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EFFECTS OF MINERAL ADMIXTURES ON THE PROPERTIES OF SELF-COMPACTING CONCRETES

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Effects of Mineral Admixtures on the Properties of Self-Compacting Concretes

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Supervisor

Assist. Prof. Dr. Mehmet GESOĞLU

by

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To my family

ABSTRACT

EFFECTS OF MINERAL ADMIXTURES ON THE PROPERTIES OF SELF-COMPACTING CONCRETES

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In this study, the effect of using different kinds of fine materials at varying percentage compositions on the properties of self-compacting concrete was investigated. Mixtures containing various combinations of fly ash, ground granulated blast furnace slag and metakaolin and a mixture incorporating only portland cement as the binder material were produced at a constant water-to-binder ratio. For each mixture, to attain a self-compacting concrete, the amount of superplasticizer to be used was determined during the slump flow test. The concretes were also tested for workability and mechanical properties. A total of 11 concrete mixtures were designed having a constant water/binder ratio of 0.32 and total binder content of 550 kg/m^3. The control mixture included only a portland cement as the binder while the remaining mixtures incorporated binary and ternary cementitious blends of portland cement. After mixing, the fresh properties of the concretes were tested for slump flow time, L-box height ratio, V-funnel flow time and unit weight. Moreover, on the separated mortar phase of the mixtures, initial and final setting times and viscosity were measured. From each mixture, three cubes were also taken to test the ultrasonic pulse velocity and compressive strength respectively. The performances of mineral admixtures used varied for different tests. When the workability is of concern, the fly ash had the most favorable effect. On the other hand, regarding the strength of concretes metakaolin had the best performance compared to the other mineral admixtures used.

Keywords: Self compacting concrete, Metakaolin, Fly ash, Ground granulated blast furnace slag, Fresh properties, Hardened properties.

ÖZET

MİNERAL KARIŞIMLARIN KENDİLİĞİNDEN YERLEŞEN BETONLARIN ÖZELLİKLERİ ÜZERİNDEKİ ETKİLERİ

YANAR, Mehmet Tolga
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Bu tez çalışmasında, değişik tür ve oranlarda mineral katkı kulanımının kendiliğinden yerlesen betonun özellikleri üzerindeki etkisi araştırılmıştır. Değişik kombinasyonlarda uçucu kül, metakaolin, curuf ve portland çimentosu içeren karışımlar ile yalnızca portland çimentosu içeren karışım aynı su/bağlayıcı madde oranıyla üretilmiştir. Elde edilen betonun kendiliginden yerleşebilme özelliği taşıması için kullanılması gereken superakışkanlaştırıcı miktarı her karışımda yayılma deneyi ile belirlenmiştir. İşlenebilirlik ve mekanik özellik testleri uygulanarak sonuçlar yorumlanmıştır. Deneysel çalışma kapsamında toplam 11 beton karışımı 0.32 su/bağlayıcı oranı ve 550 kg/m^3 toplam bağlayıcı içerecek şekilde dizayn edilmiştir. Karışımlar için portland çimentosu kullanılan temel bağlayıcı yanında birli ve ikili farklı bağlayıcı karışımları kullanılmıştır. Karışımlardan sonra taze betonun özelliklerinden slump akış zamanı, L-kutusu yükseklik oranı ve V-hunisi akış zamanı ve birim ağırlık ölçülmüştür. Daha sonra karışımlardan ayrıştırılan harç fazının ilk ve son prizlenme zamanı ve viskozitesi ölçülmüştür. Her karışımdan üç küp ve üç silindir sırasıyla ultrasonik ses hızı ve basınç dayanımları alınmıştır. Kullanılan mineral katkıların değişik testlerdeki performansları farklılıklar göstermektedir. İşlenebilirlik özelligi esas alındığında, uçucu kül içeren karışımlarda en iyi sonuçlar alınmıştır. Buna karşılık, mekanik özellik testlerinde, metakaolin kullanılan karışımların diğer mineral katkı içeren karışımlara göre daha yüksek performans sergilediği saptanmıştır.

Anahtar Kelimeler: Kendiliğinden yerleşen beton, Metakaolin, Uçucu kül, Yüksek fırın curufu, Taze özellikler, Sertleşmiş özellikler.

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LIST OF SYMBOLS / ABBREVIATIONS

d	Diameter of Slump Flow
F	Shear Force
A	Area of Plane parallel to force
N	Length of Near Field Zone
D	Diameter of Transducer
a	Flow Time 1
b	Flow Time 2
H_1	Initial Length of L-box
H_2	Interval Length of L-box
T_{500}	Slump Flow Time
T_{200}	L Box flow time in 20 cm
T_{400}	L Box flow time in 40 cm
IS	Initial Setting
FS	Final Setting
SCC	Self Compacting Concrete
SP	Superplasticizer
MA	Mineral Admixture
EFNARC	European Federation of National Trade Association
GBS	Ground Granulated Blast Furnace Slag
FA	Fly Ash
MK	Metakaolin

PC	Portland Cement
PE	Polycarboxylate Ester
ASTM	American Society for Testing and Materials
NIST	National Institute of Standards and Technology

1. INTRODUCTION

1.1 General

Self-compacting concrete was developed in Japan to facilitate the placing without vibration, and with no occurrence of segregation or bleeding. The demand for self-compacting concrete increased as its beneficial effects were better realized by the construction industries in numerous countries. As the use of self-compacting concrete became a common practice, a great amount of research was carried out on how to improve its properties such as workability, strength and durability. As a resists, new types of superplasticizers which have additional properties and eliminate the common deficiencies of the current self-compacting concretes were developed one after the other in the short history of self-compacting concrete.

As mentioned earlier SCC is a new concrete technology and therefore there aren't any standards describing the requirements of SCC. The only available standard is published by EFNARC (European Federation of National Trade Associations) (2002) which is the European federation dedicated to special construction chemicals and concrete systems (EFNARC, 2002). EFNARC lists the three workability requirements of SCC as its filling ability, passing ability and segregation resistance and just like the conventional concrete there isn't a single test method to measure the above mentioned workability parameters. Therefore, a list of test methods is described to determine the workability properties of SCC. Among these, slump flow, V-funnel and L-box are the most widely accepted and used tests. It should be mentioned here in that all these tests are empirical but quantitative test procedures to assess the workability properties of SCC.

The objective in this thesis is to investigate the effect of mineral admixtures (focused to metakaolin especially) in binary (two-component) and ternary (three-component) blends on the fresh and hardened properties of self compacting concretes. In this context three mineral admixtures, both pozzolanic and non-pozzolanic, namely, fly-ash, ground granulated blast furnace slag and metakaolin are utilized.

A total of 11 SCC mixtures were prepared and slump flow, L-box height ratio and V-funnel flow, fresh density, viscosity and setting properties are determined as for the fresh properties. Hardened properties that are considered are the compressive strength and ultrasonic pulse velocity which were determined at 28, and 90 days of age.

1.2 Scope

This thesis consists of five Chapters. Chapter 2 presents a literature review and gives a general background on SCC. This chapter includes the test methods to assess workability of SCC and the use of mineral admixtures as cement replacement.

Chapter 3 presents the experimental program, briefly explains the test procedures, and summarizes the experimental data.

Chapter 4 presents the results of the test program focusing on the fresh properties of SCC. The effect of mineral and chemical admixture on the workability and setting properties of SCC are also explained. This chapter also includes the effect of mineral and chemical admixtures on the hardened properties of SCC.

Chapter 5 gives a summary of thesis and lists the results of this research. Possible further research studies complementing this thesis are also included in Chapter 5.

2. LITERATURE REVIEW AND BACKGROUND

2. 1 Self Compacted Concrete (SCC)

2.1.1 Definitions

EFNARC (2002) defined SCC as “Concrete that is able to flow under its own weight and completely fill the formwork, even in the presence of dense reinforcement, without the need of any vibration, whilst maintaining homogeneity”. Shindoh and Matsuoka (2003) defined SCC as “concrete that has excellent deformability, high resistance to segregation, and can be filled into heavily reinforced areas without applying vibration”. From many other researches and the experimental work of this study, this definition can be suggested for SCC:

High performance self-compacting concrete that is able to flow under its own weight up to leveling, completely fill the formwork even in the presence of dense reinforcement, airs out, compacts and consolidates without the need of any vibration, whilst maintaining homogeneity due to high resistance to segregation.

2.2 Properties of Fresh SCC

2.2.1 Rheology

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, the 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 et al., 1983).

The rheology of fresh concrete, however, is most often described by the Bingham model. 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 et al., 1983). According to this model, fresh concrete must overcome a limiting stress before it can flow. Once the concrete starts to flow, shear stress increases linearly with an increase in strain rate as defined by plastic viscosity. Therefore, in order to fully describe the rheological properties of fresh concrete by the Bingham model two parameters, namely the plastic viscosity and the yield stress are necessary (Ozawa et al., 1989).

Sonebi (2004) reported that the incorporation of pulverized fuel ash and limestone powder lessened the requirement of superplasticizer necessary to obtain the desired slump. The use of these materials also improved the rheological properties and reduced the risk of cracking of concrete due to the heat of hydration, thus leaded to more durable concrete (Sonebi and Bartos, 2002) (Khayat et al., 2000).

Bouzoubau and Lachemi (2002) designed a SCC incorporating high volumes of fly ash to reduce the cost. An economical SCC having a compressive strength of 35 MPa was produced at a water-powder ratio of 0.45 and fly ash-cement replacement of 50%. It was found in the work of Ghazel and Khayat (2002) that the replacement of a large volume of cement by limestone powder decreased the cement content needed to achieve a given slump flow, viscosity, and compressive strength at early age.

Nehdi et al. (2003) conducted a study to optimize the cost-effective high volume replacement SCC for deep foundation applications. It was concluded that producing economically competitive SCC can be achieved by replacing up to 50% of portland cement with mineral admixtures. Incorporating such materials further enhanced the rheological behavior and the compressive strength even at early ages. However, the use of mineral admixtures resulted in some deleterious effect on the concretes such as great retardation in the setting time and low early strength (Bouzoubaa and Lachemi, 2001), (Brooks et al., 2000). These negative effects may be hindered by the combined use of the mineral admixtures.

Park et al (2005) investigated the influence of the cementitious materials in one, two, and three-component system on the rheology of the cement paste. The cement was partially replaced by the mineral admixtures in the paste mixture. It was found that the two and three-component systems improved the rheological properties of cement paste with only one mineral such as silica fume. To the knowledge of the authors, however, the combined use of the mineral admixtures, especially in binary, ternary, and quaternary blends, has not found adequate attention in the SCC applications in the literature.

One alternative to reduce the cost of SCC is the use of mineral admixtures, which are finely, divided materials added to concrete as separate ingredients either before or during mixing (Erdogan, 1997). If the mineral admixtures can replace some or all of the chemical admixtures without any loss in the fresh properties of SCC, the cost will be reduced especially if the mineral admixture is an industrial by-product or waste. Moreover, the mineral admixtures will also increase the durability & long-term strength.

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. Therefore, there isn't a consensus on the rheological properties of SCC that are available in the market (NIST, 1999). In a comprehensive study by NIST, a series of twelve concrete mixtures was tested by five rheometers. The mixtures had slumps ranging from 90 mm to 235 mm, but more importantly, they had a wide range of combinations of plastic viscosity. It was found that the rheometers gave different values of the Bingham constants of plastic viscosity, even for those instruments that gave these directly in fundamental units (NIST, 1999).

Banfill (2003) defined rheology as the science of the deformation and flow of matter, and the emphasis on flow means that it is concerned with the relationships between stress, strain, rate of strain, and time. Concrete and mortar are composite materials, with aggregates, cement and water as the main components. Ferraris (1999) described the concrete as really a concentrated suspension of solid particles (aggregates) in a viscous liquid (cement paste). Cement paste is not a homogeneous fluid and is itself composed of particles (cement grains) in a liquid (water). Because concrete, on a macroscopic scale, flows as a liquid, equation (1.1) is applicable. If a shear force is applied to a liquid, as shown in Figure 2.1, a velocity gradient is induced in the liquid. The proportionality factor between the force and the gradient is called the viscosity. The velocity gradient is equal to the shear rate γ•. A liquid that obeys this equation is called Newtonian.

$$\frac{F}{A} = \tau = \eta\dot{\gamma} \qquad \text{(1.1)}$$

Where

η = viscosity

$$\dot{\gamma} = \text{shear rate} = \frac{dv}{dy} \qquad \text{(1.2)}$$

(see Figure 2.1)

$$\tau = \text{shear stress} = \frac{F}{A} \qquad \text{(1.3)}$$

Where

F = shear force

A = area of plane parallel to force.

The common practice to obtain self-compactibility is to limit the coarse aggregate content and to utilize an appropriate mortar. Therefore, mortar serves as the basis for the workability properties of SCC and these properties could be assessed by investigating sieved mortars (Domone and Jin, 1999). In order to achieve self compactibility in SCC usually the sand content in mortar is limited to 40% of mortar volume. Moreover, lower water cement ratios together with superplasticizers are also used (Okamura and Ozawa, 1995).

The common practice to produce self compacting concrete is to limit the coarse aggregate content associated with its maximum size and to use the lower water-binder (powder) ratios together with appropriate superplasticizer (Okamura and Ozawa, 1995). In order to achieve a SCC of high fluidity and to prevent the segregation and bleeding during transportation and placing, the formulators have employed a high portland cement content and used superplasticizer and viscosity modifying additives (Sari et al., 1999) (Saric-Coric et al, 2003). However, the cost of such concretes remarkably increased associated with the use of high volume of portland cement and chemical admixtures. In some cases the savings in labor cost might offset the increased cost. But the use of mineral admixtures such as fly ash, blast furnace slag etc. reduced the material cost of the SCCs and also improved the fresh and hardened properties of the concretes (Şahmaran et al, 2006a) , (Bouzoubaa and Lachemi, 2001).

A number of studies have been reported in the literature concerning the use of mineral additives to enhance the self compactibility characteristics and to reduce the material cost of the SCCs.

Ferraris (1999) also explained that most of the equations used for concentrated suspensions, such as concrete, try to relate the suspension concentration to the viscosity or the shear stress to the shear rate, thus assuming that there is only one value for the viscosity of the whole system. Tables 2.1 and 2.2 give the most commonly used equations in two approaches. Equations from Table 2.1 are used to describe the flow of cement paste, but they are not applicable to concrete due to the complexity of the suspension (aggregates in a suspension (cement paste)). Table 2.2 gives equations commonly used for concrete. It should be noted that quite few of the equations described in Table 2.2 incorporates a second factor, the yield stress. The physical interpretation of this factor is that the yield stress is the stress needed to be applied to a material to initiate flow. For a liquid, the yield stress is equal to the intersection point on the stress axis and the plastic viscosity is the slope of the shear stress - shear rate plot (see Figure 2.2).

A liquid that follows this linear curve is called a Bingham liquid (Ferraris, 1999).

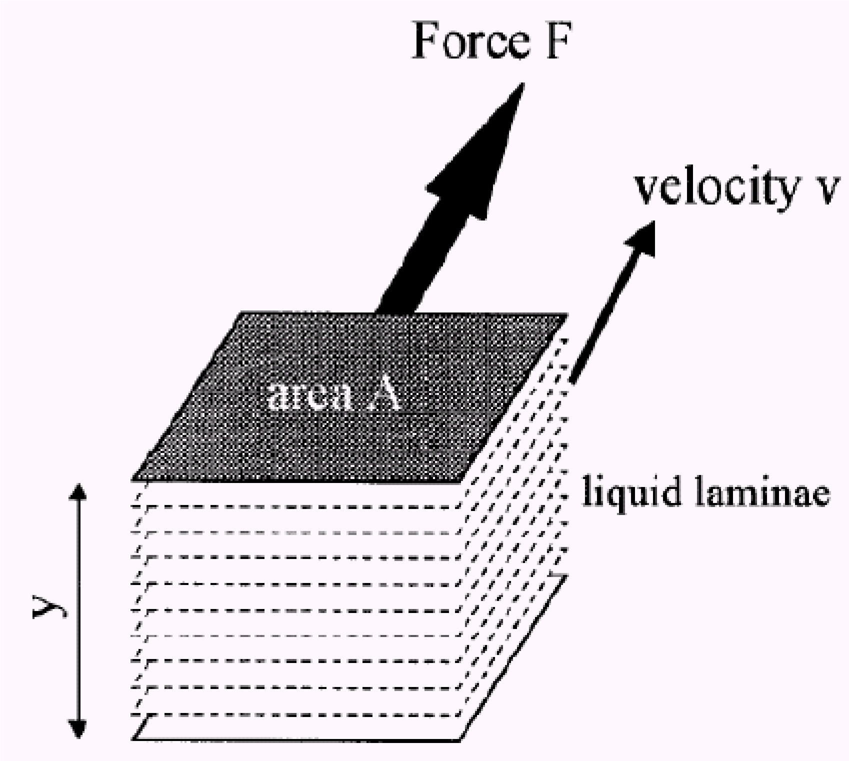


Figure 2.1 Newton's equation of viscous flow (Ferraris , 1999).

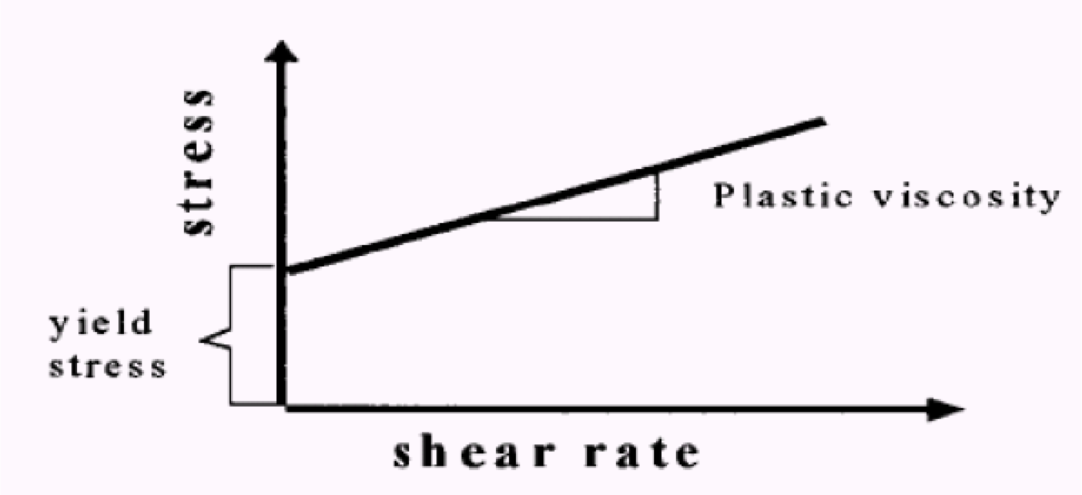


Figure 2.2 Bingham's equation for a fluid (Ferraris, 1999).

Table 2.1 Equations relating viscosity to concentration of suspension (cement paste) (Ferraris, 1999)

Equation name	**Equation**	**Hypothesis**
Einstein	$\eta = \eta 0 (1+ (\eta_i) \varphi)$	No particle interaction, dilute suspension
Roscoe	$\eta = \eta 0 (1- 1.35 \varphi)k$	Considers particle interaction
Krieger-Dougherty	$\eta / \eta 0 = (1- \varphi / \varphi max) -(\eta_i) \varphi max$	Relation between viscosity and particle packing. Takes into account the maximum packing factor
Mooney	$\eta = \eta 0 \exp (((\eta_i)\varphi) / (1-\varphi/\varphi max))$	Takes into account the maximum packing factor
Variable definitions:		
η = viscosity of the suspension φ = volume fraction of solid φmax = maximum packing factor	k = constant $\eta 0$ = viscosity of the liquid / media (η_i) = intrinsic viscosity of the suspension	

Table 2.2 Equations relating shear stress and shear rate (concrete) (Ferraris, 1999)

Equation Name	**Equation**
Newtonian	$\tau = \eta\ \gamma\bullet$
Bingham	$\tau = \tau o + \eta\ \gamma\bullet$
Herschel and Bulkley	$\tau = \tau o + K\ \gamma\bullet\ n$
Power equation	$\tau = A\ \gamma\bullet\ n$ $n = 1$ Newtonian flow $n > 1$ shear thickening $n < 1$ shear thinning
Vom Berg Ostwald-deWaele	$\tau = \tau o + B \sinh -1\ (\gamma\bullet/C)$
Eyring	$\tau = a\ \gamma\bullet + B \sinh -1\ (\gamma\bullet/C)$
Robertson-Stiff	$\tau = a\ (\gamma\bullet + C)b$
Atezeni el al.	$\tau = \alpha\ \tau 2 + \beta\ \tau + \delta$
Variable definition:	
τ = shear stress τo = yield stress	A, a, B, b, C, K, α, β, δ = constants η = viscosity $\gamma\bullet$ = shear rate

Figure 2.3a, 2.3b shows some of the idealized types of curves that can be obtained when shear stress is plotted against shear rate.

All the depicted curves can be described by one of the equations of Table 2.2 Liquids following the power law are also called pseudo-plastic fluids.

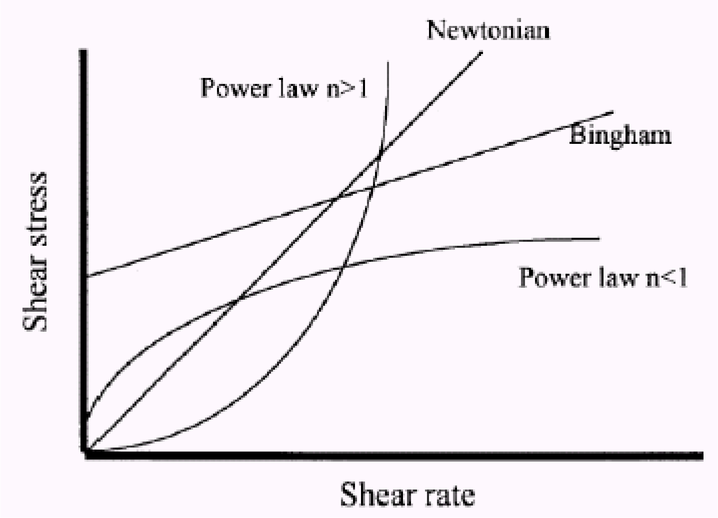


Figure 2.3.a Summary of shapes of shear stress-shear rate curves (Ferraris, 1999).

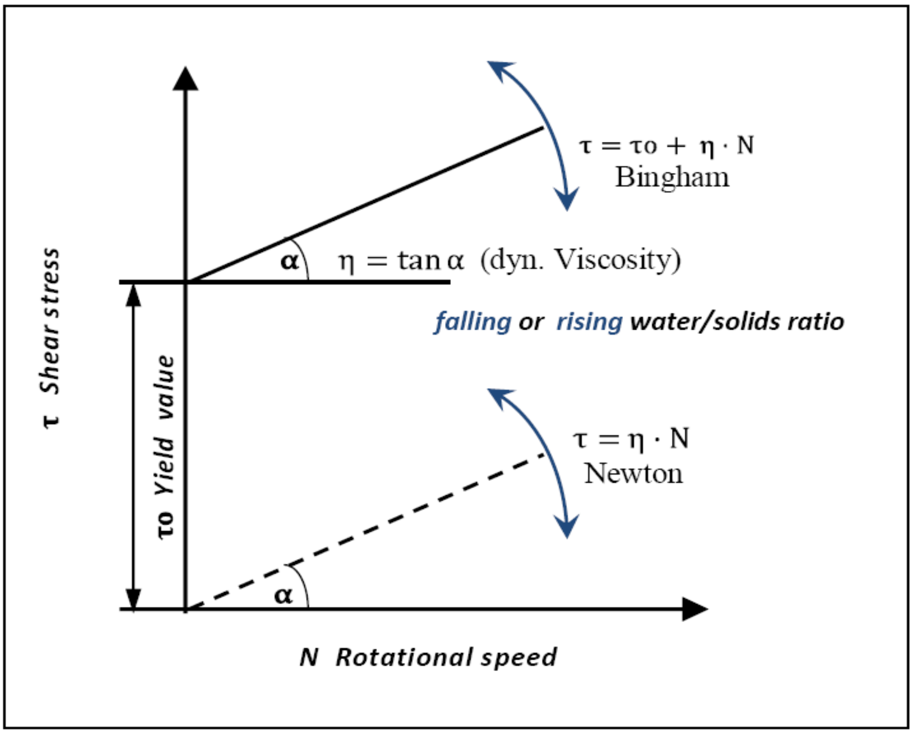


Figure 2.3.b Rheological behaviour of ultrafines/water suspensions without super-plasticizer (≈ Bingham solid), and with super-plasticizer (≈ Newtonian fluid) (Horst Grube and Jörg Rickert, 1999)

Ferraris (1999) considered that the main conclusion that can be deduced from studying the proposed equations is that all (with the exclusion of the Newtonian liquid) use at least two parameters to describe the flow. In the case of a concentrated suspension such as concrete, it has been shown that a yield stress exists.

The equations that have a physical basis which include at least two parameters, with one being the yield stress, are the Herschel-Bulkley and Bingham equations. The Herschel-Bulkley equation contains three parameters, one of which, n, does not represent a physical entity. It has been shown that in certain concretes, such as SCC, this equation is the best that describes their behavior.

Ferraris at al. (2000) stated that if the rheological properties that characterize SCC are examined, the yield stress must be zero or very low and the viscosity must be controlled.

The range of viscosities needed to obtain good consolidation without vibration and without segregation has been the topic of various papers. Most of them used semi-empirical tests such as filling ability tests to characterize concrete flow behavior.

The properties of cement paste or the mortar of SCC were found to be very important to avoid segregation. If the viscosity of the mortar is high enough, the coarse aggregate will be supported by the mortar, thus avoiding segregation. While superplasticizer decreases the yield stress, viscosities such as Viscosity Modifying Agent (VMA) or mineral admixtures are added to increase the viscosity of the paste, without significantly increasing the yield stress.

Sedran (2000) concluded that the rheology of paste or grout could be a useful tool to select a set of cement, mineral addition and superplasticizer to be included in SCC concrete.

With rheological measurements, it is possible to separate the effect of the components on the shear yield stress and the plastic viscosity. The aim, today, is to obtain a combination with a low shear yield stress and a sufficient viscosity which allows to roughly comparing the components. But the acceptable limits are not well defined simply because the question remains how to relate these properties to the concrete behavior at fresh state. More research is needed on this subject.

The rheological properties of the concrete mixtures are measured by using two rheometers, the IBB and the BTRHEOM instruments as shown in Figure 2.4 and Figure 2.5 respectively. The IBB rheometer is developed in Canada and consists of a cylindrical container holding the concrete, with an H-shaped impeller driven through the concrete in a planetary motion. The speed of the impeller rotation is first increased to a maximum rotation rate and then the rotation rate is decreased in six stages with each stage having at least two complete center shaft revolutions.

The torque (N·m) that generated by the resistance of the concrete specimen to the impeller rotation is recorded at each stage as well as the impeller rotation rate (revolutions per second) is measured by the shaft tachometer.

The BTRHEOM is a parallel plate rheometer, i.e., the concrete is sheared between two plates. The plate at the bottom is stationary and the plate at the top rotates with variable speed, similar to the impeller of the IBB rheometer. The torque that generated during rotation is recorded while the rotation rate is first increased and then decreased in stages. The rheological parameters can be calculated using the Bingham equation applied to the torque and rotation rate data of the decreasing speed portion of the test. Due to the simple geometry of the shearing area, it is possible to calculate the results in fundamental units, i.e., (Pa) for yield stress and (Pa·s) for viscosity (Sedran, 2000).

However, it can be said that the rheological philosophy involves large, expensive immobile equipment suitable for the laboratory. The results are very helpful in determining the behavior of SCC as a fluid material, but the tests are slow and most cannot be performed outside of the laboratory. Thus, many other field tests are designed and successfully used. The fresh SCC field test philosophy is much faster, very mobile, suited to laboratory or field conditions and can be performed in the field just prior to concrete placement.

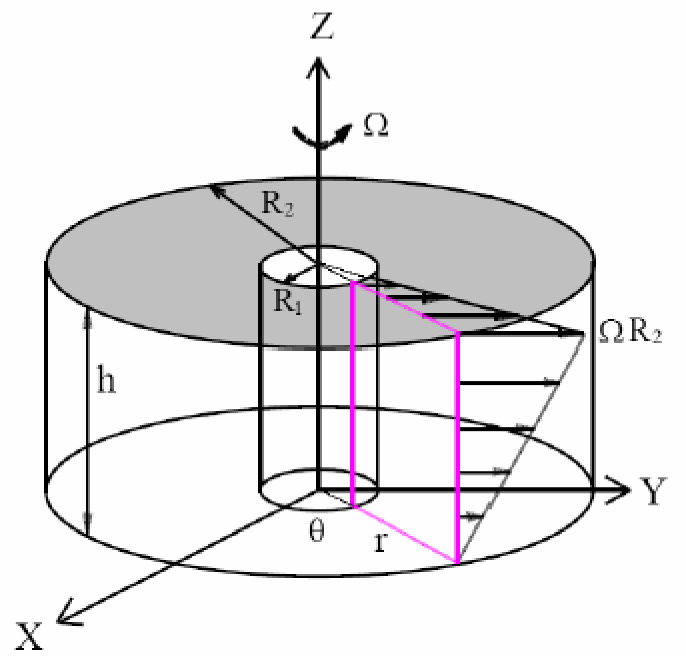


Figure 2.4 Principle of the BTRHEOM (Sedran, 2000).

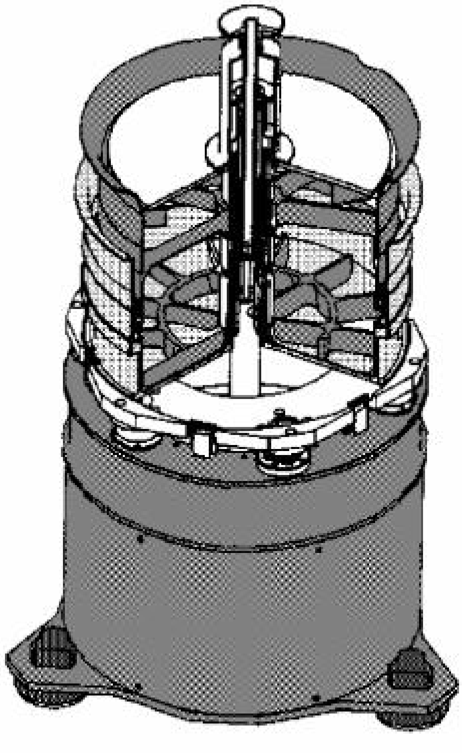


Figure 2.5 The BTRHEOM rheometer (Sedran, 2000).

2.2.2 Workability

2.2.2.1 Introduction

The ACI 116-00 (2000) defined workability as the property of freshly mixed concrete or mortar which determines the ease and homogeneity with which it can be mixed, placed, consolidated and finished.

The ASTM C 125-93 (1993) defined workability as the property that determines the effort required to manipulate a freshly mixed quantity of concrete with minimum loss of homogeneity.

Ferraris et al. (2000) illustrated that the workability is defined either qualitatively as the ease of placement or quantitatively by rheological parameters. They stated that the most common rheological parameters, used to qualify workability, are the yield stress and plastic viscosity, as defined by the Bingham or (in some cases like SCC) Herschel-Bulkley equations.

The workability of SCC is higher than the highest classes of consistence described within international standards, but a highly flowable concrete is not necessary SCC, because SCC should not only flow under its own weight but should also fill the entire form and achieve uniform consolidation without segregation.

2.2.2.2 Key Properties

SCC differs from conventional concrete in that its fresh properties are critical to its ability to be placed satisfactorily. There are three key properties of workability which need to be carefully controlled to ensure satisfactorily performance during its wet phase and for successful classification as SCC.

EFNARC (2002), Tviksta (2000), Vachon (2002), Wüstholz (2003), JSCE (1999) , and all other researchers agreed with the following statements.

“A concrete mix can only be classified as Self-compacting Concrete if the requirements for all three characteristics below are fulfilled’’:

- Filling ability, which is the ability of concrete to flow, maintaining homogeneity whilst undergoing the deformation necessary to completely fill the formwork, encasing the reinforcement and achieving compaction through its own weight. The level of fluidity of the SCC is governed chiefly by the dosing of the Superplasticizer. However, overdosing may lead to the risk of segregation and blockage.

- Segregation resistance, which is the facility of the particle suspension to maintain a cohesive state throughout the mixing, transportation and casting process. Due to the high fluidity of SCC, the risk of segregation and blocking is very high. Preventing segregation is; therefore, an important feature of the control regime. The tendency to segregation can be reduced by the use of a sufficient amount of fines (< 0,125 mm), or using a VMA.

- Passing ability, which is the ability to pass through closely spaced rebars or enter narrow sections in formwork, and to flow around other obstacles without blocking due to aggregate lock. The clearance between reinforcing bars, the volume of coarse aggregate and the rheological properties of matrix play an important role in the passing ability of SCC in congested areas.

2.2.2.3 Test Methods

Many different test methods have been developed in attempts to characterize the properties of SCC. However, due to the newness of SCC and its simultaneous development under multiple agencies, few to no testing procedures have been standardized. This has lead to the attempt of different standardization organizations to develop their own testing equipment having different dimensions and varying procedures. This becomes a problem, but is currently being addressed by organizations such as ASTM. ASTM Committee C09 on Concrete and Concrete Aggregates has begun work toward developing standards for SCC. So far no single method or combination of methods has achieved universal approval and most of them have their adherents. Similarly no single method has been found which characterizes all the relevant workability aspects so each mix design should be tested by more than one test method for the different workability parameters.

For the initial mix design of SCC, all three workability parameters need to be assessed to ensure that all aspects are fulfilled. For site quality control, two test methods are generally sufficient to monitor production quality. With consistent raw material quality, a single test method operated by a trained and experienced technician may be sufficient.

Workability tests for SCC can be broadly split into three categories: filling ability tests, passing ability tests and segregation resistance tests. Each test fits into one or more of these categories. Test methods for the three parameters are listed in Table 2.3.

Table 2.3 List of test methods for workability properties of SCC

Property	**Method**
Filling ability	Slump-flow by Abrams cone
	T50cm slump-flow
	Ormit
Passing ability	J-ring
	L-box
	U-box
	Fill-box
Segregation resistance	GTM screen stability test
	V-funnel at T5minutes
Filling ability + Segregation resistance	V-funnel

2.2.2.4 Test Methods for Assessing the Workability of SCC

As mentioned earlier, the measurement of the two parameters of the concrete flow by a rheometer is not practical, and not yet standardized. Therefore, there are other, more practical, test methods in assessing the workability of SCC. However, it should not be forgotten that these practical test methods are also not standardized by any standardization agency. The only agency that has listed these test methods is EFNARC, yet, it is also mentioned by EFNARC that these methods are descriptions and not definitive test procedures. In this section, brief descriptions of these test procedures will be provided.

2.2.2.5 Test Methods For Achieving SCC

It is important to appreciate that none of the test methods for SCC has yet been standardized, and the tests described are not yet perfected or definitive. The methods presented by Efnarc (2002) are descriptions rather than fully detailed procedures. They are mainly ad-hoc methods, which have been devised specifically for SCC. (Efnarc, 2002)

In considering these tests, there are a number of points which should be taken into account:

- one principal difficulty in devising such tests is that they have to assess three distinct, though related, properties of fresh SCC – its filling ability (flowability), its passing ability (free from blocking at reinforcement), and its resistance to segregation (stability). No single test so far devised can measure all three properties.
- there is no clear relation between test results and performance on site;
- there is little precise data, therefore no clear guidance on compliance limits;
- duplicate tests are advised;
- the test methods and values are stated for maximum aggregate size of up to 20 mm; different test values and/or different equipment dimensions may be appropriate for other aggregate sizes;

- different test values may be appropriate for concrete being placed in vertical and horizontal elements;
- similarly, different test values may be appropriate for different reinforcement densities;
- in performing the tests, concrete should be sampled in accordance with EN 12350-1. It is wise to remix the concrete first with a scoop, unless the procedure indicates otherwise. (Efnarc, 2002)

A) Slump Flow Test and T50cm Test

The slump flow is used to assess the horizontal free flow of SCC in the absence of obstructions. It was first developed in Japan (Japan Society of Civil Engineers, 1992) for use in assessment of underwater concrete. The test method is based on the test method for determining the slump. The diameter of the concrete circle is a measure for the filling ability of the concrete. (Efnarc, 2002)

Slump-flow value describes the flowability of a fresh mix in unconfined conditions. It is a sensitive test that will normally be specified for all SCC, as the primary check that the fresh concrete consistence meets the specification. Visual observations during the test and/or measurement of the T_{500} time can give additional information on the segregation resistance and uniformity of each delivery.

This is a simple, rapid test procedure, though two people are needed if the T50 time is to be measured. It can be used on site, though the size of the base plate is somewhat unwieldy and level ground is essential. It is the most commonly used test, and gives a good assessment of filling ability. It gives no indication of the ability of the concrete to pass between reinforcement without blocking, but may give some indication of resistance to segregation. It can be argued that the completely free flow, unrestrained by any boundaries, is not representative of what happens in practice in concrete construction, but the test can be profitably be used to assess the consistency of supply of ready-mixed concrete to a site from load to load. (Efnarc, 2002)

The following are typical slump-flow classes for a range of applications: SF1 (550 - 650 mm) is appropriate for:

- unreinforced or slightly reinforced concrete structures that are cast from the top with free displacement from the delivery point (e.g. housing slabs)
- casting by a pump injection system (e.g. tunnel linings)
- sections those are small enough to prevent long horizontal flow (e.g. piles and some deep foundations).

SF2 (660 - 750 mm) is suitable for many normal applications (e.g. walls, columns)
SF3 (760 – 850 mm) is typically produced with a small maximum size of aggregates (less than 16 mm) and is used for vertical applications in very congested structures, structures with complex shapes, or for filling under formwork. SF3 will often give better surface finish than SF 2 for normal vertical applications but segregation resistance is more difficult to control.

Target values higher than 850 mm may be specified in some special cases but great care should be taken regarding segregation and the maximum size of aggregate should normally be lower than 12 mm. (ENFRAC, 2005)

The slump flow is used to assess the horizontal free flow 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 spread concrete is determined as the slump flow diameter (Figure 2.6).

The slump flow test is also used to assess the properties of SCC with a slight modification to the sieve (Figure 2.7).

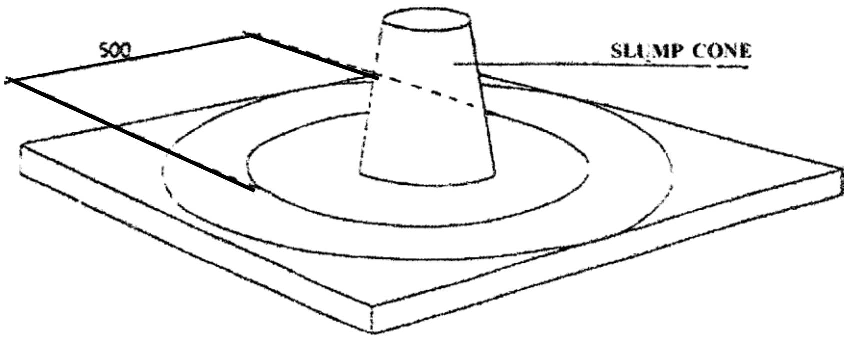


Figure 2.6 Slump flow test setup (Khurana and Topcu, 2000)

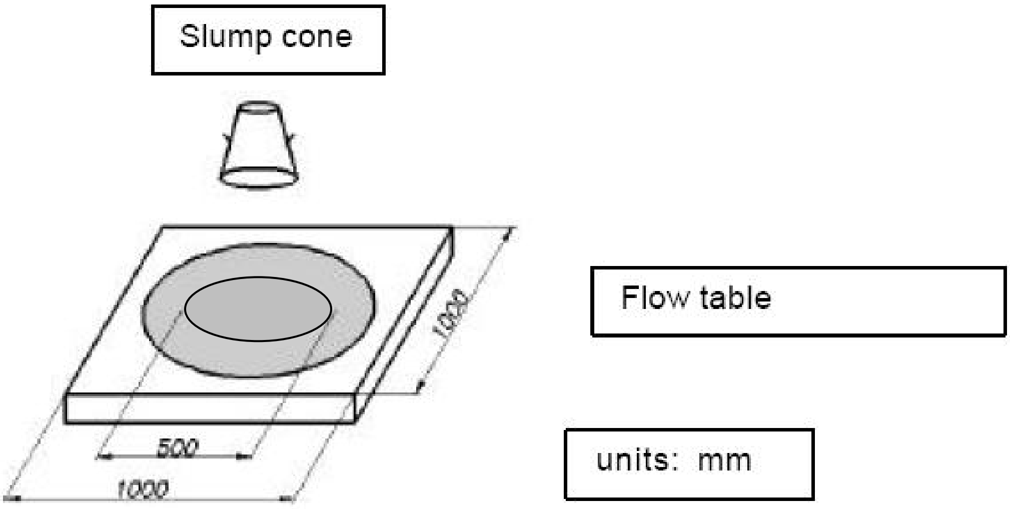


Figure 2.7 Slump flow test (Efnarc, 2002)

B) J Ring Test

The principle of the J-Ring test may be Japanese, but no references are known. The JRing test itself has been developed at the University of Paisley. The test is used to determine the passing ability of the concrete. The equipment consists of a rectangular section (30mm x 25mm) open steel ring, drilled vertically with holes to accept threaded sections of reinforcement bar. These sections of bar can be of different diameters and spaced at different intervals: in accordance with normal reinforcement considerations, 3x the maximum aggregate size might be appropriate. The diameter of the ring of vertical bars is 300mm, and the height 100 mm.

The J-Ring can be used in conjunction with the Slumpflow, the Orimet test, or eventually even the Vfunnel.

These combinations test the flowing ability and (the contribution of the J Ring) the passing ability of the concrete. The Orimet time and/or slumpflow spread are measured as usual to assess flow characteristics. The J-Ring bars can principally be set at any spacing to impose a more or less severe test of the passing ability of the concrete. After the test, the difference in height between the concrete inside and that just outside the J-Ring is measured. This is an indication of passing ability, or the degree to which the passage of concrete through the bars is restricted (Figure 2.8). (Efnarc, 2002)

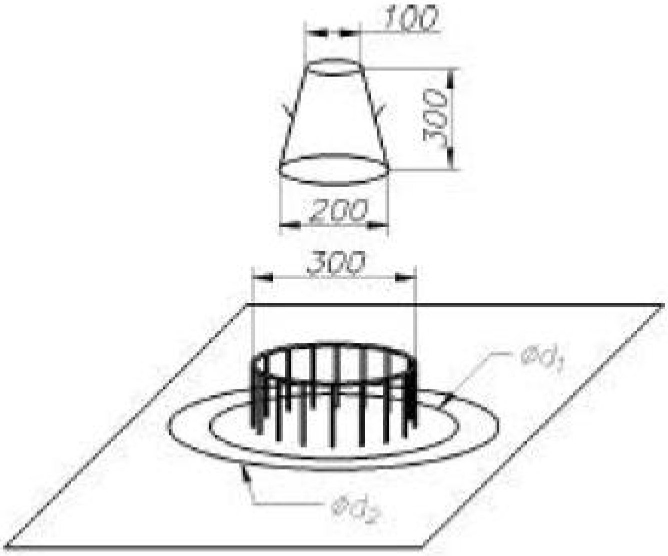


Figure 2.8 The J Ring used in conjunction with the slump flow (Efnarc, 2002)

C) V Funnel Test and V Funnel Test at T 5minutes

V funnel test was developed in Japan and used by Ozawa et al (1995). The equipment consists of a V-shaped funnel, shown in Figure 2.9. An alternative type of V-funnel, the O funnel, with a circular section is also used in Japan.

The V-Funnel is used to measure the flowability or viscosity of SCC. In this test a standard funnel is filled completely with concrete and the bottom outlet is opened allowing the concrete to flow. The V-funnel time is the elapsed time (t) in second between the opening of the bottom outlet and the time when the light becomes visible from the bottom, when observed from the top (Efnarc, 2002).

The V-funnel test is also used to assess the fresh properties of SCC with a slight modification to the V-funnel apparatus (Figure 2.9). This apparatus has been used by other researchers and was also used in this study (Domone and Jin, 1999; Golasweski and Swabowski, 2002)

The described V-funnel test is used to determine the filling ability (flowability) of the concrete with a maximum aggregate size of 20mm. The funnel is filled with about 12 litres of concrete and the time taken for it to flow through the apparatus measured. After this the funnel can be refilled concrete and left for 5 minutes to settle. If the concrete shows segregation then the flow time will increase significantly. (Efnarc, 2002)

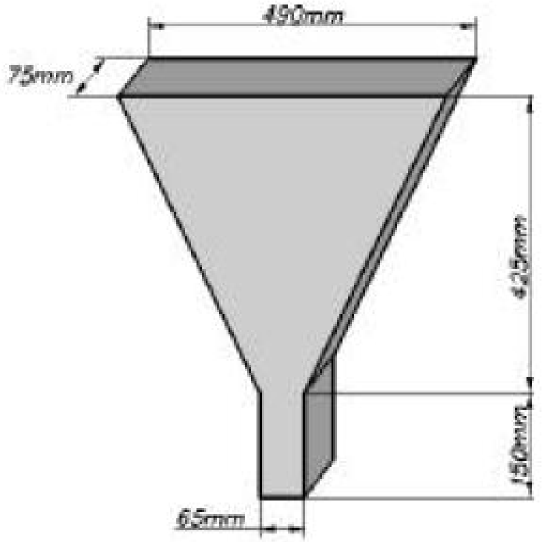


Figure 2.9 V-funnel test equipment (rectangular section) (Efnarc, 2002)

D) L-Box Test Method

In addition to the abovementioned tests there are others to determine the workability properties of SCC, such as L-box. These test procedures are all described by EFNARC and measure the passing ability of SCC in between reinforcements. these test procedures are utilized in this thesis.

This test, based on a Japanese design for underwater concrete, has been described by Petersson et al. (1996).

The test assesses the flow of the concrete, and also the extent to which it is subject to blocking by reinforcement. The apparatus is shown in figure 2.10a and 2.10b

The apparatus consists of a rectangular-section box in the shape of an ‘L’, with a vertical and horizontal section, separated by a moveable gate, in front of which vertical lengths of reinforcement bar are fitted.

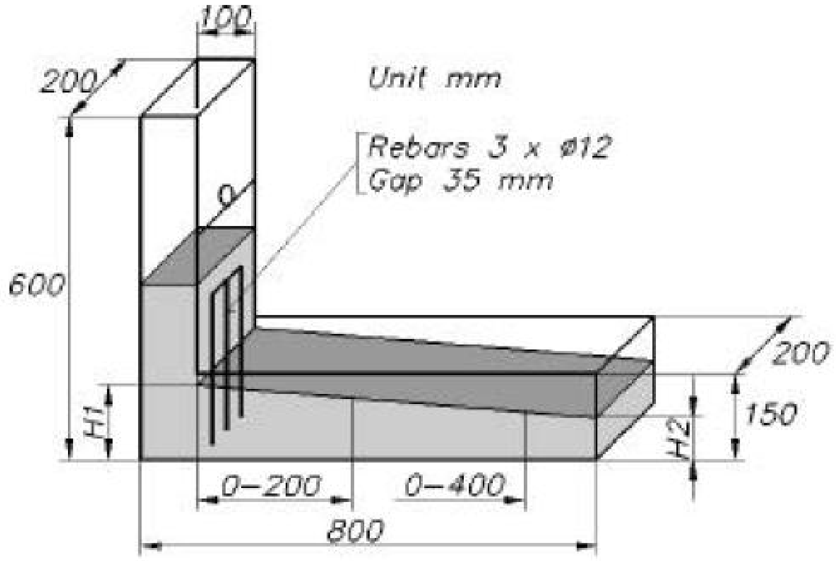


Figure 2.10a L-box (Efnarc, 2002)

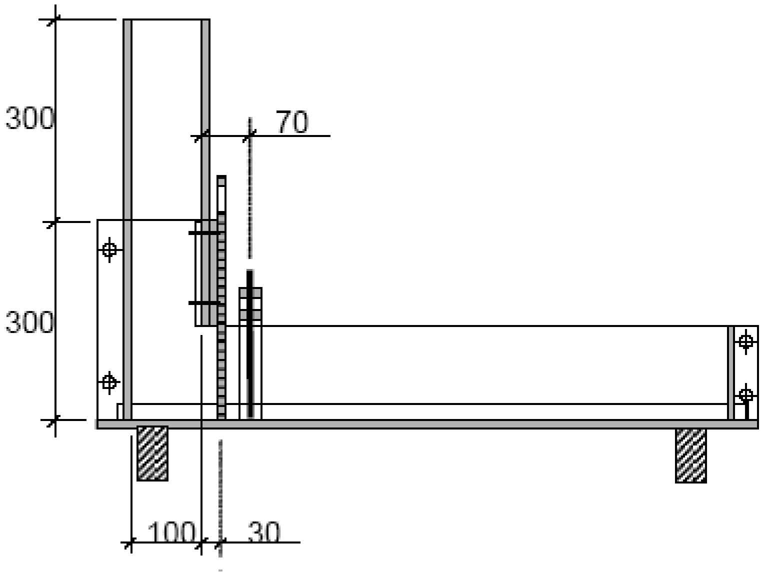


Figure 2.10b L-Box side view (Efnarc, 2005)

The vertical section is filled with concrete, then the gate lifted to let the concrete flow into the horizontal section. When the flow has stopped, the height of the concrete at the end of the horizontal section is expressed as a proportion of that remaining in the vertical section (H2/H1 in the diagram). It indicates the slope of the concrete when at rest. This is an indication passing ability, or the degree to which the passage of concrete through the bars is restricted. The horizontal section of the box can be marked at 200mm and 400mm from the gate and the times taken to reach these points measured. These are known as the T20 and T40 times and are an indication for the filling ability. The sections of bar can be of different diameters and spaced at different intervals: in accordance with normal reinforcement considerations, 3x the maximum aggregate size might be appropriate. The bars can principally be set at any spacing to impose a more or less severe test of the passing ability of the concrete. (Efnarc, 2002)

E) U-Box Test Method

The test was developed by the Technology Research Centre of the Taisei Corporation in Japan (Haykawa, 1993) Sometimes the apparatus is called a "box-shaped" test. The test is used to measure the filling ability of self-compacting concrete. The apparatus consists of a vessel that is divided by a middle wall into two compartments, shown by R1 and R2 in Figure 2.11. 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 litre of concrete then the gate lifted and concrete flows upwards into the other section. The height of the concrete in both sections is measured. (Efnarc, 2002)

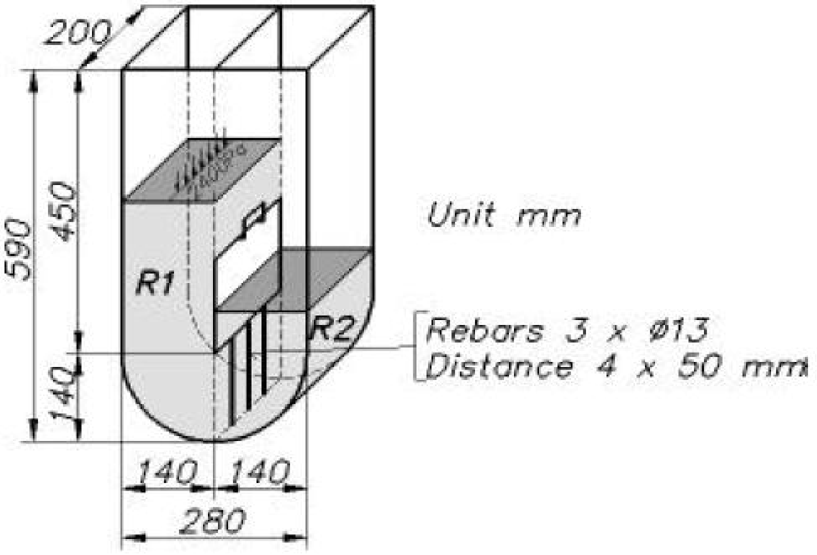


Figure 2.11 U-Box (Efnarc, 2002)

F) Fill Box Test Method

This test is also known as the ‘Kajima test ‘.The test is used to measure the filling ability of selfcompacting concrete with a maximum aggregate size of 20mm. The apparatus consists of a container (transparent) with a flat and smooth surface. In the container are 35 obstacles made of PVC with a diameter of 20mm and a distance centre to centre of 50mm: (see Figure 2.12). At the top side is put a filling pipe (diameter 100mm height 500mm) with a funnel (height 100mm). The container is filled with concrete through this filling pipe and the difference in height between two sides of the container is a measure for the filling ability. (Efnarc, 2002)

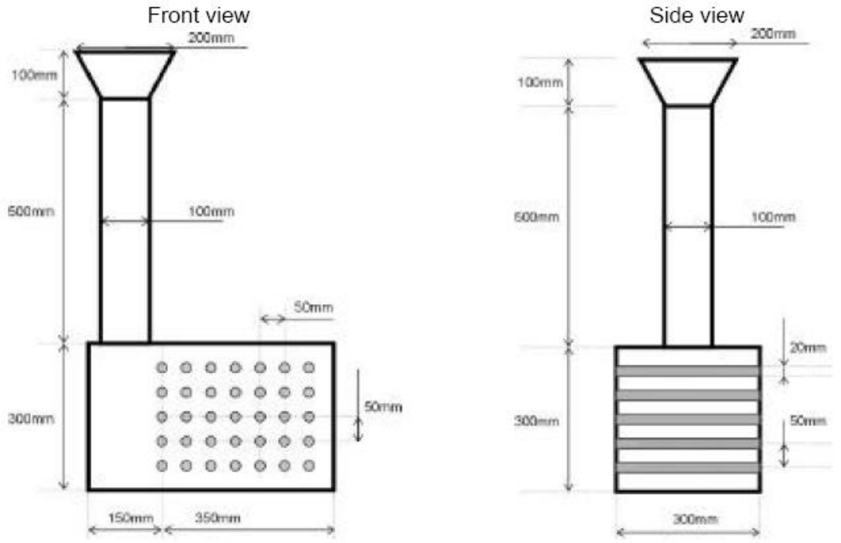


Figure 2.12 Fill Box (Efnarc, 2002)

G) GTM Screen Stability Test Method

This test has been developed by the French contractor, GTM, to assess segregation resistance (stability). It consists of taking a sample of 10 litre of concrete, allowing it to stand for a period to allow any internal segregation to occur, then pouring half of it on to a 5mm sieve of 350mm diameter, which stands on a sieve pan on a weigh scale. After two minutes, the mortar which passed through the sieve is weighed, and expressed as a percentage of the weight of the original sample on the sieve. (Efnarc, 2002)

H) Orimet Test

The Orimet was developed at the University of Paisley (Bartos, 1998) as a method for assessment of highly workable, flowing fresh concrete mixes on construction sites. The equipment is shown in Figure 2.13. The test is based on the principle of an orifice rheometer. The Orimet consists of a vertical casting pipe fitted with a changeable inverted cone-shaped orifice at its lower, discharge, end, with a quick-release trap door to close the orifice. Usually the orifice has an 80 mm internal diameter which is appropriate for assessment of concrete mixes of aggregate size not exceeding 20 mm. Orifices of other sizes, usually from 70 mm to 90 mm in diameter, can be fitted instead. Operation consists simply of filling the Orimet with concrete then opening the trapdoor and measuring the time taken for light to appear at the bottom of the pipe (when viewed from above). (Efnarc, 2002)

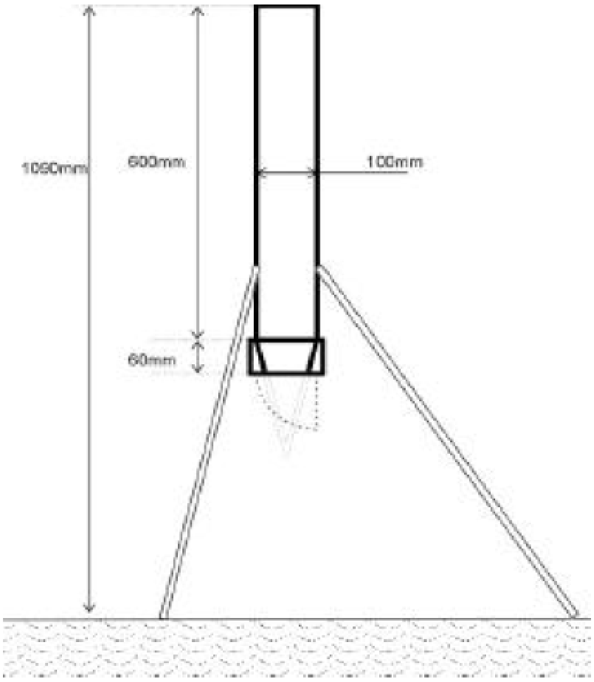


Figure 2.13 Orimet test (Efnarc, 2002)

2.2.2.6 Acceptance Criteria

Typical acceptance criteria for SCC ((EFNARC,2002), (Tviksta, 2000), (Vachon, 2002) and (JSCE, 1999)) with a maximum aggregate size up to 20 mm are shown in Table 2.4. These typical requirements shown against each test method are based on current knowledge and practice. Values outside these ranges may be acceptable if the producer can demonstrate satisfactory performance in the specific conditions, e.g, large spaces between reinforcement, layer thickness less than 500 mm, short distance of flow from point of discharge, very few obstructions to pass in the formwork, very simple design of formwork, etc.

Special care should always be taken to ensure no segregation of the mix occurs. At present, there is not a simple and reliable test that gives information about segregation resistance of SCC in all practical situations.

Table 2.4 Acceptance criteria for self-compacting concrete

Typical range of values						Method
Unit	Symbol	Minimum		Maximum		
mm	D	600**	650*	800		Slump flow by Abrams cone
sec	T50	3**	2*	25**	5*	T50cm slump flow
sec	T	6		12		V-funnel
sec	T5	0		+3		Time increase, V-funnel at T5minutes
-	Blocking Ratio(H_2/H_1)	0.8		1.0		L-box
mm	ΔH	50**	30*	0		U-box

* EFNARC

** JSCE

2.3 Mix Design Methods

2.3.1 Introduction

The basic components of the mix composition of SCC are the same as those used in conventional concrete. However, to obtain the requested properties of fresh concrete in SCC, a higher proportion of ultrafine materials and the incorporation of chemical admixtures, in particularly an effective superplasticizer, are necessary. Because of this, self-compactability can be largely affected by the characteristics of materials and mix proportion.

No standard or all-encapsulating method for determining mixture proportions currently exists for SCC. However, many different proportion limits have been listed in various publications. Therefore, a rational mix-design method for SCC using variety of materials is necessary. Mix designs of SCC must satisfy the criteria on filling ability, passing ability and segregation resistance. Multiple guidelines about mixture proportions for SCC are found, summarized in Table 2.5 and discussed in the following sections.

Table 2.5 Limits on SCC material proportions (Okamura 1995, Gibbs 1999, Zhang 2001, Takada 1998, Subramanian 2002, Nagamoto 1997 and Su 2001.)

Material	**High Fineness**	**VMA**	**Combination**
Cementitous (kg/m3)	(450-600)	(385-450)	(385-450)
Water/Cementitous Material	0.28-0.45	0.28-0.45	0.28-0.45
Fine Aggregate/Mortar (%)	35-45	~40	~40
Fine Aggregate/Total Aggregate (%)	50-58	-	-
Coarse Aggregate/Total Mixture (%)	28-48	45-48	28-48

2.3.2 Mechanism for Achieving Self-Compactability

According to the previous illustration, the method for achieving self-compactability involves not only high deformability of paste or mortar, but also resistance to segregation between coarse aggregate and mortar when concrete flows through the confined zone of reinforcing bars. Okamura and Ozawa (1995) employed the following methods for achieving selfcompactability (Figure 2.14):

- Limited aggregate content
- Low water-powder ratio
- Use of superplasticizer

They stated that the collision and contact between aggregate particles can increase as the relative distance between particles decreases and then internal stress can increase when concrete is deformed, particularly near obstacles. They also found that the energy required for flowing is consumed by the increased internal stress, resulting in blockage of aggregate particles. Limiting the coarse aggregate content, whose energy consumption is particularly intense, to a level lower than normal is effective in avoiding this kind of blockage.

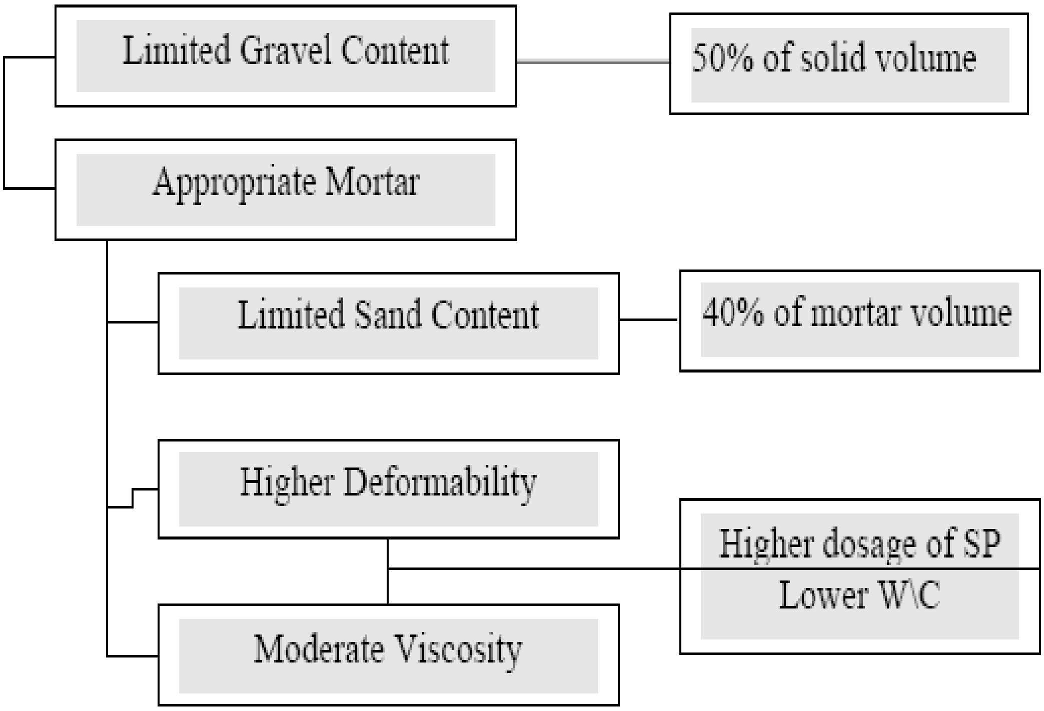


Figure 2.14 Methods for achieving self-compactability (Okamura, 1995)

On the other hand, highly viscous paste is also required to avoid the blockage of coarse aggregate when concrete flows through obstacles (Figure 2.15). When concrete is deformed, paste with a high viscosity also prevents localized increases in internal stress due to the approach of coarse aggregate particles. High deformability can be achieved only by employment of a superplasticizer and keeping the water-powder ratio to a very low value.

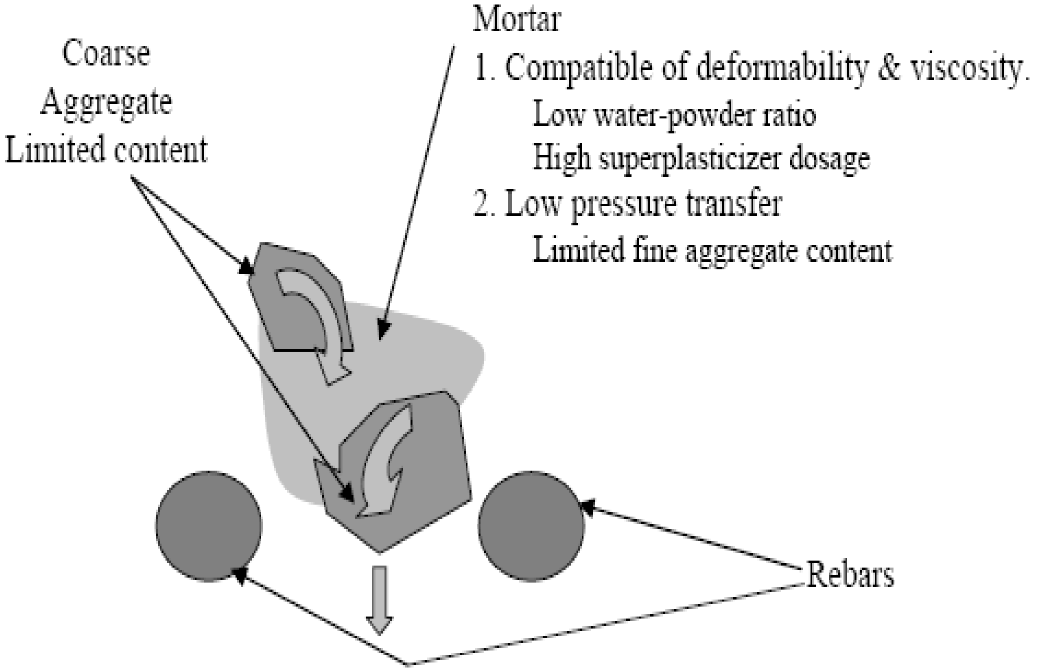


Figure 2.15 Mechanism for achieving self-compactability (Okamura, 1995)

2.3.3 Okamura and Ozawa Method

Okamura and Ozawa (1995) proposed a simple proportioning system. The coarse and fine aggregate contents are fixed so that self-compactability can be achieved easily by adjusting the water-powder ratio and superplasticizer dosage only.

- The coarse aggregate content in concrete is fixed at 50% of the solid volume.
- The fine aggregate content is fixed at 40% of the mortar volume.
- The water-powder ratio by volume is assumed as 0.9 to 1.0, depending on the properties of the powder.
- The superplasticizer dosage and the final water-powder ratio are determined so as to ensure self-compactability.

In the mix proportioning of conventional concrete, the water-cement ratio is selected to obtain the required strength. Okamura and Ozawa (1995) stated that with SCC the water-powder ratio has to be decided taking into account self-compactability because self-compactability is very sensitive to this ratio. They stated also, in most cases, the required strength does not govern the water-cement ratio because the water-powder ratio is small enough for obtaining the required strength for ordinary structures unless most of the powder in use is not reactive.

The characteristics of the powder and superplasticizer largely affect the mortar property, and so the proper water-powder ratio and superplasticizer dosage cannot be fixed without trial mixing at this stage.

2.3.4 EFNARC Approaches

EFNARC (2002) stated that in designing the mix, it is most useful to consider the relative proportions of the key components by volume rather than by mass. This institute adopted two approaches for designing SCC.

First Approach;

Indicative typical ranges of proportions and quantities in order to obtain selfcompactability are given below, and further modifications will be necessary to meet strength and other performance requirements.

- Water/powder ratio by volume of 0.80 to 1.10. Typically water content does not exceed 200 litre/m3.
- Total powder (cement + mineral admixtures) content ranges from 0.16 to 0.24 by volume of the mix.
- Coarse aggregate content is normally 28 to 35 per cent by volume of the mix.
- The sand content balances the volume of the other constituents.

Generally, it is advisable to design conservatively so as to ensure that concrete is capable of maintaining its specified fresh properties despite the anticipated variations in raw material quality. Some variations in aggregate moisture content should also be expected and allowed for at mix design stage. Normally, viscosity-modifying admixtures are useful tools for compensating for the fluctuations due to any variations of the sand grading and the moisture content of the aggregates.

Laboratory trials should be used to verify properties of the initial mix composition. If necessary, adjustments to the mix composition should then be made. Once all requirements are fulfilled, the mix should be tested at full scale at the concrete plant or at site.

In the event that satisfactory performance cannot be obtained, consideration should be given to fundamental redesign of the mix. Depending on the apparent problem, the following courses of action might be appropriate:

- using additional or different types of filler, (if available);
- modifying the proportions of the sand or the coarse aggregate;
- using a viscosity modifying agent, if not already included in the mix; adjusting the dosage of the superplasticizer and/or the viscosity modifying agent;
- using alternative types of superplasticizer (and/or VMA), more compatible with local materials;
- adjusting the dosage of admixture to modify the water content, and hence the water/powder ratio.

Second approach;

This approach is based on a method developed by Okamura (1995). The sequence is determined as:

A) Definition of the desired air content (mostly 2%) : air content may generally be set at 2 per cent, or a higher value specified when freeze thaw resistant concrete is to be designed.

B) Determination of coarse aggregate volume: coarse aggregate volume is defined by bulk density. Generally coarse aggregate content (D> 4 mm) should be between 50 per cent and 60 per cent. When the volume of coarse aggregate in concrete exceeds a certain limit, the opportunity for collision or contact between coarse aggregate particles increases rapidly and there is an increased risk of blockage when concrete passes through spaces between steel bars. The optimum coarse aggregate content depends on the following parameters:

- Maximum aggregate size. The lower the maximum aggregate size, the higher the proportion of coarse aggregate.
- Crushed or rounded aggregates. For rounded aggregates, content higher than for crushed aggregates can be used.

C) Determination of sand content: sand, in the context of this mix composition procedure is defined as all particles larger than 0,125 mm and smaller than 4 mm. Sand content is defined by bulk density. The optimal volume content of sand in the mortar varies between 40 – 50% depending on paste properties.

D) Design of paste composition : initially the water: powder ratio for zero flow (βp) is determined in the paste, with the chosen proportion of cement and additions. Flow cone tests with water/powder ratios by volume of e.g. 1.1, 1.2, 1.3 and 1.4 are performed with the selected powder composition, (see Figure 2.16) The point of intersection with the y - axis is designated the βp value. This βp value is the water adsorbed on the powder surface together with that required to fill the voids in the powder system and provide sufficient dispersal of powder and is used mainly for quality control of water demand for new batches of cement and fillers.

E) Determination of optimum volumetric water/powder ratio and superplasticizer dosage in mortar :

Tests with flow cone and V-Funnel for mortar are performed at varying water/powder ratios in the range of (0.8 – 0.9) βp and dosages of superplasticizer. The superplasticizer is used to balance the rheology of the paste. The volume content of sand in the mortar remains the same as determined above.

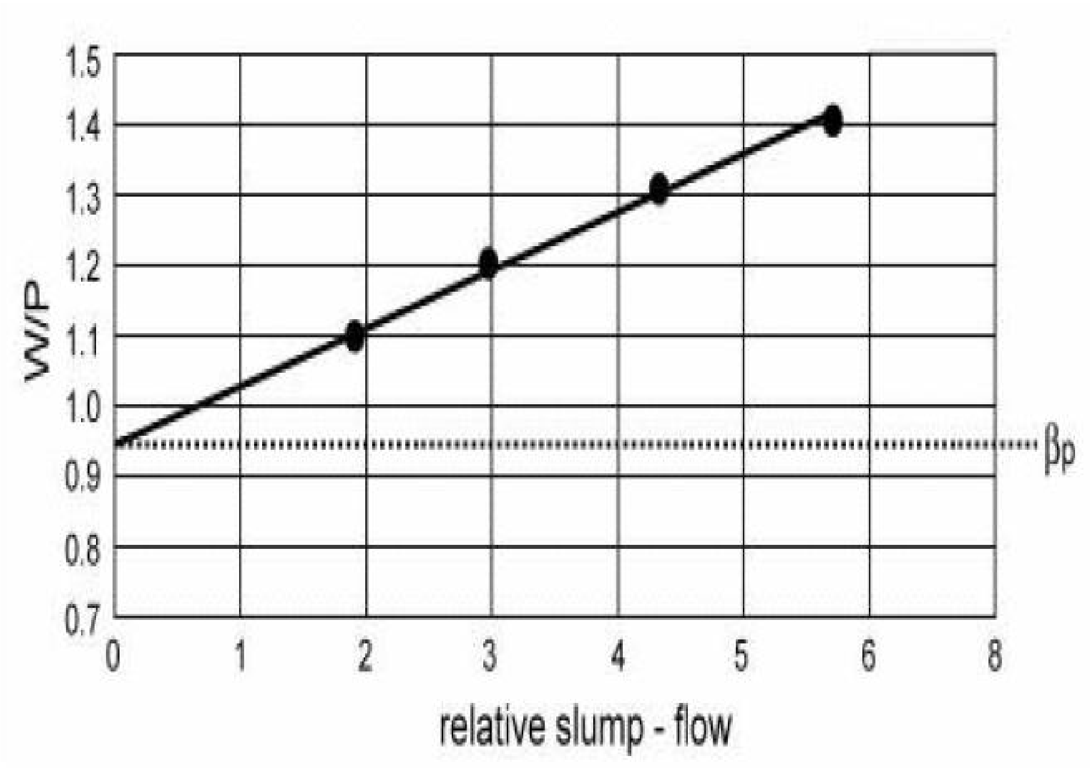


Figure 2.16 Determination of water/powder ratio βp (EFNARC, 2002)

2.3.5 CBI Method (Swedish Cement and Concrete Research Institute)

Tviksta (2000) summarized CBI mix design method as follows. Based on the requirement for the element to be cast, e.g. strength, durability and free space between reinforcement, the minimum amount of paste can be calculated. Using the aggregate's grading curve and nature of aggregate (natural or crushed), the calculation is performed by using a "risk curve" (for the type of aggregate used). The risk curve is related to the grading curve and void space between aggregates. This calculation gives the minimum paste content for sufficient passing ability. For a house building concrete with better passing ability, the void content is determined for the aggregate to give the minimum paste content. The paste content (filler amount) can sometimes be higher because of segregation resistance reasons. A certain excess amount must be used for workability reasons. Superplasticizers are then used and adjusted to give the right filling ability (normally slump flow).

2.3.6 LCPC Model (Laboratoire Central des Ponts et Chausse´es (France).)

Tviksta (2000) also described LCPC model for SCC mix design as follows; It consists of determining certain properties of the selected components (packing density, real density, absorption, grading curve etc). These data are introduced into specially designed software with built-in models to predict the flow behavior, the passing ability and the risk of segregation. The software is then used to estimate the actual content of each component as to meet the set of requirements. The theoretical optimum mix is later adjusted by lab tests.

2.3.7 Other Methods

Gibbs (1999) stated that the following practical rules of thumb for the proportioning of SCC mixtures exist:

- Coarse aggregate content should be limited to 700-800 kg/m3 (about 50% of the total volume)
- Paste not less than 40% of the volume of the mixture
- Low sand content in the mortar (40-50% by volume)
- Water/powder ratio not more than 0.5.

Visual summary of the suggestions as listed by Subramanian and Chattopadhyay (2002) is given in Figure 2.17. The numbers shown in the figure are based on SCC using a rounded gravel aggregate. Subramanian and Chattopadhyay (2002) advised to make adjusting to the proportions by incorporating more fines when a crushed angular aggregate is used.

Boral Materials is a concrete materials company (Zhang, 2001). Their own method of developing SCC is called (BMTI Approach). This method provides limits on proportions according to Table 2.6.

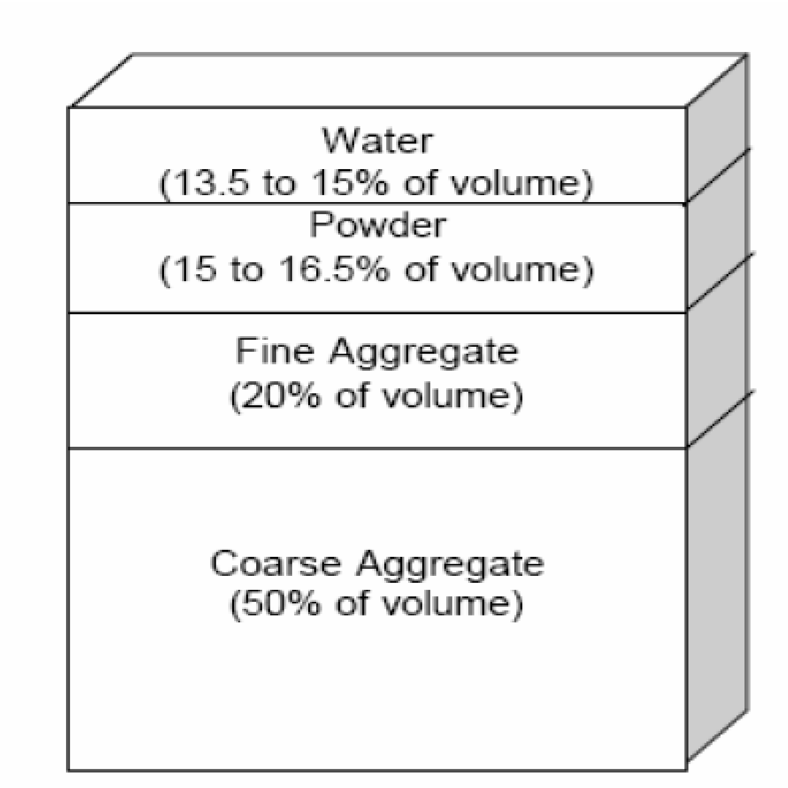


Figure 2.17 Visual summary of SCC proportion suggestions by Subramanian and Chattopadhyay (2002)

2.4 Influences of SCC Constituents

2.4.1 Introduction

The materials used for SCC are selected from those used by the conventional concrete industry. Typical materials used for SCC are as follows: coarse aggregate, fine aggregate, cement, mineral admixtures and chemical admixtures (superplasticizer, viscosity-modifying agents).

Gibbs (1999) stated that SCC can be designed and constructed using a broad range of normal concreting materials, and that this is essential for SCC to gain popularity.

The constituent materials, used for the production of SCC should generally comply with the requirements of international standards. The materials should be suitable for the intended use in concrete and do not contain harmful ingredients in such quantities that may be detrimental to the quality or the durability of the concrete, or cause corrosion of the reinforcement.

The works of many researchers assigned that the properties and amounts of concrete constituents have important effects on rheological behavior, stability, blocking, strength etc of a certain SCC.

Table 2.6 Boral materials SCC proportion limits (Zhang, 2001)

High-Fines Approach	**High-Viscosity Approach**	**BMTI Approach**
• Cementitous (~650 kg/m3) • Fine Aggregate. > 50%** Total Aggregate Content • Imparts a low viscosity mixture that will flow and compact • Aggregate gradation is critical • Limited stability & rheological control • Increase in creep & shrinkage potential	• Incorporates a viscosity modifying admixture (VMA) • Changes rheology of concrete • Less sensitive to aggregate Gradation • Provides fluidity and segregation resistance • Cementitous system (385 to 450 kg/m3) • Coarse aggregate ~ 50%**	• Combination of high-fines and high-viscosity approach • Incorporates VMA • Cementitous system (385 to 450 kg/m3) • Incorporate 15 to 50%** fly ash • Cement content limited to strength content • Use high range water reducing admixture

**Percentage of volume

2.4.2 Cement

EFNARC (2002) stated that the general suitability (for producing SCC) is established for cement conforming to EN 197-1(European standard (cement–composition, specifications and conformity criteria - part 1: Common Cements) has been used instead of BS 12 (Zhang, 2001).).

Emborg (2000) stated that the influence of variation of cement on SCC is, so far, not clearly documented but some observations have been made during the production of this new concrete. Emborg assigned an example, in Sweden serious problems of achieving target consistency during 90 minutes have arisen during winter/spring 2000. The main reasons have been the variations of gypsum addition at the cement manufacturing and the variations of other production moments that lead to the well known problem of false set and rapid set to which the SCC is more sensitive.

2.4.3 Mixing Water

EFNARC (2002) stated that the suitability of mixing water is the same as in conventional concrete.

It is well known that the amount of water in normal concrete is of particular importance for the properties at the fresh stage, i.e. the workability, and of course for the properties of hardened concrete by affecting the water/cement ratio. For SCC, the amount of water is even more important and in mix design methods of this family of concrete, water is addressed in several relations such as: water/total fines (powder + fine aggregate) and water to powder ratio.

Figure 2.18 shows some data from literature where it is seen that, for a certain SCC without viscosity agent, the amount of water (here: ratio of water to total fines) is quite limited.

Concerning the amount of water, experiments by Sakai et al (1994) showed a strong influence on slump flow when the amount of water is changed by ± 5 kg/m^3

(equaling a change in moisture content by 0.7 % of sand), (see Figure 2.19). By adding a viscosity agent, these variations were limited.

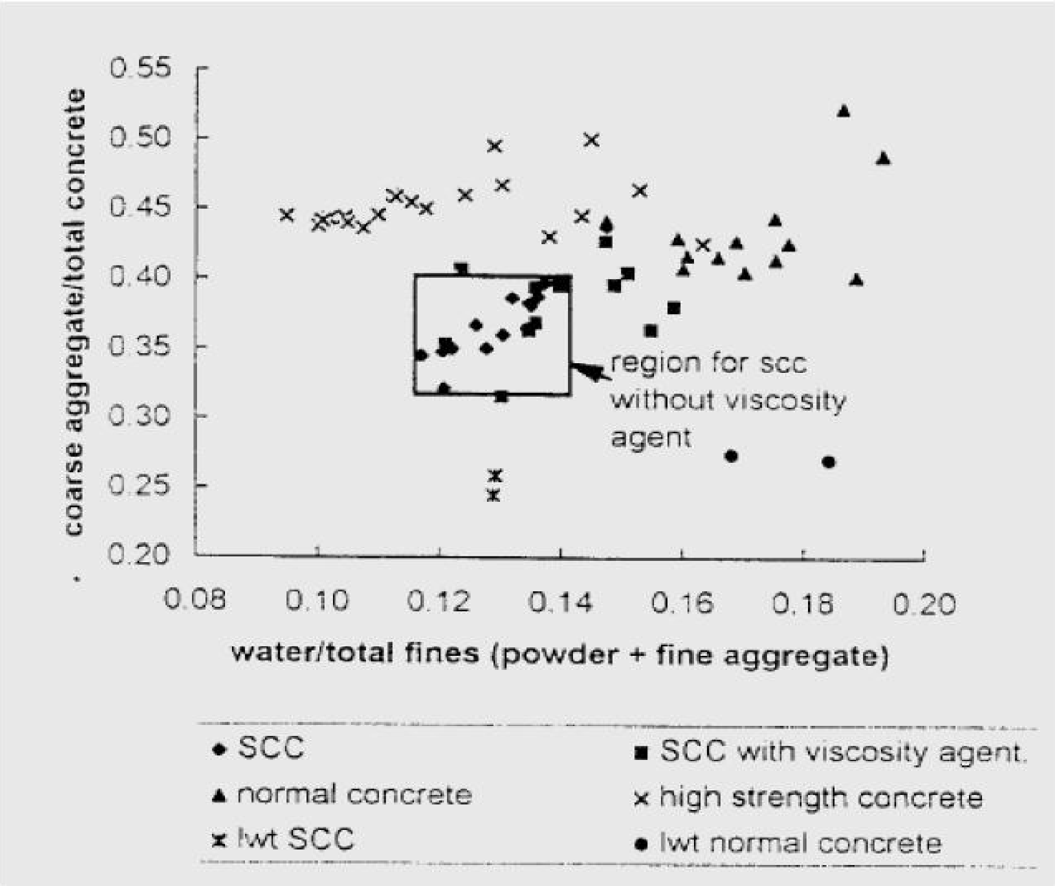


Figure 2.18 Influence of water/total fines on concrete mix optimization (Emborg, 2000)

2.4.4 Aggregates

The coarse aggregate chosen for SCC is typically round in shape, well graded and smaller in maximum size than that used for conventional concrete; typical conventional concrete could have a maximum aggregate size of 37.5 mm or more. In general, a rounded aggregate and smaller aggregate particles aid in the flowability and deformability of concrete as well as in the prevention of segregation.

Crushed stone or angular aggregates can be successfully used in SCC; however, adjustments to the mixture proportions must be made in order to increase the amount of flowability (as compared to an SCC created with round gravel). Petersson (1999) stated that both natural and crushed aggregates can be successfully used in SCC as long as attention is given to the amount of paste necessary to avoid blocking of the aggregates (crushed coarse and fine aggregates require more paste, while uncrushed aggregates and smaller maximum size require less paste).

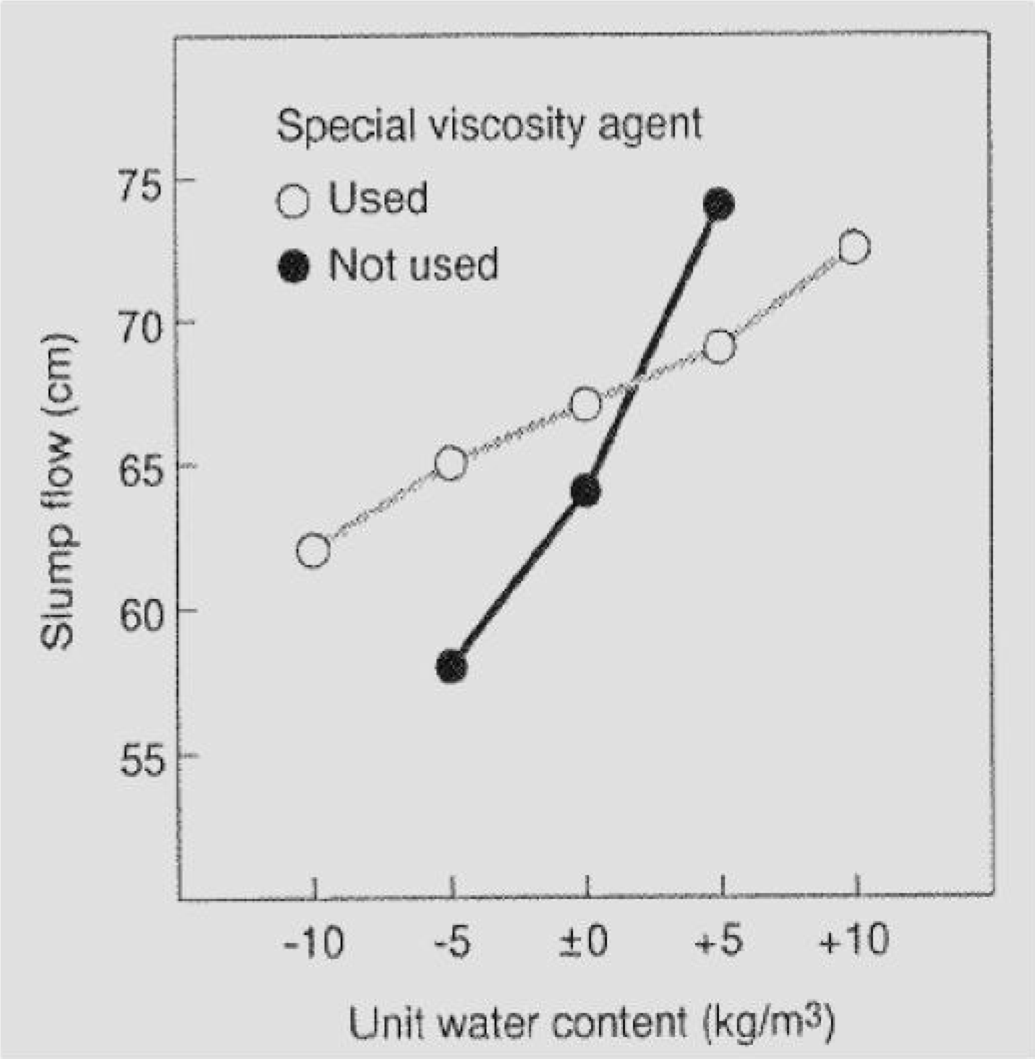


Figure 2.19 Slump flow with and without viscosity agent when water content is varied (w\c ratio: 0.53). (Sakai, 1994)

Gradation is an important factor in choosing a coarse aggregate, especially in typical uses of SCC where reinforcement may be highly congested or the formwork has small dimensions. Gap-graded coarse aggregate promotes segregation to a greater degree than does well-graded coarse aggregate.

As with conventional concrete construction, the maximum size of the coarse aggregate for SCC depends upon the type of construction. Typically, the maximum size of coarse aggregate used in SCC ranges from approximately 10 mm to 20 mm. Petersson (1999) also stated that the most common maximum aggregate size is in the range of 16 to 20 mm. When these smaller coarse aggregate sizes are considering, it should be noted that for mixtures with aggregate having a maximum size of 10 mm, no suitable methods are found to check segregation. Gibbs (1999) explained that SCC requires restrictions on aggregate size, but only as it would for conventional concrete. This is supported by the statement that work on the Brite-EuRam project at Paisley University (Sonebi, 2000) successfully used 20 mm aggregate, even with moderately heavy reinforcement, and the SCC poured into the Honshu-Shikoku bridge anchorage actually included 40 mm aggregate as its main volume fraction (Gibbs, 1999).

Bartos (2000) stated that the need for cohesion and resistance to segregation affects the choice of materials to a greater extent than conventional concrete; coarse sands may be unsuitable for SCC because of the extent to which they promote bleeding. It is usually regarded that the smaller the aggregate, the more drying shrinkage will occur; but the larger the aggregate, the more difficult it will be to attain the necessary flowability, deformability and segregation resistance for the mixture. However, Neville (2000) stated that the factor that most affects shrinkage in concrete is the total amount of aggregate. Su et al. (2002) stated that the sand/total aggregate (S/A) ratio is an important material parameter of SCC and the rheological properties increase with an increase in the S/A ratio. On the other hand, this ratio affects the hardened properties of SCC, especially elastic modulus. They found that, the proper S/A ratio for SCC is suggested to be 47.5%.

2.4.5 Mineral admixtures

2.4.5.1 Background

Mineral admixtures, additions, or supplementary cementitious materials have long provided the means to improve the fresh and hardened properties of concrete and at the same time reduce the cost of concrete materials.

Mindess and Young (1981) defined mineral admixtures as "finely ground solid materials added to improve the workability of fresh concrete and the durability of hardened concrete. They subdivided this class of admixtures into:

- Materials of low reactivity.
- Cementitious materials.
- Pozzolanic materials.

Mehta (1986) defined mineral admixtures as "finely divided siliceous materials added to concrete in relatively large amounts, generally in the range 20 to 100 percent by weight of Portland cement, and classified them as:

- Cementitious like ground granulated blast-furnace slag.
- Cementitious and pozzolanic like high-calcium fly ash.
- Highly active pozzolanas like condensed silica fume & rice husk ash.
- Normal pozzolanas like low-calcium fly ash & natural materials.
- Weak pozzolanas are like slowly cooled blast-furnace slag & field burnt rice husk ash.

Neville (2000) used the term “cementitious materials” for all the powdered materials, and defined pozzolanas as a natural or artificial materials containing silica in a reactive form. He also defined the fillers as very finely-ground materials of about the same fineness as Portland cement, owing to their physical properties, which have a beneficial effect on some properties of cement, such as workability, density, permeability, capillarity, bleeding or cracking tendency.

EFNARC (2002) and the British Cement Association (BS EN 206–1/8500) defined additions as “Finely-divided inorganic materials used in concrete in order to improve certain properties or to achieve special properties”, and classified them into two categories:

- Type I (semi-inert) additions like finely crushed (lime stone, dolomite or granite), filler aggregate, pigments …etc.
- Type II (pozzolanic or latent hydraulic) like silica fume, metakaolin, rice husk ash, fly ash, ground granulated blast-furnace slag …etc.

BS EN 206–1 : 2000 places little restriction on the use of additions, simply stating that additions of Type I and Type II may be used in concrete in quantities as used in the ‘initial tests’. Initial tests are defined in BS EN 206–1 : 2000 Annex A, as those required to demonstrate that all the specified requirements for the fresh and hardened concrete are satisfied. These initial tests may consist of laboratory work or long-term experience.

Aitcin (1998) and Bentur (2002) stated that the overall composition of mineral admixtures is defined within the ternary diagram CaO-SiO2-Al2O3 shown in Figure 2.20.

2.4.5.2 A Brief Description about Some Mineral Admixtures

Fly ash, ground granulated blast-furnace slag, silica fume, and natural pozzolans, such as calcined shale, calcined clay or metakaolin, are materials that, when used in conjunction with portland or blended cement, contribute to the properties of the hardened concrete through hydraulic or pozzolanic activity or both (Figure 2.21- Photographic view). A pozzolan is a siliceous or aluminosiliceous material that, in finely divided form and in the presence of moisture, chemically reacts with the calcium hydroxide released by the hydration of portland cement to form calcium silicate hydrate and other cementitious compounds. Pozzolans and slags are generally categorized as supplementary cementitious materials or mineral admixtures. (PCA, 2003)

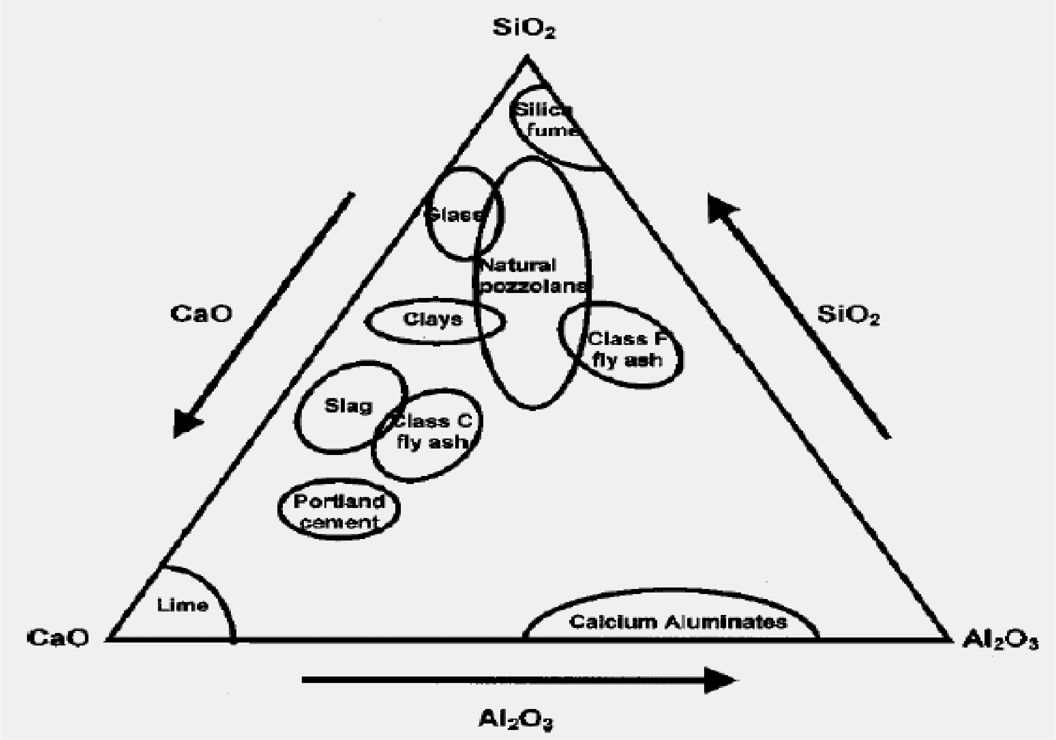


Figure 2.20 Ternary diagram representing overall composition of cementitious materials (Bentur, 2002)

Figure 2.21-Photographic view of supplementary cementitious materials. From left to right, fly ash (Class C), metakaolin (calcined clay), silica fume, fly ash (Class F), slag, and calcined shale. (PCA, 2003)

Traditionally, fly ash, slag, calcined clay, calcined shale, and silica fume were used in concrete individually. Today, due to improved access to these materials, concrete producers can combine two or more of these materials to optimize concrete properties. (PCA, 2003)

A) Fly Ash

Fly-ash is a finely divided residue of the very fine ash resulting as a byproduct from the combustion of powdered coal in power plants. The fineness of fly-ash which ranges from 1 to 150 µm affects its pozzolanic properties and the workability of concrete by reducing the water demand. Furthermore, the permeability of fly-ash concrete is normally less than that of concrete made without fly-ash. The reason of such a decrease in permeability is that the calcium hydroxide liberated by the hydration of calcium silicate compound (C2S and C3S) reacts with pozzolans and leads to the formation of additional calcium-silicate-hydrates which reduces the capillary pore spaces (Erdogan, 1997).

Fly ash, the most widely used supplementary cementitious material in concrete, is a byproduct of the combustion of pulverized coal in electric power generating plants. Upon ignition in the furnace, most of the volatile matter and carbon in the coal are burned off. During combustion, the coal’s mineral impurities (such as clay, feldspar, quartz, and shale) fuse in suspension and are carried away from the combustion chamber by the exhaust gases. In the process, the fused material cools and solidifies into spherical glassy particles called fly ash (Figure 2.22). The fly ash is then collected from the exhaust gases by electrostatic precipitators or bag filters. (PCA, 2003)

Fly ash is primarily silicate glass containing silica, alumina, iron, and calcium. Minor constituents are magnesium, sulfur, sodium, potassium, and carbon. Crystalline compounds are present in small amounts. The relative density (specific gravity) of fly ash generally ranges between 1.9 and 2.8 and the color is generally gray or tan. (PCA, 2003)

The Fly Ash mineral admixtures were used in this thesis study as one of admixture in mixtures.

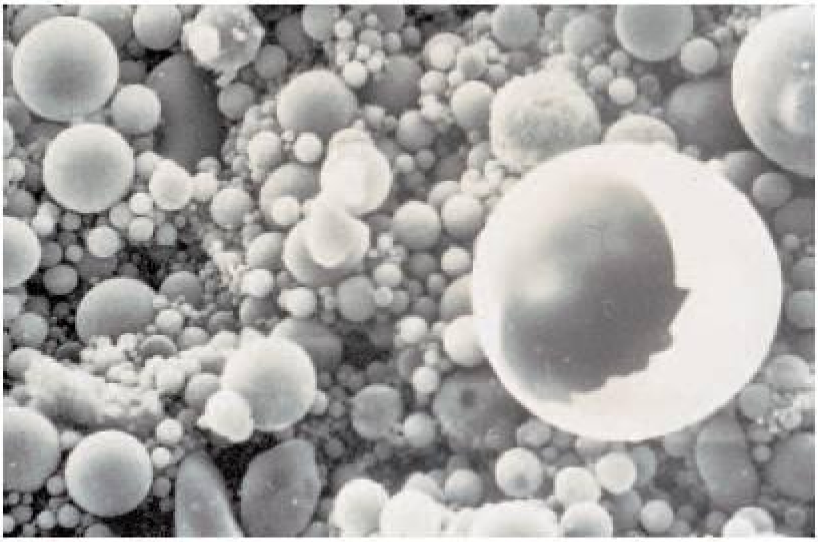


Figure 2.22 Scanning electron microscope (SEM) micrograph of fly ash particles at 1000X. Although most fly ash spheres are solid, some particles, called cenospheres, are hollow (as shown in the micrograph). (PCA, 2003)

B) Ground granulated blast-furnace slag

Granulated blast furnace slag was first developed in Germany in 1853 (Malhotra 1996). Ground slag has been used as a cementitious material in concrete since the beginning of the 1900s (Abrams and Duff 1925). Ground granulated blastfurnace slag, when used in general purpose concrete in North America, commonly constitutes between 30% and 45% of the cementing material in the mixtures (PCA, 2000).

Ground granulated blast-furnace slag (Figure 2.23-Photographic view), also called slag cement, and is made from iron blast-furnace slag; it is a nonmetallic hydraulic cement consisting essentially of silicates and aluminosilicates of calcium developed in a molten condition simultaneously with iron in a blast furnace. The molten slag at a temperature of about 1500°C (2730°F) is rapidly chilled by quenching in water to form a glassy sandlike granulated material. The granulated material, which is ground to less than 45 microns, has a surface area fineness of about 400 to 600 m^2/kg Blaine. The relative density (specific gravity) for ground granulated blastfurnace slag is in the range of 2.85 to 2.95. The bulk density varies from 1050 to 1375 kg/m^3 (66 to 86 lb/ft3) (PCA, 2000).

The rough and angular-shaped ground slag (Figure 2.24) in the presence of water and an activator, NaOH or CaOH, both supplied by portland cement, hydrates and sets in a manner similar to portland cement. However, air-cooled slag does not have the hydraulic properties of water-cooled slag (PCA, 2000).

Figure 2.23-Photographic view of ground granulated blast-furnace slag.

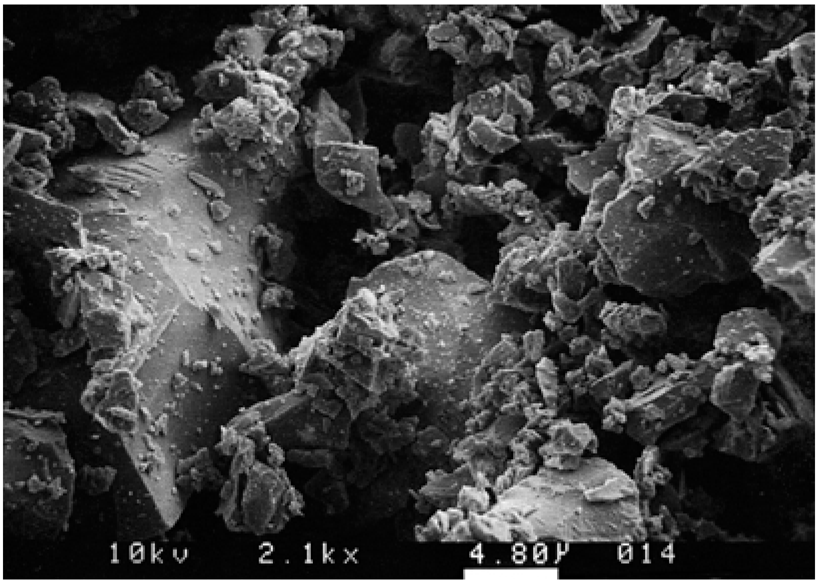


Figure 2.24 Scanning electron microscope micrograph of slag particles at 2100X (PCA, 2000).

The Granulated blast furnace slag mineral admixtures were used in this thesis study as one of admixture in mixtures.

C) Limestone Powder

BS 7979, Specification for limestone fines for use with Portland cement defined limestone fines as a fine powder obtained from the processing of limestone, and stated that there is uncertainty over whether limestone fines should be classified as a Type II or Type I addition. It is less reactive than Type II addition, but research shows that it may have slight reactivity as well as any physical effects conferred by virtue of its fine particle size. It can be concluded from the results of many researches that limestone powder has a good performance in both fresh and hardened SCC.

D) Filler aggregate

BS EN 12620, Aggregates for concrete including those for use in roads and pavements (BS EN 12620) is currently in the course of preparation. This standard is expected to include 'filler aggregate', that is sufficiently fine for at least 75% to pass a 0.063 mm sieve.

E) Pigments

BS EN 12878, Pigments for the coloration of building materials (BS EN 12878) based on cement and lime – Specifications and methods of test is a substance, generally in the form of fine particles, whose sole purpose is to color cement- and lime-based building materials. It may be either organic or inorganic.

F) Metakaolin

Calcined clays are used in general purpose concrete construction much the same as other pozzolans. They can be used as a partial replacement for the cement, typically in the range of 15% to 35%, and to enhance resistance to sulfate attack, control alkali-silica reactivity, and reduce permeability. Calcined clays have a relative density of between 2.40 and 2.61 with Blaine fineness ranging from 650 m2/kg to 1350 m2/kg. Calcined shale may contain on the order of 5% to 10% calcium, which results in the material having some cementing or hydraulic properties on its own. Because of the amount of residual calcite that is not fully calcined, and the bound water molecules in the clay minerals, calcined shale will have a loss on ignition (LOI) of perhaps 1% to 5%. The LOI value for calcined shale is not a measure or indication of carbon content as would be the case in fly ash. (PCA, 2003)

Metakaolin is a highly pozzolanic material produced by calcining China clay at temperatures of 700 – 900°C. There is no British Standard for metakaolin but its use is permitted by BS 8500 with an appropriate Agreement Certificate (BS EN 206–1/8500 : 2002).

Zia et al. (1997) stated that the use of 5% and 10% metakaolin is found to be very similar to the use of similar percentages of silica fume in terms of permeability, frost durability and mechanical properties.

Metakaolin is ground to an average particle size of about 1 to 2 micrometers. Metakaolin is used in special applications where very low permeability or very high strength is required. In these applications, metakaolin is used more as an additive to the concrete rather than a replacement of cement; typical additions are around 10% of the cement mass. (PCA, 2003)

The most common natural pozzolans used today are processed materials, which are heat treated in a kiln and then ground to a fine powder (Figures. 2.25, 2.26 and 2.27-Photographic view); they include calcined clay, calcined shale, and metakaolin. (PCA, 2003)

The Metakaolin mineral admixtures were used in this thesis study as one of admixture in mixtures.

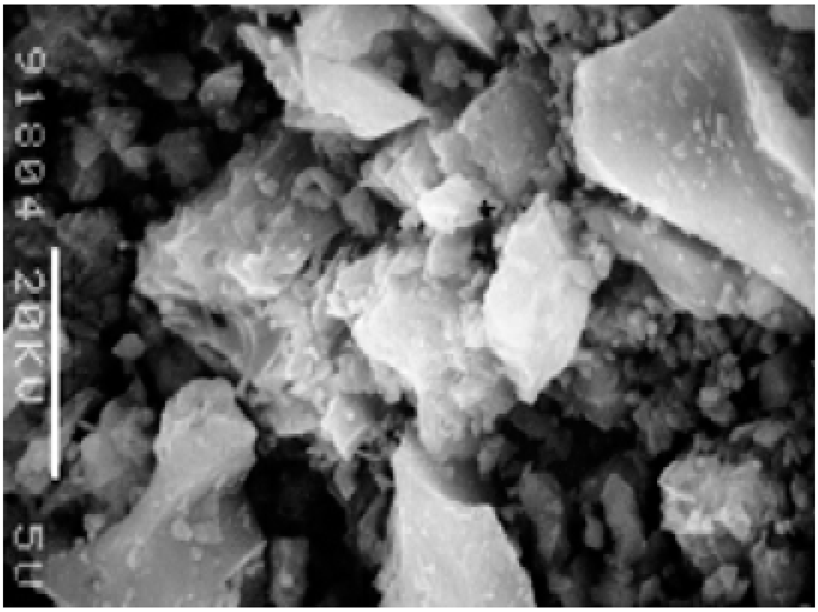


Figure 2.25 Scanning electron microscope micrograph of calcined shale particles at 5000X. (PCA, 2003)

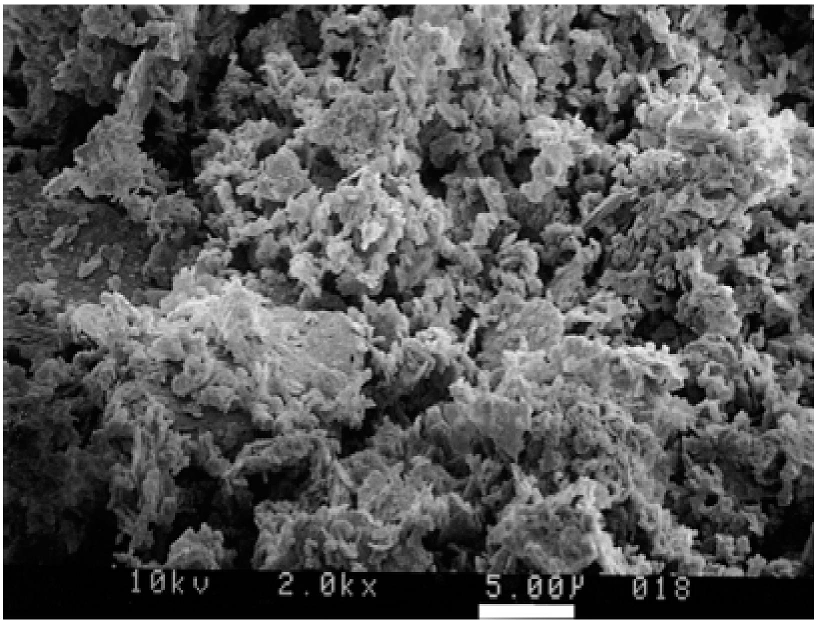


Figure 2.26 Scanning electron microscope micrograph of calcined clay particles at 2000X. (PCA, 2003)

Figure 2.27 Photographic view of metakaolin, a calcined clay. (PCA, 2003)

G) Fine Powder from Recycled Aggregate

Corinaldesi et al. (2002) have found that the use of fine powder from recycled aggregates produced by grinding demolished concrete performs very well as fine filler for the manufacture of SCC. The behavior of this powder in reducing segregation and increasing compressive strength is much better than fly ash and very close to that of silica fume.

H) Ultra Fine Amorphous Colloidal Silica (UFACS)

Skarp and Sakar (2000) illustrated that the ultra fine amorphous colloidal silica (nanosilica) is based on silica particles of 5-50 nm which are much smaller than those of silica fume (micro silica) which contains particles as “big” as 0.1-1 µm. Precipitated silica (another type of amorphous silica) also contains particles with the same size of colloidal silica and the main difference is that the former tends to aggregate (Figure 2.28).

Silica fume, also referred to as microsilica or condensed silica fume, is a byproduct material that is used as a pozzolan (Figure 2.29-Photographic view). This byproduct is a result of the reduction of high-purity quartz with coal in an electric arc furnace in the manufacture of silicon or ferrosilicon alloy. Silica fume rises as an oxidized vapor from the 2000°C (3630°F) furnaces. When it cools it condenses and is collected in huge cloth bags. The condensed silica fume is then processed to remove impurities and to control particle size. (PCA, 2003)

Condensed silica fume is essentially silicon dioxide (usually more than 85%) in noncrystalline (amorphorous) form. Since it is an airborne material like fly ash, it has a spherical shape (Figure 2.30). It is extremely fine with particles less than 1 µm in diameter and with an average diameter of about 0.1 µm, about 100 times smaller than average cement particles. (PCA, 2003)

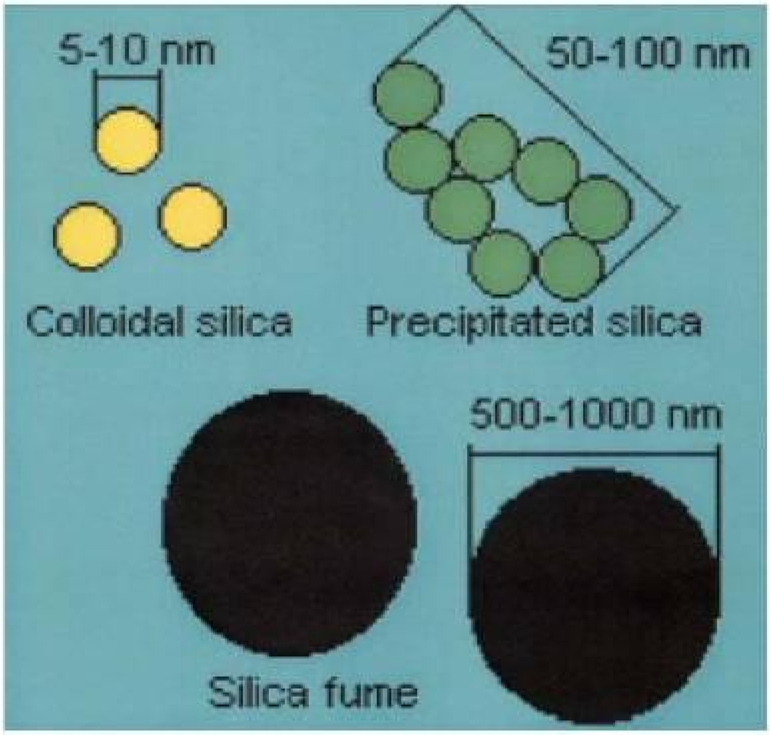


Figure 2.28 Colloidal silica vs. precipitated and silica fume (Skarp, 2000).

They also stated that at a dosage of 3-5%, it is able to reduce bleeding and increase the resistance to segregation. Due to the very high specific surface area (80-1000 m2/g) and the spherical shape of the colloidal silica particles (Figure 2.31), UFACS enhances the stability of SCC, particularly when the filler content is low. Moreover, UFACS increases the tolerance levels in SCC arising from errors in water additions made under mixing (Figure 2.32). Chemical composition of minerals described in Figure 2.33

Figure 2.29 - Photographic view of silica fume powder. (PCA, 2003)

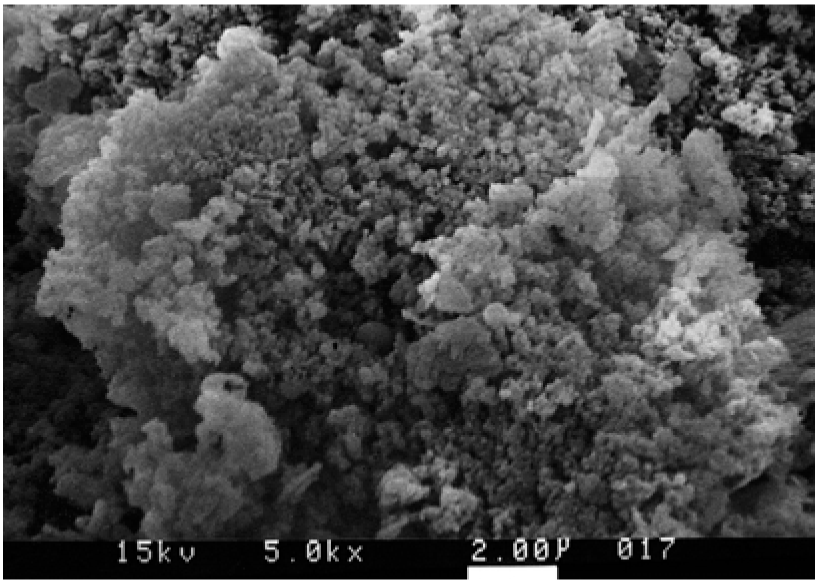


Figure 2.30 Scanning electron microscope micrograph of silicafume particles at 20,000X. (PCA, 2003)

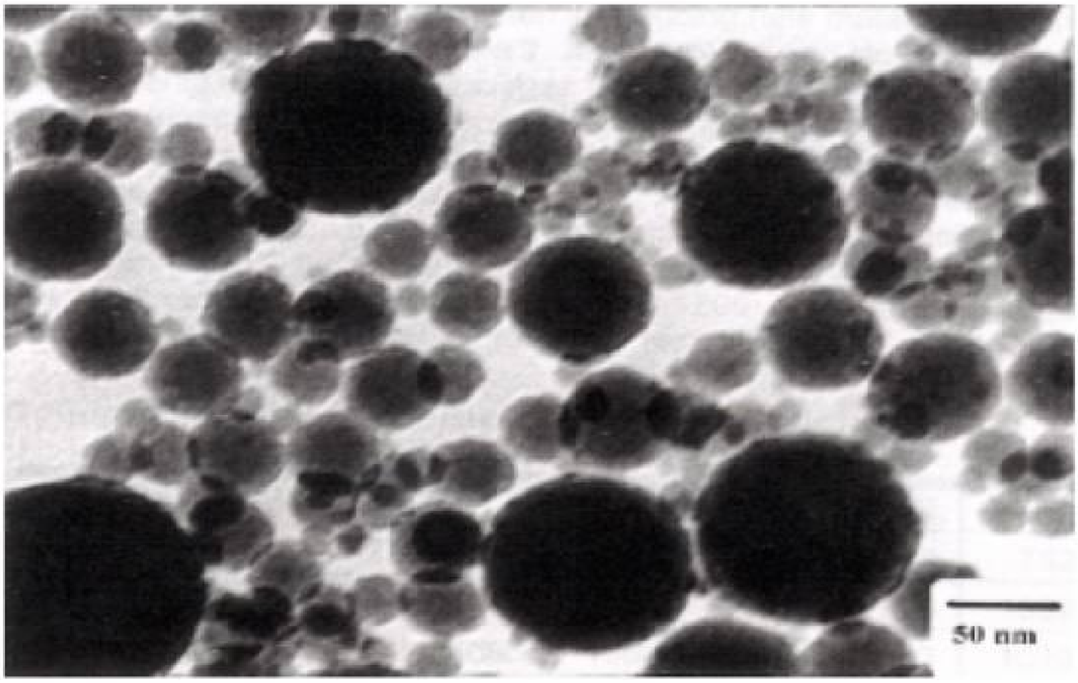


Figure 2.31 Ultra fine amorphous colloidal silica particles under transmission electron microscope (Skarp, 2000).

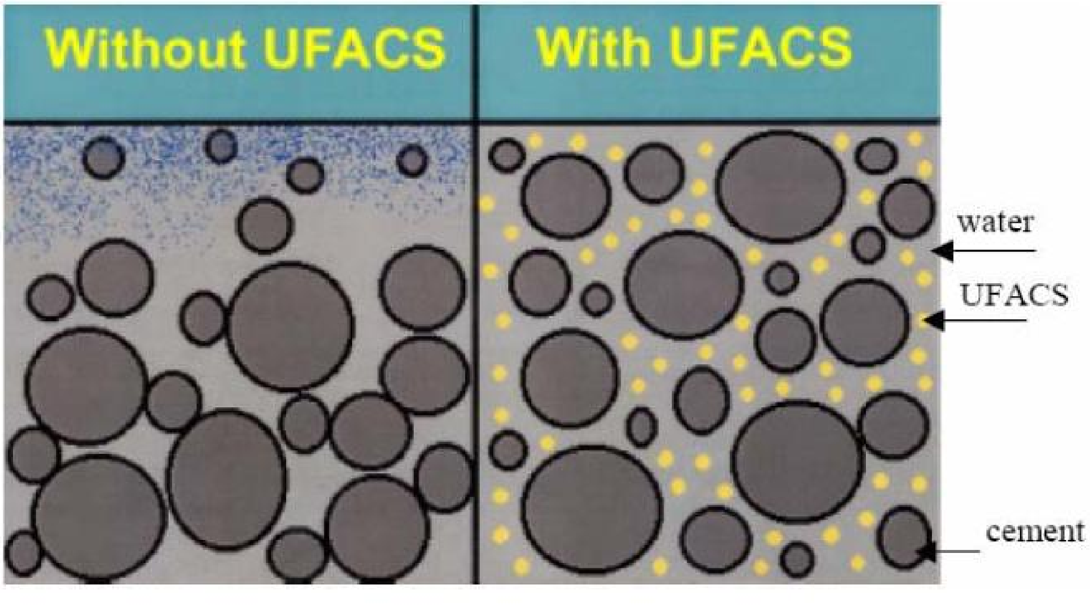


Figure 2.32 UFACS improves safety and tolerance towards errors in the concrete (Mahawish, 2005)

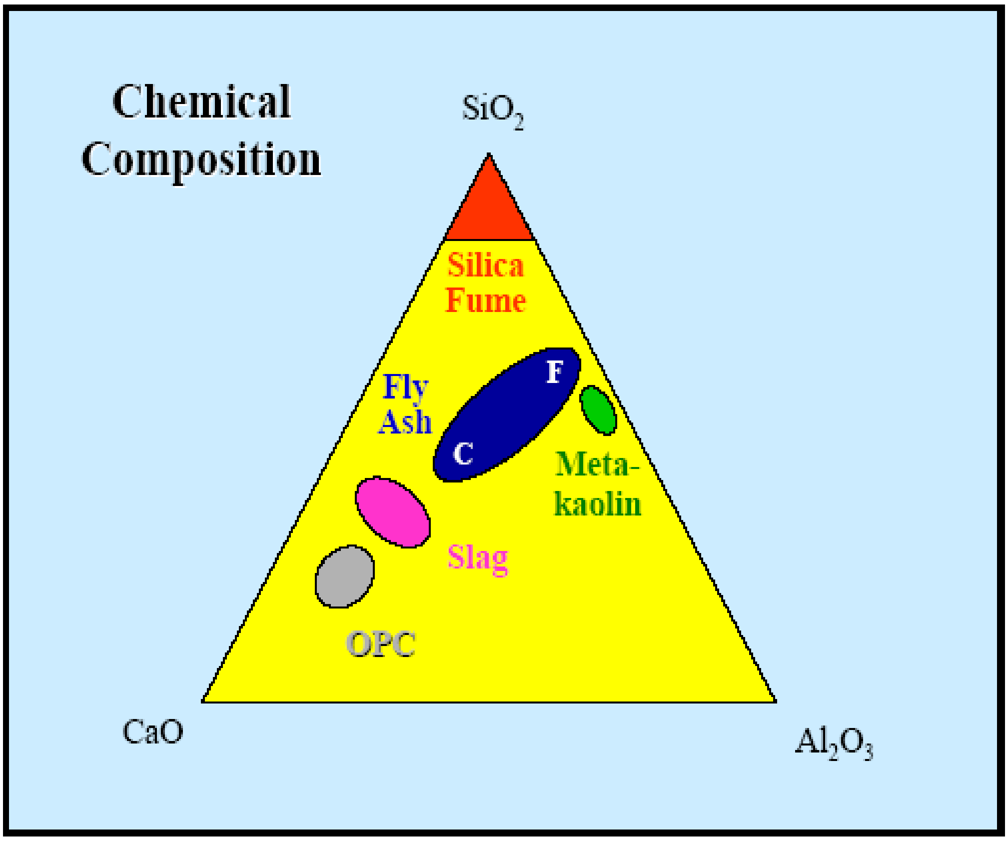


Figure 2.33 Chemical compositions of minerals. (Thomas, 2002)

2.4.5.3 Microstructure of Minerals

Recent microstructural analysis of geopolymers carried out using predominantly Scanning Electron Microscopy (SEM) has identified regions of the binder that have been labeled 'geopolymeric gel' (Palomo et al., 1999b; Phair et al., 2000; Lee and van Deventer, 2002b; c; d; Cheng and Chiu, 2003; Yip et al., 2003a; Yip and van Deventer, 2003), such as identified in Figure 26 in the preceding section. The chemical composition of these regions determined by Energy Dispersive X-ray analysis (EDX) has been reported to vary between Si/Al ratio of 1.6-2.0 (Xu and van Deventer, 2002b;c); however, the molecular structure of these regions is yet to be identified. The microscopic understanding of geopolymeric gel is hindered though, since most analysis has been completed on binders synthesized from impure materials such as fly ash and ground granulated blast furnace slag (GBS), which contain a large amount of unreacted material and unknown quantities of impurities dispersed in the gel (Palomo et al., 1999b; Lee and van Deventer, 2002a; b; c; Yip and van Deventer, 2003). Therefore, the microstructure of geopolymeric composites, not the geopolymeric binder itself, have been the object of interest in published investigations.

A typical SEM micrograph of a fly ash geopolymer is presented in Figure 26. Several characteristics of these systems can be observed. Firstly, the microstructure is extremely inhomogeneous. The material contains a high fraction of unreacted fly ash, bound together by geopolymeric gel in the interstices of the unreacted particles. Furthermore, in order to provide a representative view of the microstructure, the field of view is large for SEM analysis, in the order of 10000 µm2. This results in a poor microscopic understanding of the structure of the gel binder itself, because the gel binder is no longer the focus of the investigation. The morphology and large amount of unreacted fly ash is prohibitive for collection of high quality SEM images. The large spherical particles often dislodge from the binder during sample preparation, which complicates the analysis of the cross section. The uneven surface then compromises the accuracy of EDX analysis, since both a flat and chemically homogenous material is assumed. The high level of unreacted material also makes it difficult to determine the nominal Si/Al ratio of specimens for comparison with measurements made by EDX, based on the known Si/Al ratios of the components.

The use of metakaolin (calcined kaolin clay) as an aluminosilicate source eliminates many of these issues. Metakaolin provides a more pure readily characterized starting material. The chemical content is closely constrained approximately at a Si/Al ratio of the particle morphology is more uniform and understood, being similar to the plate structure of the kaolin from which it is formed. By use of phase pure kaolin clay as a starting material, the final metakaolin is pure and highly reactive. All of these factors greatly enhance the ability to synthesize geopolymeric materials that are more highly reacted and with a more well understood chemical content than specimens synthesized form industrial waste derived aluminosilicates. Metakaolin-based geopolymers are a convenient 'model system' upon which analysis can be carried out, without the unnecessary complexities introduced by the use of fly ash or slag as raw materials. The microstructure of a typical metakaolin geopolymer is shown in

Figure 2.34. It can be observed that the microstructure is extremely homogeneous, contains only a small fraction of material left unreacted, is representative at higher magnification, and is readily polished to higher tolerances compared to the fly ash specimen in Figure 2.35. Therefore, the use of metakaolin allows for more detailed analysis of the properties, chemical composition and structure of the geopolymeric binder.

The microstructure of geopolymeric binders with different compositions has not been investigated in isolation. Xu and van Deventer (2002a; b; c) briefly noted some of the microstructural details of mixed clay/feldspar geopolymers, once again focusing on the existence of unreacted material and their morphology.

Rowles and O'Connor (2003) completed an optimization of compressive strength of geopolymers based on metakaolin by variation in the chemical composition, with several SEM micrographs of different matrices being provided. However, no link was demonstrated between the microstructure of specimens with their mechanical properties.

Kriven and Bell (2004) and Kriven et al. (2003; 2004b) have recently focused on identifying the morphology, microstructure and properties of geopolymeric gels derived from high purity raw materials, including calcined phase pure kaolin and synthetic atomically homogeneous amorphous mixed oxide powders.

The work of Kriven et al. (2003; 2004b) follows from the original high resolution electron microscopy studies of van Jaarsveld (2000b) and Cheng and Chui (2003). Bell and Kriven (2004) have shown some systematic differences in the pore structure of geopolymers dependent on the alkali cation mixture in the activating solution, and a high level of microscopic resolution of the geopolymeric gel (Kriven et al., 2003).

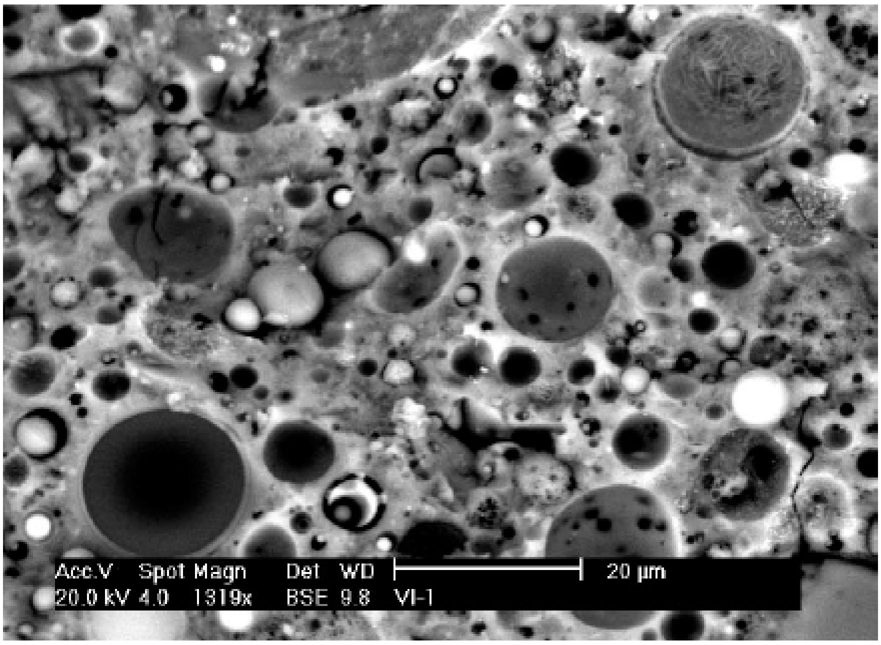


Figure 2.34 The SEM micrograph of fly ash derived geopolymer, from Lee (2002).

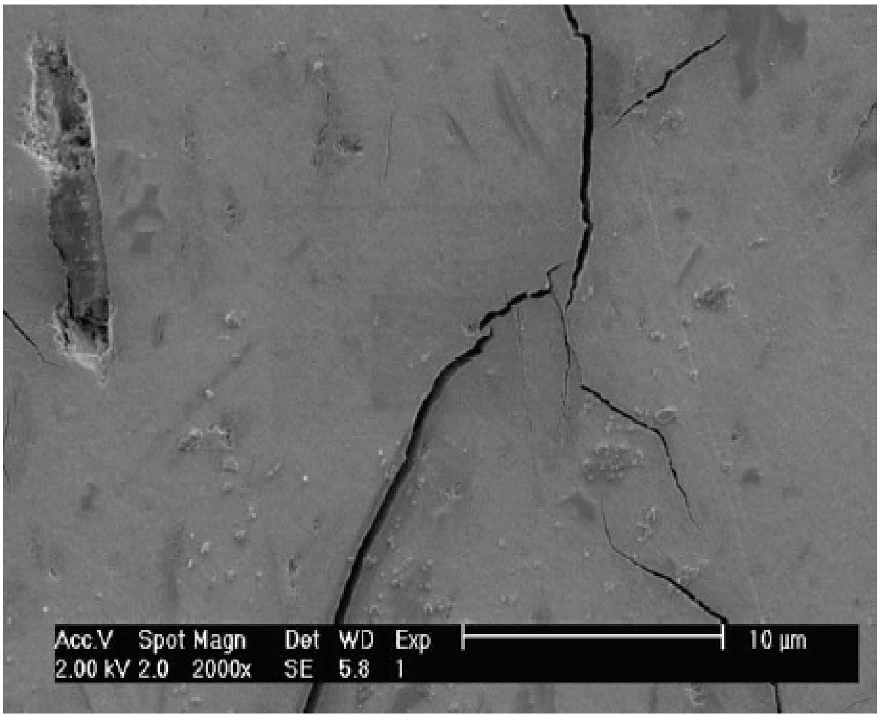


Figure 2.35 SEM micrograph of a geopolymer derived from metakaolin.

2.4.6 Chemical Admixtures

As explained earlier, chemical admixtures such as superplasticizer are important materials used for the production of SCC. Therefore, effects of these chemical admixtures on the properties of SCC have been investigated by other researchers (Sakata et. al., 2003). In a research conducted by Golasweski and Swabowski (2002) mortars of given superplasticizer type and dosage with different cements show clear differences in rheological properties of SCC. The research revealed that polycarboxylate ester (PE) type superplasticizer is more effective than naphthalene sulphate acid (NSA) superplasticizer. Used in the same dosage, this superplasticizer makes it possible to obtain mortars with considerably reduced workability loss. The characteristic of mortars with superplasticizer is high plastic viscosity, which is an advantage from a segregation point of view. It was also concluded that the type, chemical and phase composition of the cement are also important factors for the performance of superplasticizer.

Two types of chemical admixtures are commonly used in the production of SCC: superplasticizers and viscosity modifying agents VMA. Recently, shrinkage reducing admixture (SRA) has been used as new type (Collepardi, 2003).

Superplasticizer is essential for the creation of SCC. In recent times, the evolution of superplasticizers has become rapid and results in ever-improving synthetic chemical admixtures. These newer products will continue to evolve and improve; at the current time, the superplasticizer best suited for SCC is of the newer polycarboxylate type.

Conventional Superplasticizers, such as those based on sulphonated melamine and naphthalene formaldehyde condensates, at the time of mixing, are absorbed onto the surface of the cement particles. This absorption takes place at a very early stage in the hydration process. The sulphonic groups of the polymer chains increase the negative charge on the surface of the cement particle and dispersion of the cement occurs by electrostatic repulsion.

Polycarboxylate Superplasticizer is differentiated from the conventional Superplasticizer in that it is based on a unique carboxylic ether polymer with long lateral chains. This greatly improves cement dispersion. At the start of the mixing process, the same electrostatic dispersion occurs, as described previously, but the presence of the lateral chains, linked to the polymer backbone, generates a steric hindrance which stabilizes the cement particles capacity to separate and disperse. This mechanism provides flowable concrete with greatly reduced water demand (MBT, 2002).

Okamura and Masahiro (2003) summarized the requirements for superplasticizer in SCC as:

- High dispersing effect for low water/powder ratio: less than approx. 100% by volume.
- Maintenance of the dispersing effect for at least two hours after mixing.
- Lower sensitivity to temperature changes.

The job of superplasticizer is to impart a high degree of flowability and deformability; however, the higher dosages (when compared to conventional concrete) generally associated with SCC can lead to a high degree of segregation. When a superplasticizer is only used, concrete tends to segregate due to the loss in yield stress of the concrete coupled with the fact that materials with different specific gravities reside within the mixture. One of the main characteristics of SCC is segregation avoidance, also referred to as “stability” of SCC.

Three methods exist for increasing the viscosity of concrete, and these will be referred to as in the following approaches:

- VMA Approach
- High Fines Approach
- Combination Approach

All methods use a superplasticizer to increase the fluidity of the mixture. The difference between the three approaches lies in the method used to combat the segregation that will occur when superplasticizers are used. The desired mixture should result in a fluid mixture that is viscous enough to avoid segregation.

The VMA Approach uses a chemical admixture to increase the viscosity of the mixture.

Addition of another chemical admixture (besides the super plasticizer) further increases the complexity of the mixture chemistry.

According to Petersson (1999), up to 10 % of filler can be replaced by using a viscosity modifying agent; but this cannot replace the filler. His findings also showed that when VMA is used, the workability over time decreases compared with mixtures with only fillers, and that this is a difficulty when VMA is used for SCC.

The recommendations of the project also showed that with modern superplasticizers and filler, no VMA is normally necessary; and only for special applications a VMA should be used. He also stated that when a VMA is used the early-age strength considerably decreases.

Hodgson (2003) stated that the use of increased amounts of fine material (the High Fines Approach) appears to be the most suitable.

2.5 Mineral Admixtures in SCC

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. There are two groups of mineral admixtures. The first group has pozzolanic properties and the second group doesn't have any pozzolanic effect and are also termed as fillers. A pozzolanic property is defined for materials that exhibit binding property when they are hydrated in the presence of hydrated lime so they can replace the portland cement. Some kinds of Natural pozzolans, and artificial pozzolans such as fly-ash and metakaolin and ground granulated blast furnace slag are examples of such mineral admixtures (Erdogan, 1997).

Nonpozzolanic fillers are frequently used to optimize the particle packing and flow behavior of cementitious paste in SCC mixes. Moreover Improvement of fine-particle packing can considerably enhance stability and workability of fresh concrete (Bartos, 1998; Bonavetti, 2000), as well as increase the density of paste matrix and interfacial transition zone (ITZ) in hardened concrete (Corinaldesi et al., 2002; Domone and Jin, 1999).

The increasing waste production and public concerns about the environment lead people to search for the possibility of reusing materials from building demolition. If these waste materials are suitably selected, ground, cleaned and sieved, they can be profitably used in concrete.

Other mineral admixture for cement replacement is metakaolin which is produced by controlled thermal treatment of kaolin and known to have pozzolanic properties (Dunster et al., 1993). A study about kaolin conducted by Batis et al. (2004) concluded that metakaolin improves the compressive strength and the 10% addition shows the optimum contribution to the strength development. The use of metakaolin, either as a sand replacement up to 20%, or as a cement replacement up to 10%, improved the corrosion behavior of mortar specimens. Higher percentages of metakaolin, however, decreased the corrosion resistance.

Collepardi (2002) stated that the most important basic principle for flowing and cohesive concretes including SCCs is the use of superplasticizer combined with a relatively high content of powder materials in terms of Portland cement, mineral additions, ground filler and/or very fine sand.

Ramsburg and Neal (2003) stated that the successful production of SCC is dependent on arriving at an appropriate balance between the yield stress and the viscosity of the paste. Specially formulated high range water reducers are used to reduce the yield stress to a point to allow the desired free flowing characteristics of the concrete.

However, this alone may result in segregation if the viscosity of the paste is not sufficient to support the aggregate particles in suspension. To achieve the desired viscosity, it is customary to use either high cement content, VMA, or both. An alternate methodology is to employ a supplementary cementitious material that can increase the cohesion or viscosity of the paste as well as provide the desired early strength.

It may be expected that, for the same w/p ratio, increasing the volume of fine particles such as mineral admixtures 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 mineral admixture is also an important factor for the workability characteristic of the concrete. For example, it is reported that for the same workability the round and spherical geometry of the fly ash particles generally help to decrease the water requirement of concrete mixture (Erdogan, 1997).

In a study conducted by Ferraris et al. (2000) the effect of fly-ash on the rheological properties of cement paste were studied. In that research four types of fly-ash with mean particle sizes of 18 m, 10.9 m, 5.7 m and 3.1 m were used. The fly-ash with mean particle size 3.1 m was term as ultra fine fly-ash (UFFA). It was concluded that replacement of cement with UFFA leads to a decrease in high range water reducer dosage at a given yield stress and viscosity.

Bosiljkov (2002) concluded that if a high volume of filler was added to the SCC mix, the required self-compacting properties were achieved at a lower water/(cement + filler) ratio, and it also appeared that the addition of filler improves the 28-day compressive strength of concrete mixes due to the filler effect and improved fine-particle packing.

Metakaolin is a white pozzolan made by heating kaolin clay to temperatures of 600-800 ºC. It reacts rapidly with the calcium hydroxide in the cement paste, converting it into stable cementitious compounds, thus refining the microstructure of concrete, thereby reducing its permeation properties. Whilst a limited amount of research data exists, relatively little information is available on various physical properties of concrete made with metakaolin which would allow the development of a comprehensive mix design procedure. (Basheer et al., 1999)

An adverse effect of replacing the portland cement with mineral admixture is the increase in setting times of mixture. One study by Vu et al. (2001) studied the effect of calcined kaolinite on setting time of portland cement. Vu et al. (2001) concluded that the addition of calcined kaolinite to portland cement increases the normal consistency of blended portland cement mixture. Blending portland cement by 10-20% calcined kaolinite by weight not significantly altered the setting time, but exceeding this range caused a significant increase in the observed setting time.

2.5.1 Influence of Mineral Admixture on the Fresh State

It is usually reported that, if the volume concentration of a solid is held constant, the addition of mineral admixtures improves concrete performance but reduces workability. The most common reason for poor workability is that the addition of a fine powder will increase the water demand due to the increase in surface area. However, in certain cases, it is reported in the literature that the use of fine mineral admixtures can reduce the water demand or increase the slump. Lange et al. (1997) measured the water demand of mortars with increasing additions of a very fine blast furnace slag. He found that, for a specific flow, an optimum amount of blast furnace slag reduces the water demand of the mortar. Ferraris et al. (2001) explained that the workability enhancement is due to the reduction in inter-particle friction by the easily roll of spherical particles (of certain fine mineral admixtures) over one another. The spherical shape also minimizes the particle's surface to volume ratio, resulting in low fluid demands. Sakai et al. (1997)

Sakai et al. (1997) reported that a higher packing density is obtained with spherical particles as compared to crushed particles in a wet state, and this result in lower water retention in the spherical case and subsequently low water demand for a specific workability.

Sakai et al.(1997), also, reported that there is a strong dependence of fluidity on the average particle size of mineral admixture. It was explained that, at an optimal particle size, the packing density is maximum, which helps to achieve fluidity. Collins and Sanjayan (1999) reported that in concrete containing alkali-activated ground granulated slag as the binder, the workability is improved by replacing part of the binder with ultra fine materials. It was also reported that some similar materials (in particle size) are not effective in improving the workability (Ferraris et al., 2001).

Domone and Jin (1999) found that the workability retention of mortars for SCC is dependent on a combination of factors including the powder composition and the type and dosage of super plasticizer. They also found that mixes with ternary blends of powders may provide a beneficial combination of properties. They stated that there is scope for work to define optimum blends for the combination of fresh, early age and hardened properties required.

Petersson (1999) mentioned recommendations for the gradation of mineral admixtures (he referred to these materials used to increase the viscosity of the mixture as “filler” in SCC to, if possible, avoid a grading curve that coincides with the cement’s grading curve. Petersson (1999) went on to state that a relative flat grading curve, compared with the cement, gives good workability with a reasonable amount of admixture.

Holt and Schodet (2002) concluded from their work on the early age shrinkage of SCC that the high amount of limestone powder added to SCC compared with reference concrete resulted in lower shrinkage because of the restraint provided by stiffening paste before setting time.

2.5.2 Influence of Mineral Admixture on the Hardened State

Neville (2000) and Aitcin (1998) stated that most of supplementary cementitious materials have one feature in common, which is they contain some form of vitreous reactive silica which, in the presence of water, can combine with lime, at room temperature, to form calcium silicate hydrate of the same type as that formed during the hydration of Portland cement. They stated also that the silica has to be amorphous, that is, glassy, because crystalline silica has very low reactivity.

Neville (2000) illustrated that other researchers found that $CaCO3$, which is common filler, reacts with $C3A$ and $C4AF$ to produce $3CaO.Al2O3.CaCO3.11H2O$, and becomes partly incorporated into the C-S-H phase. Neville stated that this effect on the structure of the hydrated cement paste is beneficial.

British Cement Association (BS EN 206–1/8500 : 2002) stated that the additions can influence many concrete properties, including:

- sulfate resistance;
- chloride resistance;
- protection against reinforcement corrosion;
- freeze/thaw resistance; - chemical resistance;
- strength;
- permeability;
- abrasion resistance;
- heat generation
- aesthetic properties such as color.

The previous reference also stated that in some circumstances, specific additions at specific proportions may be specified to enhance selected properties of the concrete. Ramsburg and Neal (2002) also stated that in the pre-cast industry early age strength is a critical factor, and to maintain an efficient production schedule, the concrete strength has to be sufficient for stripping and handling by an age of about 14 to 18 hours. Therefore, the additions to be used would not only have to complement the SCC technology, but also to be capable of achieving early-age strength similar to the standard production mix.

Many researchers (mentioned in 2.4.6.8) evaluated the hardened properties of SCC, and made a comparison with the same properties of the conventional concrete. All of them found that there is a significant improvement in hardened SCC properties.

Based on their experimental investigations and a large number of test results taken from the literature, Holschemacher and Klug (2002) created a database with regard to the hardened properties of SCC. They stated the following:

1. The reasons for the possible differences between the hardened properties of SCC and the conventional concrete are mentioned in the following facts:

- Better microstructure and homogeneity of SCC: Many investigations, carried out by means of efficient microscopes, show an improved microstructure of SCC opposite to normal vibrated concrete. So, the void ratio of SCC in the interfacial transition zone between cement paste and aggregate is essentially lower and the pores are distributed much more evenly.
- Higher content of ultra fine materials & addition of additives: High content of ultra fine materials, usage of effective super plasticizer, and if necessary, stabilizer characterize the special composition of SCC. The addition of concrete additives and admixtures, necessary for SCC, with the production of conventional concrete is an exception, or at least their percentage at SCC is considerably higher.

2. Some of the published test results show that an increase of the cement content and a reduction of filler content at the same time increase the initial concrete strength and the ultimate concrete strength.
3. If limestone powder is used, higher compressive strengths are noticeable at the beginning of the hardening process.
4. There is a tendency of a higher splitting tensile strength of SCC. Likely as not, the reason for this fact is given by the better microstructure, especially the smaller total porosity and the more even pore size distribution within the interfacial transition zone of SCC. Further, on denser cement, matrix is present due to the higher content of ultra fines.
5. A relative lower modulus of elasticity can be expected, because of the high content of ultra fines and additives as dominating factors and, accordingly, minor occurrence of coarse and stiff aggregates at SCC.

6. The denser microstructure of the cement paste can be achieved by the addition of fillers with fineness larger than that of cement, whereby the shrinkage dimension is positively affected.
7. The bond between reinforcement and concrete is influenced by various parameters, both from the reinforcing bar and from the surrounding matrix. Within SCC, the main interesting factors are the grading of the aggregates and the ultrafine material content, the consistency and application of super plasticizer and stabilizer. Depending on the mix design and the modified test specimens it was found out, that the bond behavior in SCC is better than normal vibrated concrete.

2.5.3 Concluding Remarks

From the work of prior researchers and many others, {Ramsburg et al., (2003), Ozylidirim & Lane (2003), Naike et al. (2003), Kim et al. (1998), Dietz1 & Ma (2000), Kumar & Kaushik (2002), Ma & Dietz1 (2002), Folarin et al. (1998), Poon et al. (2003), Persson (2003), Dehn et al. (2000), Daczko (2003), and Johansen & Hammer (2002)}, it can be concluded that the use of additional cement size materials is necessary for the production of SCC, and the type, amount, fineness, particle distribution size and the number of these materials have a significant influence on fresh and hardened properties of SCC.

Ferraris et al. (2001) stated that at present, this selection cannot be predicated from physical or chemical characteristics of the mixture, and can be only determined using properly designed test.

2.6 Methods of Achieving Deformability

To achieve self compactability in SCC high deformability of the paste or the mortar and the resistance to segregation between coarse aggregate and mortar when concrete flows through the confined zone of reinforcing bars is needed. Okamura and Ozawa (1995) have listed the following requirements to achieve self compactability of concrete:

- Limited aggregate content.
- Low water-powder ratio.
- Use of superplasticizer

In a SCC, the amount of coarse aggregate has to be reduced since moving them requires more energy. The reduction in the coarse aggregate content will be balanced by an increase in the paste volume which inturn increases the aggregate inter particle distance hence reducing the contact and friction among the aggregate particles (Okamura and Masahiro 2003).

The addition of water will help to reduce both the yield stress and viscosity to achieve fluidity in SCC. However, extra water can reduce viscosity to such an extent that segregation may occur. Therefore, water-powder ratio of SCC is usually limited.

The addition of Superplasticizer reduces the yield stress without significant viscosity reduction. The effect of Superplasticizer on the Bingham constants was studied earlier by Jacek Golasweski and Januz Swabowski. In their study, the water to powder ratio of a paste was maintained at 0.32 with various combinations of portland cement and admixtures. The dosage of Superplasticizer was expressed as percentage of total powder content.

3. EXPERIMENTAL STUDY

The objective of this study is to investigate the effects of mineral admixtures on the fresh properties of SCC. In this respect, three mineral admixtures, namely, fly-ash, ground granulated blast furnace slag and metakaolin were used in preparing SCC. A total of 11 mixes were prepared at a total binder content of 550 kg/m2 and at a constant water-binder ratio (w/b) of 0.32. The fresh properties that were determined are the initial and final setting times, slump flow diameter, V-funnel flow time and density. The hardened properties are compressive strength and ultrasonic pulse velocity which were determined at 28 and 90 days of age.

3.1 Materials

This section will present the chemical and physical properties of the all ingredients. The relevant ASTM (American Society for Testing and Materials) procedures were followed for determining the properties of materials used in this investigation.

3.1.1 Portland Cement

An ordinary Turkish Portland Cement CEM I 42.5 R conforming to the Turkish Standard TS EN 197-1 (which mainly based on the European EN 197-1) manufactured by Adana Çimento was used. The physical properties and the chemical composition of the cement are presented in Table 3.1. It has a blaine finess of 3260 cm2/g and specific gravity of 3.15 g.

3.1.2 Mineral Admixtures

The mineral admixtures used in the experimental program were a class F fly ash (FA), a ground granulated blast furnace slag (GBS), and Metakaolin (MK). The Fly ash was obtained from Ceyhan Yumurtalık Thermal power plant and GBS was obtained from Iskenderun ferrochrome plant. The metakaolin was imported from USA. Their physical and chemical properties are presented in Table 3.2.

Table 3.1 Physical properties and chemical composition of portland cement

Oxide	**Determined as (%)**	**ASTM C150 Limits**
CaO (%)	62.58	-
SiO_2 (%)	20.25	-
Al_2O_3 (%)	5.31	-
Fe_2O_3 (%)	4.04	-
MgO (%)	2.82	max. 6.0%
SO_3 (%)	2.73	max. 3.5%
K_2O (%)	0.92	-
Na_2O (%)	0.22	-
LOI(Loss of Ignition) (%)	3.02	Max. 3.0%
Property	**Determined as**	**ASTM C150 Limits**
Specific Gravity	3.15	-
Blaine Fineness (cm^2/g) S	3260	min 2800
Color	Gray	-

3.1.3 Chemical Admixtures

A commercially available polycarboxylic-based superplasticizer (Glenium 51) was used to give a coincident workability. The properties of the superplasticizer are given in Table 3.3

Table 3.2 Chemical and physical properties of mineral admixtures

Chemical analysis (%)	**Fly ash**	**GBS**	**Metakaolin**
CaO	4.24	34.12	0.78
SiO_2	56.2	36.41	52.68
Al_2O_3	20.17	10.39	36.34
Fe_2O_3	6.69	0.69	2.14
MgO	1.92	10.26	0.16
SO_3	0.49	-	-
K_2O	1.89	0.97	0.62
Na_2O	0.58	0.35	0.26
Loss of ignition	1.78	1.64	0.98
Specific gravity	2.25	2.79	2.50
Blaine Fineness (cm^2/g)	2870	4180	12000

Figure 3.1 – Photographic view of aggregates and minerals

Table 3.3 Properties of the chemical admixtures

Properties	**Superplasticizer**
Color tone	Dark brown
State	Liquid
Specific gravity (kg/l)	1.07
Chemical description	Modified polycarboxylic type polymer
Recommended dosage	%1-2 (% binder content)
Freezing point	-4 ºC
Chloride content	None
Nitrate content	None

Figure 3.2 – Photographic view of superplasticizer

3.1.4 Aggregates

The coarse aggregate used was a river gravel with a nominal maximum size of 16 mm. As fine aggregate, a mixture of natural river sand and crushed limestone was used with a maximum size of 5 mm. The particle size gradation obtained through the sieve analysis and physical properties of the fine and coarse aggregates are presented in Table 3.4 and The specific gravity and absorption of the sand is presented in Table 3.4

Table 3.4 Properties of fine aggregate and sieve analysis

Sieve Size (mm)	**Fine aggregate size**		**Coarse aggregate Size**
	River sand	**Crushed sand**	
16	100	100	100
8	100	100	31.5
4	86.6	95.4	1.0
2	56.7	63.3	0.5
1	37.7	39.1	0.5
0.5	25.7	28.4	0.5
0.25	6.7	16.4	0.4
Fineness modulus	2.87	2.57	5.66
Specific gravity	2.66	2.45	2.72
Absorption (%)	0.55	0.92	0.45

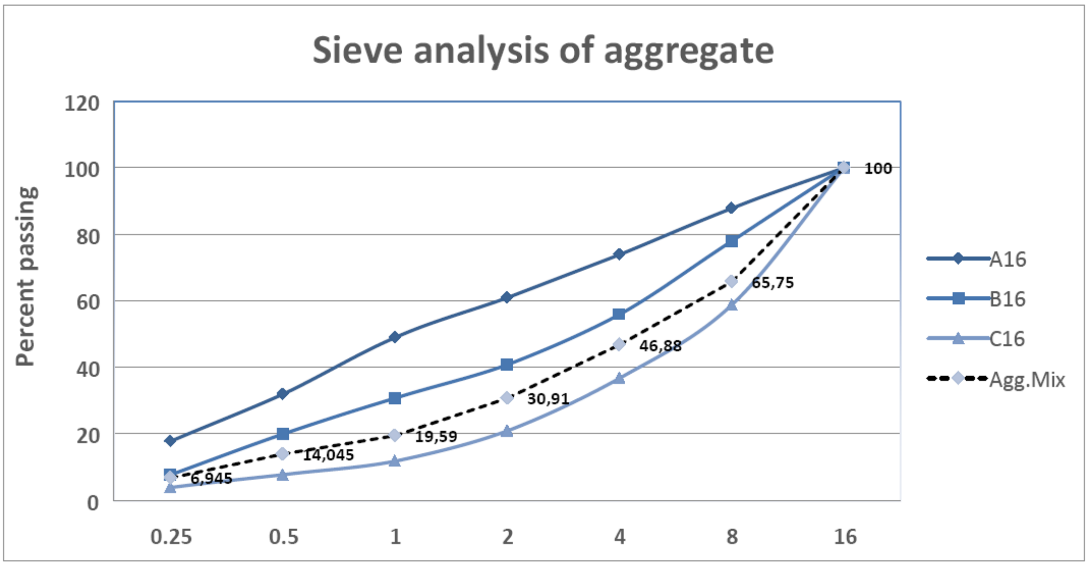


Figure 3.3 Aggregate grading curve and zones

3.2 Concrete Mix Properties and Casting

3.2.1 Concrete Mixture Proportioning

A total of 11 concrete mixes were designed having a constant water/binder ratio of 0.32 and total binder content of 550 kg/m3. Portland cement, natural sand, crashed sand, coarse aggregate, drinkable water, Fly ash, Metakaolin, Ground Granulated Blast Furnace Slag and Superplasticizer are used for mixtures. The amount of Superplasticizer was not constant. The control mixture included only ordinary portland cement (PC) as the binder while the remaining mixtures incorporated binary (PC+FA, PC+GBS, PC+MK) and ternary (PC+FA+MK, PC+GBS+MK) cementitious blends in which a proportion of Portland cement was replaced with the mineral additives. The replacement ratios for both FA and GBS were 20 and 40%, respectively while those of MK were 5 and 10% in binary cementitious blends. The replacement ratios for both FA and GBS in ternary cementious blends, however were 15 and 30% respectively while those of MK were 5 and 10% by weight of cement. The mix M11 (30GBS10MK) in Table 3.5, for example, includes 30% GBS and 10% MK. When preparing ternary mixtures, FA and GBS were considered as the similar type cementitious materials so that they were equally used in the mixtures in which both being appeared. The mix design data are provided in Table 3.5.

3.2.2 Concrete Casting and Test Specimens

In the production of SCC, the mixing sequence and duration are so important that the procedure for batching and mixing proposed by Khayat et al. (2000) was employed to supply the same homogeneity and uniformity in all mixtures. The batching sequence consisted of homogenizing the fine and coarse aggregates for 30 sec in a rotary planetary mixer, then adding about half of the mixing water into the mixer and continuing to mix for one more minute. Thereafter, the aggregates were left to absorb the water in the mixer for one minute. After cement and mineral additives were added, the mixing was resumed for another minute. Finally, the SP with remaining water was introduced, and the concrete was mixed for 3 min and then left for 2 min rest. Eventually, the concrete was mixed for additional two minutes to complete the mixing sequence. The concretes were designed to give a slump flow of 70±3cm which was achieved by using the superplasticizer at varying amounts. For this, trial batches were produced for each mixture till the desired slump flow was obtained.

Table 3.5 Mix design of SCC's (in kg/m3)

Mix No	**Mix Description**	**W/B**	**Water**	**PC**	**FA**	**GBS**	**MK**	**Natural sand**	**Crushed sand**	**Coarse agg.**	**SP**
M1	Control-PC	0.32	176	550.0	0	0	0.0	522	206	935	8.43
M2	20FA	0.32	176	440.0	110	0	0.0	512	202	917	7.43
M3	40FA	0.32	176	330.0	220	0	0.0	502	198	899	7.43
M4	20GBS	0.32	176	440.0	0	110	0.0	520	205	931	10.43
M5	40GBS	0.32	176	330.0	0	220	0.0	518	204	928	10.00
M6	5MK	0.32	176	522.5	0	0	27.5	520	205	932	11.00
M7	10MK	0.32	176	495.0	0	0	55.0	519	205	929	11.00
M8	15FA5MK	0.32	176	440.0	82.5	0	27.5	513	202	919	8.00
M9	30FA10MK	0.32	176	330.0	165	0	55.0	504	199	903	6.00
M10	15GBS5MK	0.32	176	440.0	0	82.5	27.5	519	205	929	8.00
M11	30GBS10MK	0.32	176	330.0	0	165	55.0	516	204	924	8.00

Slump flow, V-funnel, L-box, Brookfield rheometer, and ELE penetration resistance instrument were used to test the workability, passing ability, viscosity, and setting time of SCCs. From each concrete mixture, three 150 mm cubes and three 100*200mm cylinders were also taken for measuring the compressive strength of the concretes. Before the compression tests, UPV measurements were also conducted on the same samples. The cube and cylinder specimens were cast in one layer without any compaction and vibration. After 24 hrs casting, they were demoulded and stored in lime saturated water until the date of testing at 28 and 90 days.

3.2.3 Specimen Preparation

Concretes were prepared using a standard mixer. The mixing procedure for the SCCs is described in Figure 3.4. The setting times are determined from one batch and later, the workability properties are determined and a total of 3 cubic mortars with a dimension of 150 mm, 3 cylinders with a dimension of 100*200 mm are prepared for the hardened property testing. After casting, the specimens are cured at 23 ºC ± 1.7 ºC until the age of testing (Figure 3.4).

Processes of SCC Production are
Firstly;

- PC, Minerals, Water, Aggregates and SP were measured according to Mix design rates. The prepared materials are divided to three part in one 1/5 rate and two 2/5 rates.
- Aggregates were poured and mixed homogenously in the concrete mixer in 1/5 rate and water with superplasticizer in 1/3 rate were added and mixed again.
- Cement and admixtures were added and mixed
- Water with superplasticizer in 2/3 rate were added and mixed again.
- Slump test were realized if test results are acceptable. In other case superplasticizer rates can be increased or decreased according to slump flow diameter and process should be renewed.
- SCC were wet sieved and so viscosity test and setting time tests were realized with wet sieved Self Compacting Mortars.
- Weight of a empty cube was measured and filled with concrete and measured again for density measurement.
- Cubes and cylinders were filled for hardened concrete tests.

Secondly;

- Aggregates were poured and mixed homogenously in concrete mixer in 2/5 rate and water with superplasticizer in 1/3 rate were added and mixed again.
- Cement and admixtures were added and mixed
- Water with superplasticizer in 2/3 rate were added and mixed again.
- V-Funnel Tests were realized, concrete and weather heat were measured
- Cubes and cylinders were filled for hardened concrete tests.

Thirdly;

- Aggregates were poured and mixed homogenously in concrete mixer in 2/5 rate and water with superplasticizer in 1/3 rate were added and mixed again.

- Cement and admixtures were added and mixed
- Water with superplasticizer in 2/3 rate were added and mixed again.
- L Box Tests were realized, concrete and weather heat were measured
- Cubes and cylinders were filled for hardened concrete tests.

Fourthly;

- Strength Tests, UPV Tests and Density tests were realized.

Finally;

- The manufacturing process of the mixtures was illustrated schematically in Figure 3.4.

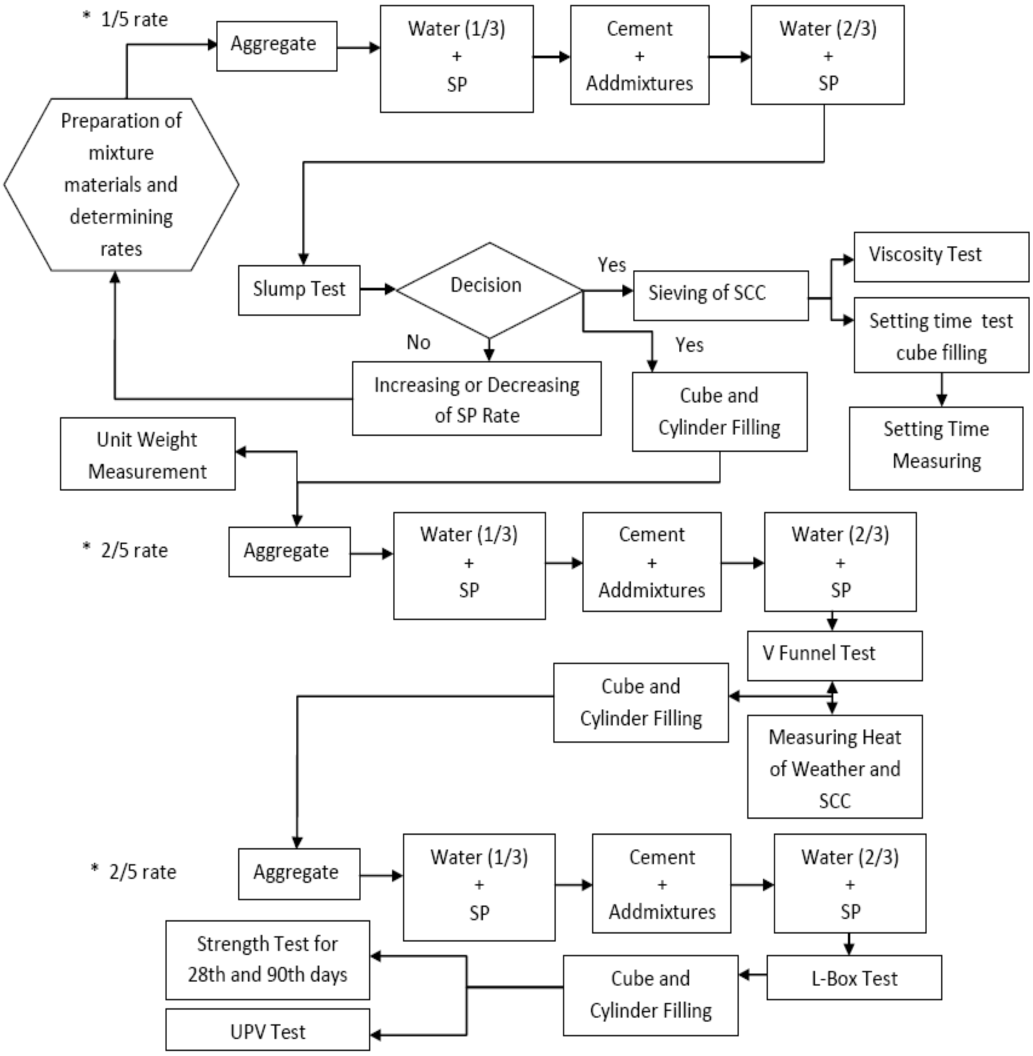


Figure 3.4 Specimen process map

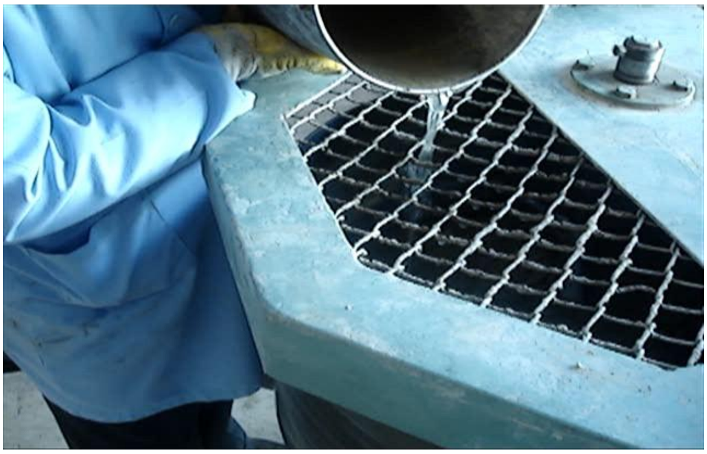
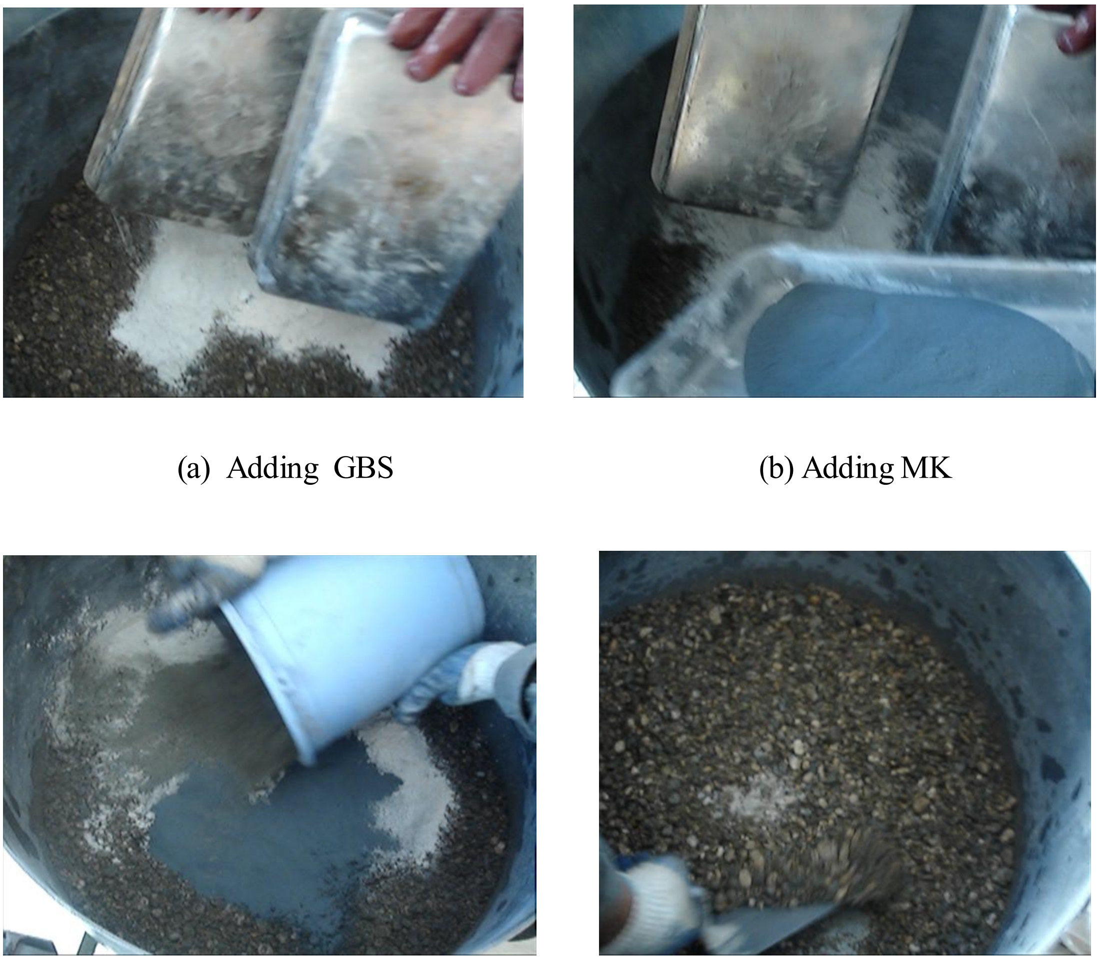


Figure 3.5 – Photographic view of adding water and SP



(a) Adding GBS

(b) Adding MK

(c) Adding PC

(d) Mixing

Figure 3.6a, b, c, d Photographic view of mixing process of minerals and aggregates

3.3 Tests for Fresh Properties

3.3.1 Determination of Slump Flow

The slump flow of all the mixtures was kept constant at about 70±3 cm while the slump flow time was measured. In addition, L-box and V-funnel tests were performed according to the procedure recommended by EFNARC committee (European Federation for Specialist Construction Chemicals and Concrete Systems). The subsequent diameter of the mortar is measured in two perpendicular dimensions and the average is reported as the final diameter. Finally the relative slump is calculated by the following procedure;

- Simultaneously, stopwatch is started and the time taken is recorded for the concrete to reach the 500mm.
- Spreading of circle. (This is the T50 time).
- The final diameters of the concrete in two perpendicular directions are measured.
- The average of the two measured diameters is calculated. (This is the slumpflow in mm).

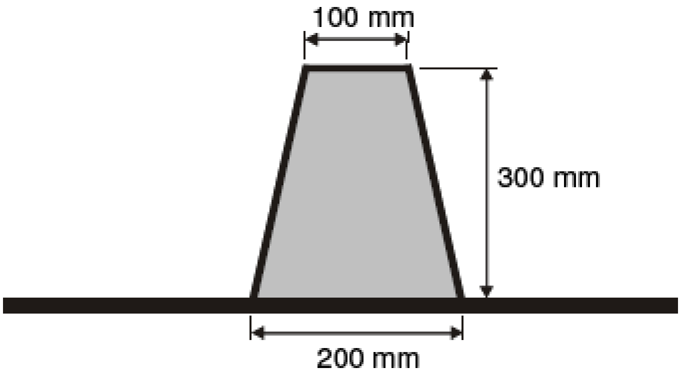


Figure 3.7 Schematic representation of the slump cone

Figure 3.8 Photographic view of flow table

(a) Slump figure

(b) Poured

(c) Measurement 1

(d) Measurement 2

Figure 3.9a, b, c, d – Photographic view of slump flow test

3.3.2 Determination of V-funnel Flow Time

The V-funnel flow test for SCC is also described by EFNARC. The funnel is filled completely with SCC and the bottom outlet is opened, allowing the concrete to flow. The flow of mortar is the elapsed time (t) 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.

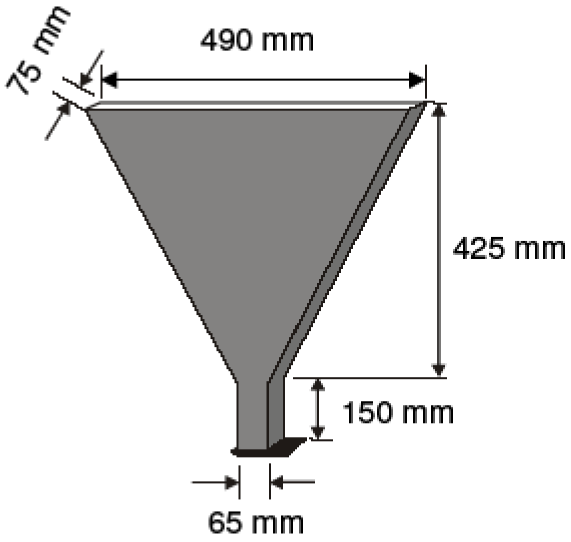


Figure 3.10 Schematic representation of the V-funnel

(a) V-funnel (b) Measurement of V-funnel flow time

Figure 3.11a, b - Photographic view of V-funnel

3.3.3 Determination of L-Box Height Ratio

This test assesses the flowability of SCC, and the extent to which it is subjected to blocking by reinforcement. The L-box test consists of an L-shaped apparatus (Figure 3.12 and 3.13a). The vertical and horizontal sections are separated by a movable gate, in front of which a reinforcing bar obstacle is placed (Khayat et al., 2004). The box is filled completely with fresh concrete and the hatch of L-box is opened, allowing the concrete to flow.

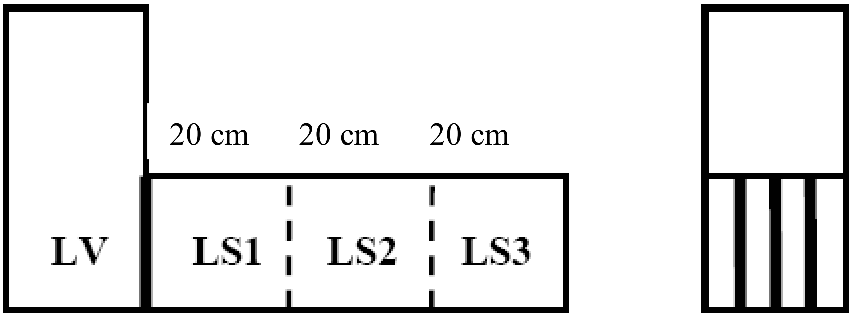
The vertical section is filled with concrete and left to rest for one minute. Then, the gate is lifted and concrete flows under its own weight through the reinforcement into the horizontal section.

The L-box test procedure was modified so that more information regarding the horizontal segregation resistance of the concrete could be obtained. For this purpose, the horizontal section was divided into two sections, each about 20 cm. in length. When the flow ceased, the concrete height was measured at a minimum of six points along the flow direction to determine the volume of concrete in each section.

The flow of mortar is the elapsed time (t) in seconds between the opening of the hatch and the time when the concrete flow is stopped, the box bottom level is divided to three part (each of 20 cm.) (figure) to measure flow time two times, and concrete height was measured from top of box vertical storage from beginning H1 and final point H2 of it. The relative concrete box level (L-box height ratio) is then calculated as:

$a = 15\text{ cm.} - H1$ and $b = 15\text{ cm} - H2$. …………………………………………....(3.1)

b/a…………………………………………………………………………....(3.2)



Side view Front view

Figure 3.12 Schematic representation of the L box

(a) L-Box (b) L Box Filling

(c) Measurements of T_{200} and T_{400} (d) Measurement of H_2 and H_1

Figure 3.13a, b, c, d Photographic view of the L box apparatus and test procedure

3.3.4 Determination of Setting Time

Initial and final setting times of the self compacting concrete mixtures were determined by means of a setting time apparatus conforming the ASTM C/C 403M-99. (Figure 3.16) The test was performed on a mortar which was obtained by sieving freshly mixed concrete through a 5 mm sieve. Then the mortar was placed in a 100 mm cube container and stored in a controlled environment of 20±2 0C and 65±5% relative humidity throughout the test duration (Figure 3.15). At regular time intervals, the force required for a needle to penetrate 25 mm in to the mortar was measured. From a plot of penetration resistivity versus elapsed time, the initial and final setting times were determined. The former and the latter are defined as the times at which the penetration resistance reaches values of 3.5 and 27.6 MPa, respectively.

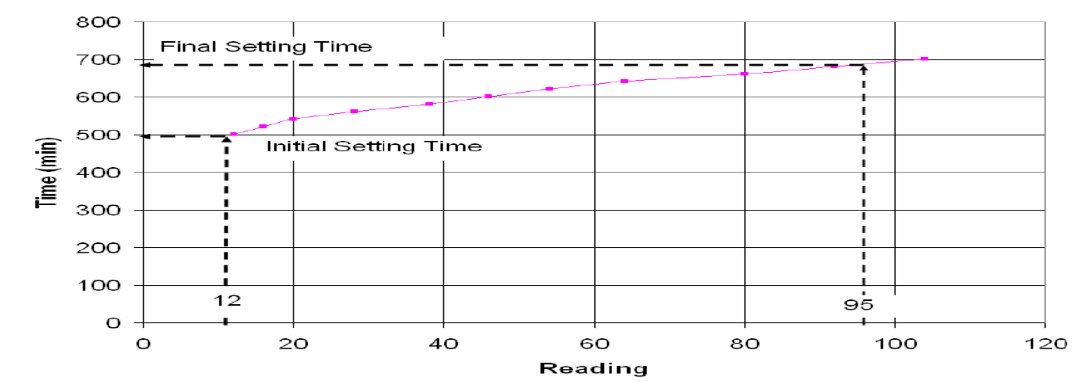


Figure 3.14 Determination of initial and final setting time by interpolation

Figure 3.15 Photographic view of setting time procedure

Figure 3.16 Photographic view of setting time test apparatus

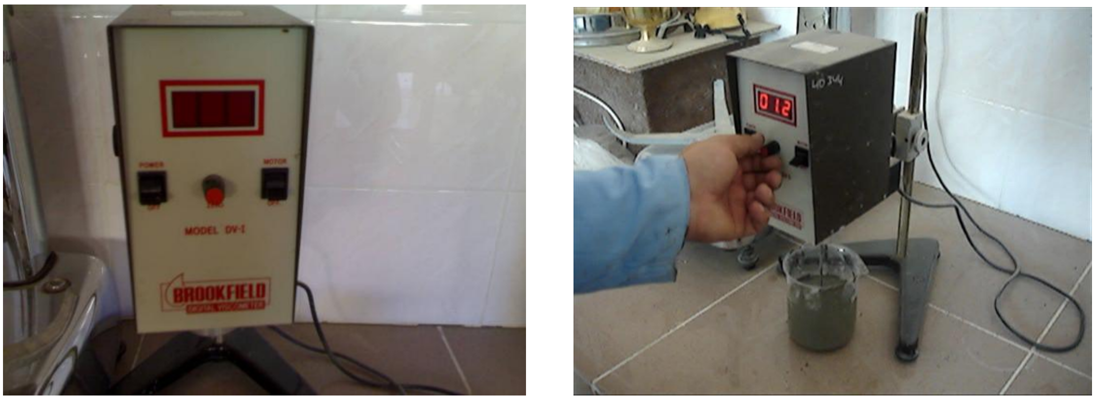
3.3.5 Determination of Viscosity

Viscosity was measured on the mortar phase of the SCC. For this, a part of fresh concrete for each mix was wet sieved on a vibrating sieve through a mesh size of 5mm size as in the case the setting time measurement (see Figure 3.17a, b, and c, d). The separated matrix mortar was then taken as the sample for determination of viscosity (Xing and Isamu, 2004). Viscosity measurements were performed using a Brookfield DV-E model viscometer. It is a rotational viscometer with a smooth-walled concentric cylinder. Viscosity of the concretes was measured at different rotational speeds. Moreover, the time dependent viscosity of the concretes were determined so as to prevent the inaccurate yield stress and unusual viscosity readings at low stress levels resulting from the wall slip (Felekoglu et al, 2006a). The measurements were realized at the seven rotational speeds (1, 2.5, 5, 10, 20, 50, and 100 rpm) at 0, 20 and 40 minutes after mixing.

(a) Sieve

(b) Sieving of SCC

(c) Sieved mortar



(d) Brookfield test apparatus

(e) Measuring of viscosity

Figure 3.17a, b, c, d, e Photographic view of viscosity test apparatus and procedure

3.3.6 Determination of Density

A three dimensions of the cubic specimens were measured using a caliper of 0.01 mm. resolution and their weights were also measured with a balance of 0.01 gr. resolution at freshly. Using these data the density of the specimens were determined. (see Figure 18a, b)

(a) Measurement of cube (b) Filling of cube

Figure 3.18a, b Photographic view of density measurement procedure

3.4 Tests for Hardened Properties

3.4.1 Determination of Compressive Strength

Compressive strengths are determined at 28, and 90 days of age. The test was conducted in accordance with ASTM C 109/C 109M-01 using a universal testing machine (Figure3.19c, d). The average of three test specimens was computed for the aforementioned concrete properties.

(a) Fresh SCC (b) Hardened SCC

(c) Compressive strength test device (d) Pressure bars

Figure 3.19a, b, c, d Photographic view of compressive strength test apparatus and procedure

3.4.2 Determination of Ultrasonic Pulse Velocity

The UPV measurement is described in ASTM C 597-83. The testing system consists of a pulser/receiver unit with a built-in data acquisition system and a pair of narrow band, 150 kHz transducers. 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 (Figure 3.20). 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 28 and 90 days of age were nondestructively monitored.

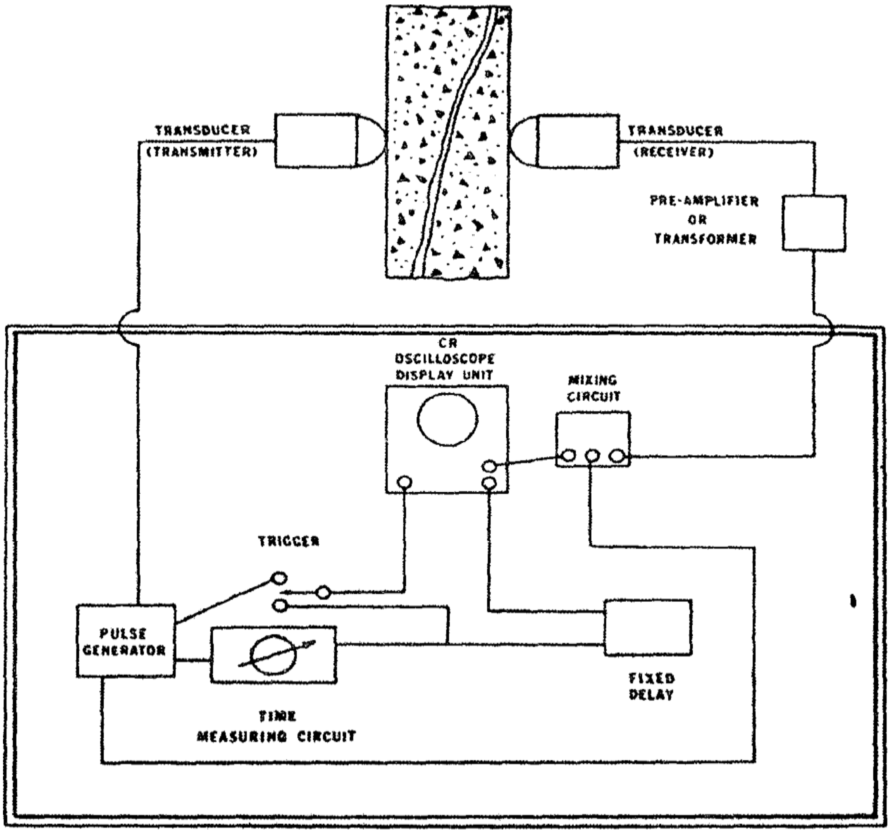


Figure 3.20 UPV testing on cubic specimens (ASTM)

Figure 3.21 Photographic view of UPV test apparatus

4. TEST RESULTS AND EVALUATION

4.1 Fresh Properties

According to EFNARC, a concrete mix can only be classified as SCC if the requirements for filling, passing and segregation resistivity characteristics are fulfilled. The fresh properties of the concretes measured, namely, slump flow time (T_{500}), slump flow diameter, V-funnel time and L-box height ratios accompanied by the minimum and maximum levels proposed by EFNARC are presented in Table 4.1 for various concrete mixtures of binary and ternary systems. Slump flow diameters of all mixtures were kept in the range of 670 to 730 mm throughout the study. Included in Table 4.2 is also the initial and final setting times in minutes.

4.1.1 Slump Flow

Generally, the effect of adding mineral admixtures was to decrease the slump flow time except for 10% MK addition. Slump flow time (T_{500}) was generally shorter than 5 sec except for the control mix (M1) and the mixture containing %10 MK (M7) indicating that the mineral additives remarkably reduced the slump flow time of the SCCs. The use of FA appeared to be the most effective pozzolan in the reduction of the slump flow time. The concretes with only MK had a slump flow of as high as 5 sec but this value decreased to 4 and 3 sec for the concretes with the ternary systems of FA+MK and GBS+MK, respectively, at 5% replacement level (Figure 4.1).

Table 4.1 shows that addition of FA and GBS decreased while MK extended the slump flow time remarkably in comparison to control concrete. The highest decrease in slump flow time was achieved at the 40% FA replacement ratio (Mixture M3). It was observed from Figure 4.1 that increasing the FA replacement ratio from 20% to 40% reduced the T_{500} time from about 4 to 2 sec while increasing the GBS content did not alter the T_{500} value. However, when the MK content was increased from 5 to 10%, the slump flow time extended from 5 to 6 sec. Thus, this mixture violated the EFNARC limitation.

Table 4.1 Fresh concrete properties

Mix No	**Mix ID**	**Slump flow**		**L-box**			**V-funnel flow time**
		T_{500} (sec)	**D (cm)**	**T_{200} (sec)**	**T_{400} (sec)**	**H_2/H_1**	**(sec)**
M1	Control-PC	6.00	67.0	7.0	17.0	0.79	14.0
M2	20FA	4.00	73.0	5.0	7.0	0.93	17.0
M3	40FA	2.21	73.0	3.0	6.0	0.96	7.0
M4	20GBS	3.20	70.0	3.0	7.5	0.88	11.0
M5	40GBS	3.30	70.0	5.0	15.0	0.94	15.0
M6	5MK	5.00	72.5	5.0	13.0	0.90	18.0
M7	10MK	6.00	73.0	7.0	20.0	0.89	18.0
M8	15FA5MK	4.00	73.0	4.6	10.4	0.91	15.4
M9	30FA10MK	4.40	71.0	4.0	7.7	0.91	13.4
M10	15GBS5MK	3.00	73.0	2.0	5.0	0.98	15.0
M11	30GBS10MK	4.00	72.5	6.0	16.0	0.83	20.0
Acceptance criteria of SCC suggested by EFNARC							
Minimum		2	65	-	-	0.8	6
Maximum		5	80	-	-	1	12

When the slump flow time of the mixtures with the ternary blends of PC+FA+MK or PC+GBS+MK was investigated, Figure 4.1 have revealed that the adverse affect of using MK on the T_{500} time can be remarkably remedied. Take, for example the mixtures M8 to M11, all of which having T_{500} values of shorter than that of the EFNARC limitation in spite of the fact that these mixtures contained MK at varying amounts. The best compromise was found for the mixture containing 15% GBS and 5% MK which led to a T_{500} time of about 3 sec. Therefore, test results suggest that the ternary use of the mineral admixtures showed superior performance in terms of T_{500} time than the binary use of these materials, especially the use of only MK.

The slump flow diameter of the concretes were designed to be in between 70±3 cm. as shown in Figure 4.2. Thus, all the mixtures have fulfilled the EFNARC criteria in terms of slump flow diameter. However, to be able to achieve the desired flow diameter, the superplasticizer was used at varying amounts. Test results showed that using FA at any replacement level increased the flow diameter of the concretes. GBS or MK, on the other hand, reduced the flow diameter probably owing to their higher specific surface values. Thus, apart from the control concrete, the concretes containing only GBS or MK needed higher superplasticizer content to reach the same flow diameter as seen in Table 3.5.

The effect of using the mineral admixtures in ternary blends was to increase the flow diameter of the mixtures. Moreover, the superplasticizer demand for the mixture to reach a flow diameter satisfying EFNARC limitation lessened with the use of the ternary blends.

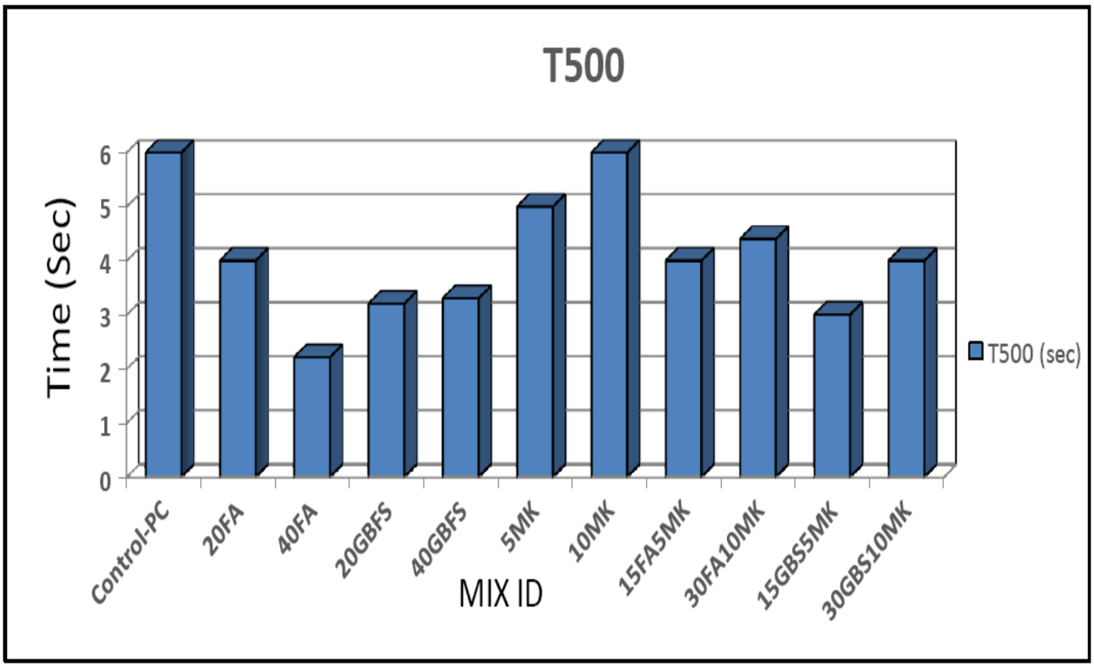


Figure 4.1 Slump flow time T_{500}

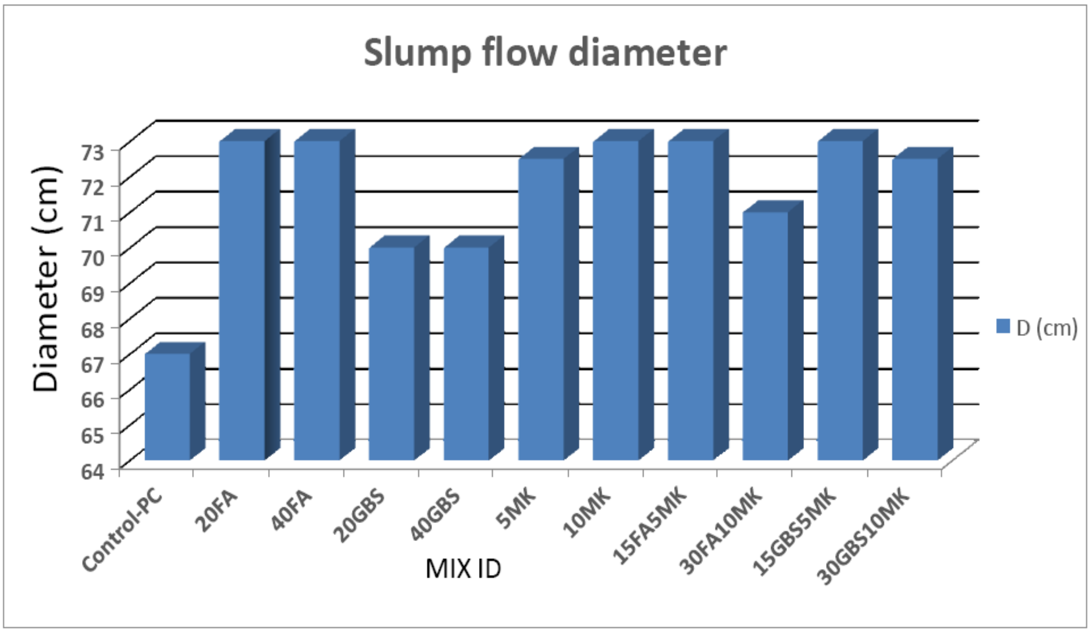


Figure 4.2 Slump flow diameter measurement results

4.1.2 V-funnel Flow Time

The variation in the V-funnel flow time of the mixtures is given in Table 4.1 and plotted in Figure 4.3. As it seen in Figure 4.3 that the time measured via the V-funnel flow was in the range of 7 to 20 sec. Although the substantially longer V-funnel flow time for some of the mixtures, the authors observed that all of concrete mixtures filled the molds by their own weights and authors did not detect any segregation or considerable bleeding in any of the mixtures during the slump flow test at the production stage of concretes.

The lowest and the highest limitations of EFNARC for the V-funnel flow time are 6 and 12 sec., respectively. According to this criteria, only the mixtures M3 and M4 may be classified as SCC. However, their upper limit can be extended to as high as 46 sec as stated in the literature (Felekoğlu et al., 2006b).

The V-funnel flow time of the control mixture was 14 sec. Binary use of FA at 20 and 40% replacement levels, respectively, increased this value to 17 sec. but then decreased to as low as 7 sec. at 40% replacement level. A similar result was stated by

Şahmaran (2006b). In his study the FA addition extended the V-funnel flow time from 10.7 to 19.2 sec when the FA replacement 40% to 50%. In a similar way to at the FA as used at 20% replacement level. Binary use of the MK remarkably prolonged the V-funnel flow time of the mixture, irrespective of replacement level. The main reason for this behavior may be attributed to the higher specific surface of the MK associated with its absorption based on its clayes origin which in turn remarkably increased the viscosity of the mixtures. The concretes with only MK had a V-funnel flow time of about 18 sec irrespective of replacement level. Using the GBS in binary blends reduced the V-funnel flow time at 20% replacement level while it increased the flow time when used at 40% replacement level.

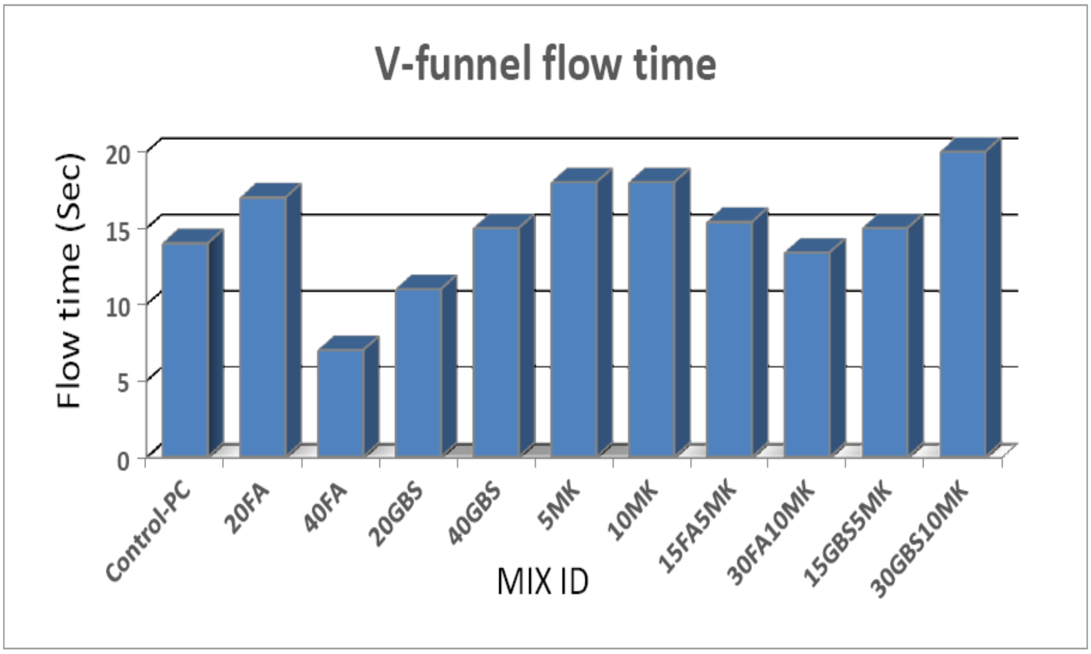


Figure 4.3 V funnel flow time measurement results

The behavior of the concrete containing binary blends of mineral admixtures seen in V-funnel flow time was also observed in the concretes having the ternary blends. The concretes with 30% GBS and 10% MK had a flow time of as high as 20 sec which reduced to 13.4 sec for the mixture of 30% FA and 10% MK. However, there was no clear distinction between the mixture containing 5% MK and 15% FA or GBS both of which having a flow time of about 15 sec.

4.1.3 L-Box Height Ratio

Passing ability of the self compacting concretes was measured by means of the L-box test. The test provided H_2/H_1 ratios as a measure of the flowability among reinforcing bars. The variation in the L-box height ratios (H_2/H_1) is presented in Table 4.1 and graphically depicted in Figure 4.4. It was clearly observed that almost all of the concrete satisfied the EFNARC limitation in terms of L-box height ratio. H_2/H_1 values ranged from 0.79 to 0.98 depending mainly on the binder used in the concrete production. The lowest one belonged to the control concrete while the concrete having ternary mixture of 15% GBS and 5% MK had the highest ratio. It is evident in Figure 4.4 that the concretes containing one or more of the mineral admixtures had higher H_2/H_1 values. Therefore, it is suggested that the concretes with mineral admixtures have better flow properties than the control concrete.

When the binary use of the mineral admixtures is considered, Figure 4.4 shows that, there is an increasing tendency in the L-box height ratios with increasing the replacement ratio for both PC-FA and PC-GBS concretes. Incorporating FA increased the L-box height ratio from 0.79 to 0.93, thereafter to 0.96 for every 20% replacement level, respectively. Similarly, the concretes with GBS had L-box ratios of 0.88 and 0.94 at 20 and 40% replacement levels, respectively. The concretes with MK showed similar behavior, as well. Using MK in the binary blends impart better flow properties in terms of higher H_2/H_1 ratios, irrespective of replacement level.

The behavior seen in the binary systems was also observed for the concretes made with ternary blends of mineral admixtures. Especially at 20% replacement level the flowability characteristics of the concretes with ternary blends were much better than those of the concretes with binary cementiatious blends.

Apart from the H_2/H_1 ratio, L-box test also provided T_{200} and T_{400} times which are the durations to be taken for the fresh mixture to reach a distance of 200 and 400 mm along the horizontal section from the sliding door, respectively. These results gave some indication about the easy flow of the concrete mixtures with mineral admixtures compared to the control mixture. The test results for T_{200} and T_{400}

durations of the fresh concretes are provided in Table 4.1 and plotted in Figure 4.5. T_{200} and T_{400} durations for the control mixture were about 7 and 17 sec, respectively. However, replacing PC with FA fairly reduced these values, to 5 and 7, and 3 and 6 sec at 20 and 40% replacement levels, respectively. A similar behavior was observed for the GBS concretes in that addition of GBS greatly reduced the T_{200} and T_{400} times of the concretes. Incorporating the metakaolin, on the other hand, did not alter the behavior at 10% replacement level while slight reduces the T_{200} and T_{400} durations at 5% replacement level. The concretes with the ternary systems (FA+MK, GBS+MK) provided better performance in terms of flow properties as seen in Table 4.1. Both T_{200} and T_{400} durations of these concretes were generally shorter than those with binary mixtures. The shortest T_{200} and T_{400} times of 2 and 5 sec, respectively were achieved for the concrete with 15% GBS and 5% MK.

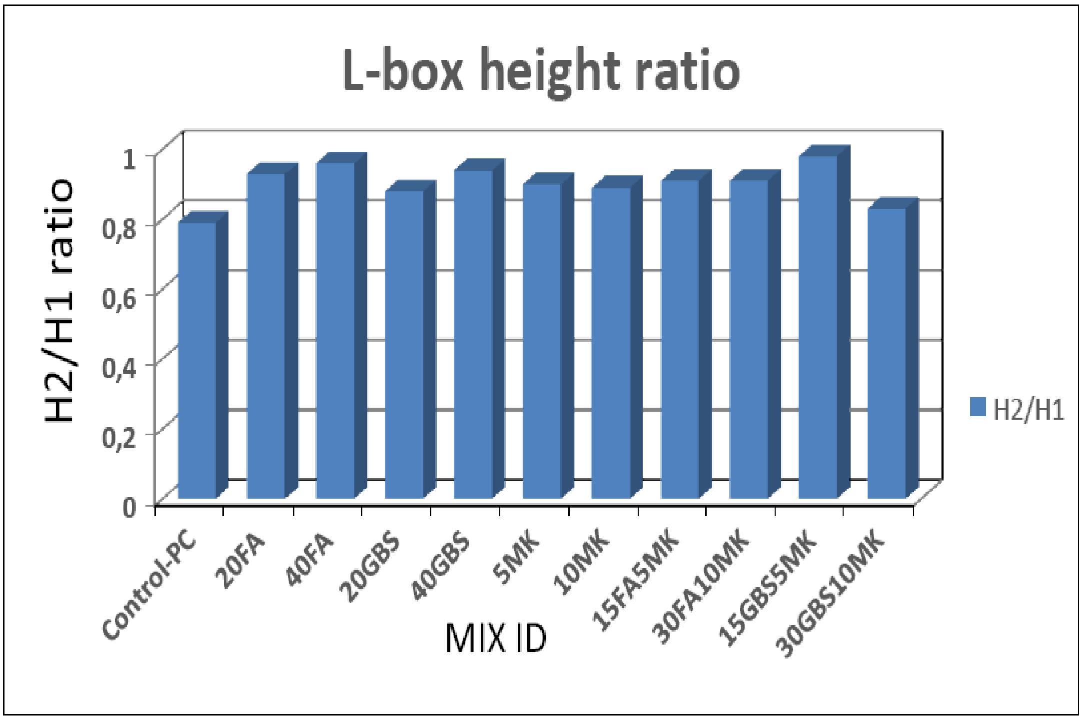


Figure 4.4 L box height ratio measurement results

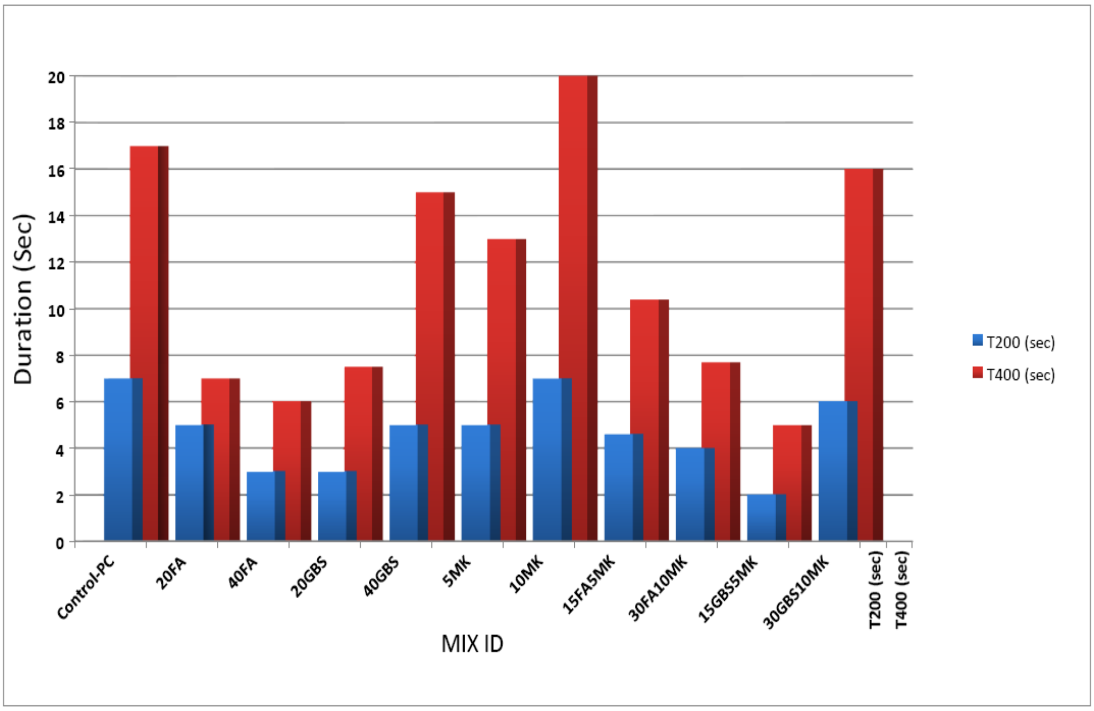


Figure 4.5 L box T_{200} and T_{400} measurement results

4.1.4 Initial Setting (IS)– Final Setting (FS) Times

Previous research indicates that setting times of concrete are influenced by water/binder ratio, dosage; source and type of admixtures, as well as the composition of cement used (Brooks et al., 2000), (Alshamsi at al., 1993), (Naik and Singh., 1997) and (Eren at al., 1995). In this study, all of the above mentioned criteria were kept constant to obtain consistent results. Initial (IS) and final (FS) setting times for the different concrete mixtures are given in Table 4.2 and graphically depicted in Figure 4.6. There is a clear trend that the binary use of FA and GBS with ordinary Portland cement (PC) significantly prolonged the initial and final setting times of the SCCs. Moreover, the effect of increasing the replacement level of both FA and GBS was to increase further the setting times of the concretes. Brooks et al. (2000) attributed this retardation to the combined effect of a lower cement content and higher effective superplasticizer dosage relative to the weight of cement since part of the cement was replaced by the mineral admixtures. Of all 11 concrete mixes, the greatest retardation in initial and final setting times belonged to the concretes containing 40% FA which had an IS and FS of 653 and 740 minutes, respectively. In the literature, there is a general agreement on the retardation of IS and FS times of the concretes containing FA and GBS. The addition of MK up to 10% increased the initial and final setting time of SCC, as well. As mentioned before the same trend was also observed in the binary use of FA and GBS. However, increasing of initial and final setting times with using MK were very small when compared to FA and GBS. Vu et al. (2001) emphasized that the addition of calcined kaolinite to portland cement increases the normal consistency of blended portland cement mixture. Blending portland cement by 10-20% calcined kaolinite by weight not significantly altered the setting time, but exceeding this range caused a significant increase in the observed setting time.

Effects of MK on setting time and consistency of mortars were determined by Batis et al (2004). The MK blended cement demand significantly more water than the relatively pure cement and this phenomenon is attributed to high fineness of MK. The increase of MK content causes significant increase of the water demand. PC with 10% MK showed the lowest water demand compared with the other blended cements. The initial and final setting time of MK cements is higher than the setting time of pure cement. When the concretes with ternary blends of PC, MK, FA or GBS were evaluated from the view point of setting time, it was observed that the inclusion of MK at 10% replacement level remarkably diminished the delay in the setting time of the concretes with only PC plus FA or GBS. The concrete containing 40% GBS had IS and FS times of 465 and 700 minutes, respectively, while the values were 367 and 467 minutes for the concrete with 30% GBS and 10% MK as seen in Table 4.2 and Figure 4.6. A similar behavior was observed in the case of the concretes of MK and FA in that the addition of 10% MK reduced the setting times of the concretes. The combined use of the 5% MK and 15% GBS or 15% FA in the concretes, however, prolonged both the initial and final setting times of the concretes when compared to those with the binary blends of FA or GBS at 20% replacement level. Indeed, the concrete having a 20 % FA had the IS and FS times of 500 and 557 minutes, respectively while the former and the latter were 527 and 617 minutes for the companion concrete with 15% FA and 5% MK (see Table 4.2). This finding indicates that of 20% replacement level FA or GBS are the mineral admixtures governing the delay in setting time rather than MK. However, when the content of

MK is increased to 10% as in the case of the mixtures M9 and M11, There is a marked reduction in the delay of the setting time of the concretes.

Table 4.2 Setting time

MIX NO	Mix ID	INITIAL SET	FINAL SET
M1	Control-PC	332	449
M2	20FA	500	557
M3	40FA	653	740
M4	20GBS	436	595
M5	40GBS	465	700
M6	5MK	397	498
M7	10MK	409	512
M8	15FA5MK	527	617
M9	30FA10MK	485	578
M10	15GBS5MK	491	610
M11	30GBS10MK	367	467

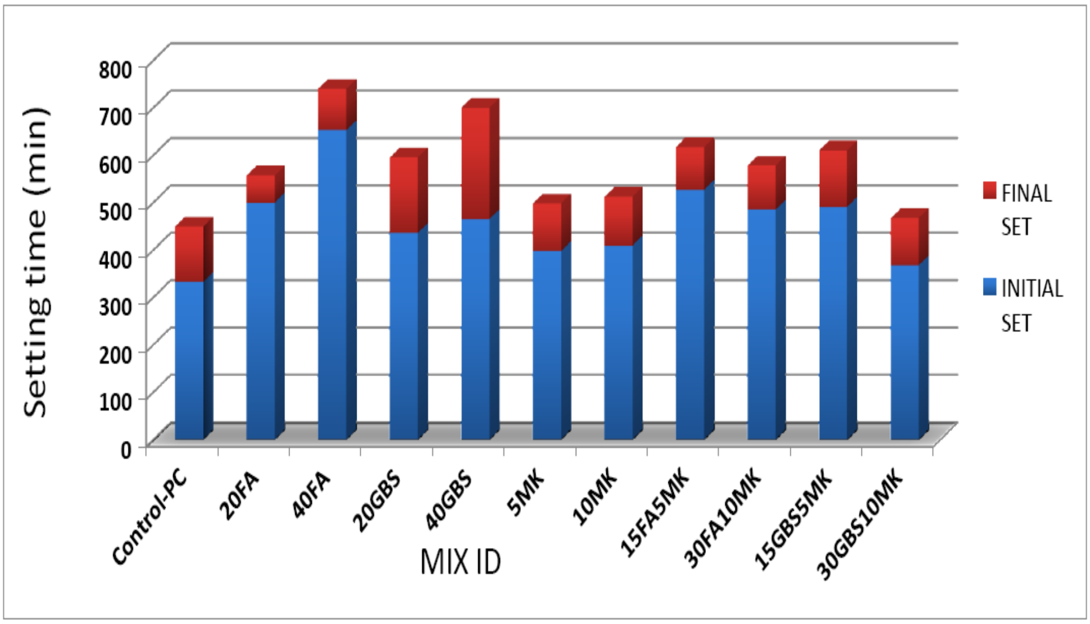


Figure 4.6 Initial and final set measurement results

4.1.5 Viscosity

The rotational speed (rpm) and viscosity (cP) of the concrete mixtures were drawn which yielded similar tendency, irrespective of measuring time. As reported in Felekoglu et al. (2006a), the equation of $\mu=a\gamma b$ was well fitted with measurements, where μ is the viscosity in centipoises, and γ is the rotational speed in revolutions per minute. The constants a and b were calculated using the best fit equations. The correlation coefficients and the values of constants a and b for all concrete mixtures are given in Table 4.3. The time dependent variations in the viscosity of the concretes are plotted in Figure 4.7, 4.8 and 4.9. As seen from the figures, the replacement of FA and GBS with cement decreased the values of viscosity, irrespective of time of measurement. However, the metakaolin concretes had consistently higher viscosity values than those of the control concrete, and/or FA and GBS binary blends. It was shown that the replacement of cement by FA and GBS resulted in a reduction in a water demand and the superplasticizer dosage to maintain the same workability with the control mixture. In contrast, the replacement of cement by MK increased the superplasticizer demand, which inturn resulted in a more viscous behavior. Higher the superplasticizer used, the concrete becomes more viscous owing to the its shear thickening effect (Cyr et al., 2000).

It is evident in Figure 4.7 that the viscosity of the control concrete exhibited a reduction with increasing FA or GBS content. In the case of MK concrete, however, the viscosity was inversely proportional to the mineral admixture incorporated. Therefore, to hinder the adverse effect of using MK the ternary mixtures were found to be appropriate remedies. Indeed, the concretes with the ternary cementious blends (FA+MK or GBS+MK) had consistently lower viscosity values than the concretes made only with binary blends of MK.

Figure 4.7 to 4.9 also represent the time dependent development of viscosity of SCCs with binary and ternary blends. It was also observed that the high rotational speed reduced the viscosity of all of the concrete mixtures. This indicated that the SCCs of high workability can be obtained through mixing by high shear rate blenders. Moreover, all of the concretes exhibited more viscous behavior with time. Sun et al.

(2006) reported a similar behavior in that viscosity became nonlinear and increased with time. The effects of using FA and GBS were to decrease the viscosity of the concretes, it can also be postulated from the test results that among the mineral admixtures used, the MK is the most effective cementitious material. (Table 4.3)

Table 4.3 Viscosity rates

Mix No	**T=0**			**T=20**			**T=40**		
	A	**B**	**R2**	**A**	**b**	**R2**	**a**	**B**	**R2**
M1	4103	-0.2618	0.67	4580	-0.3517	0.63	5712	-0.3793	0.63
M2	4708	-0.4424	0.74	5797	-0.5016	0.83	6872	-0.5381	0.90
M3	3052	-0.2481	0.68	2991	-0.2295	0.63	4079	-0.3742	0.81
M4	3895	-0.2488	0.58	4905	-0.3493	0.75	6583	-0.4901	0.71
M5	1974	-0.1375	0.69	2200	-0.1774	0.85	2567	-0.2706	0.91
M6	8991	-0.3263	0.81	11197	-0.3688	0.82	17651	-0.488	0.91
M7	6473	-0.1642	0.44	9017	-0.2375	0.69	14191	-0.3227	0.87
M8	2904	-0.1514	0.33	3871	-0.2205	0.50	6458	-0.3683	0.87
M9	11741	-0.4114	0.84	12219	-0.4429	0.77	23840	-0.6689	0.93
M10	3205	-0.1135	0.24	4052	-0.0939	0.30	5410	-0.1441	0.41
M11	4454	-0.0995	0.32	7393	-0.1566	0.29	16478	-0.4936	0.93

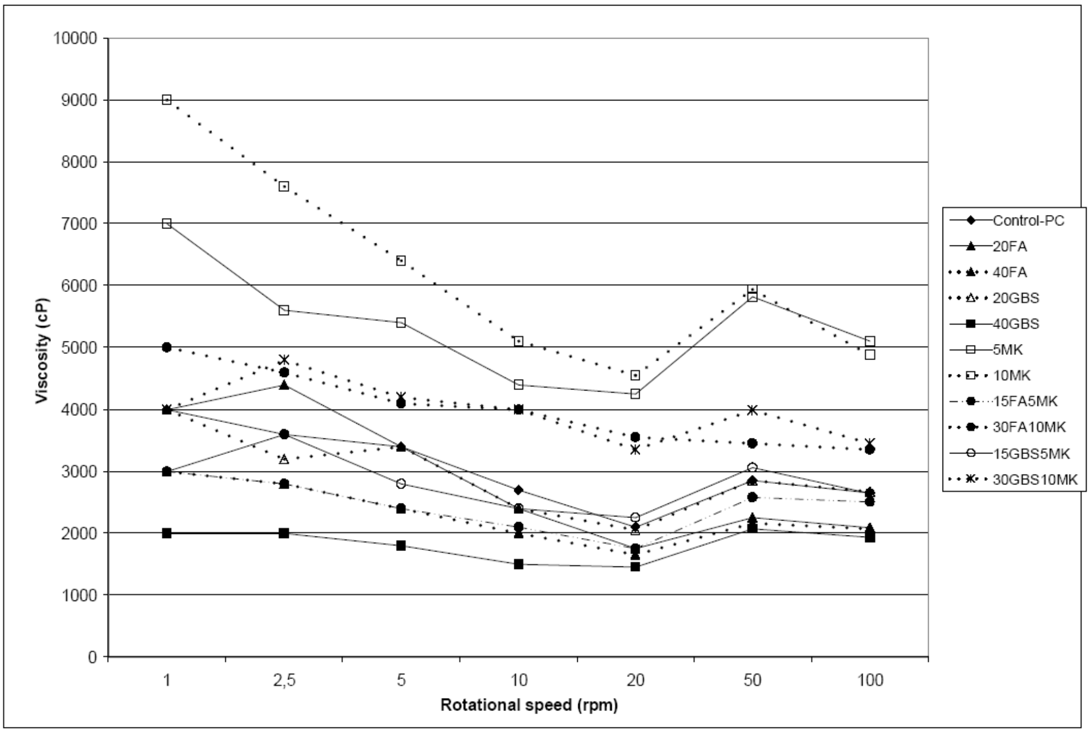


Figure 4.7 T = 0 viscosity rates

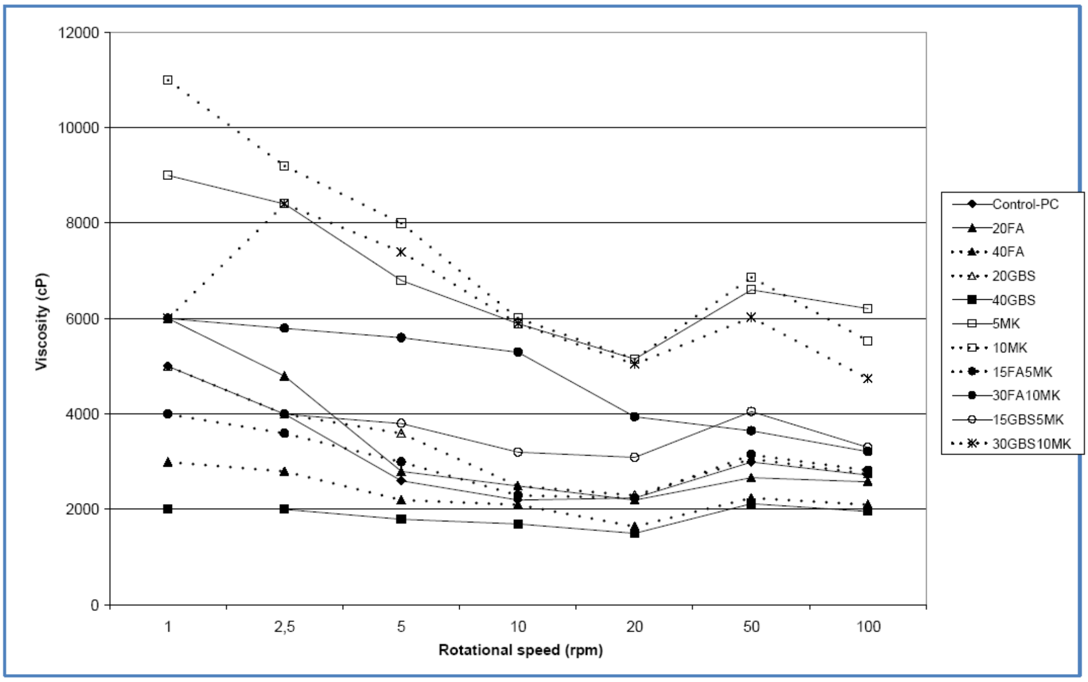


Figure 4.8 T = 20 viscosity rates

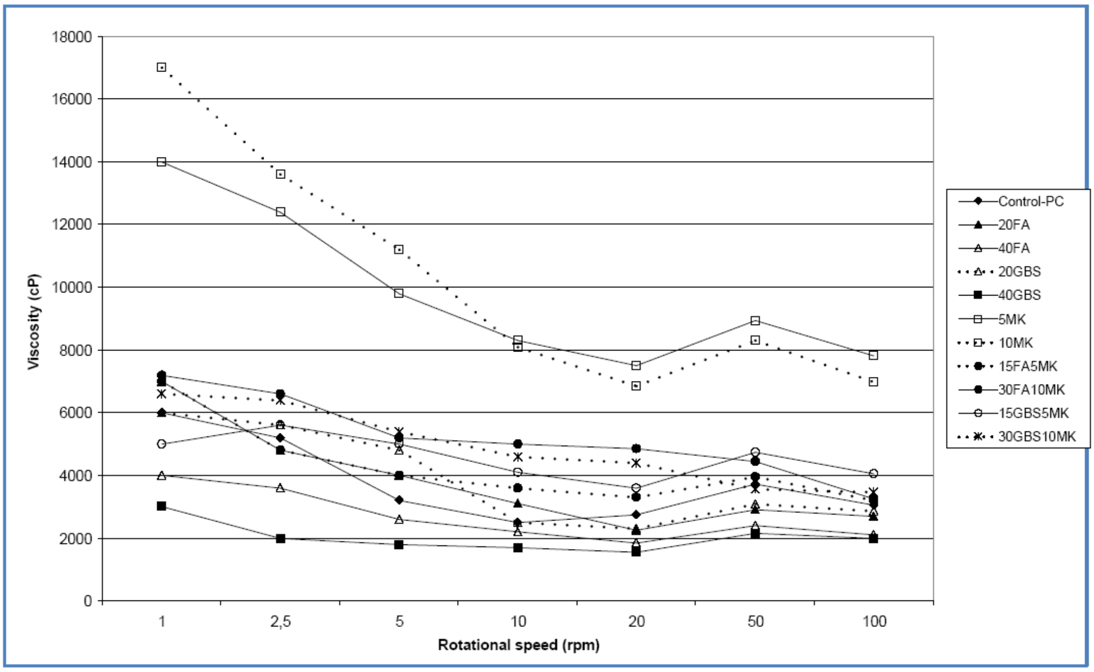


Figure 4.9 T = 40 viscosity rates

4.1.6 Fresh Density

Fresh unit weight of the concretes were measured during casting and given in Table 4.4. The variation in the unit weight of the concretes depending on the binder type and content is graphically shown in Figure 4.10. The control mixture had a fresh density of 2515 kg/m^3 while the fresh density of the remaining 10 mixtures containing one or more of the supplementary cementitious materials ranged from 2450 to 2586 kg/m^3. The lowest unit weight was achieved for the mixture with 40% FA while the highest one belonged to the mixture of 20% GBS.

It was also observed in Figure 4.10 that replacing PC with FA always decreased the unit weight of the concretes. In the case of the mixtures containing GBS or MK, on the other hand, the unit weight increased with incorporating the mineral admixtures. Due to the lower specific gravity and specific surface, The FA replacement reduced the unit weight. GBS and especially MK have higher specific surface in comparison to PC; thus their use in the concrete generally provided an increase in the unit weight of the mixtures probably owing to their filling effects.

Table 4.4 Unit weight (kg/m^3)

Mix No	Mix ID	Unit Weight
M1	Control-PC	2515
M2	20FA	2458
M3	40FA	2450
M4	20GBS	2586
M5	40GBS	2551
M6	5MK	2558
M7	10MK	2564
M8	15FA5MK	2528
M9	30FA10MK	2485
M10	15GBS5MK	2546
M11	30GBS10MK	2520

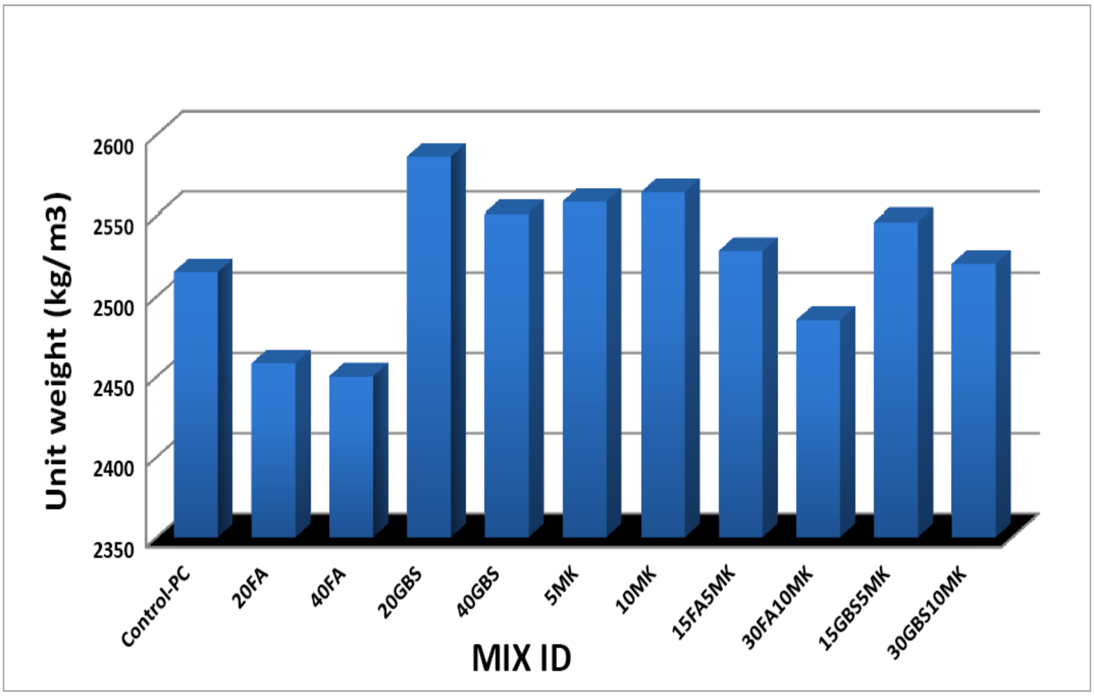


Figure 4.10 Unit weight of mixes

4.2 Hardened Properties

The hardened properties that were determined for all of the 11 concretes were ultrasonic pulse velocity and strength at 28 and 90 days. Table 4.5 presents the averages of the UPV and compressive strength of all the specimens tested.

Table 4.5 Ultrasonic pulse velocity (UPV) and compressive strength of SCCs

Mix No	**Mix ID**	**Compressive Strength (MPa)**		**UPV (m/sec.)**	
		28 days	**90 Days**	**28 Days**	**90 Days**
1	Control-PC	80.9	91.1	5042	5068
2	20FA	69.8	84.4	5042	5068
3	40FA	60.9	77.9	4936	5068
4	20GBS	75.1	86.8	4959	5120
5	40GBS	80.1	92.6	4985	5209
6	5MK	96.3	103.5	5051	5303
7	10MK	91.4	100.1	5025	5276
8	15FA5MK	81.0	95.0	5042	5294
9	30FA10MK	84.2	91.2	4959	5206
10	15GBS5MK	89.7	106.2	5017	5267
11	30GBS10MK	81.2	103.8	5034	5285

4.2.1 Compressive Strength

Figure 4.11 shows the change in the compressive strength of the concretes. It was observed from the figure that there was a marked reduction in the compressive strength of the concretes with increasing FA content while the concretes having GBS had comparable strength values to that of the control concrete, irrespective of the replacement level. The Metakaolin concretes, on the other hand, had consistently higher compressive strength than the control one. In the case of ternary use of PC, FA and MK, the compressive strength also gradually decreased but rate of reduction greatly lessened compared to the case in the binary use of PC and FA. However, the ternary use of PC, GBS and MK provided a positive effect in increasing the compressive strength, especially at 90 days. The concrete having 95% PC and 5% MK had a compressive strength of as high as 96.3 MPa at 28 days. The concrete having 80% PC, 15% GBS, and 5% MK had a compressive strength of as high as 106.2 MPa at 90 days. The ternary use of PC, FA and MK resulted in a reduction in the compressive strength in comparison with binary use of MK. The test results suggested that it was the FA among the mineral admixtures used that governed the reduction in the compressive strength of the SCCs.

In metakaolin blended cement concretes, MK contributes to the strength of concrete not only at 28 days mainly by filling effect but also at the later ages (90 days) due to the fast pozzolanic reaction (Poon, 2006).

In the literature, the use of MK up to 10% performed the best, which resulted in the highest strength over the control concrete at all test ages (Kasım, 2006). Contrary to the literature, as shown Figure 4.11 the highest compressive strength was obtained at 5% MK binary and ternary use of MK + GBS at 90 days of age in this experimental study.

Figure 4.11 also exhibits that the concretes with the ternary blends of MK+GBS had lower 28-day compressive strength than the concretes made with only MK. Take for instance M6 (5% MK) and M10 (15% GBS + 5% MK). The former and the latter had compressive strength of about 96 and 90 MPa, respectively. At 90 days, however, the compressive strength of M10 reached a value of as high as 106 MPa exceeding that of the M6 (103 MPa). Therefore, the combined used of the GBS and MK appeared to be much more effective on the compressive strengths at later ages.

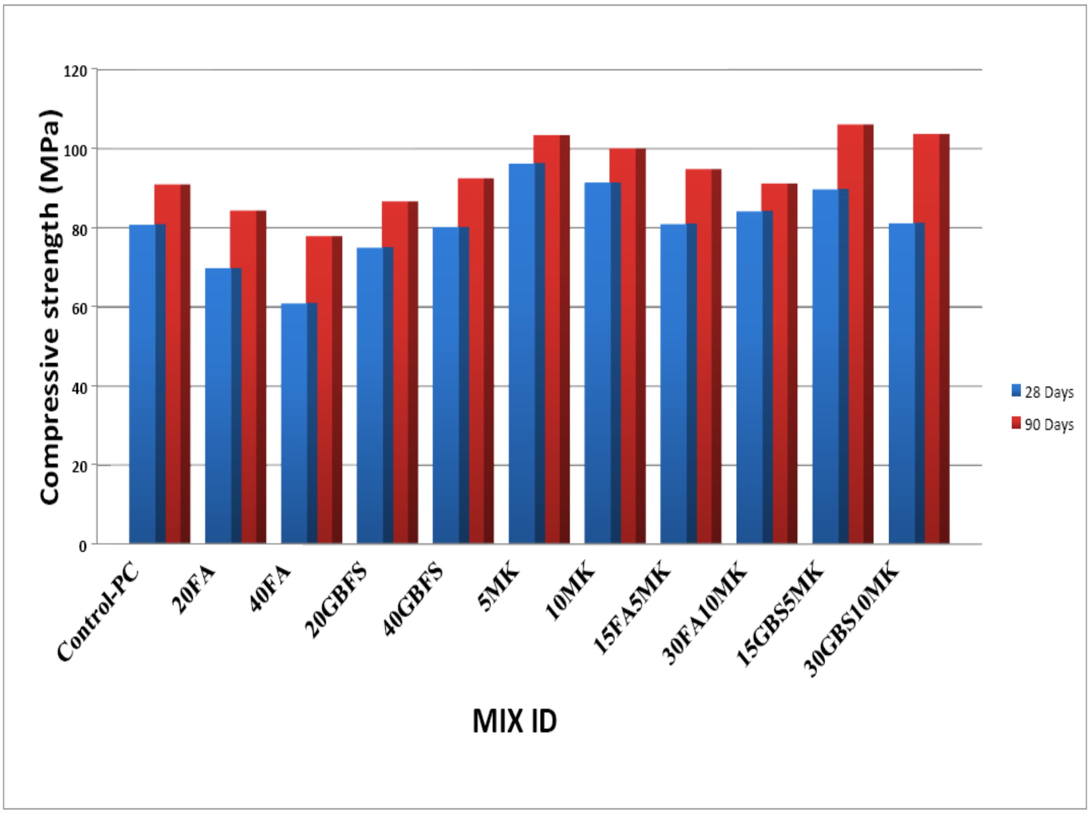


Figure 4.11 Compressive strengths of mixes

4.2.2 UPV

The UPV of concretes are given in Table 4.5 and plotted in Figure 4.12. The values ranged from 4936 to 5294 m/sec. Similar to the compressive strength, the concrete with 5% MK had the highest UPV value. Whitehurst (1951) classified the concretes as excellent, good, doubtful, poor and very poor for UPV values of 4500 m/s and above, 3500–4500, 3000–3500, 2000–3000 and 2000 m/s, respectively. The UPV all of the concretes produced in this study were greater than 4500 m/s so that the rating of the concretes was shown as excellent.

When compared to the compressive strength, the UPV values were much less affected by the mixture compositions. In a similar way to the compressive strength, the UPV of all the concretes increased with time. At 28 days, UPV ranged from 4936 to 5042 m/sec, but at 90 days of measurement the values were in between 5068 and 5303 m/sec.

It was observed from Table 4.5 and Figure 4.12 that, the concretes with FA had comparable or even less UPV values than the control mixture at both 28 and 90 days. Similarly the concretes with GBS and/or MK, generally longer 90-day UPV than that of the control mixture. Concrete only with 5% MK longer 28-day UPV than the control mixture. When the 90-day UPV measurement were considered, however, the UPV of these concretes exceeded that of the control. The highest 90-day UPV value of 5303 m/sec was measured for the concrete with 5% MK.

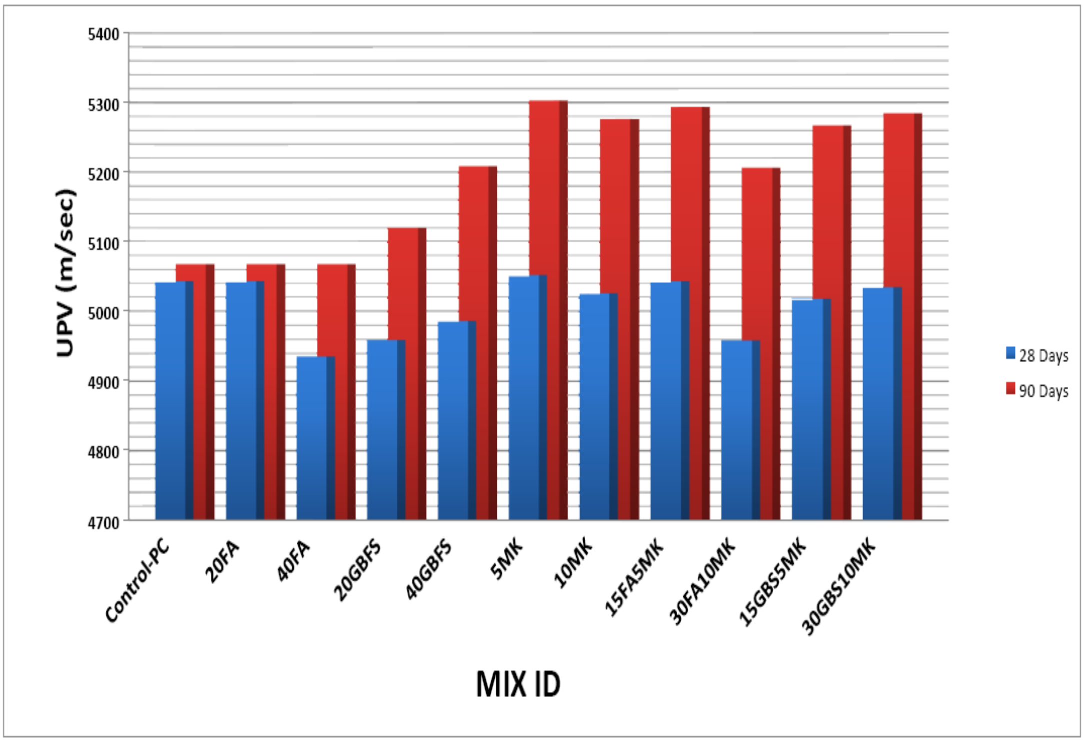


Figure 4.12 UPV values of mixes

5. SUMMARY AND CONCLUSIONS

Self compacting concrete (SCC) is considerably a new concrete technology. SCC can be defined as a concrete with very high flowability together with a good stability. The common practice to obtain self-compactibility is to limit the coarse aggregate content and to utilize an appropriate mortar. Since, mortar serves as the basis for the workability properties of SCC.

In this study, a total of 11 mixtures of SCCs were prepared using binary and ternary blends of mineral admixtures. The fresh and hardened properties of SCCs were determined.

Based on the findings of the study the following conclusions may be drawn:

1. Incorporating the mineral admixtures improved fresh properties of the self compacting concretes. Slump flow time of the concretes containing any of the mineral admixtures was shorter than that of the control mixture with only portland cement except for %10 MK.

2. In a similar way to the slump flow, all mixtures but the control satisfied the EFNARC limitation given for the L-box height ratio. Especially, the concretes with binary use of FA provided slightly better performance in terms of L-box test.

3. Only 40% FA and 20% GBS mixtures fulfilled the V funnel flow time acceptance criteria of EFNARC. Except for aforementioned two mixes, did not fulfill the EFNARC V funnel acceptance criteria

4. There is a clear trend that the binary use of FA, GBS and MK with ordinary portland cement (PC) significantly prolonged the initial and final setting times of the SCCs. Use of MK, however, reduced both the former and the latter according to FA and GBS.

5. Different from MK, incorporation of FA and GBS reduced the viscosity of the concrete mixtures containing binary blends of mineral admixtures. Using these materials in ternary blends improved the rheology of the concretes when compared to the mixtures with only MK.

6. It was observed that the concretes containing FA had generally lower compressive strength. However, ternary blends of MK and GBS provided a concrete with compressive strength of as high as 106 MPa exceeding that of the control one.

7. Use of mineral admixtures also improved the workability properties of SCCs. Among the mineral admixtures used, FA and GBS proved to be good alternatives to increase the workability properties of the concretes. MK, however, can not be used alone as they adversely affect the workability.

8. UPV could be used to nondestructively assess the internal structure of SCC's. Even though, the measured parameters were different, there was a good correlation between the compressive strength and UPV of the concretes.

9. Slump flow time and V-funnel flow time were found to be related to the viscosity of the concrete. The L-box height ratio and slump flow diameter were not much affected by the viscosity.

10. The delayed pozzolanic reaction of fly ash was responsible for a longer setting time when compared to a self compacting concrete mixture with GBS and MK.

11. Fly ash replacement affected ultrasonic pulse velocity to a lesser degree when compared to compressive strength. This was because of the fact that the addition of fly ash reduced the total volume of pores due to its lower specific gravity which produced a denser concrete microstructure.

12. Binary blend of MK in a ratio of %5 provided the best compressive strength value in comparison of %10 MK blend.

13. When the strength properties of the concretes are taken into account, the best mixture appeared to be the M10 which contained 15% GBS and 5% MK.

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