Nehdi at. al., 2004].

1.2 Research Objectives and Scope

The objective of this study was to determine the effects of high volumes of high-lime and low-lime fly ash replacement both on the fresh and hardened properties of SCC. The workability properties of SCCs were observed through, slump flow time and diameter, V-funnel flow time, L-box height ratio, U-box height difference and segregation ratio. The rheological parameters, relative yield stress and relative plastic viscosity, were also determined. Other fresh properties that were determined included the initial and final setting times and temperature rise of the SCC. Later, hardened properties were evaluated by compressive strength, split tensile strength and drying shrinkage and the permeation properties were evaluated by absorption, sorptivity and rapid chloride permeability tests.

Within the scope of the experimental test program, eleven SCC mixtures were prepared. As a binder one of the control mixture included only portland cement. Remaining mixtures had high-lime and low-lime fly ashes replacing from 30% to 70 % by weight of PC. For all the mixtures, the total amount of cementitious material (cement + fly ash) and the amount of superplasticizer were kept constant. Water was added to the mixture until the SCC characteristics were observed.

In chapter 2, properties of fresh SCC, rheology of concrete, and effect of fly ash on fresh and hardened properties of concrete are discussed. In chapter 3, experimental program, materials properties and tests on fresh and hardened properties of SCC are discussed. The results of the experimental studies are presented and discussed in Chapter 4. The correlation between the rheological parameters and fresh properties of SCC is discussed. The correlation between permeability tests is also discussed in that chapter. The conclusions of the research and recommendations for further studies are presented in Chapter 5.

CHAPTER 2

LITERATURE REVIEW AND BACKGROUND

2.1 Introduction

Self compacting concrete (SCC) is a relatively new concrete technology; therefore standards describing its requirements have not yet been established. The only available guideline is published by EFNARC (European Federation of National Trade Associations), a European federation dedicated to special construction chemicals and concrete systems [EFNARC, 2002]. In this guideline, the three workability requirements of SCC are listed as its filling ability, passing ability and segregation resistance.

- Filling ability is the ability of SCC to flow into all spaces within the formwork under its own weight.
- Passing ability is the ability of SCC to flow through congested sections such as spaces between steel reinforcing bars, under its own weight.
- Segregation resistance is the ability of SCC to stay uniform during and after casting.

Just like conventional concretes, a single test method that can measure and quantify all the abovementioned workability requirements of SCC does not exist. Therefore a list of test methods is described in that guideline to determine

the workability properties of SCC. Among these slump flow, V-funnel, L-box, U-box, and GTM sieve stability test are the most widely accepted and used tests. All these tests are empirical but quantitative test procedures to assess the workability properties of SCC.

To achieve these workability requirements, Okamura and Ouchi suggested a SCC mixture design procedure focusing on three essential aspects [Okamura and Ouchi, 2003]:

- Reduce the coarse aggregate content in order to reduce the friction, or the frequency of collision between them,
- Increase the paste content to further increase fluidity,
- Manage the paste viscosity to reduce the risk of aggregate blocking.

Different approaches have also been used by other researchers. One such method considers SCC to be composed of two constituents; coarse aggregates and mortar. The rheology of mortar is then adjusted to achieve SCC with the incorporation of superplasticizer (SP) and viscosity modifying admixture (VMA) [Saak et. al., 2001]. Therefore, the rheology of paste and mortar is an important property, characterizing the flow behavior of SCC.

The rheological properties of fluid-like materials, such as pastes and even mortars could be determined by conventional rheometers. However, when high volumes of coarser solids are introduced into a liquid medium, determining the rheological properties could be quite difficult. However, some researchers have developed concrete rheometers to assess the workability of SCC [Banfill et. al., 2001].

2.2 Rheology of Concrete

Characteristic phenomena of liquid and gas to immediately deform when subjected to small shearing stresses is called “flow”. The study of flow process that deals with relations between stress, strain and their time dependent derivative is called “rheology” [Ozawa et. al., 1989]. In practice, rheology is concerned with materials whose flow properties are more complicated than those of a simple fluid (liquid or gas) or an ideal elastic solid [Tattersall and Banfill, 1983; Ferraris, 1999]. The rheological (flow) properties of concrete are important for the construction industry because concrete is usually put into place in its plastic state.

Concrete and mortar are considered as composite materials, with aggregates, cement, and water as the main components. In its fresh state, concrete can be considered as a concentrated suspension of solid particles (aggregates) in a viscous liquid (cement paste). However, cement paste is not actually a homogeneous fluid and is itself composed of particles (cement grains) in a liquid (water).

Generally, for fluids the flow behavior is classified into two: Newtonian fluid and non-Newtonian fluid. For a Newtonian fluid, the shear stress divided by the rate of shear is constant and called the coefficient of viscosity (μ) which is a physical characteristic of the material (Figure 2.1). In a non-Newtonian fluid, when the shear rate is varied, the shear stress does not vary with the same proportion and the viscosity of a non-Newtonian fluid changes as the shear rate varies [Ferraris, 1999].

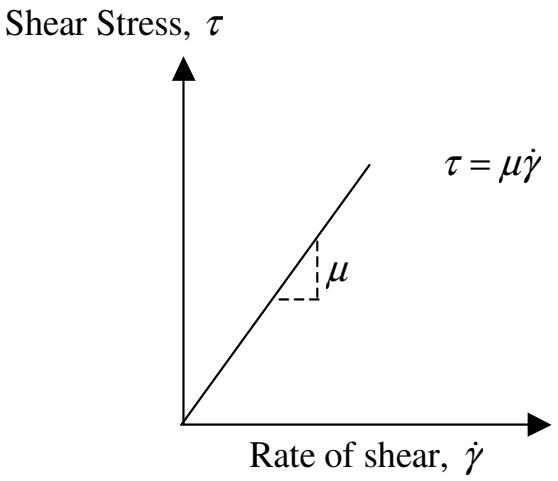


Figure 2.1 Newtonian fluid

Paste, mortar, and concrete are often considered as non-Newtonian fluids [Ferraris, 1999; Ferraris et. al., 2001]. The rheology of fresh concrete is most often described by the Bingham model (Figure 2.2). In this model the flow curve has an intercept on the stress axis, indicating a minimum stress which is required to start the flow [Tattersall and Banfill, 1983]. According to this model, fresh concrete must overcome a limiting stress (yield stress, τ_0) before it can flow. Once fresh concrete starts to flow, shear stress will increase linearly with an increase in strain rate as defined by plastic viscosity. The plastic viscosity is a measure of the ease of flow, once the yield stress is overcome. Therefore, in order to fully describe the rheological properties of fresh concrete by Bingham model, two parameters, namely the plastic viscosity and the yield stress are necessary [Ozawa et. al., 1989].

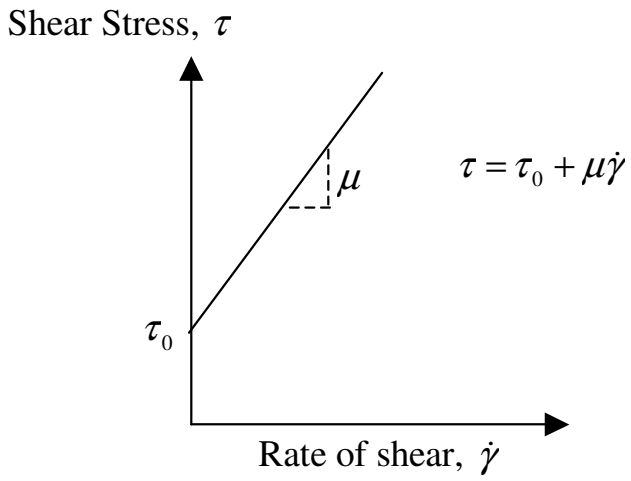
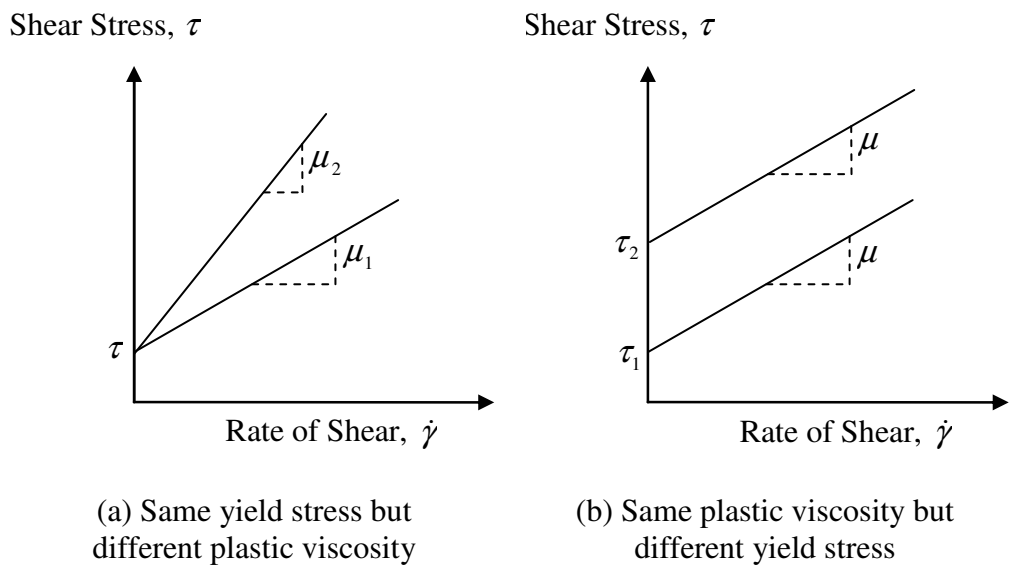


Figure 2.2 Bingham model

The lower the yield stress, the lesser is the resistance of concrete to start flowing. In addition, a higher viscosity prevents segregation but provides high resistance to the flow of concrete. It is important for a SCC to have a lower yield stress and a moderate viscosity to ensure better flow and segregation properties [Saak et. al., 2001; Lacombe et. al., 1999]. Most of the widely used workability tests are unsatisfactory in characterizing the flow behavior of concrete as they measure only one parameter. Figure 2.3 shows how two concretes with one identical parameter will have very different flow behaviors. Therefore, it is important to use a test that will describe the concrete flow, by measuring more than one parameter [Ferraris, 1999].



(a) Same yield stress but different plastic viscosity

(b) Same plastic viscosity but different yield stress

Figure 2.3 Concrete rheology [Ferraris, 1999]

The rheological properties of fresh concrete are determined by the so-called rheometers, which measure the shear stress at varying shear rates. Unfortunately the inherent properties of concrete make it impossible to use the rheometers designed for neat fluids without any solid particles. Even though this is the case, there are several commercially available rheometers specially designed for concrete. In a comprehensive study performed by National Institute of Standards (NIST), five of these rheometers were tested comparatively with the aim of comparing the measurements to provide data to establish correlations among them [Banfill et. al., 2001]. All the rheometers were based on different principles and could be grouped as follows:

BML and CEMAGREF-IMG: The CEMAGREF-IMG and the BML were coaxial cylinder rheometers in which one cylinder (inner cylinder for the CEMAGREF-IMG and outer for the BML) was rotated at increasing and decreasing speed and the torque induced by the concrete on the inner cylinder was measured.

BTRHEOM: The BTRHEOM was a parallel plate rheometer. The concrete was placed in a cylindrical container with a fixed bottom plate. A top plate embedded in the concrete was rotated at increasing and then decreasing speeds and the torque was measured.

IBB, Two-Point: The IBB and Two-Point rheometers were based on rotating an impeller in fresh concrete contained within a cylindrical vessel. The speed of rotation of the blade was increased and then decreased while the concrete resistance or torque was measured.

As the flow pattern of the concrete could be mathematically modeled for the coaxial rheometers (BML, CEMAGREF-IMG) and for the parallel-plate rheometer (BTRHEOM), for these three rheometers rheological characteristics in fundamental units were calculated. The Two-Point test rheometer required indirect methods using calibrating fluids of known viscosity to convert quantitative data into the fundamental units needed. On the other hand, the IBB was not calibrated with a fluid and therefore, the results were not reported in fundamental units. The rheological properties of twelve concrete mixtures with slumps ranging from 90 mm to 235 mm were determined using these five rheometers. It was found that the rheometers resulted in different values of Bingham constants of yield stress and plastic viscosity. However, it was also found that all mixtures were ranked statistically in the same order for both Bingham constants. It was finally concluded that a wider range of mixtures including SCC should be studied in order to address the issues such as slip at the concrete/wall interface, or confinement of concrete between moving parts of the rheometers [Banfill et. al., 2001]. Generally, a consensus on the rheological properties of concrete mixtures as determined by the commercially available rheometers does not exist even for conventional concretes.

2.3 Workability Requirements of SCC

A successful SCC should fill congested structural sections and restricted elements by flowing around various obstructions under its own weight without exhibiting segregation. Basic workability requirements of a successful SCC are summarized by Khayat as shown in Figure 2.4. These requirements can be obtained by tailoring the concrete mixture to insure good balance between deformability, stability and risk of blockage.

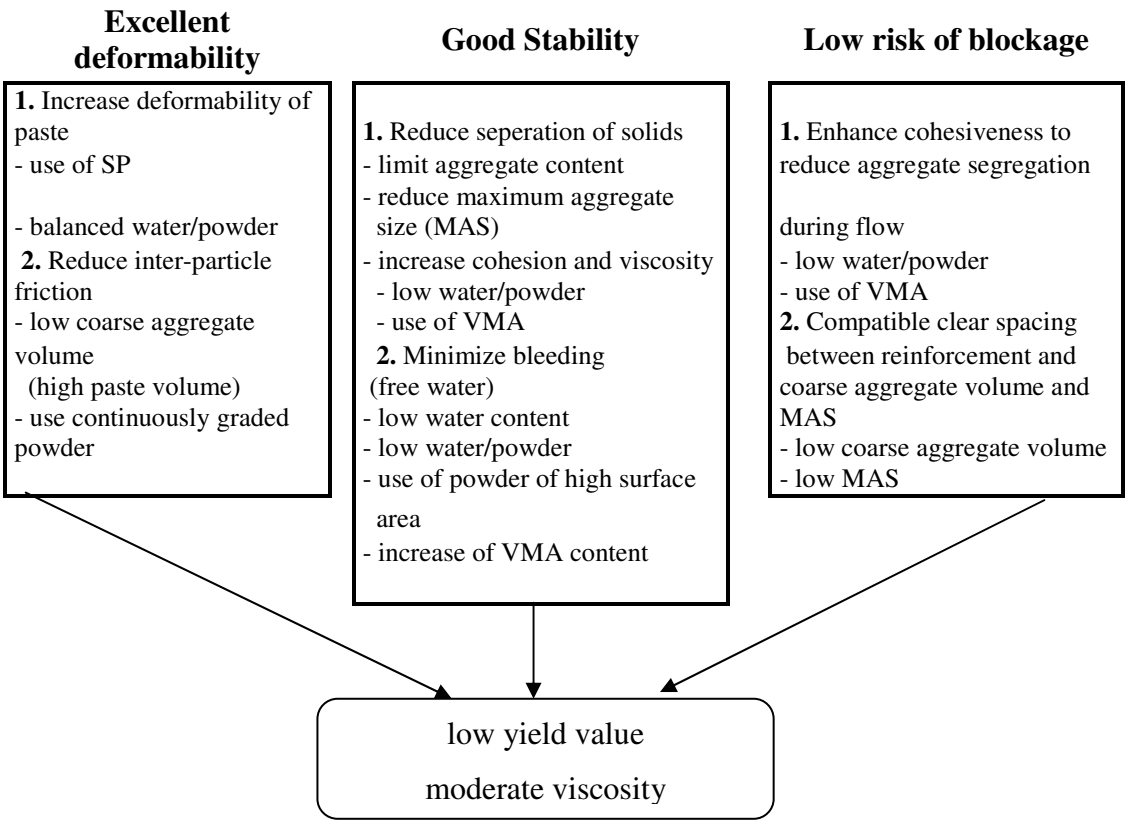


Figure 2.4 Workability requirements for successful casting of SCC [Khayat 1999]

2.3.1 Excellent deformability

Deformability of fresh concrete is defined as the ability of concrete to undergo a change in its shape under its own weight, even in the vicinity of obstacles that can interfere with its flow [Khayat, 1999]. Maximum deformability refers to the maximum flow value, while speed of deformability takes into account the rate of deformation. For example, a highly viscous concrete designed for underwater placement can attain a slump flow of 570 mm (high deformability) after 15 sec., compared with SCC proportioned with a higher water content to fill a restricted section that can attain the same deformability after only 5 sec. (high deformability speed) [Khayat, 1999]. These flow notions are, of course, related to the yield value and the viscosity of the concrete.

As shown in Figure 2.4, it is important to insure both high flowability (low-yield stress) and high resistance to segregation (moderate viscosity) to secure an SCC that can flow readily around various obstacles and achieve good filling capacity. The deformability of concrete is closely related to that of the cement paste which increases with the incorporation of superplasticizers (SP) [Khayat, 1999]. Unlike water addition that reduces both the yield stress and viscosity, incorporation of SP lowers mostly the yield stress, and results in a limited drop in viscosity. The effect of SP on Bingham constants was studied earlier by Golasweski and Swabowski (2004). In their study, the water to powder ratio of a paste was maintained at 0.36 with various combinations of Portland cement and limestone powder. The dosage of SP was expressed as percentage of total powder content. As seen from Table 2.1, it is clear that yield stress decreases drastically as the SP dosage is increased. However, the effect on viscosity is relatively small [Golasweski and Swabowski, 2004]. Therefore, it can be concluded that using SPs, a highly flowable concrete can be obtained without a significant reduction in cohesiveness.

A reduction in the water – powder ratio (W/P) can also limit the deformability of the cement paste. Here, the term powder refers to the cement and mineral admixtures (fly ash, silica fume, natural pozzolan, limestone powder, etc.). An increase in W/P ratio can secure high deformability; however, it can also reduce the cohesiveness of the paste and mortar leading to segregation of fine and coarse aggregate particles, and can cause blockage of the flow [Khayat, 1999]. Therefore, a balance is needed when increasing the W/P ratio to enhance the deformability without a substantial reduction in cohesiveness.

Table 2.1 Bingham constant for pastes with W/P of 0.36

Powder (%)		SP	Yield Stress	Plastic Viscosity
Cement	Limestone	(%)	(Pa)	(Pa.s)
65	35	0.10	33.4	0.26
		0.20	10.8	0.21
		0.30	1.4	0.17
55	45	0.10	23.3	0.22
		0.20	10.2	0.21
		0.30	4.3	0.19
45	55	0.10	12.8	0.20
		0.20	6.3	0.18
		0.30	2.6	0.16

Another important parameter that affects deformability is the interparticle friction between the solids in the mixture (coarse aggregate, sand, and powder materials). Such solid-to-solid friction increases the internal resistance to flow, thus limiting the deformability and speed of flow of fresh concrete [Okamura and Ouchi, 2003]. The extent of interparticle friction increases when the concrete flows through restricted spacing because of the greater collision between these solids. The use of SP can disperse cement grains and reduce

interparticle friction, and enable a reduction in water content while maintaining the required levels of flowability and viscosity [Khayat, 1999].

Reducing the coarse and fine aggregate volumes and increasing the paste volume are also essential in improving the deformability. The incorporation of cementitious materials and fillers can also reduce interparticle friction. It is important to note that the selection of proper combinations of binary or ternary binders, i.e. cementitious materials, should take into account the effects of such binders on the adsorption of water and admixtures, on the workability loss and temperature rise, as well as on the development of engineering properties and durability of SCC mixtures. It is important to minimize fluidity loss until the end of casting since loss in deformability can substantially limit the filling capacity and self compactibility of the concrete.

2.3.2 Good stability

Another primary parameter necessary to provide self compacting properties is the stability, i.e., the resistance to segregation and bleeding of concrete. It is important to note that a highly flowable concrete that exhibits adequate stability while pouring may undergo some segregation during a pumping operation. This is because of the fact that the apparent viscosity at such shear rates can be significantly lower than that at rest due to the pseudo-plastic nature of concrete [Khayat, 1999]. Such shear rates can be high locally as the concrete flows around various obstacles. Therefore, when the concrete flows through restricted areas, such as between closely spaced reinforcement, it is important to insure that it has sufficient viscosity to maintain uniform suspension of solid particles. As concrete deforms around a restricted section, a portion of the coarse aggregate can begin to segregate, which can result in an increase in aggregate density leading to coagulation and arching of the aggregate, and hence blockage of the flow [Nanayakkara et. al. 1988, Ozawa et. al. 1989,

Ozawa et. al. 1992]. As shown in Figure 2.4, enhancement of stability involves reduction in coarse aggregate content and lowering the maximum aggregate size (MAS). It is also important to increase the cohesion of the mix to enhance the bond between the mortar and the coarse aggregate, hence to insure uniform flow of both phases.

In addition to provide adequate stability during placement, the concrete should also have proper stability, after its cast till it hardens. This will minimize the migration of free water towards the surface (bleeding) and segregation of suspended solid particles [Khayat, 1999]. This is important to secure homogeneous properties of the hardened concrete. The lack of stability can weaken the interface between the aggregate and cement paste, and increase the tendency to develop local microcracking that can increase permeability and reduce mechanical properties. Bleeding can also result in the accumulation of porous cement paste under the lower half of horizontally embedded reinforcement and under the ribs of vertically positioned bars. The surface settlement of fresh concrete, which is related to the segregation of concrete, can reduce the effective protection of concrete reinforcement and further contribute to the reduction in bond strength [Khayat, 1998]. Insuring adequate stability is especially critical in deep structural elements where highly flowable concrete can exhibit segregation, bleeding, and surface settlement that reduce strength, stiffness, bond to reinforcing steel, and durability. The decrease of bleeding can involve the reduction of water content through the reduction of W/P ratio and incorporation of SP, and use of VMA and/or high volume of cementitious materials and fillers to bind some of the free water [Khayat, 1999].

2.3.3 Low risk of blockage

The third property essential to enhancing self compaction is a reduction in the risk of blockage resulting from the flow in narrow spaces. The risk of blockage

can be reduced by providing adequate viscosity, by insuring good suspension of solid particles during flow which can then reduce interparticle friction and limit deformability and the ability to properly fill the formwork [Khayat, 1999]. To prevent blockage of concrete flow among closely spaced obstacles, concrete should have adequate cohesiveness by reducing the W/P ratio and/or incorporating an adequate dosage of a viscosity modifying admixture (VMA). As the clear spacing between the obstacles in the congested section decreases, the coarse aggregate volume and MAS should be reduced to limit interparticle collision in the vicinity of reinforcement and hence the risk of blockage.

2.4 Use of Mineral Admixtures in Concrete

Mineral admixtures are finely divided solids which are added to concrete to improve its workability, strength, durability, economy, and to control the rate of hydration. Mineral admixtures can be grouped into two: pozzolans and fillers. A pozzolan is a siliceous or aluminosiliceous material, which in itself possesses little or no cementitious value but will, in finely divided form and in presence of moisture, chemically reacts with the calcium hydroxide released by the hydration of portland cement to form compounds possessing cementitious properties [ASTM C 125]. Natural pozzolans, and artificial pozzolans such as fly ash, silica fume and ground granulated blast furnace slag are examples of such mineral admixtures [Erdoğan, 1997]. Fillers, however, do not have pozzolanic properties and are assumed as inert materials.

Mineral admixtures can either be used as a separate ingredient or used as a replacement to portland cement [Mindess et. al. 2003]. In either case they constitute part of the total cementitious system, and an optimum amount should be used in order not to cause any harmful effects [Kosmatka et. al., 2002].

Mineral admixtures such as limestone powder (LP), natural pozzolans, and fly ash (FA) are often used to increase the viscosity and to reduce the cost of SCC. Among these materials FA has been reported to improve the mechanical properties and durability of concrete when used as a cement replacement material [Bilodeau et. al., 1994].

2.5 Use of Fly Ash in Concrete

Fly ash is a finely divided residue of the very fine ash obtained as a by product from the combustion of powdered coal in power plants. The fly ash particles are typically spherical, ranging in diameter from less than 1 µm up to 150 µm. The fineness of fly ash (determined using the Blaine apparatus) is typically in the range of 250 to 600 m^2/kg [Neville, 1995]. The type of dust collection equipment determines the range of particle sizes in a particular fly ash. The fineness of fly ash affects its pozzolanic properties and the workability of concrete by reducing the water demand. Fly ash consisting of clean, glassy, spherical particles are able to reduce water requirement [Mehta, 1983]. The specific gravity of fly ash generally ranges between 1.9 and 2.8 and the color is generally gray or tan [Halstead, 1986].

According to American Society for Testing and Materials (ASTM), there are two classes of fly ash (Table 2.2): Class C, which is normally produced from lignite or subbituminous coals and Class F, which is normally produced from bituminous coals [ASTM C 618]. Class C fly ashes differ from Class F fly ashes in that they are self-hardening even without the presence of cement.

Table 2.2 Specifications for fly ash [ASTM C 618]

Class of Ash	ASTM Specification
Class C	$SiO_2 + Al_2O_3 + Fe_2O_3 > 50\%$
Class F	$SiO_2 + Al_2O_3 + Fe_2O_3 > 70\%$

According to Canadian Standards Association CSA A23.5, it is proposed to have three categories of fly ash characterized as low, intermediate, or high calcium content (Table 2.3). The main purpose of classifying fly ashes for use in concrete is to distinguish between ashes that have different effects on the properties of fresh and hardened concrete.

Table 2.3 Specifications for fly ash [CAN/CSA A23.5]

Class of Ash	% CaO
F	<8
CI	8-20
CH	>20

2.5.1 Effects of fly ash on the fresh properties of concrete

Generally, it may be expected that, for the same water-powder (W/P) ratio, increasing the volume of fine particles such as fly ash will result in a reduction in the workability of concrete. The reason is the increase in water demand due to an increase in the surface area of particles. However, it is also well known that the shape of fly ash is also an important factor for the workability characteristic of concrete. For example it is reported that for the same workability the round and spherical geometry of fly ash particles generally help to decrease the water requirement of a concrete mixture [Erdoğan, 1997; Kurita et. al., 1998].

In a study conducted by Ferraris et. al. [2001], the effect of fly ash on the rheological properties of cement paste was studied. In that study four types of fly ash with mean particle sizes of 18 μm, 10.9 μm, 5.7 μm and 3.1 μm were used. The fly-ash with a mean particle size 3.1 μm was termed as ultra fine fly

ash (UFFA). It was concluded that replacement of cement with UFFA leads to a decrease in the high range water reducer dosage at a given yield stress and viscosity. The fine particles of fly ash, generally improved the workability and flowability by reducing the size and volume of voids, thus requiring less water to produce a concrete of given consistency.

Experiments carried out by Ozawa et. al. [1989] focused on the influence of mineral admixture, like fly ash, on the flowing ability and segregation resistance of self compacting concrete. They found out that the flowing ability of the concrete improved remarkably when portland cement was partially replaced with fly ash. After trying different proportions of mineral admixtures, they concluded that 10-20% of fly ash by mass of the cementitious materials showed the best flowing ability and strength characteristics. Fly ash was also reported to reduce the bleeding process in concrete, hence improved the bond between aggregate and matrix [Dhir et. al., 1982].

Dietz and Ma [2000] in their research, showed a possible application of lignite fly ash (LFA) for the production of SCC. The lignite fly ash having some characteristics of potential hydraulic materials, improved the rheological properties of the fresh concrete because of its fineness, which is a primary advantage for SCC. Self-compacting concrete with lignite fly ash showed a good flowing ability and high self-compactability. It was discovered that, if 10% to 25% of cement is replaced by LFA, the water requirement will be reduced. This is favorable for the workability of the fresh concrete. The reduced water requirement indicated that the grains of the cement - LFA mixture were more densely compacted. The volume between the particles, which should be filled with water, became smaller due to the denser packing. Furthermore, the spherical LFA particles favorably affected the workability of the mixture.

In a study undertaken by Bouzoubaâ and Lachemi [2001], it is possible to design SCC with high volumes of Class F fly ash by replacing up to 60% of cement with Class F fly ash. In that study, incorporating high volumes of Class F fly ash confirmed that the dosage of superplasticizer decreased with an increase in the percentage of fly ash to achieve the desired workability.

Şahmaran and Yaman [2005] developed a hybrid fiber reinforced SCC with a high volume coarse fly ash (50% of fly ash replacement). The FA had a relatively low specific gravity and Blaine fineness of 2.01 and 2420 cm^2/g, respectively. The percentage of fly ash retained when wet sieved on a 45-µm sieve was 46. Therefore, this FA failed to meet the fineness requirements of ASTM C 618. The coarse fly ash increased the workability characteristics of SCC mixtures.

The use of fly ash may extend the setting time of concrete. Jawed and Skalny [1981] found that Class F fly ashes retard early C_3S hydration. Grutzeck, Wei, and Roy [1984] also found retardation with Class C fly ash. Bouzoubaâ and Lachemi [2001] stated that the setting times of SCC, incorporating 40 to 60% Class F fly ash, were found to be 3 to 4 hours longer than the control concrete. The setting characteristics of concrete are influenced by ambient and concrete temperature; cement type, source, content, and fineness; water content of the paste; water soluble alkalies; use and dosages of other admixtures; the amount of fly ash; and the fineness and chemical composition of fly ash [Plowman and Cabrera, 1984]. Therefore, it is advisable that before using an unknown FA in producing concrete, its influence on the setting time should be investigated.

2.5.2 Effects of fly ash on the hardened properties of concrete

Effect on Strength

Strength at any given age and the rate of strength gain of concrete are affected by the characteristics of the particular fly ash, the cement with which it is prepared, and the proportions of each used in the concrete [EPRI CS-3314, 1984]. The relationship between tensile strength and compressive strength for concrete with fly ash is not different from that of concrete without fly ash. Compared with concrete without fly ash, proportioned for equivalent 28-day compressive strength, concrete containing a typical Class F fly ash may develop lower strength at 7 days of age or before when tested at room temperature [Abdun-Nur, 1961]. If equivalent 3-day or 7-day strength is desired, it may be possible to provide the desired strength by using accelerators or water-reducers, or by changing the mixture proportions [Bhardwaj et. al., 1980; Swamy et. al., 1983]. Test results indicate that silica fume can be used, for example, in fly ash concrete to increase the early-age strength; simultaneous use of silica fume and fly ash resulted in a continuing increase in 56- and 91-day strengths indicating the presence of sufficient calcium ion for both the silica fume reaction and the longer term fly ash reaction to continue [Carette and Malhotra, 1983]. Also, Mukherjee et. al. [1982] showed that increased early strengths can be achieved in fly ash concrete by using high-range water reducing admixtures to reduce the water to cementitious material ratio to at least as low as 0.28.

After the rate of strength contribution of portland cement slows down, the continued pozzolanic activity of fly ash contributes to increased strength gain at later ages if the concrete is kept moist; therefore, concrete containing fly ash with equivalent or lower strength at early ages may have equivalent or higher strength at later ages than concrete without fly ash [Erdoğan, 1996; Erdoğan, 1991]. This higher rate of strength gain will continue with time and result in

higher later age strengths than can be achieved using additional cement [Berry and Malhotra, 1980]. Using 28-day strengths as a reference, Lane and Best [1982] reported strength increases of 50 percent at one year for concrete containing fly ash, as compared with 30 percent for concrete without fly ash. Other tests, comparing concrete with and without fly ash showed significantly higher performance for the concrete containing fly ash at ages up to 10 years [Mather, 1965]. The ability of fly ash to aid in achieving high ultimate strengths has made it a very useful ingredient in the production of high-strength concrete [Blick et. al., 1974; Schmidt and Hoffman, 1975; Joshi, 1979].

Class C fly ashes often exhibit a higher rate of reaction at early ages than Class F fly ashes [Smith et. al., 1982; Erdoğan, 1996]. Even though Class C fly ash displays increased early age activity, strength at later ages in high-strength concrete appears to be quite acceptable. Cook (1982) with Class C fly ash and Brink and Halstead (1956) with Class F fly ash showed that, in most cases, the pozzolanic activity increased at all ages proportionally with the percent passing the 45-μm (No. 325) sieve. Class C fly ashes typically give better strength results at 28 days compared to Class F fly ashes. Cook (1981) and Pitt and Demirel (1983) reported that some Class C fly ashes were as effective as portland cement on an equivalent-mass basis. However, certain Class C fly ashes may not show the later-age strength gain typical of Class F fly ashes [Yuan and Cook, 1983].

Naik and Singh (1997) conducted tests on concretes containing between 15% and 25% by mass Class F and Class C fly ashes, to evaluate compressive strength. The effects of moisture and temperature during curing were also examined. The results of the research showed that concretes containing Class C fly ash and were moist cured at 23°C developed higher early age (1 to 14 days) compressive strengths than concretes with Class F fly ash. The long-term (90 days and greater) compressive strength of concretes containing fly ash was not

significantly influenced by the class of fly ash. An adverse effect of replacing the portland cement with fly ash is the increase in setting times of mixture.

Effect on Drying Shrinkage

Drying shrinkage of concrete is affected by the fractional volume of paste, the water content, cement content and type, and the type of aggregate. In those cases where the addition of fly ash increases the paste volume, drying shrinkage may be increased slightly if the water content remains constant. If there is a reduction in the water-content, shrinkage should be about the same as concrete without fly ash. Davis et. al. [1973], studied different fly ash-cement mixtures and found no apparent differences in drying shrinkage between concrete with up to 20 percent fly ash content and non-fly ash concrete. Dunstan [1984] and Symons and Fleming [1980] found that increased fly ash content resulted in slightly less drying shrinkage. Kosmatka et. al. [1995] reported that the drying shrinkage of small, plain concrete specimens with fly ash (without reinforcement) ranges from 400 to 800 micro-strain when exposed to air at 50% humidity.

Bouzoubaa and Lachemi [2001] studied the drying shrinkage of SCC incorporating high volumes of fly ash. The drying shrinkage for SCC incorporating Class F fly ash were low and did not exceed 600 micro-strain at the end of 224 days. No difference was noticed between the drying shrinkage of the control concrete and SCC incorporating fly ash.

Effect on Permeability

Concrete is permeable to water to the extent that it has interconnecting void spaces through which water can move. Permeability of concrete is governed by many factors such as the amount of cementitious materials, water content, aggregate grading, consolidation, and curing efficiency. Powers et al. [1959]

showed that the degree of hydration required to eliminate capillary continuity from ordinary cement paste cured at standard laboratory conditions was a function of the water to cementitious materials ratio and time. Required time ranged from 3 days at a water to cement ratio of 0.40 to 1 year at a water to cement ratio of 0.70.

Calcium hydroxide liberated by hydrating cement is water-soluble and may leach out of hardened concrete, leaving voids for the ingress of water. Through its pozzolanic properties, fly ash chemically combines with calcium hydroxide and water to produce C-S-H, thus reducing the risk of leaching calcium hydroxide. Additionally, the long-term reaction of fly ash refines the pore structure of concrete to reduce the ingress of chloride ions. As a result of the refined pore structure, permeability is reduced [Manmohan and Mehta, 1981]. Fly ash can improve the permeability of concrete due to its capability of transforming large pores of concrete into small pores and reducing micro cracking in the transition zone [Mehta and Monterio, 1997].

Nehdi et. al. [2004] studied the chloride permeability of SCC with high volume replacement materials (fly ash and slag). They concluded that, SCC with 50% replacement of portland cement can improve the workability and chloride permeability.

2.6 High Volume Fly Ash Concrete

The amount of fly ash in concrete for structural use is generally limited to 15 to 25% of the total cementitious materials. Concretes having large amounts of FA (usually above 50%) are termed as high-volume fly ash (HVFA) concrete. HVFA concrete was initially developed for mass concrete applications to reduce the heat of hydration [Bilodeau and Malhotra, 2000]. Canada Centre for

Mineral and Energy Technology (CANMET) first developed high volume fly ash concrete for structural use by the late 1980's [Malhotra, 1990].

High volume fly ash concrete for structural use became practical due to the advances of superplasticizers. An exploratory investigation of high volume fly ash concrete, conducted by CANMET, was first reported by Malhotra [1990] in 1986. In this investigation, low calcium fly ash was used in the proportion of 56% of the weight of the total cementitious material. Unit water content was kept low and a high degree of workability was achieved using superplasticizers. A lower temperature rise in large concrete blocks and a higher modulus of elasticity compared to portland cement concrete with equivalent strength were reported. On the other hand, a higher dosage of superplasticizer was reported to delay the setting time, but the setting delays did not appear to affect the strength development of concrete [Sivasundaram et. al., 1991].

Lower temperature rise was reported for high volume fly ash concrete. The adiabatic temperature rise, measured from concrete cylinders cured in an autogenous curing box similar to that described in Procedure of ASTM C 684, was between 9 and 14 ^{0}C above the ambient temperature for fly ash from different sources [Carette et. al., 1993]. While the temperature rise for the control portland cement mixes was 25 ^{0}C above the ambient temperature.

The early compressive strength of the high volume fly ash concrete mixes was significantly lower than that of portland cement concrete mixes with equivalent 28-day compressive strength. However, there was a more significant long term strength increase for high volume fly ash concrete mixtures [Langey et. al., 1989].

An important feature of high volume fly ash concretes was their high modulus of elasticity and low drying shrinkage and creep in comparison with the control

portland cement concrete [Sivasundaram et. al., 1991; Langey et. al., 1989]. This was considered to be the result of unhydrated fly ash particles acting as fine aggregate [Sivasundaram et. al., 1991].

The rapid chloride permeability is also reported to decrease with the use of high volumes fly ash. The resistance of concrete to chloride ion penetration was measured by the rapid chloride ion permeability test of AASHTO Standard T 227-83 (1986). For concrete mixes with a W/P ratio of 0.33 and with fly ashes from 8 different sources in the U.S., the total charge passed ranged from 221 to 635 coulombs at 91 days, and from 119 to 179 at 1 year [Malhotra and Carette, 1993].

CHAPTER 3

EXPERIMENTAL STUDY

3.1 Introduction

The objective of this study was to assess the effects of high volumes of high-lime and low-lime fly ash replacements on the fresh and hardened properties of SCCs. SCCs were prepared by keeping the total mass of cementitious materials constant at 500 kg/m^3, in which 30, 40, 50, 60 or 70% of cement, by mass, was replaced by high-lime and low-lime fly ash. For comparison, a control SCC mixture without any fly ash was also produced. The fresh properties of the SCCs were observed through, slump flow time and diameter, V-funnel flow time, L-box height ratio, U-box height difference, segregation ratio and the rheological parameters (relative yield stress and relative plastic viscosity). Relations between workability and rheological parameters were sought. Other fresh properties that were determined included, initial and final setting times and temperature rise of the SCC. The hardened properties were monitored for 360 days. These properties included the compressive strength, split tensile strength, ultrasonic pulse velocity, drying shrinkage, chloride permeability, absorption and sorptivity.

3.2 Materials

3.2.1 Cement

The cement used in all mixtures was a normal portland cement CEM I 42.5R (PC), which correspond to ASTM Type I cement. It had a specific gravity of 3.18 and Blaine fineness of 3629 cm^2/g. Chemical composition and physical properties of cement are presented in Table 3.1. The particle size distributions of PC, obtained by a laser scattering technique, is given in Figure 3.1.

Table 3.1 Properties of the portland cement, fly ash, and limestone powder

Chemical Composition	PC	FA_H	FA_L	LP
CaO (%)	63.27	10.07	2.21	54.97
SiO_2 (%)	19.61	48.08	54.13	0.01
Al_2O_3 (%)	5.86	25.87	25.73	0.17
Fe_2O_3 (%)	3.40	4.54	6.43	0.05
MgO (%)	0.95	1.46	2.12	0.64
SO_3 (%)	2.45	0.55	0.11	0.00
K_2O (%)	0.54	1.22	4.33	0.00
Na_2O (%)	0.47	0.73	0.47	0.00
Loss on Ignition (%)	3.02	1.01	1.34	43.66
Physical Properties				
Specific Gravity	3.18	2.27	2.08	2.70
Blaine Fineness (m^2/kg)	362.9	306.0	289.0	-

3.2.2 Fly ash

Throughout the study, two different fly ashes were used. One fly ash, which had a lime content of 10.07 %, was called high-lime fly ash (FA_H). The other

fly ash, which had a lime content of 2.21 %, was called low-lime fly ash (FA_L). Chemical composition and physical properties of fly ashes are given in Table 3.1. The particle size distributions of FA_H and FA_L are provided in Figure 3.1. Figures 3.2 and 3.3 illustrate the particle morphology of high-lime and low-lime fly ashes. The scanning electron microscope (SEM) images showed that the particles of low-lime fly ash had rather smooth spherical particles in comparison to the high-lime fly ash.

Mineralogical composition of the two fly ashes was also determined using X-ray diffraction (XRD) analysis (Figure 3.4). For both types of fly ashes, XRD patterns showed quartz as the major crystalline phase with a broad hump indicating the presence of amorphous content. The high-lime fly ash also contains anhydrite ($CaSO_4$), lime (CaO), hematite (Fe_2O_3), mullite ($Al_6Si_2O_3$) and feldspar crystalline phases. On the other hand, low-lime fly ash contains hematite (Fe_2O_3) and mullite ($Al_6Si_2O_3$).

3.2.3 Limestone powder

Limestone powder (LP) was used as a fine material (5 µm average diameter) in all mixtures. LP was a by product of marble extraction with a $CaCO_3$ content of 98%. The chemical composition and physical properties of the limestone powder is also presented in Table 3.1. Figure 3.1 also shows the particle size distribution of the LP used in this study.

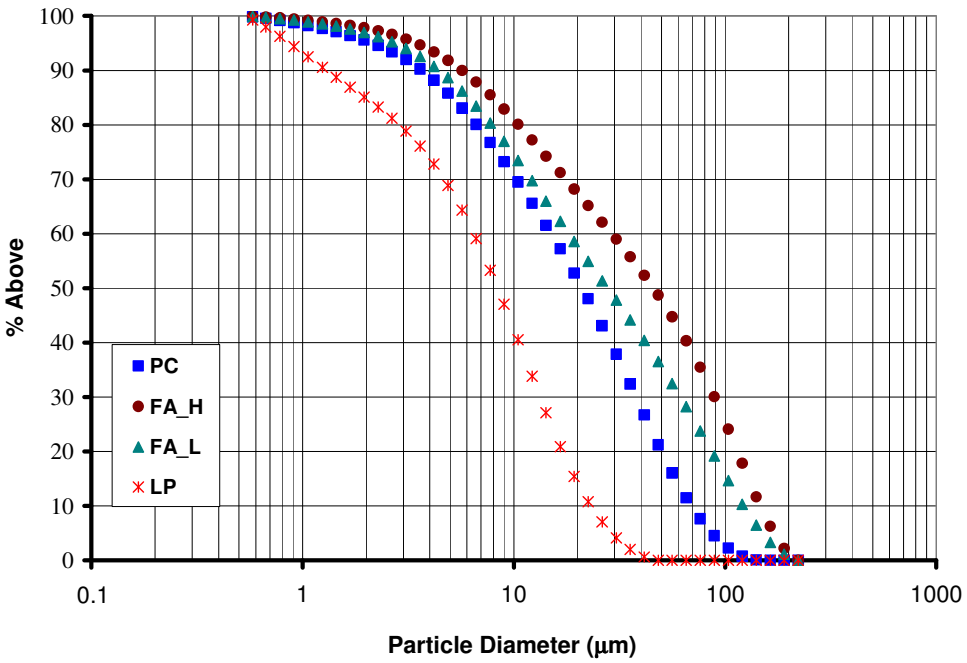
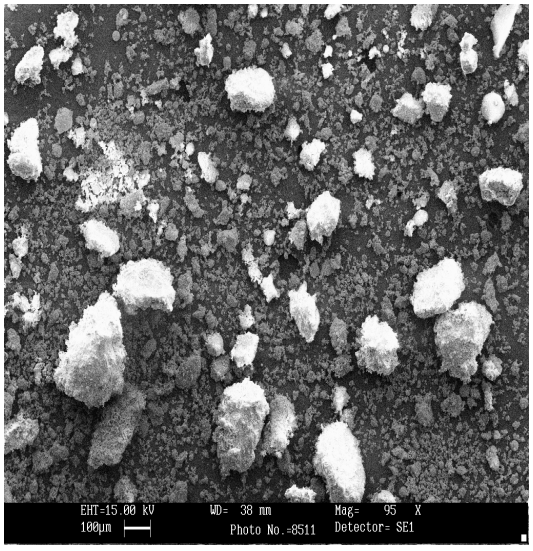
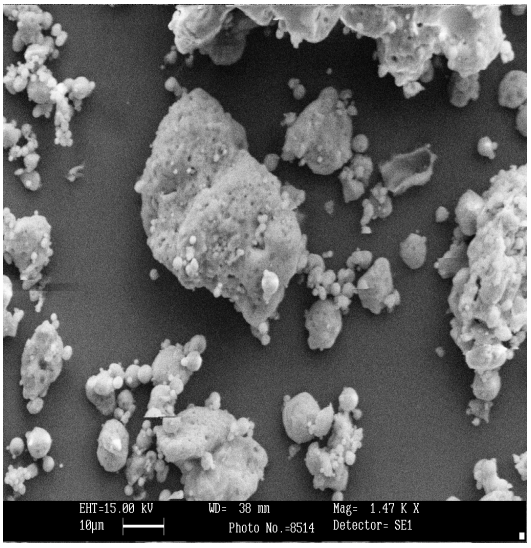


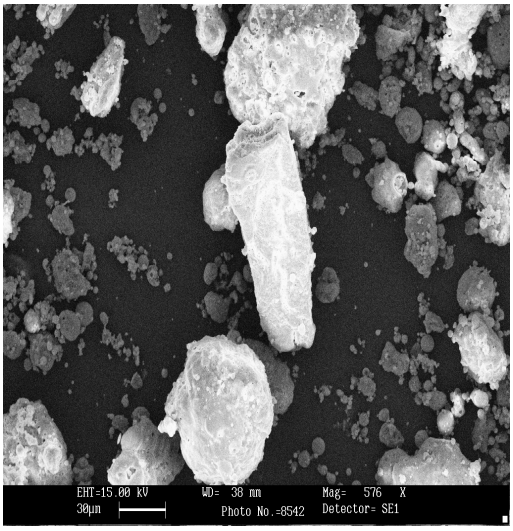
Figure 3.1 Particle size distribution of portland cement, fly ash, and limestone powder



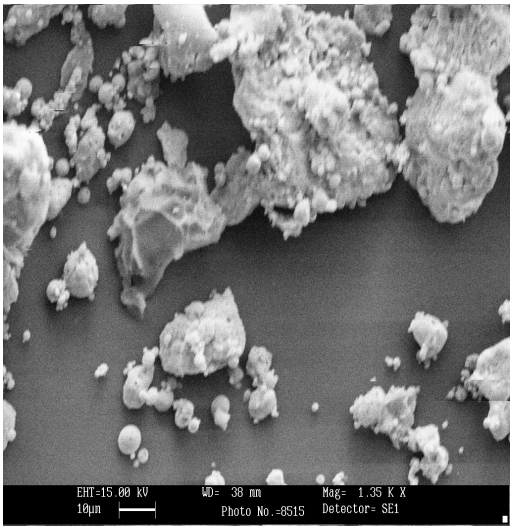
(a)



(b)



(c)



(d)

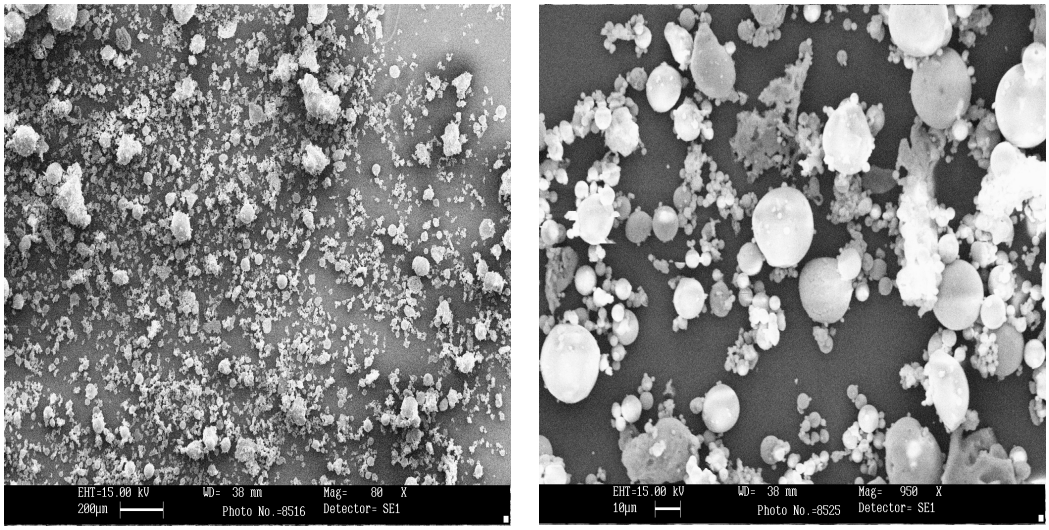
Figure 3.2 Secondary electron image of high-lime fly ash

(a) General distribution of particles in high-lime fly ash

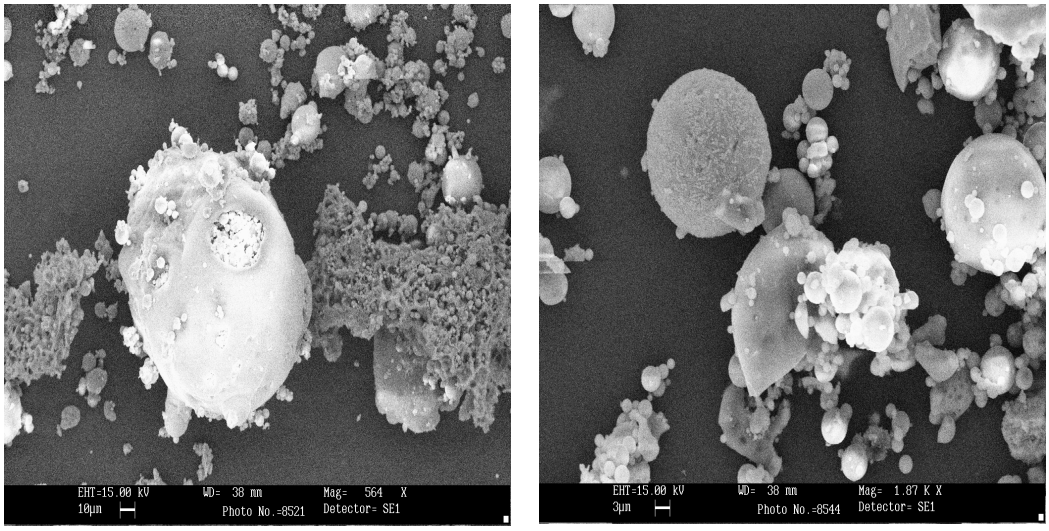
(b) Clay and spherical particles in high-lime fly ash

(c) Anhydrite particles in high-lime fly ash (angled structure)

(d) Unburned carbon in high-lime fly ash



(a) **(b)**



(c) **(d)**

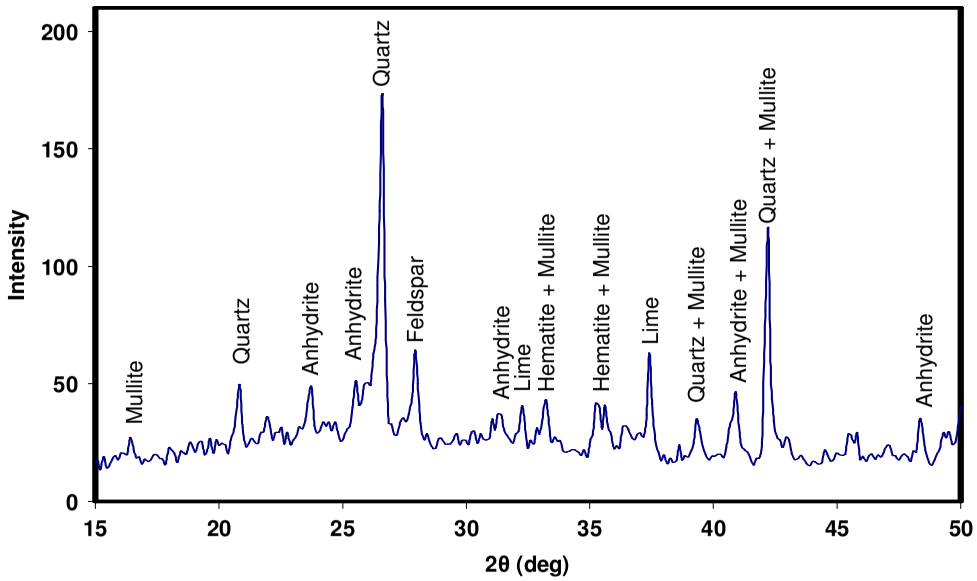
Figure 3.3 Secondary electron image of low-lime fly ash

(a) General distribution of particles in low-lime fly ash

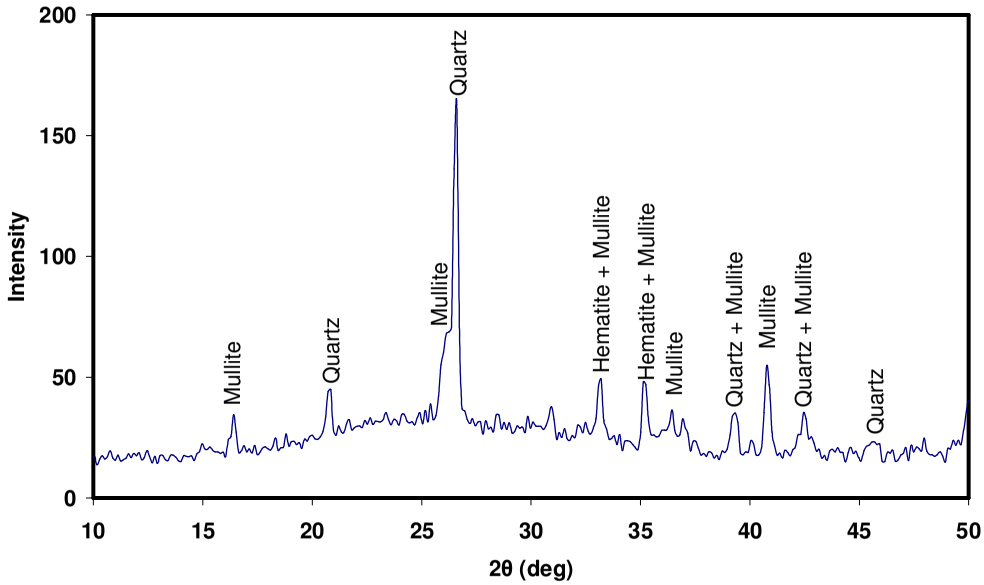
(b) Spherical particles in low-lime fly ash

(c) Unburned carbon in low-lime fly ash

(d) Quartz and hematite crystals in low-lime fly ash



(a) FA_H



(b) FA_L

Figure 3.4 XRD patterns of fly ashes

3.2.4 Aggregates

A crushed limestone with a maximum nominal size of 20 mm was used as the coarse aggregate and natural river sand was used as the fine aggregate in preparing the concrete mixtures. The coarse aggregate was separated into different size fractions and recombined to a specific grading. The grading or particle size distribution of coarse and fine aggregates was determined in accordance with ASTM C 136. Table 3.2 presents the grading of fine and coarse aggregate, respectively. The coarse and fine aggregates had specific gravities of 2.70 and 2.40, and water absorption of 0.3% and 2.4%, respectively.

Table 3.2 Aggregate grading

Sieve size (mm)	% Passing	
	Fine	Coarse
20.00	100.0	100.0
12.70	100.0	73.2
9.50	100.0	45.7
4.75	100.0	0.0
2.36	67.0	-
1.18	44.2	-
0.60	23.1	-
0.30	5.2	-
0.15	0.0	-

3.2.5 Superplasticizer

A polycarboxylic-ether type superplasticizer (SP) with a specific gravity of 1.08, pH of 5.7 and a solid content of 40%, produced by a local manufacturer, was used in all concrete mixtures. The SP used in this study had a significant price advantage over other commercially available superplasticizers. Thus, from an engineering point of view, the use of this SP and investigation of its performance in SCC are also found to be valuable.

3.3 Experimental Program

3.3.1 Mixture proportions

The proportions of the mixtures are summarized in Table 3.3. As seen from Table 3.3, eleven concrete mixtures were prepared. As a binder the control mixture included only PC. Remaining mixtures had a high-lime fly ash and a low-lime fly ash replacing from 30% to 70% by weight of PC. For all the mixtures, the total amount of cementitious material (PC+FA) and the amount of chemical admixture were kept constant. Water was added to the mixture until the SCC characteristics were observed; therefore, the water-cementitious material ratio (W/CM) was not kept constant and was observed to change between 0.29 and 0.35.

3.3.2 Preparation and casting of test specimens

The mixing procedure is important in producing SCC to reach the same properties. The sequence of mixing must allow sufficient time for the through mixing of all the constituents. The concrete mixtures were prepared at about 5 minutes with a 150-liter rotating planetary mixer, located at the Middle East

Technical University, Materials of Construction Laboratory. All materials were weighed precisely and added in a sequence to the mixer. The mixing procedure utilized for all the concrete mixture was as follows:

- The mixer was first mildly dampened with water.
- The sand, LP and coarse aggregate were first mixed with 1/3 of mixing water for 1 minute.
- The cementitious materials (cement or cement + fly ash) and 1/3 of mixing water was then added and mixed for additional 1 minute.
- Finally, rest of water and superplastisizer were pre-mixed and added to the mixer and mixed for 3 minutes. The total elapsed time of the mixing sequence was approximately 5 minutes.

Table 3.3 Mixture proportions

Mix ID	W/CM*	Ingredient (kg/m^3)							
		Water	PC	FA_H	FA_L	LP	Aggregate		SP
							Fine	Coarse	
1	0.35	173.5	500	0	0	71.0	967	639	6.75
2	0.35	173.5	350	150	-	69.2	939	621	6.75
3	0.35	175.5	300	200	-	68.3	927	613	6.75
4	0.35	173.9	250	250	-	67.8	920	608	6.75
5	0.35	173.5	200	300	-	67.1	912	603	6.75
6	0.35	173.5	150	350	-	66.4	902	597	6.75
7	0.34	169.0	350	-	150	69.0	937	620	6.75
8	0.32	162.0	300	-	200	68.9	935	618	6.75
9	0.30	149.5	250	-	250	69.3	941	622	6.75
10	0.30	149.5	200	-	300	68.4	929	614	6.75
11	0.29	142.8	150	-	350	68.2	927	613	6.75

* CM: Cementitious Material (PC+FA)

When the mixing procedure was completed, tests were conducted on the fresh concrete to determine slump flow time and diameter, V-funnel flow time, L-box height ratio, U-box height difference, segregation ratio, initial and final setting times, and air content. Relative yield stress and relative plastic viscosity for all SCC mixtures were also determined using the concrete rheometer. Segregation and bleeding were visually checked during the slump flow test. The temperature rise of the concrete was measured using a Ø150*300-mm cylinder of fresh concrete. From each concrete mixture, forty Ø100*200-mm cylinders were cast for the determination of compressive strength, split tensile strength and permeation tests and four Ø70*280-mm cylinders were cast for the determination of drying shrinkage. All specimens were cast in one layer without any compaction. At the age of 24 hours, the specimens were removed from the molds and stored in lime saturated water at 21±2 ^{0}C until the date of testing.

3.4 Tests on Fresh Self Compacting Concrete

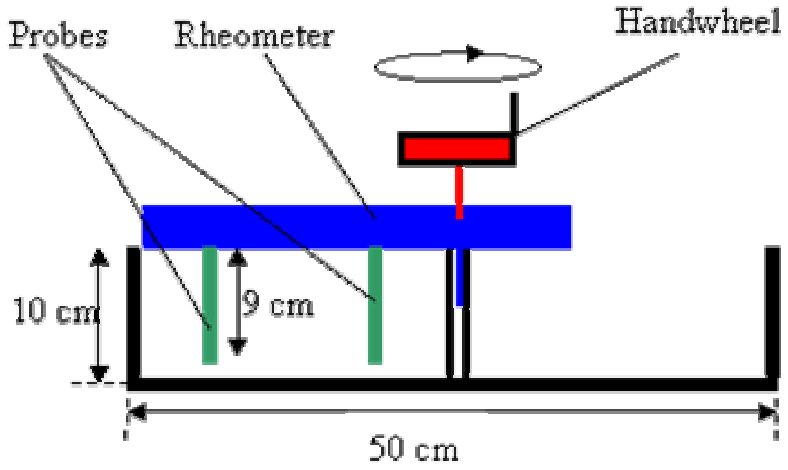
Determining the rheological properties of concrete is rather complex because of the large spread of particle sizes and the hydration reactions, which are time dependent. In this approach, fresh concrete can be considered as coarse aggregates suspended in liquid mortar. In this experimental study, rheological parameters of SCC (relative yield stress and relative plastic viscosity) were measured using a commercially available concrete rheometer. The workability methods used in this study are given and standardized by the Self-Compacting-Concrete Committee of EFNARC (European Federation for Specialist Construction Chemicals and Concrete Systems) [EFNARC, 2002] and measure the free and restricted deformability (slump flow, L-box height ratio, and U-box height difference) and stability (V-funnel flow time, slump flow time, and segregation ratio) of an SCC mixture. Initial and final setting times and temperature rise of SCC mixtures were also determined.

3.4.1 Concrete rheometer

Rheological parameters of SCC were determined using a commercially available concrete rheometer (Figure 3.5). The concrete is placed in a sample container and the rheometer with two probes is turned one round as shown in Figure 3.5. In the rheometer unit, there is an integrated sensor for the measurement of angular velocity, and for each probe there are sensors for the measurement of momentum. The data of each probe, the angular velocity and the distance to the shaft are used to obtain the flow curve. Nearly hundred angular velocities and momentums per probe are recorded for each test. The rheology of fresh concrete is considered to be represented by the Bingham model. Therefore the flow curve is a straight line and the rheological parameters (relative yield stress and relative plastic viscosity) can be easily determined by linear regression:

$$T = g + Nh$$

where g (Nmm) and h [Nmm/(m/sec)] are constants corresponding to relative yield stress and relative plastic viscosity, respectively. Figure 3.6 shows a typical plot of torque (T in Nmm) versus speed (N in m/sec). Linear regression analysis was performed on the data. The slope of the line defines relative plastic viscosity (h) and the intersection point with the y-axis defines relative yield stress (g). The measured relative yield stress of SCC was quite low, in fact nearly zero, and sometimes determined as negative. The physically impossible negative yield stresses of SCC were also reported by other researchers [Ferraris et. al., 2001].



Cross-Section

General View

Figure 3.5 The concrete rheometer

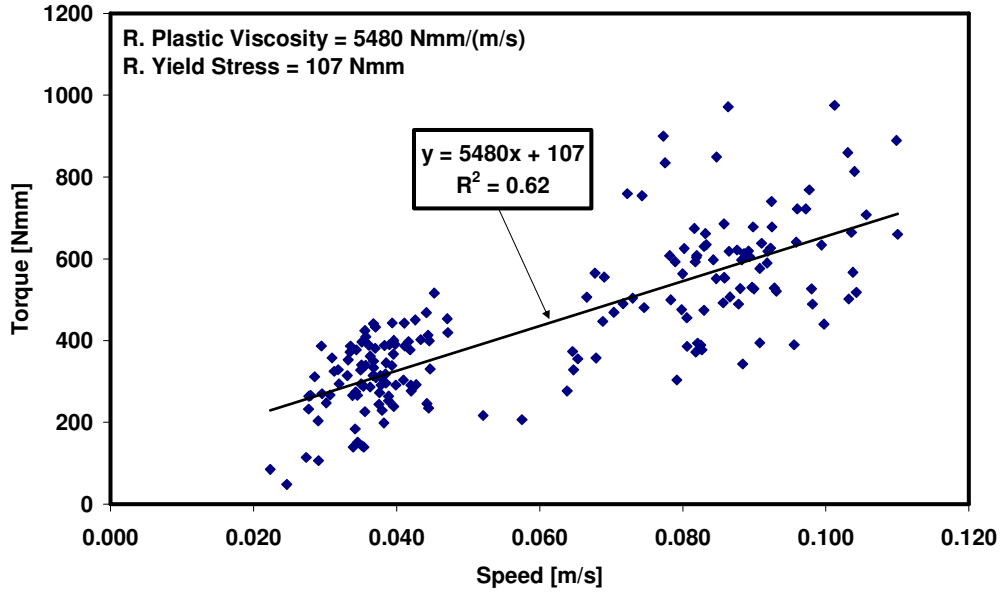


Figure 3.6 Typical flow curve obtained using the concrete rheometer

3.4.2 Slump flow

The slump flow is used to assess the horizontal free flow (deformability) of SCC in the absence of obstructions. The procedure for the slump flow test and the commonly used slump test are almost identical. In the slump test, the change in height between the cone and the spread concrete is measured, whereas in the slump flow test the diameter of the spread concrete is determined as the slump flow diameter (D) (Figure 3.7). According to Nagataki and Fujiwara [1995], a slump flow diameter ranging from 500 to 700 mm is considered as the slump required for a concrete classified as SCC. According to Specification and Guidelines for SCC prepared by EFNARC (2002), a slump flow diameter ranging from 650-800 mm can be accepted for SCC. In the slump flow test, concrete's ability to flow and its segregation resistance can also be measured. To measure these properties, the time (T_{50}) it takes for the concrete to reach a 50 cm spread circle and any segregation border between the

aggregates and mortar around the edge of spread are recorded. EFNARC suggests a T_{50} of 2 to 5 sec. for SCC.

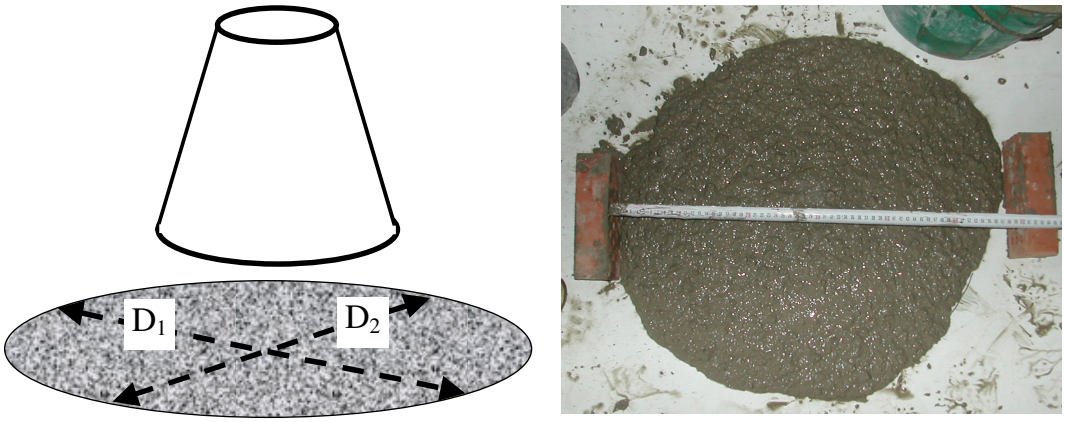


Figure 3.7 Slump flow test

3.4.3 V-funnel

V-funnel test is performed to assess the flowability and stability of the SCC. The funnel (Figure 3.8) is filled completely with concrete and the bottom outlet is opened, allowing the concrete to flow. The V-funnel flow time is the elapsed time ($t_{V\text{-}f}$) in seconds between the opening of the bottom outlet and the time when the light becomes visible from the bottom when observed from the top. Good flowable and stable concrete would consume short time to flow out. According to Khayat et. al. (1997), a $t_{V\text{-}f}$ which is less than 6 sec. is recommended for a concrete to qualify as a SCC. According to EFNARC [2002], $t_{V\text{-}f}$ ranging from 6 to 12 sec. is considered adequate for a SCC.

Figure 3.8 V-funnel

3.4.4 L-box

The L-box (Figure 3.9) consists of vertical and horizontal section in the shape of "L". The vertical section is filled with concrete, and then the gate is lifted to let the concrete flow into the horizontal section. After the test is complete, the level of concrete in the vertical section is recorded as H_1; the level of concrete in the horizontal section is recorded as H_2. The L-box value is simply H_2/H_1. Typical acceptance values according to EFNARC (2002) are in the range of 0.8 to 1.0. If the concrete was perfectly level after the test is complete, H_2/H_1 would be equal to 1.0; if the concrete was too stiff to flow to the end of the horizontal section it would be equal to 0.

3.4.5 U-box

In addition to the slump flow test, V-funnel test and L-box test, U-box test (Figure 3.9) is performed to assess the flow of the concrete, and also the extent

to which it is subject to blocking by reinforcement. The apparatus consists of a vessel that is divided by a middle wall into two compartments. An opening with a sliding gate is fitted between the two sections. Reinforcing bars with nominal diameters of 13 mm are installed at the gate with centre-to-centre spacing of 50 mm. This creates a clear spacing of 35 mm between the bars. The left hand section is filled with about 20 liter of concrete then the gate is lifted and concrete flows upwards into the other section. The height of the concrete in both sections is measured. The U-box value is the difference in height between two sections.

Figure 3.9 U-box and L-box

3.4.6 GTM sieve stability

The segregation test developed by the French contractor, GTM, was used to assess segregation resistance of SCC mixtures in this study. This test was conducted by gently pouring 2 liter of concrete on to a 5 mm sieve, and the

mass of mortar which passed through the sieve was weighed. The segregation ratio was taken as the ratio of mortar passing through the sieve to that weight of original sample on the sieve.

3.4.7 Air content

The air content of freshly mixed concrete by the pressure method was determined in accordance with ASTM C 231.

3.4.8 Setting time

The setting time of concrete is determined by the mortar contained in it. Initial setting time and the hardness development of SCC was determined by the penetrometer shown in Figure 3.10. This test procedure is in accordance with ASTM C 403. A mortar sample is obtained by sieving the fresh SCC through 4.75 mm sieve. The mortar is then discharged to a 15 x 15 cm cubic mold and stored at 23 ^{o}C temperature. At regular intervals, the resistance of mortar to penetration by the standard needle is measured. The force divided by the area of the bearing surface of the needle yields the penetration resistance. The initial setting time is the elapsed time, after the initial contact of cement and water, required for the mortar sieved from the concrete to reach penetration resistance of 3.5 MPa. The corresponding resistance for the final setting time is 27.6 MPa.

Figure 3.10. Apparatus for testing setting time [ASTM C 403]

3.4.9 Temperature rise and heat of hydration

Temperature rise of the concrete was measured using a 150×300-mm cylinder of fresh concrete that had been placed in an autogenous curing chamber (Figure 3.11) immediately after casting. Temperature logger (Figure 3.11) was placed at the inside surface of the chamber. The temperature was continuously monitored at 1 min. interval for 72 hours to characterize the quantitative heat of hydration for each mixture. Figure 3.12 shows a typical plot of temperature rise (^{0}C) versus time (hours).

Figure 3.11 Autogenous curing chamber and temperature logger

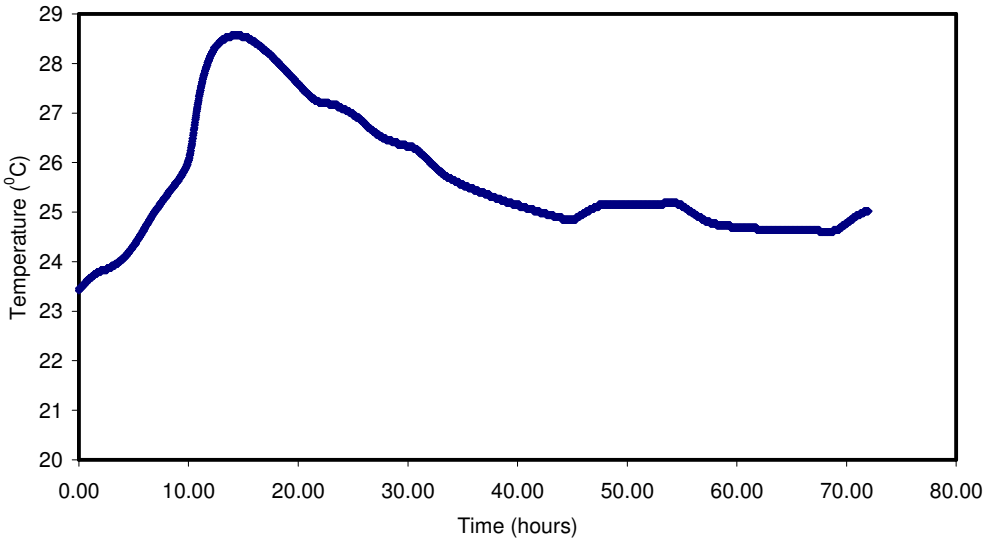


Figure 3.12 Typical temperature rise in 15×30 cm concrete cylinder

Heat of hydration of cements was determined by heat of solution method according to ASTM C 186 (Standard Test Method for Heat of Hydration of Hydraulic Cement). In this method, first the heat of solution of dry cement and than the heat of solution of partially hydrated cement are measured by dissolving them in the mixture of nitric acid and hydrofluoric acid solutions. The difference between these two values gives the heat of hydration of cement for the age of partially hydrated cement.

In order to apply the method, cement-fly ash pastes with the same W/CM ratio of the concrete mixtures were prepared as mentioned in ASTM C 186. For each mixture, the prepared pastes were cured isothermally at 23.0±2.0 ºC. The heats of hydration for each type of cement-fly ash pastes were measured at 3rd and 7th days.

At the beginning of the investigation, the hydration heats of cement and/or fly ash pastes hydrated to 1st and 2nd days were also planned to be measured. However, it was observed that the accuracy of the test results decreased as the age of the sample decreased. The accuracy is low at early ages because the possibility of losing moisture and carbonation during the grinding process is very high, which directly affects the result of the experiment.

There was another difficulty for the application of the standard at very early ages. As the amount of fly ash within the mixture increases, the rate of strength development also decreases. So some pastes, which contain high amounts of mineral admixtures such as 60% and 70% of fly ash, did not gain enough rigidity to be ground at the first two days, which is essential for applying the procedure.

3.5 Tests on Hardened SCC

Tests performed on cured concrete specimens consist of the compressive strength, split tensile strength, density, ultrasonic pulse velocity (UPV), drying shrinkage, absorption tests, sorptivity tests and rapid chloride permeability tests (RCPT).

3.5.1 Compressive strength

The compressive strength test was conducted in accordance with ASTM C 39 using a universal testing machine. The compressive strength of 100×200-mm cylinders was determined at 7, 28, 90, 180 and 360 days. A total of fifteen cylinders were tested for each mixture. The compressive strength was computed from the average of three cylinders at each age.

3.5.2 Split tensile strength

ASTM C 496 method was used to measure split tensile strength of concrete. The split tensile strength of SCC was determined using 100×200-mm cylinders at 28, 90 and 180 days. The split tensile strength was reported as the average of three cylinders for each age.

3.5.3 Drying shrinkage

In a dry environment, concrete can experience drying shrinkage. Drying shrinkage is essentially a volume change that takes place over time due to moisture loss. Drying shrinkage is a major concern because it can cause cracking of concrete elements due to structural restraints on the concrete [Mindess et. al., 2003]. Drying shrinkage is affected by a wide range of

variables which include the shape of the element, the mix proportions, the chemical and physical properties of the raw materials, and the environment to which the element is exposed.

ASTM C 157 procedure was used to determine the drying shrinkage of concrete. Four 70×280-mm cylinders were used to measure the drying shrinkage. After demolding, all the specimens were cured in lime-saturated water for 28 days and then stored in laboratory condition at 23±4 ^{0}C, and 50±4% relative humidity. The drying shrinkage for each specimen was measured up to 360 days. Figure 3.13 shows a length comparator with a concrete shrinkage specimen.

Figure 3.13 Length measurement of the concrete specimen for the determination of drying shrinkage

The length comparator readings at each test age were compared with the initial length comparator reading to calculate the shrinkage of concrete which was measured in micro-strains. The values in Table 3.4 are used to evaluate test results [Goodspeed, 1998].

Table 3.4 Shrinkage grades [Goodspeed, 1998]

Shrinkage (Micro-strains)	Description
<400	Good
400-600	Moderate
600-800	Poor
>800	Very Poor

3.5.4 Ultrasonic pulse velocity and density

All dimensions of the cylindrical specimens were measured using a caliper of 0.01-mm. resolution and their weights were measured with a balance of 0.1 g. accuracy at 7, 28, 90, 180 and 360 days. Using these data the density of the specimens was determined.

The UPV measurement is described in ASTM C 597. The testing system consists of a pulser/receiver unit with a built-in data acquisition system and a pair of narrow band, 50 kHz transducers (Figure 3.14). UPV measurements were conducted with the transducers firmly coupled to the opposite ends of the specimens using a coupling gel (petroleum jelly) between the transducer and the specimen. UPV computation requires the acquisition of the pulse arrival time and specimen length. Pulse arrival time describes the elapsed time between the time of pulse application and arrival on the opposite face of the specimen. UPV was computed as the specimen length divided by the elapsed

time. Using the UPV measurements the internal structure of SCC at 7, 28, 90, 180 and 360 days of age were nondestructively monitored.

Figure 3.14 UPV testing on cylindrical specimens

3.5.5 Absorption

This test is based on ASTM C 642 for determining the volume of permeable voids in hardened concrete. This test determines the absorption of the concrete expressed as the percentage of the absorbed water over the dry mass of concrete.

Four Ø100×50-mm disc specimens were dried in an oven at 105±5 ^{o}C to a constant weight. The specimens were then immersed in water and weighed every 24 hours to check the increase in mass, until the increase in mass was less than 0.5 % of the heavier mass which defines the saturation stage (Figure

3.15). In this test, water absorption can only take place in pores which were emptied during drying and filled with water during the immersion period. These pores can be considered as permeable pores and therefore, the absorption of the concrete sample after immersion in water until saturation indicates its permeability. At a result of this test, the total volume of permeable pores was determined.

Figure 3.15 Absorption test [ASTM C 642]

3.5.6 Sorptivity

This test was based on Hall's sorptivity test [Hall, 1989]. The sorptivity test consists of registering the increase in mass of a disc specimen (Ø100×50-mm) at given intervals of time when permitted to absorb water by capillary suction (Figure 3.16). The specimens were dried according to the procedure described in absorption test. In this test, only one surface of the specimen is in contact with water, with the depth of water between 3 to 5 cm. The sides of the

specimen were sealed with a silicone rubber coating in order to have one-directional flow through the specimen. This could also prevent evaporation from the non-immersed sides of the specimen.

The amount of water absorbed at various times was determined by removing the specimen from the water, drying off excess surface water and weighing the specimen using an electronic balance of 0.1 g. resolution. These weighings were done 1, 2, 3, 4, 6, 9, 12, 16, 20, 25, 36, 49, 64, 81, 100 and 120 minutes after the start of test.

The rate of absorption (i in mm), defined as the change in mass (g) divided by the cross sectional area of the test specimen (mm^2) and the density of water at the recorded temperature (g/mm^3), was plotted against square root of time ($t^{1/2}$ in $min^{1/2}$). Figure 3.17 shows a typical plot of absorption rate (i) against square root of time ($t^{1/2}$). The slope of the obtained line defines the sorptivity of the specimen during the initial two hours of testing. Each sorptivity value (s in $mm/min^{1/2}$) is the average of four tests performed on four nominally identical specimens. This test was chosen as it measures the rate of ingress of water into unsaturated concrete.

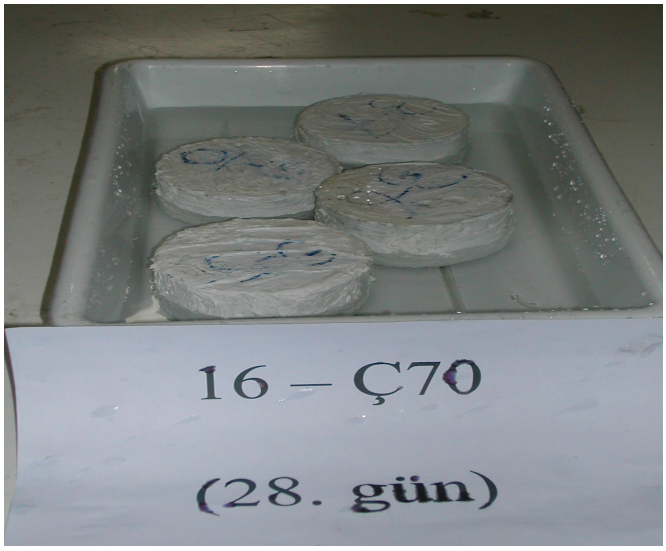


Figure 3.16 Sorptivity test

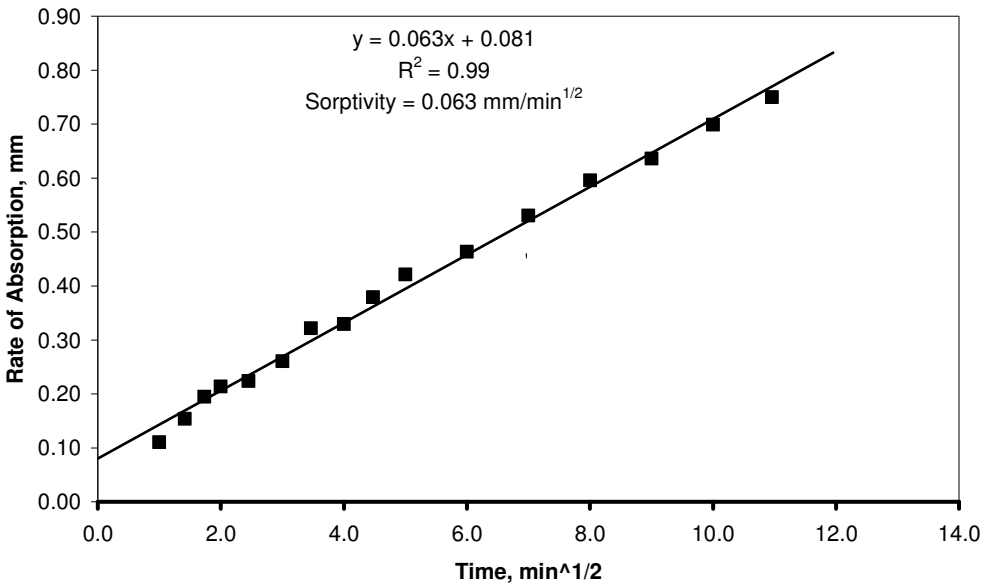


Figure 3.17 Typical plot of rate of absorption (i) versus ($t^{1/2}$)

3.5.7 Rapid chloride permeability

This test is based on the ASTM C 1202 (AASHTO T 277) for determining the chloride permeability of hardened concrete. In this test, a water saturated 50-mm thick, 100-mm diameter concrete specimen is subjected to a 60 V applied DC voltage for 6 hours. One end of the specimen is in contact with 0.3 M NaOH solution, the other end with 3.0 % NaCl solution. The total charge passed during six hours is determined.

A commercial test equipment capable of integrating direct current flow over time to give readings in coulombs was used. The equipment was equipped with automatic printer output at every 30 minutes and programmed to terminate the test automatically after 6 hours. The chloride permeability of the specimens was expressed as: the total charge passed in coulombs during the test period of 6 hours, which was given by:

$$Q = 900\ (I_0 + 2I_{30} + 2I_{60} + \ldots + 2I_{300} + 2I_{330} + I_{360})$$

where:

Q = charge passed (coulombs),
I_0 = current (Amperes) immediately after voltage is applied,
I_t = current (Amperes) at t min. after voltage is applied.

A photograph of the equipment used is shown in Figure 3.18. Four replicate specimens were tested at the same time. Table 3.5 shows a typical raw data output from the rapid chloride permeability test equipment.

The total charge passed, in coulombs, is related to the concrete's ability to resist chloride ion penetration. As more chloride ions migrate into the concrete, more current can pass through and the total charge passed increases. A high value for total charge passed indicates that the concrete is highly penetrable. A

low value for total charge passed indicates that the concrete has low penetrability. Table 3.6, based on the ASTM C 1202, is used to evaluate test results obtained from rapid chloride permeability test.

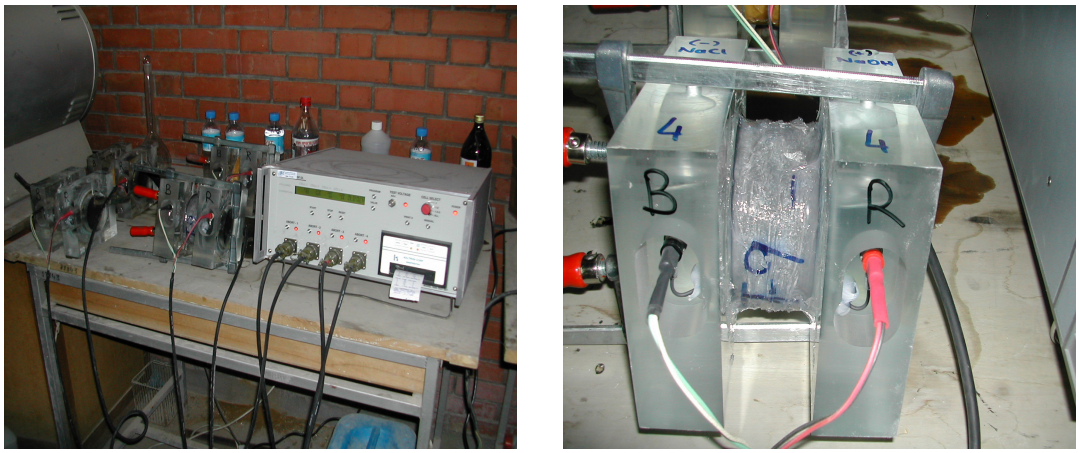


Figure 3.18 Rapid chloride permeability test (ASTM C 1202)

Table 3.5 Typical raw data output from the RCPT equipment

Time (min)	Current (mA)				Charge (Coulomb)			
	Cell No				Cell No			
	1	2	3	4	1	2	3	4
1	89	107	98	101	5	6	6	6
30	94	115	106	107	167	202	185	188
60	98	120	110	112	340	415	379	386
90	102	127	114	115	521	638	582	592
120	106	132	118	120	709	872	792	806
150	110	138	121	122	903	1115	1009	1025
180	111	140	126	126	1102	1367	1233	1250
210	113	145	127	128	1306	1626	1463	1479
240	115	149	131	130	1512	1891	1697	1712
270	115	151	132	132	1721	2162	1933	1948
300	117	155	130	133	1932	2439	2170	2187
330	119	157	131	134	2144	2720	2406	2428
360	120	159	130	135	2358	3005	2643	2671

Table 3.6 Chloride ion penetrability based on charge passed

Charge Passed (Coulombs)	Chloride Ion Penetrability
>4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very Low
<100	Negligible

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Fresh Concrete Properties

In this experimental program, the three workability properties, deformability, stability, and risk of blockage, are determined by slump flow time and diameter, V-funnel flow time, L-box height ratio, U-box height difference, segregation ratio and the rheological parameters, relative yield stress and relative plastic viscosity. In addition to the workability properties, setting times and temperature rise were also measured for all SCC mixtures. Results of these tests are summarized in the proceeding sections.

4.1.1 Slump flow and slump flow time (T_{50})

The slump flow and slump flow time to reach 50 cm diameter are shown for all eleven concrete mixtures in Table 4.1. The slump flow diameters (D) of all mixtures were in the range of 665 to 775 mm and the slump flow was within the range established by EFNARC. Thus, all mixtures are qualified for SCC as they exhibited satisfactory slump flow. The slump flow times (T_{50}) of all concrete mixtures are less than 4.4 sec. The slump flow of mixtures 7 and 10 are 1.3 and 1.9 sec., respectively and considered to be low. These concretes

exhibited very high flowability (low viscosity). When the flowability of SCC mixtures are very high (slump flow times less than 2 sec.), segregation and/or bleeding may occur. However, during the slump flow test, visual inspection of fresh concrete did not indicate any segregation or considerable bleeding in any of the mixtures.

Table 4.1 Fresh properties of SCC with regards to slump flow, slump flow time and V-funnel flow time

Mix ID	W/CM	% of FA	Slump flow D (mm)	Slump flow T_{50} (sec)	V-funnel flow time t_{V-f} (sec)
1	0.35	0	665	4.2	12.7
2	0.35	30	715	3.1	15.8
3	0.35	40	730	2.0	10.7
4	0.35	50	710	4.4	19.2
5	0.35	60	740	2.5	12.8
6	0.35	70	725	3.9	15.8
7	0.34	30	765	1.3	10.2
8	0.32	40	745	2.3	11.7
9	0.30	50	738	3.5	15.1
10	0.30	60	770	1.9	9.4
11	0.29	70	775	2.2	10.9
EFNARC Recommends		**Min**	650	2.0	6.0
		Max	800	5.0	12.0

The effect of fly ash type and volume on the slump flow diameter and time is shown in Figure 4.1. As seen in the figure, for both types of fly ashes, the use of fly ash increased the slump flow diameter thus the deformability of concrete

mixtures when compared to the control mixture. Up to a 20% increase in deformability was observed. However, when the slump flow time is considered, the addition of both types of fly ash significantly reduced the slump flow time (T_{50}) which is a measure of the stability. The fluctuation in the slump flow times is as a result of difficulty in estimating the time that concrete reached 50 cm of slump flow diameter.

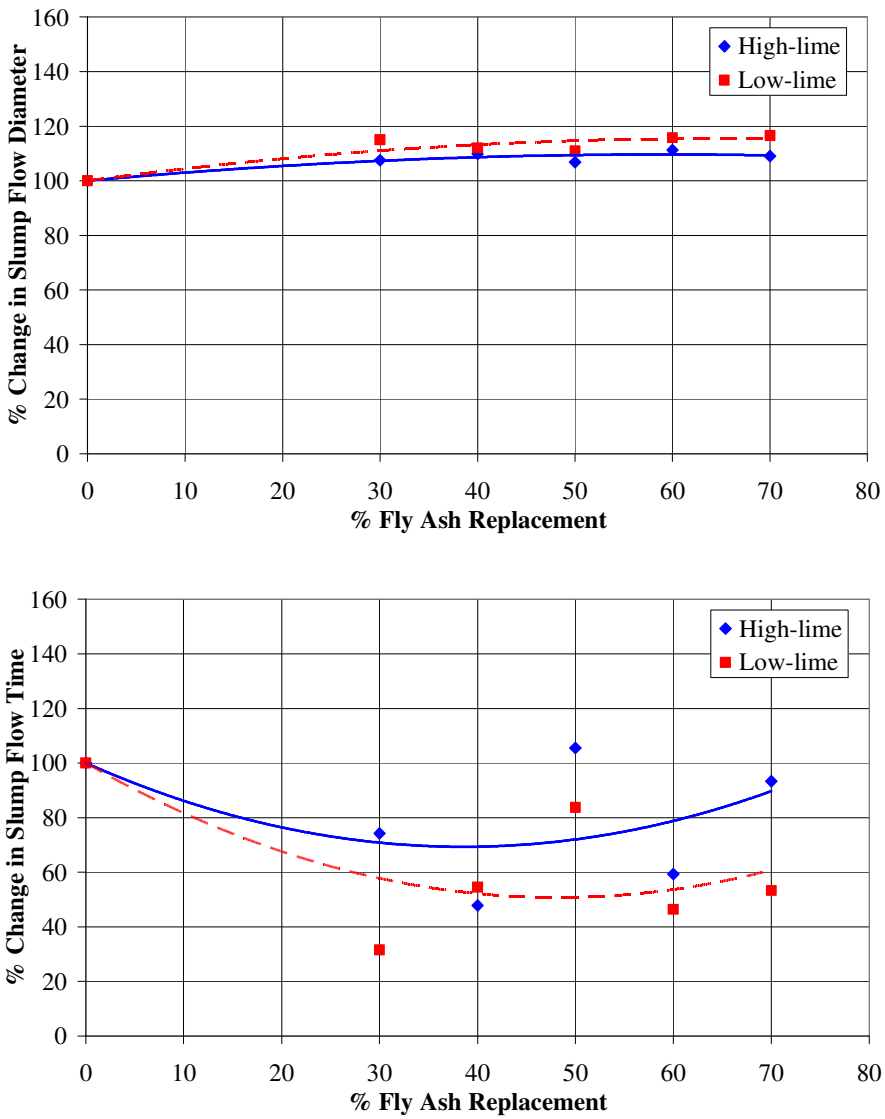


Figure 4.1 Effect of fly ash type on the slump flow diameter and time

4.1.2 V-funnel

The results of the V-funnel test are also shown in Table 4.1. The V-funnel flow times ($t_{V\text{-}f}$) were in the range of 9.4 to 19.2 sec. According to EFNARC, the accepted range of V-funnel flow time for SCC is 6 to 12 sec. as seen in the table. Most of the mixtures in this study exceeded this limit. However, all concrete mixtures filled the molds under their own weights without the need for any vibration.

The effect of fly ash type and volume on the V-funnel flow time is shown in Figure 4.2. As seen in that figure, the addition of low-lime fly ash reduced the V-funnel flow time when compared with high-lime fly ash. The smooth and spherical surface characteristics of low-lime fly ash are presumed to be the reason for this decrease. The fluctuation in the V-funnel flow times is also high because of the difficulty in determining the duration during the V-funnel test as this duration is highly dependent on the person.

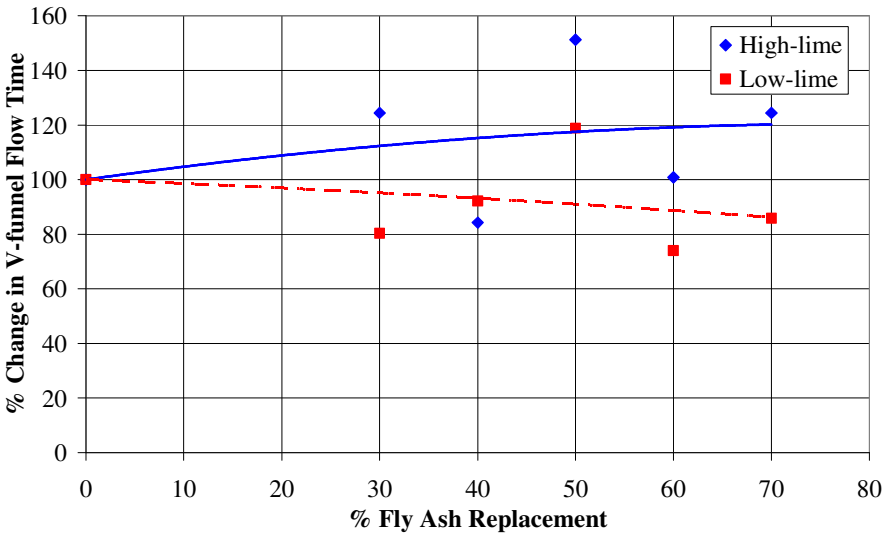


Figure 4.2 Effect of fly ash type on the V-funnel flow time

4.1.3 L-box and U-box

The L-box (h_2/h_1) and U-box (h_1-h_2) test results are presented in Table 4.2. The L-box and U-box tests were used to assess the self compactability and flowability of concrete. The L-box height ratios were in the range of 0.85 to 0.95 and U-box height difference was in the range of 5 to 50 mm. According to EFNARC, all concrete mixtures were SCC except the control mixture. The U-box height difference for the control mixture was 50 mm, which is higher than the acceptance limit. However, other workability properties of control mixture were suitable for SCC.

Also observed in Table 4.1 and Table 4.2 is the change in W/CM ratio for approximately the same workability measure, i.e. the same D, T_{50}, and $t_{V\text{-}f}$. The control and the high-lime fly ash (FA_H) SCC mixtures had higher W/CM ratio than low-lime fly ash (FA_L) SCC mixtures. The water reducing effect of low-lime FA was increased with increased replacement level but in high-lime FA replacement, the water reducing effect was not observed. As observed in the secondary electron image of the fly ashes (Figure 3.2 and Figure 3.3), the geometry of the high-lime FA was of irregular shape with a rough surface texture. However, the low-lime FA had spherical shape particles with smooth surface texture. Therefore, the lubricating effect of the spherical particle shape and the smooth surface characteristics were the main reasons for a decrease in the W/CM ratio, which was also mentioned by other researchers [Wei et. al., 2003].

Table 4.2 Fresh properties of SCC with regards to L-box, U-box and segregation ratio.

Mix ID	W/CM ratio	% of FA	L-box (h_2/h_1) (mm/mm)	U-box (h_1-h_2) (mm)	Segregation ratio (SR) (%)
1	0.35	0	0.87	50	2.4
2	0.35	30	0.95	5	6.3
3	0.35	40	0.85	10	10.5
4	0.35	50	0.90	5	9.5
5	0.35	60	0.85	5	6.6
6	0.35	70	0.85	10	1.6
7	0.34	30	0.95	10	8.3
8	0.32	40	0.95	15	6.7
9	0.30	50	0.88	15	4.2
10	0.30	60	0.95	20	10.7
11	0.29	70	0.95	10	6.2
EFNARC Recommends		**Min**	0.80	0	0.0
		Max	1.00	30	15.0

4.1.4 GTM sieve stability

Self compacting concrete differs from conventional concrete in the following three characteristic features: Filling ability, passing ability and segregation resistance. An increase in the filling and passing ability of concrete is known to increase the risk of segregation. GTM sieve stability test method was used to determine the segregation resistance of SCC. EFNARC stated that a stable SCC should exhibit a segregation ratio lower than 15%. The results of segregation ratio are presented in Table 4.2. According to segregation ratio

observed from the GTM screen stability test, all concrete mixtures have lower segregation ratio than the upper limit specified by EFNARC.

4.1.5 Rheological measurements

The two rheological properties, relative yield stress and relative plastic viscosity, were determined using a commercially available concrete rheometer which was described in section 3.4.1. The results obtained are provided in Table 4.3.

Table 4.3 Rheological properties of SCC mixtures

Mix ID	W/CM ratio	% of FA	Relative yield stress (g)	Relative plastic viscosity (h)
			(Nmm)	(Nmm)/(m/s)
1	0.35	0	107	5480
2	0.35	30	94	7683
3	0.35	40	-42	7135
4	0.35	50	121	11480
5	0.35	60	89	7012
6	0.35	70	-3	7990
7	0.34	30	111	3382
8	0.32	40	76	4172
9	0.30	50	46	6477
10	0.30	60	51	2781
11	0.29	70	-30	5386

4.1.6 Comparison of rheological and workability properties

To identify any linear correlation between the fresh concrete tests, coefficients of determinations (R^2) between any of the two fresh tests were calculated and presented in Table 4.4. An R^2 of 1.00 shows that the two tests are perfectly correlated, which was the case if one test is compared to itself as presented in the diagonal terms of Table 4.4. If there is no correlation or a weak linear correlation, the value of R^2 gets closer to zero. As seen from that table, higher correlations are observed between the slump flow time, V-funnel flow time and relative plastic viscosity because these tests are related to the viscosity of concrete (Figure 4.3). For example, in the V-funnel test, the concrete starts to flow when the yield stress is exceeded. Therefore, the measured value is related to the viscosity. Moreover, the correlations between slump flow time (T_{50}) and relative plastic viscosity (h) are relatively weak, because flow is not completely uniform during the slump flow test and it is very difficult to estimate the time that concrete has gained 50 cm of slump flow diameter. This fact was also stated by Nielsson and Wallevik (2003). On the other hand, there seems to be a good correlation between the slump flow time and diameter since these parameters are obtained from the same test (Figure 4.4). In fact, the slump flow diameter is known to be an estimate of the deformability of concrete which is related to the yield stress.

Another observation that could be made from Table 4.4 is the less correlated terms, L-box height ratio, relative yield stress and segregation ratio. The L-box height ratio measures the passing ability of concrete in between reinforcement which cannot be determined by other tests used in this study. The relative yield stress obtained from Bingham's model may not be easily determined for self compacting concretes, since it is nearly zero and sometimes even found as negative. For the same reason, it was also mentioned in the literature that yield stresses when determined by two different apparatus may totally be non-correlated for SCCs [Ferraris, 1999]. Therefore, these two parameters are not

necessarily correlated to the viscosity of concrete. On the other hand, segregation ratio obtained from GTM sieve stability test measures the stability of concrete that is related with its viscosity. In spite of simplicity of this test, the repeatability of results may be doubtful. Furthermore, the results are very sensitive to the height of the concrete poured onto the sieve. Therefore, results of this test were not correlated with the other viscosity tests.

Table 4.4 Coefficient of determinations between the fresh concrete tests

	(h_2/h_1)	D	T_{50}	$t_{V\text{-}f}$	SR	h	g
(h_2/h_1)	***1.00***	0.26	0.21	0.09	0.12	0.24	0.05
D	0.26	***1.00***	**0.61**	0.29	0.20	0.25	0.13
T_{50}	0.21	**0.61**	***1.00***	**0.71**	0.31	**0.50**	0.06
$t_{V\text{-}f}$	0.09	0.29	**0.71**	***1.00***	0.10	**0.78**	0.09
SR	0.12	0.20	0.31	0.10	***1.00***	0.01	0.00
h	0.24	0.25	**0.50**	**0.78**	0.01	***1.00***	0.00
g	0.05	0.13	0.06	0.09	0.00	0.00	***1.00***

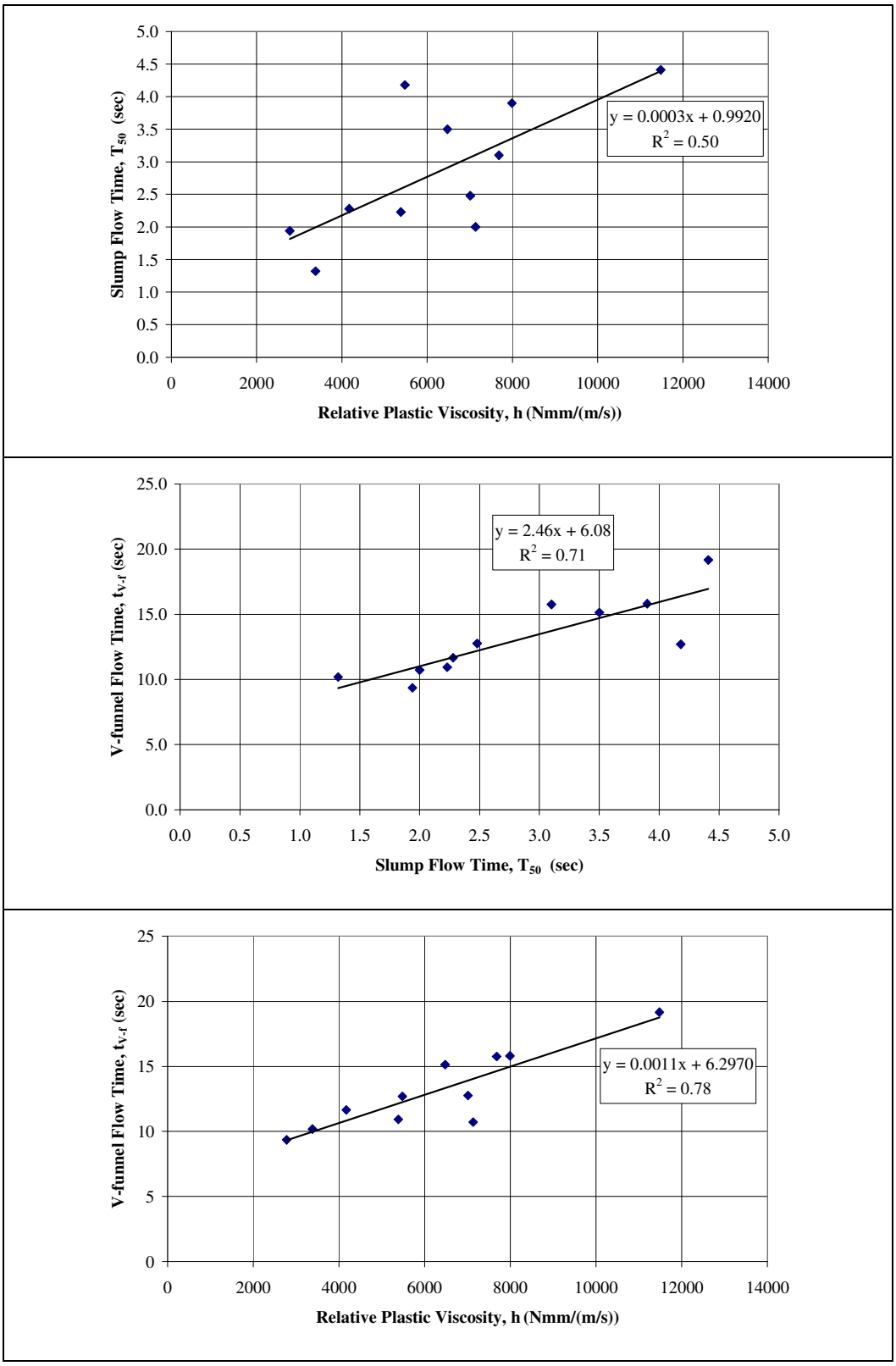


Figure 4.3 Relations between fresh tests that are related to viscosity of concrete

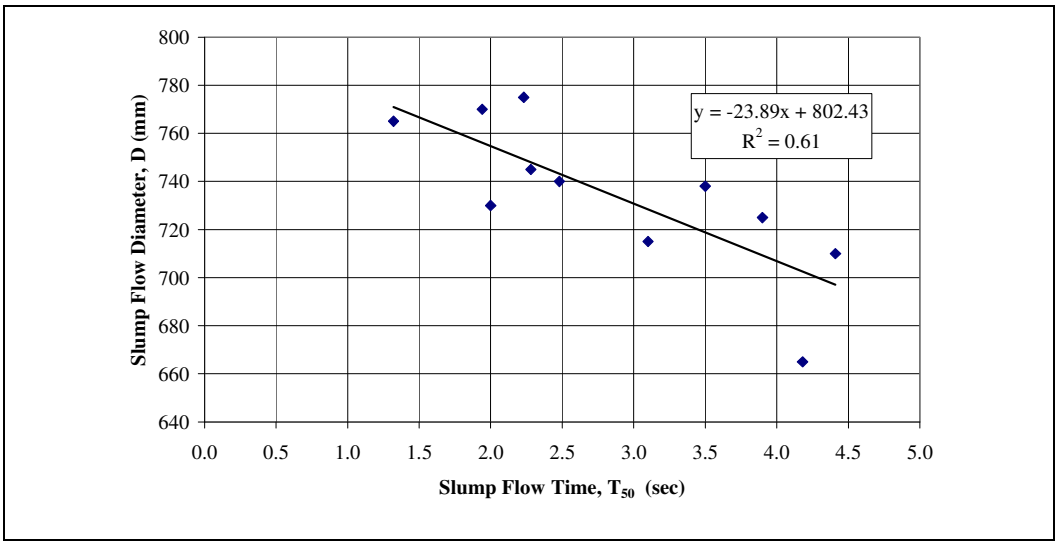


Figure 4.4 Relation between slump flow time and slump flow diameter

4.1.7 Setting time

The results of initial and final setting times are presented in Table 4.5. The initial setting time of SCC was found to be ranging from 273 minutes to 625 minutes, while the final setting time was found to be in the range of 425 minutes and 995 minutes. Figure 4.5 demonstrates the influence of fly ashes on the initial and final setting times of the SCC mixtures. The initial and final setting times of SCC vary proportionally with the percentage of fly ash and W/CM ratio. As a result of the decreased water content, the powder concentration is increased; causing an increase in the volume of hydration product [Mirza et. al., 2002], and thus SCC takes shorter time to set. SCC mixtures containing fly ash show longer setting times than the control mixtures. As seen from Figure 4.5, use of high-lime fly ash significantly prolongs both the initial and the final setting time of the SCC mixtures at the same W/CM ratio. This phenomenon is attributed the decreased concentration of cement (up to 70% of portland cement replaced by fly ash). On the other hand, the use of low-lime fly ash slightly affected the initial and final setting

times due to the reduction in W/CM ratio. As a result of the decreased water content, the cementitious material concentration is increased; causing an increase in the volume of the hydration product [Mirza et. al., 2002], and thus SCC takes a shorter time to set.

Table 4.5 Setting times, air content and unit weight of SCC mixtures

Mix ID	W/CM ratio	% of FA	Setting time (min)		Air content	Fresh unit weight
			Initial	Final	(%)	(kg/m^3)
1	0.35	0	273	425	1.4	2385
2	0.35	30	340	625	1.6	2325
3	0.35	40	433	695	2.6	2263
4	0.35	50	468	718	2.2	2225
5	0.35	60	485	805	3.4	2200
6	0.35	70	625	995	3.2	2188
7	0.34	30	390	508	3.2	2260
8	0.32	40	395	535	3.2	2248
9	0.30	50	404	559	2.5	2230
10	0.30	60	476	659	3.2	2220
11	0.29	70	481	680	4.0	2213

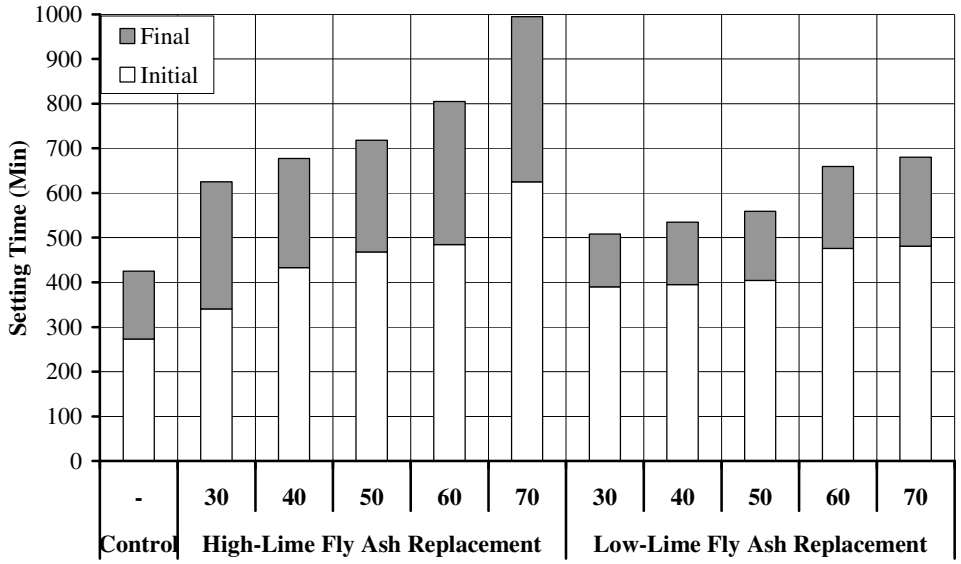


Figure 4.5 Setting time of SCC mixtures

4.1.8 Temperature rise and heat of hydration

Maximum temperature rise measured during the first 3 days for all SCC mixtures are presented in Figure 4.6. Maximum temperature rise of the control concrete (SCC without fly ash) was 5.2 ^{0}C, and the maximum temperature rise for all of the fly ash SCCs was considerably lower than control mixture, and ranged from 2.5 to 4.6 ^{0}C. No significant relation between the percentage of high lime fly ash and maximum temperature rise was observed. On the other hand, there are significant differences for maximum temperature rise between SCC mixtures incorporating low-lime fly ash. This demonstrates the potential of the high volume low-lime fly ash SCC system for reducing the temperature rise in large concrete members due to its low cement content and the slow pozzolanic activity of the low-lime FA.

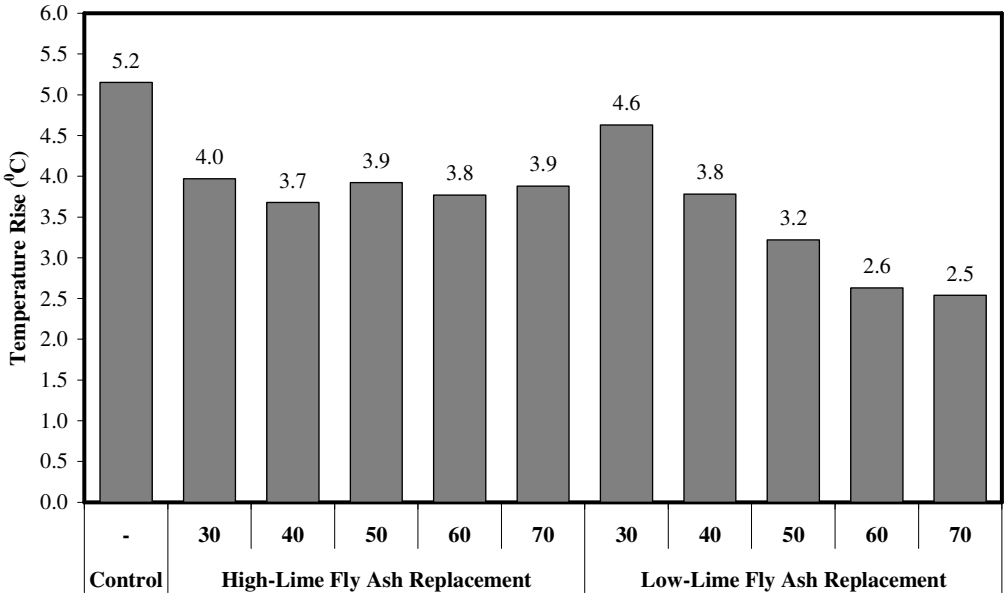


Figure 4.6 Maximum temperature rise for all SCC mixtures

The results of the heat of hydration tests are given in Table 4.6. Although the application of this method to the blended cements (fly ash + cement) is questionable because of the possible undissolved part of the blended cement, the results seem to be logical as the heat of hydration values decrease with increasing amount of fly ash as expected and as obtained from maximum temperature rise determination. For the blended cements, there is some amount of undissolved part in the mixture of nitric and hydrofluoric acid solution. However, at the early ages this undissolved part does not contribute to the hydration reactions. Therefore it can be concluded that application of this method gives an idea about of the hydration heat of cements used in this investigation.

The results obtained in this part are also compatible with the maximum temperature rise test. However, although the maximum temperature in the concrete specimens does not have a regular trend for high-lime fly ash replacement, the heat of hydration decreases regularly as the amount of

replacement increases. For low-lime fly ash replacement, both the maximum temperature rise for concrete specimens and the heat of hydration of cement pastes show a similar trend.

Table 4.6 Heat of hydration of cement-fly ash pastes

Mix ID	W/CM ratio	% of FA	Heat of Hydration, kj/kg	
			3 days	7 days
1	0.35	0	232.2	313.4
2	0.35	30	209.4	287.8
3	0.35	40	201.8	254.6
4	0.35	50	165.9	169.9
5	0.35	60	132.2	151.7
6	0.35	70	109.7	148.7
7	0.34	30	156.8	257.2
8	0.32	40	155.5	240.3
9	0.30	50	135.2	196.9
10	0.30	60	122.8	186.8
11	0.29	70	118.3	175.4

4.2 Hardened Concrete Properties

4.2.1 Compressive strength

The compressive strength test results are given in Table 4.7. Each strength value is an average of 3 specimens. The compressive strength of SCC mixtures were in the range of 14.9 to 55.9, 32.8 to 62.2, 39.4 to 69.9, 43.0 to 71.0 and 51.8 to 75.6 MPa at 7, 28, 90, 180 and 360 days, respectively. As it was expected, increasing the FA content reduced the compressive strength considerably, especially at earlier ages. At 7 days, compared to the control mixture the cylinder compressive strength was reduced by 29 % in average for a 30 % fly ash replacement, and by 70 % for a 70 % fly ash replacement. While at 28 days, the strength of the 30 % fly ash containing SCC mixtures was only slightly lower (12 % in average) than the control mixture, though a 70 % fly ash replacement still resulted in a 46 % average strength reduction.

At later ages, the contribution of fly ash to compressive strength became more pronounced. At 90 and 180 days, however, the differences between compressive strength of the control mixture and the mixtures containing FA reduced, especially for the mixtures with low-lime FA. The reason behind this observation was the slower activity of the low-lime FA. Moreover, the 90, 180 and 360-day compressive strengths were higher for the low-lime FA when compared to the high-lime FA because of the reduced W/CM ratio for those mixtures. At the end of 360 days, the compressive strength of SCC mixtures with 30 and 40 % low-lime FA replacement were equal (75.6 MPa) and higher than the control mixture (74.1 MPa). Dunstan (1986) points out that the contribution of fly ash to strength is more sensitive to the W/CM ratio than the contribution of cement, and consequently concrete containing fly ash should be prepared at a W/CM ratio as low as possible. The results of equal strength at the end of 360 days for 30 and 40% of low-lime fly ash replacement confirmed

that at a lower W/CM ratio, the contribution to concrete strength by fly ash was greater than at a higher W/CM ratio as the W/CM ratio was 0.34 and 0.32 for the SCC incorporating 30 and 40 % low-lime fly ash, respectively.

Table 4.7 Compressive strength of SCC

Mix ID.	W/CM ratio	% of FA	Compressive Strength (MPa)				
			7 days	28 days	90 days	180 days	360 days
1	0.35	0	55.9 [4.5]*	62.2 [3.3]	69.9 [5.09]	71.0 [1.7]	74.1 [7.4]
2	0.35	30	40.6 [0.5]	57.3 [4.7]	64.9 [4.1]	66.2 [1.4]	70.7 [4.8]
3	0.35	40	37.4 [1.5]	59.1 [3.5]	61.5 [1.5]	68.3 [1.7]	67.3 [1.0]
4	0.35	50	24.5 [4.3]	40.8 [4.9]	47.1 [3.4]	51.0 [3.9]	54.6 [3.1]
5	0.35	60	21.9 [1.2]	38.1 [2.9]	48.8 [3.2]	51.7 [4.4]	56.4 [6.6]
6	0.35	70	14.9 [3.2]	34.4 [2.7]	39.4 [9.6]	43.0 [2.4]	51.8 [2.2]
7	0.34	30	38.6 [3.2]	52.4 [3.0]	64.9 [0.7]	69.2 [4.0]	75.6 [1.8]
8	0.32	40	34.5 [4.7]	52.3 [4.1]	63.2 [5.3]	67.2 [2.8]	75.6 [5.2]
9	0.3	50	32.0 [2.4]	47.5 [2.3]	59.9 [1.2]	68.7 [2.5]	70.0 [3.2]
10	0.3	60	22.8 [4.8]	39.9 [3.5]	52.1 [3.5]	62.6 [3.8]	65.8 [4.4]
11	0.29	70	18.3 [2.4]	32.8 [3.4]	45.0 [2.5]	53.7 [0.6]	61.6 [1.8]

* Numbers in parentheses are the coefficients of variation (%).

The abovementioned observations are graphically shown in Figure 4.7. In the figure, the compressive strengths at all ages are normalized with the compressive strength of the control mixture at that age. Therefore, at each age, % compressive strength versus % FA replacement data were plotted. As seen in Figure 4.7, from 7 to 360 days the compressive strengths of SCC mixtures with FAs are increasing to reach the compressive strength of the control mixture. For example, at 30% FA replacement, only 90% of the compressive strength of the control mixture could be obtained (for both FA types) at 28 days, whereas at 360 days the compressive strengths were more or less the same depending on the FA type. However, as the FA replacement level increased up to 70%, the compressive strength reductions were more visible. For example, at 70% replacement level only 55% of the compressive strength could be achieved at 28 days, for both FA types. At 360 days, however, only 70% of the compressive strength was achieved for high-lime FA and only 84% was achieved for low-lime FA.

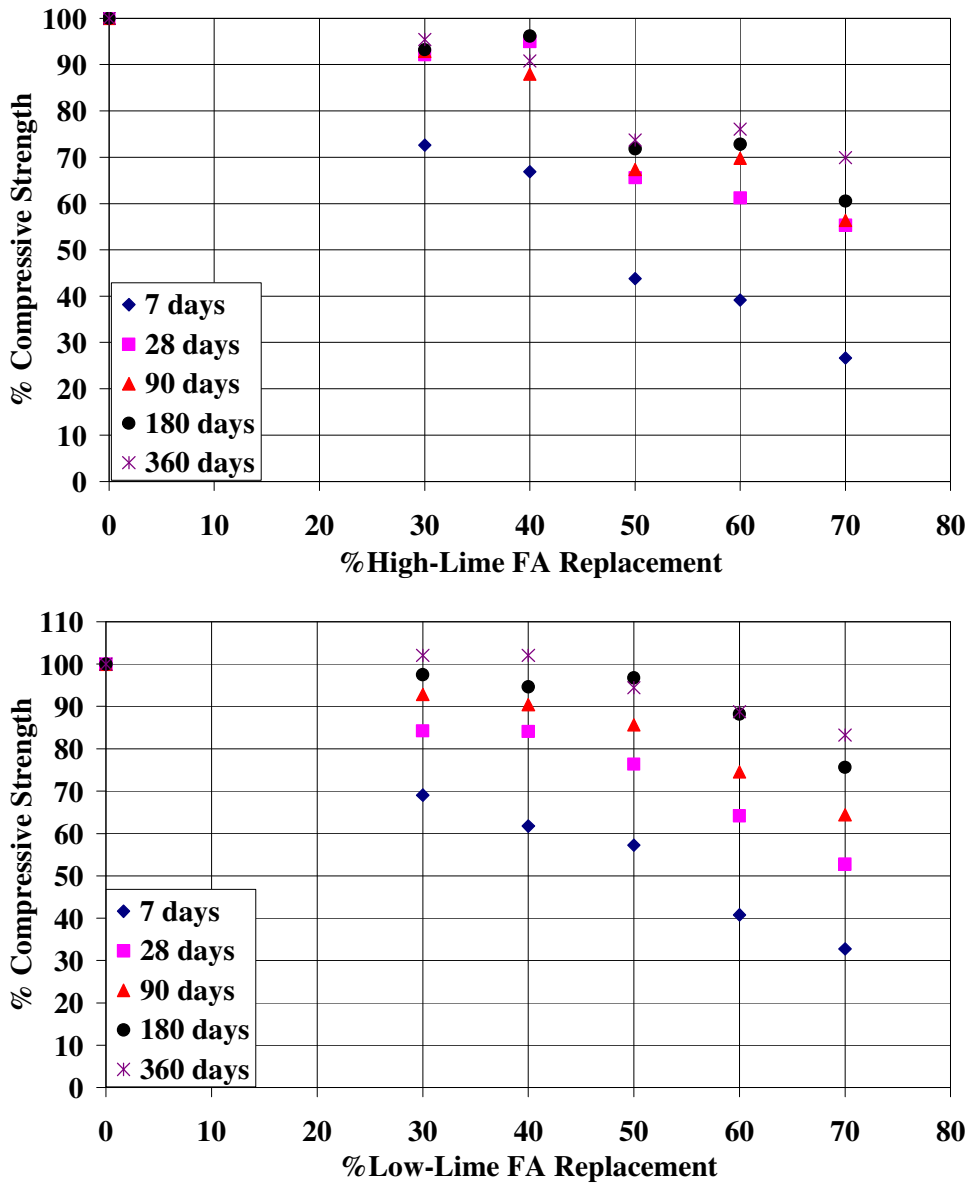


Figure 4.7 Compressive strength reduction in SCC mixtures with FA replacement

4.2.2 Split tensile strength

The results of split tensile strength tests at 28, 90 and 180 days are presented in Table 4.8. The results are average of 3 specimens. The split tensile strength

ranges from 3.22 to 5.07 MPa, 3.64 to 5.14 MPa and 4.19 to 5.64 MPa at 28, 90 and 180 days, respectively. The split tensile strength of all SCC mixtures increased with age. The results showed that, an increase in the fly ash content decreased the split tensile strength of the SCC especially at 28 days. On the other hand, SCC mixtures containing 30-50% fly ash replacement showed higher split tensile strength than SCC mixtures containing 60-70% fly ash replacement. This indicates that up to a 50% of fly ash replacement may have positive effects on the interfacial bond between the paste and aggregates. The mixtures containing 60-70% fly ash showed lower tensile strength, probably due to the weaker bond between the matrix and the aggregates. This may be attributed to the unhydrated FA particles that are present in the matrix, acting as fillers that are present because of the lack of a CH compound.

Table 4.8 Split tensile strength of SCC

Mix ID.	W/CM ratio	% of FA	Split Tensile Strength (MPa)		
			28 days	90 days	180 days
1	0.35	0	5.07 [6.9]*	5.14 [9.4]	5.55 [12.4]
2	0.35	30	4.39 [6.2]	4.89 [11.2]	4.94 [3.6]
3	0.35	40	4.50 [3.1]	4.84 [10.9]	5.64 [6.9]
4	0.35	50	3.40 [2.4]	4.36 [17.3]	4.73 [3.4]
5	0.35	60	3.22 [9.0]	3.92 [7.2]	4.35 [4.4]
6	0.35	70	3.44 [6.8]	3.64 [21.9]	4.19 [2.2]
7	0.34	30	4.71 [3.4]	5.06 [6.5]	5.09 [14.2]
8	0.32	40	3.87 [13.4]	4.15 [6.1]	5.29 [16.3]
9	0.3	50	4.03 [8.2]	4.74 [7.3]	5.22 [9.8]
10	0.3	60	3.69 [6.0]	4.44 [26.1]	4.90 [2.0]
11	0.29	70	3.26 [4.2]	3.72 [15.3]	4.55 [2.4]

* Numbers in parentheses are the coefficients of variation (%)

In Figure 4.8, the split tensile strengths at all ages are normalized with the split tensile strength of the control mixture at that age. Therefore, at each age, % split tensile strength versus % FA replacement data were plotted. From these figures, observations similar to compressive strength could be made. At lower fly ash replacement levels (30 - 40 %), the split tensile strengths were similar to that of control mixture and as the replacement level increased split tensile strength reductions were more visible for both fly ash types.

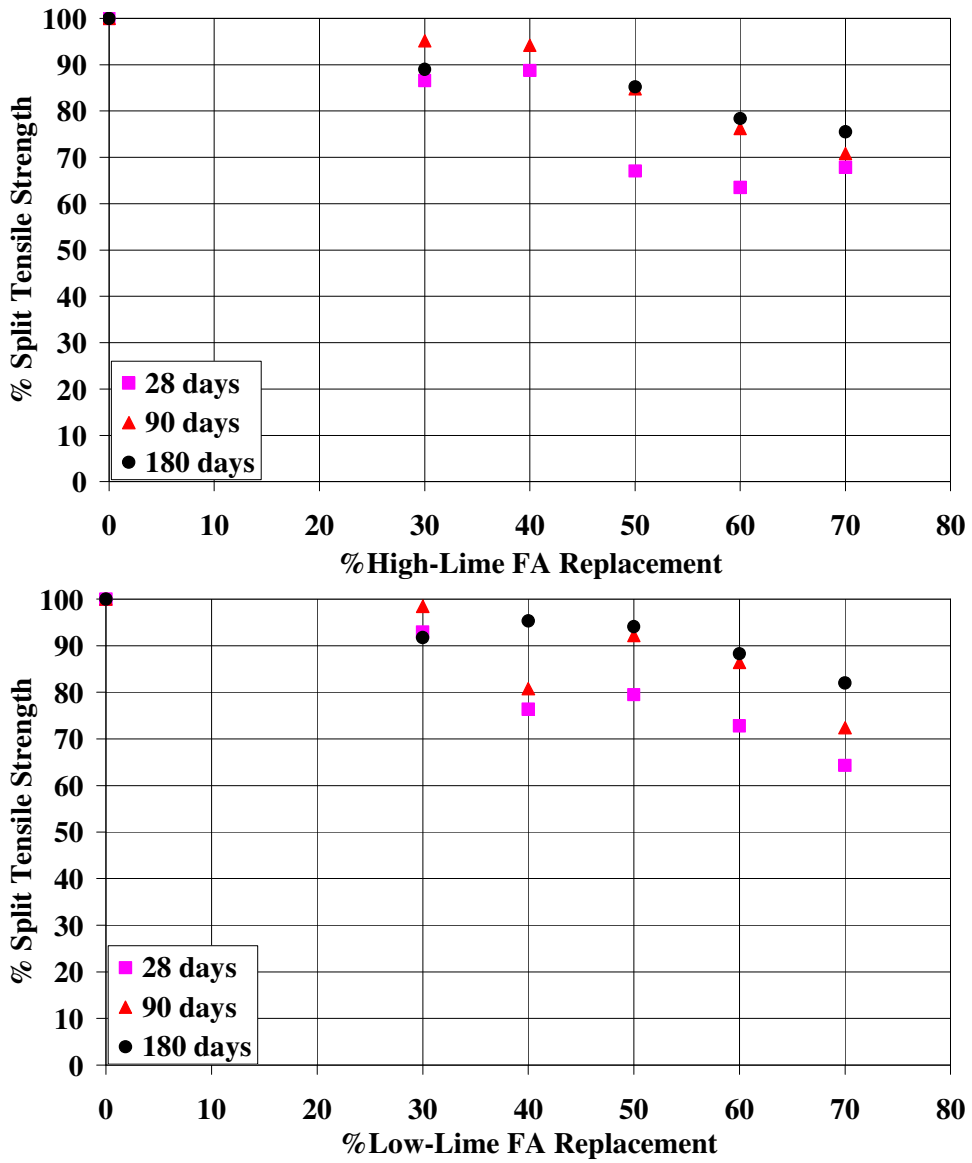


Figure 4.8 Split tensile strength reduction in SCC mixtures with FA replacement

The relation between split tensile strength and compressive strength is presented in Figure 4.9. It can be concluded that the two mechanical properties are highly correlated.

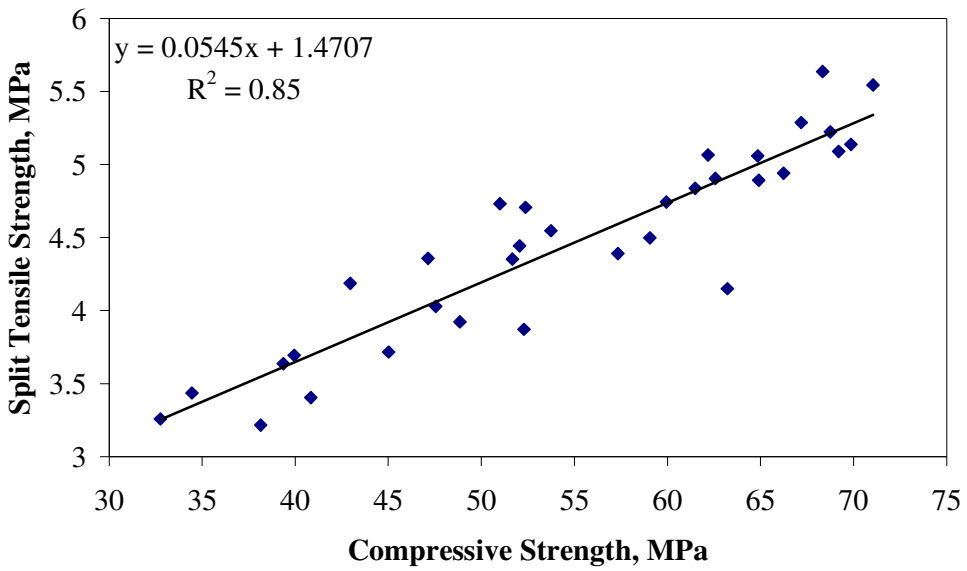


Figure 4.9 Relation between the compressive and the split tensile strength

4.2.3 Drying shrinkage

Drying shrinkage test results obtained at 7, 14, 28, 56, 112, 225 and 360 days for all SCC mixtures are presented in Table 4.9. The SCC mixtures produced in this study had nearly the same W/CM ratio so varying water requirements was not a factor for different drying shrinkage values. The drying shrinkage strains at the age of 360 days ranged between 362 and 695 micro-strain. SCC mixtures with no fly ash (Mix 1) had exhibited the highest drying shrinkage of 695 micro-strain at the end of 360 days. There are no definite trends relating fly ash content to shrinkage which are consistently visible throughout the data.

Performance grades for drying shrinkage are given in Table 3.4 in Chapter 3. All SCC mixtures with fly ash have a shrinkage grade of moderate except Mix 7 at the end of 360 days. Bouzoubaa and Lachemi (2001) also reported that any significant difference for drying shrinkage between normal concrete and SCC incorporating fly ash could not be found.

Table 4.9 Drying shrinkage of SCC mixtures

Mix ID	W/CM ratio	% of FA	Shrinkage Strain,× 10^{-6}						
			7 days	14 days	28 days	56 days	112 days	225 days	360 days
1	0.35	0	214	296	363	475	512	690	695
2	0.35	30	105	113	237	324	337	460	499
3	0.35	40	83	112	137	240	306	405	457
4	0.35	50	104	237	299	410	413	408	462
5	0.35	60	76	97	244	391	350	376	411
6	0.35	70	71	120	202	322	352	365	452
7	0.34	30	13	103	200	303	337	347	362
8	0.32	40	2	46	120	288	375	355	449
9	0.30	50	31	123	255	293	365	391	473
10	0.30	60	83	122	377	425	442	534	598
11	0.29	70	74	115	319	337	395	380	427

4.2.4 Unit weight and ultrasonic pulse velocity (UPV)

Table 4.10 presents the dry and saturated surface dry unit weight of all SCC mixtures at 28 days. The ultrasonic pulse velocity (UPV) and density were measured for all SCC mixes at 7, 28, 90, 180 and 360 days. Table 4.11 presents

the averages and the coefficient of variations of the UPV of all specimens tested. At all ages UPV of 6 specimens were measured.

Table 4.10 Unit weight of SCCs

Mix ID	W/CM ratio	% of FA	Unit weight (kg/m^3)	
			Dry	SSD*
			28 d.	28 d.
1	0.35	0	2282	2380
2	0.35	30	2242	2325
3	0.35	40	2204	2293
4	0.35	50	2166	2297
5	0.35	60	2171	2271
6	0.35	70	2095	2192
7	0.34	30	2242	2330
8	0.32	40	2233	2316
9	0.30	50	2241	2302
10	0.30	60	2233	2291
11	0.29	70	2216	2273

*** SSD: Saturated Surface Dry**

As seen from Table 4.11, the use of fly ash in SCC caused also reductions in the UPV. The reduction in the UPVs was just about in line with the reduction in the compressive strength. The relation between compressive strength and UPV was presented in Figure 4.10. Good correlation (R^2 = 0.75) was found between the compressive strength and UPV. However, more experimental data are needed to establish a better relation.

Table 4.11 Ultrasonic pulse velocity of SCCs

Mix ID.	W/CM ratio	% of FA	UPV (m/s)				
			7 days	28 days	90 days	180 days	360 days
1	0.35	0	4853 [1.8]*	4996 [1.6]	5034 [1.6]	5037 [1.5]	5092 [1.5]
2	0.35	30	4714 [1.7]	4916 [1.5]	4939 [2.0]	4943 [1.4]	4965 [1.2]
3	0.35	40	4716 [2.5]	4916 [1.7]	4902 [1.0]	4923 [1.4]	4929 [2.5]
4	0.35	50	4594 [0.8]	4800 [0.9]	4849 [0.5]	4856 [0.8]	4861 [1.3]
5	0.35	60	4471 [1.5]	4700 [0.9]	4772 [1.0]	4777 [1.0]	4737 [1.1]
6	0.35	70	4231 [1.8]	4518 [2.1]	4601 [1.8]	4603 [1.7]	4553 [1.6]
7	0.34	30	4687 [2.1]	4891 [1.9]	4942 [2.2]	4948 [2.0]	4949 [2.9]
8	0.32	40	4667 [2.6]	4830 [2.1]	4887 [2.2]	4887 [2.1]	4904 [2.7]
9	0.30	50	4723 [2.4]	4903 [1.9]	4943 [1.9]	4991 [1.8]	5006 [1.6]
10	0.30	60	4637 [1.9]	4819 [1.7]	4877 [1.7]	4910 [1.2]	4918 [1.7]
11	0.29	70	4537 [1.6]	4794 [1.4]	4884 [1.4]	4909 [1.2]	4931 [0.9]

* Numbers in parentheses are the coefficients of variation (%).

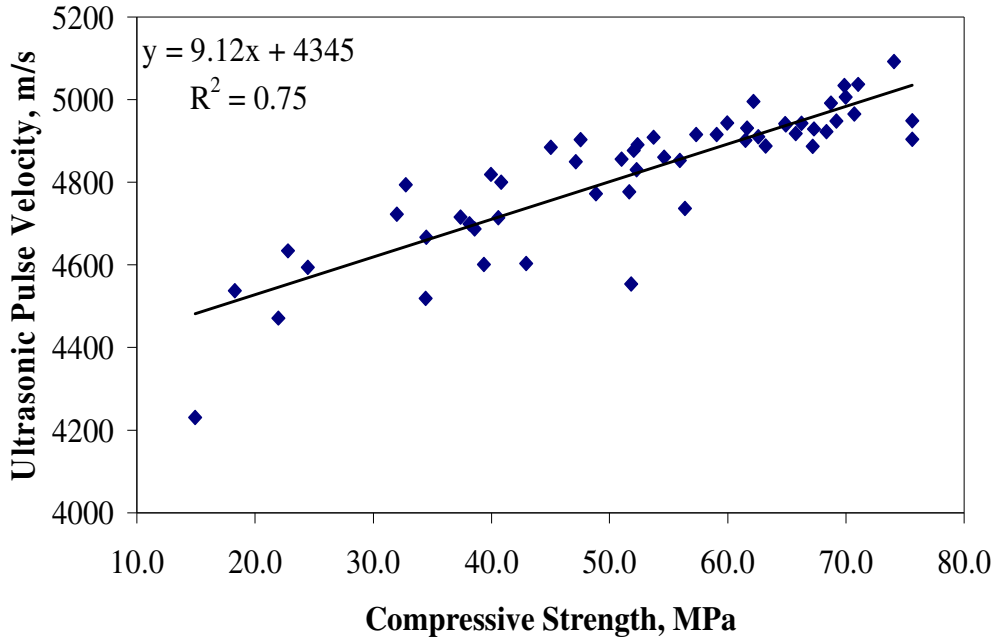


Figure 4.10 Relation between compressive strength and UPV

When the UPV data of 28 and 360 days are normalized with the UPV of the control mixture at that age (Figure 4.11), it can be shown that the reduction in the UPVs was not as drastic as the compressive strength. At 70% replacement level at 360 days, highest reductions were observed in the high-lime FA mixtures, which was on the order of 10%. Therefore, it can be concluded that FA replacement affected UPV to a lesser degree when compared to compressive strength. This is because of the fact that the addition of fly ash affected the pore structure and produced a denser concrete microstructure.

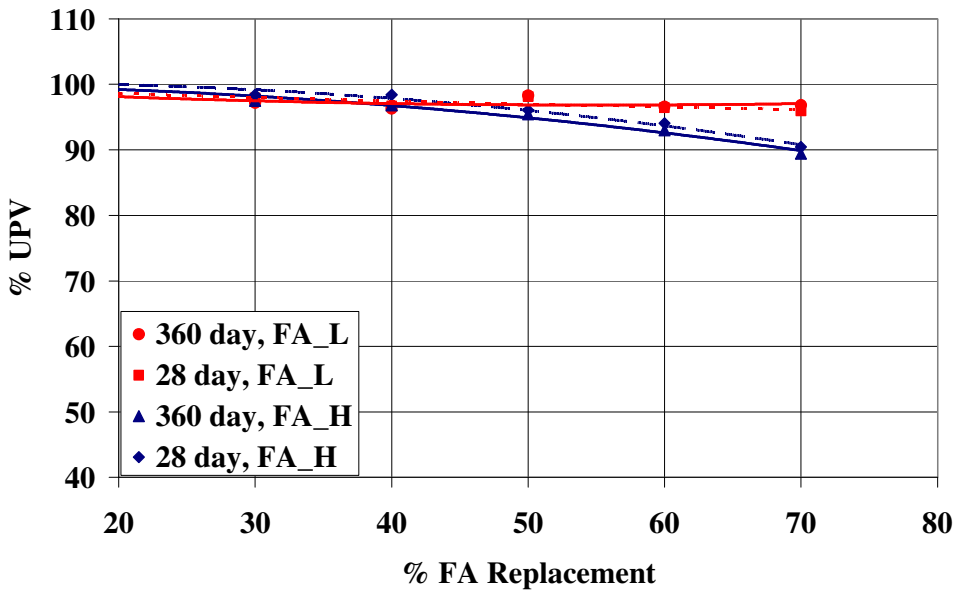


Figure 4.11 UPV reduction in SCC mixtures with FA replacement at 28 and 360 days

4.2.5 Rapid chloride permeability (RCPT)

Figure 4.12 shows the rapid chloride ion permeability of all SCC mixtures measured at 28, 90, 180 and 360 days. The classification ranges given in the ASTM C 1202 are illustrated graphically in Figure 4.12 by horizontal gridlines. When FA was incorporated in the SCC mixtures, RCPT tests showed a reduction in chloride permeability regardless of the FA type. For SCC mixtures containing high-lime FA, chloride ion permeabilities were always lower than the permeability values for the control concrete at the same W/CM ratio. Increases in high-lime FA content showed no significant effect on permeability. The permeabilities of concrete with low-lime FA were also lower than the concrete mixture without FA and the reductions increased with the increasing FA content. At the end of 180 and 360 days, all chloride ion permeability results for the high and low-lime FA were nearly same. The effect of FA on the permeability properties of concretes was also studied by other researchers. For example, Shi (2004) states that the use of supplementary

cementing materials such as fly ash may have a significant effect on the permeability of concrete as measured by the RCPT test. The use of fly ash generally improves the permeability of concrete by reducing the pore sizes and micro-cracking in the transition zone [Mehta and Monteiro, 1997].

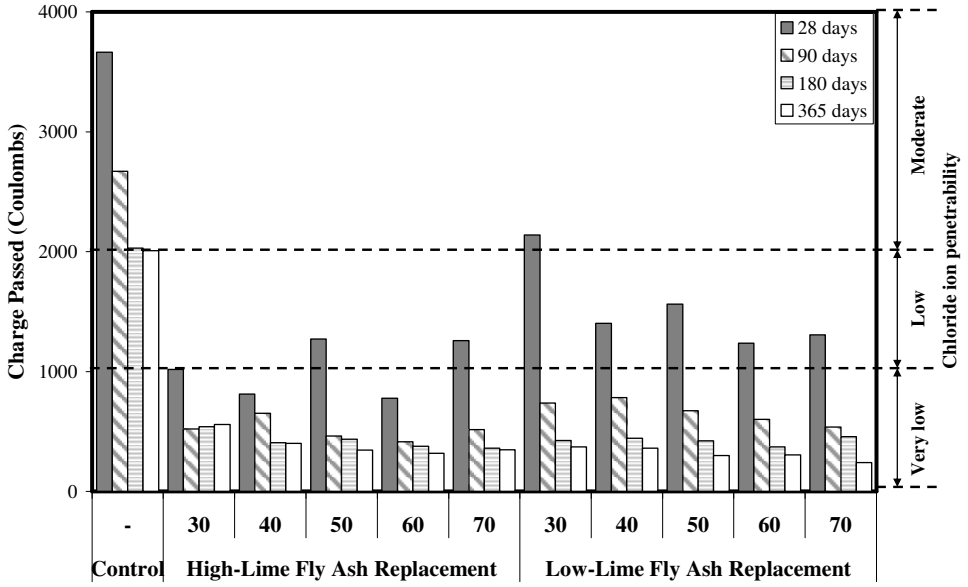


Figure 4.12 Total charge passed after 6 hours for SCC mixtures

4.2.6 Absorption and sorptivity

Both absorption and sorptivity tests are based on water-flow into unsaturated concrete, through large connected pores. Therefore, they both are considered as relative measures of permeability. Table 4.12 and 4.13 presents the absorption and sorptivity of the SCC mixtures determined at 28, 90, 180 and 360 days, respectively. As seen in Table 4.12 and 4.13, both of these test methods resulted a rather crude resolution as dictated by their relatively high coefficient of variation at all ages. The reduction in permeability from 28 days of age to 90

days of age was measurable. On the other hand there was not any measurable reduction in the permeability beyond 90 days of age.

Table 4.12 Absorption test results

Mix ID	W/CM ratio	% of FA	Volume of permeable pores, (%)			
			28 days	90 days	180 days	360 days
1	0.35	0	10.4 [5.6]*	8.5 [9.3]	8.5 [6.6]	8.7 [10.8]
2	0.35	30	8.3 [3.5]	7.3 [6.6]	7.0 [4.0]	6.8 [8.8]
3	0.35	40	8.8 [4.6]	6.0 [9.1]	6.3 [15.7]	6.3 [6.4]
4	0.35	50	13.0 [11.3]	6.4 [6.0]	6.6 [2.1]	6.1 [11.9]
5	0.35	60	10.0 [12.1]	6.5 [4.8]	6.3 [15.7]	6.3 [5.2]
6	0.35	70	9.7 [5.3]	7.9 [10.9]	7.4 [5.6]	7.2 [7.7]
7	0.34	30	8.8 [4.9]	6.5 [13.0]	5.4 [15.9]	5.3 [16.1]
8	0.32	40	8.3 [3.9]	7.1 [7.9]	6.1 [7.2]	5.6 [4.5]
9	0.30	50	6.1 [4.6]	5.7 [5.6]	6.1 [9.2]	5.4 [12.4]
10	0.30	60	5.7 [8.1]	5.5 [13.9]	5.3 [3.5]	5.2 [0.8]
11	0.29	70	5.7 [9.0]	5.1 [5.5]	4.9 [5.5]	5.0 [1.4]

* Numbers in parentheses are the coefficients of variation (%).

Table 4.13 Sorptivity test results

Mix ID	W/CM ratio	% of FA	Sorptivity Index, (mm/min$^{1/2}$)			
			28 days	90 days	180 days	360 days
1	0.35	0	0.104 [25.3]	0.090 [20.2]	0.053 [20.7]	0.059 [9.5]
2	0.35	30	0.090 [2.5]	0.063 [7.4]	0.056 [27.6]	0.055 [19.4]
3	0.35	40	0.079 [11.3]	0.042 [6.3]	0.051 [21.5]	0.052 [19.1]
4	0.35	50	0.123 [1.3]	0.052 [11.5]	0.057 [15.0]	0.053 [2.2]
5	0.35	60	0.077 [25.2]	0.047 [7.3]	0.047 [14.8]	0.046 [22.3]
6	0.35	70	0.074 [1.4]	0.067 [8.5]	0.066 [10.8]	0.063 [9.5]
7	0.34	30	0.071 [8.0]	0.038 [13.3]	0.046 [16.2]	0.044 [16.4]
8	0.32	40	0.074 [16.1]	0.036 [14.0]	0.040 [26.4]	0.040 [16.2]
9	0.30	50	0.057 [2.6]	0.041 [13.4]	0.043 [6.2]	0.040 [16.1]
10	0.30	60	0.048 [10.5]	0.043 [22.0]	0.039 [17.2]	0.038 [18.9]
11	0.29	70	0.048 [10.4]	0.039 [6.6]	0.023 [16.7]	0.034 [9.3]

4.2.7 Correlations between the permeability test results

Absorption and sorptivity tests are based on measuring the ingress of water to the capillary pores of an unsaturated concrete, whereas RCPT test is based on the electrical conductivity of the concrete specimen through its connected capillary pores. Therefore, all these test measures are not direct measures of concrete's permeability, but are known to correlate with direct permeability. The relations between each of these permeability measures are presented in Figure 4.13. As seen in that figure, the highest correlations were observed between the volume of permeable pores and the sorptivity, as they measure the same property, i.e. the ingress of water to unsaturated concrete. The correlations between RCPT and the other two permeability measures are quite weak.

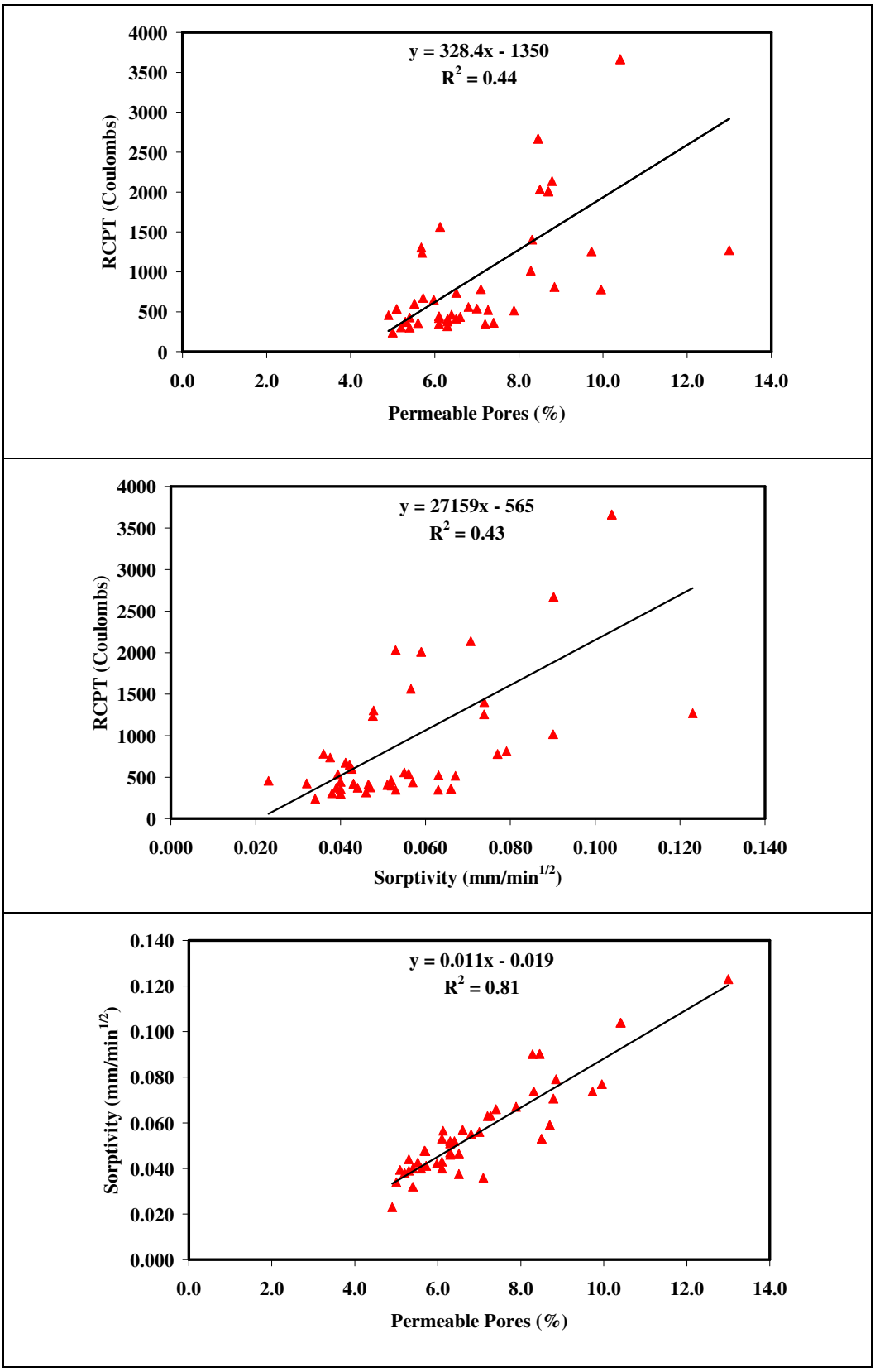


Figure 4.13 Relations of different permeation properties

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

This thesis discusses an experimental program carried out to investigate the effects of incorporating high volume fly ash replacement on the flow characteristics of SCC in the fresh state, and mechanical and permeation properties in the hardened state. Two types of fly ash (low-lime and high-lime) were used. The following conclusions can be drawn according to the results of this study:

- The geometry and surface roughness of the FA affected the workability properties of SCC. In this study, the low-lime FA particles had a spherical geometry and a smooth surface, therefore caused a reduction in the water requirement of SCC.

- Slump flow time, V-funnel flow time and the relative plastic viscosity were found to be related to the viscosity of concrete. The segregation resistance, L-box height ratio, U-box height difference and slump flow diameter were not affected by viscosity. No significant correlation was observed between the relative yield stress and the other workability test results of SCC.

- Decreased concentration of cement was responsible for a longer setting time when compared to a SCC mixture with an equivalent cementitious material content without fly ash. The reduced amount of water and the fineness of the low-lime FA also reduced the setting time of SCC when compared to the mixtures prepared with the high-lime FA.

- The addition of both low-lime and high-lime FAs reduced the rate of hydration reactions due to the pozzolanic activities, thus reduced the temperature rise of the SCC mixtures and heat of hydration of the paste.

- Incorporation of both types of fly ashes at high volumes resulted in an acceptable SCC. Even though, replacing 60 % and 70 % Portland cement with FA resulted in considerable compressive and split tensile strength reductions at early ages, these reductions were partially off-set after 28 days. Moreover, it can be concluded that incorporating high volumes of FA made it possible to produce normal strength SCC with 28 day compressive strengths of 33 to 40 MPa.

- UPV could be used to assess nondestructively the internal structure of concretes. Even though the measured parameters were different, there was a good correlation between the compressive strength and UPV test results. On the other hand, FA replacement affected UPV to a lesser degree when compared to compressive strength. For example, with a 70% replacement of cement by high-lime FA, the reduction in UPV was 10%, compared to 30% reduction in the compressive strength at 360 days.

- For the drying shrinkage, both low-lime and high-lime fly ashes reduced the shrinkage of SCC mixtures. However, there are no definite trends relating fly ash inclusion level to drying shrinkage.

- When evaluating the durability of SCC by its permeability as measured by RCPT, absorption and the sorptivity tests, addition of FA at high volumes seemed to be beneficial (especially low-lime FA), leading to a more durable concrete. The volume of permeable pores as measured with the absorption test had a reasonably good linear correlation with the sorptivity test as measured within the first two hours of immersion due to the fact that both tests were based on measuring the ingress of water to the capillary pores of an unsaturated concrete. However, both of these test methods could not measure the reduction in permeability after 90 days. After 90 days, the reduction in the permeability was measurable, especially with the rapid chloride permeability test.

- The experimental work demonstrated that it was possible to improve the SCCs performance by adding high volumes of FA which also led to the consumption of this industrial waste, thus leading to a two-fold benefit.

Further investigations have to be carried out regarding the self compacting concrete. One major topic, which has to be studied, is related to the influence of different maximum aggregate size on the rheological properties of self compacting concrete. Also, a detailed investigation has to be carried out in order to obtain an appropriate relationship between the fresh concrete tests. In this study, self compacting concrete was produced by using high volumes of low-lime and high-lime fly ash. In future studies, feasibility of using different types of mineral admixtures can also be used for the production of self compacting concrete.

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Publications

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Awards

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