Effect of Metekaolin and Calcined Kaolin on Workability and Rheological Properties of Self Compacting Concrete

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Ömer KAZAZ

ABSTRACT
EFFECT OF METAKAOLIN AND CALCINED KAOLIN ON WORKABILITY AND RHELOGICAL PROPERTIES OF SELF COMPACTING CONCRETE

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In this study, the effectiveness of calcined impure local kaolin (CK) and commercially available high reactivity metakaolin (MK) on the workability and rheological properties of self-compacting concretes (SCCs) were investigated. Moreover, the compressive strength and ultrasonic pulse velocity of hardened SCCs were measured at the end of 28 days of water curing. After proper heat treatment, CK was utilized as a supplementary cementitious material. In order to observe and compare the influences of CK and MK, three replacement levels (0%, 5%, and 10%) were assigned. The SCCs with 0.35 water-to-binder ratio and 550 kg/m^3 total binder content were designed for the testing. The workability tests applied were slump flow diameter, slump flow time (T_{50cm}), V-funnel flow time, and L-box height ratio. For the rheological testing of fresh SCCs, ICAR rheometer was used to find the rheological parameters. The flow diameter of the SCCs were adjusted to be in the range of 700±20 mm. The test results indicated that the SCCs incorporating CK had lower loss of workability than MK incorporated ones. However, the hardened properties of SCCs with MK was better than control and CK included ones.

Keywords: Calcined kaolin, Fresh properties, Metakaolin, Rheology, Self compacting concrete

ÖZET

METAKAOLEN VE KALSİNE KAOLENİN KENDİLİĞİNDEN YERLEŞEN BETONUN İŞLENEBİLİRLİK VE REOLOJİK ÖZELLİKLERİNE ETKİSİ

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Bu çalışmada, ticari olarak mevcut olan yüksek reaktiviteli metakaolen (MK) ve saflaştırılmamış kalsine yerel kaolenin (KK) kendiliğinden yerleşen betonun (KYB) işlenebilirlik ve reolojik özelliklerine olan etkisi araştırılmıştır. Bunun yanı sıra KYB'ların 28 günlük kür süresi sonunda basınç dayanımı ve ultrasonik ses geçiş hızı değerleri ölçülmüştür. Uygun ısıl işlem sonrası, kalsine kaolen bağlayıcı malzeme olarak kullanılmıştır. KK ve MK'nin etkilerini incelemek ve karşılaştırma amaçlı olarak bu malzemeler toplam bağlayıcının %0, %5, ve %10'u oranında çimento ile ağırlıkça yer değiştirilerek kullanılmışlardır. KYB'lar su bağlayıcı oranı 0.35 ve toplam bağlayıcı miktarı 550 kg/m^3 olarak tasarlanmışlardır. İşlenebilirlik için yayılma çapı ve süresi, V hunisi akış süresi, L kutusu yükseklik oranı deneyleri yapılmıştır. KYB'ların reolojik özelliklerinin tespiti için ICAR reometresi kullanılmıştır. KYB yayılma çapı 700±20 mm olarak ayarlanmıştır. Yapılan deneylerin sonuçlarına göre KK içeren KYB'ların işlenebilirlik kaybının MK içeren KYB'lara göre daha az olduğu gözlemlenmiştir. Bununla beraber MK içeren KYB'ların sertleşmiş özellikleri, kontrol betonuna ve KK içerenlere göre daha iyi sonuçlar vermektedir.

Anahtar Kelimeler: Kalsine kaolen, Taze özellikler, Metekaolen, Reoloji, Kendiliğinden yerleşen beton.

To my dear parents,

brother,and my fiance

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LIST OF SYMBOLS/ABREVIATIONS

ASTM	American standart for testing materials
CH	Calcium hydroxide
CK	Calcined impure kaolin
CSH	Calcium silicate hydrates
FA	Fly ash
GGBFS	Ground granulated blast furnace slag
HRWRA	High range water-reducing admixtures
HVFA	High volume fly ash
MK	Metakaolin
NSA	Naphtlhalane sulphate acid
PA	Polycarboxylate acid
PC	Portland cement
PE	Polycarboxylate ester
SCC	Self compacting concrete
SF	Silica fume

SP	Superplasticizer
UFFA	Ultra fine fly ash
UPV	Ultrasonic pulse velocity
VMA	Viscosity modifying admixtures
VSI	Visual stability ındex
w/p	Water powder ratio

CHAPTER 1

INTRODUCTION

1.1 Background

Due to its superior workability property compared to conventional concrete, self compacting concrete (SCC) has become a popular materials of construction (Ghezal et al., 2002; Khayat et al., 2002; Felekoğlu et al., 2007; Gesoğlu et al., 2007; Güneyisi et al., 2010; Sakata et al., 1999; Ferraris et al., 2000; Bouzoubaa et al., 2001; Lachemi et al., 2004). There are various aspects that should be considered during mix design of SCC such as flowability, homogeneity, self compactability, stability, etc. Since loss of uniformity and segregation are the most troublesome concerns in fresh SCC, the researchers has generally focused on elimination such problems by exploiting some viscosity modifying agents **(**Heikal et al., 2013; Beigi et al., 2013). Rheology of self compacting concrete (SCC) has a paramount importance since it may be considered as an indicator to define workability precisely. Yield stress which initiates the concrete to flow is the main components of rheological behavior. If yield stress is considered as the pressure required to enable concrete to move, viscosity stands for how fast the concrete moves, once yield stress has been exceeded. Moreover, rheology of SCC can be a solid criteria that should be taken into account during the mixture design of SCC. A large body of collection of the studies on workability and rheological properties of SCC have been undertaken by researchers (Heikal et al., 2013; Beigi et al., 2013; Jalal et al., 2013; Belaidi et al., 2012; Gesoğlu et al., 2012; Schwartzentruber et al., 2006; Boulekbache et al., 2012; Ghoddousi et al., 2010; Boukendakdji et al., 2009; Güneyisi et al., 2008). For example in the study of Saak et al. (2001), a design methodology based on an assumption that minimum viscosity with the yield stresses is required for restraining segregation has been proposed. In the study of Schwartzentruber et al. (2006), it was indicated that rheological properties, i.e. viscosity and shear yield stress demonstrated good correlation with empirical test results for flowable mixes. Additionally, they emphasized that based on the mixing procedures adopted in the experimental program the rhelogical properties of cement pastes were greatly affected. Moreover, their test results underlined the fact that there are interactions between superplasticizer and viscosity enhancing admixture used in the design of SCC. Boulekbache et al. (2012) studied the variation of the yield stress of concrete due to fiber addition. They concluded that addition of a volume fraction of steel fibers ranging from 0.5% to 1% slightly increases the yield stress of the concrete. Moreover, it was reported that the yield stress of the mixture affected distribution and orientation of fibers.

Kaolin which is considered as the most used raw material for ceramic and paper industries can be converted to metakaolin (MK) by means of a heat treatment called calcination. This treatment provides driving off chemically bound water and leads alteration of the crystalline structure (Siddique et al., 2009; Badogiannis et al., 2005;

Shvarzman et al., 2003; Chandrasekhar, 1996). Since MK necessitates a thorough refinement to change the color, exclude inert impurity, and adjust particle grading, it is different from the other mineral admixtures obtained as a result of industrial processes such as silica fume, blast-furnace slag, and fly ash. Calcined kaolin has extensively been investigated since the mids of 1990's for improving performance of cement based composites (Mermerdaş et al., 2013; Güneyisi et al., 2013; Nadeem and Memon, 2013; Güneyisi et al., 2012; Vejmelková et al., 2010; Kim et al., 2007; Poon et al., 2006; Caldarone et al., 1994). Moreover, in some of the recent studies, it was reported that non purified calcined kaolin can be used as mineral admixture to be used for improving hardened properties of concretes (Güneyisi et al., 2012; Badogiannis et al., 2005; Shvarzman et al., 2003; Mermerdaş et al., 2013). For example, in the study of Shvarzman et al. (2003), it was noticed that beneficial properties of metakaolin as a mineral admixture can be conserved even at lower than 30% of kaolinite content. Moreover, in the study of Güneyisi et al. (2012) , it was pointed out that kaolin containing 38% kaolinite had comparable pozzolanic reactivity with those having more kaolinite content (up to 54%).

Surveying the available technical literature, it has been found out that there is not any investigation regarding the fresh properties of SCCs containing calcined impure kaolin. In the current study, variation in workability and rheological properties of SCCs due to incorporation of calcined impure kaolin was presented. Moreover, the characteristics of SCCs produced with high reactivity metakaolin was measured for comparison purpose. The fresh properties were assessed in terms of viscosity measurements by rheometer, flowability by V-funnel tests and slump flow, and passing ability by L-box height ratio. Compressive strength and ultrasonic pulse velocity of the hardened SCCs were also measured at the end of 28 days of water curing.

1.2 Outline of the Thesis

Chapter 1 Introduction: Aim and objectives of the thesis were introduced.

Chapter 2 Literature Rewiew and Background: A literature review was conducted on the properties of SCCs. The previous studies on the use of metakaolin and kaolin for producing self compacting concrete were provided.

Chapter 3 Experimental Study: Materials, mixtures, casting, curing conditions, and test methods were described.

Chapter 4 Test result and Discussions: Indıcation, evaluation, and discussion of test result were presented.

Chapter 5 Conclusion: Conclusion of the thesis was given.

CHAPTER 2

LITERATURE REVIEW

2.1 General

There is an opinion as to the fact that the self compacting concrete (SCC) is an innovative material that can be placed and compacted under its own-weight without requiring compaction or vibration, and also, it leads to enough cohesion to handle it with proper segregation resistance. SCC guarantee good filling, and provide convenient structural response of limited areas and highly supported structural members. It was in Japan in the late 1980's. Purpose of its development is to use it mainly for highly blocked-up and supported structures in seismic regions. It also provides a better environment to work by eradicating the vibration noise. Now, it has been used largely in many countries for various practices and structural form. One of its main advantage is that it can minimize the material cost (Corinaldesi et al., 2002).

The advantages include:

- ✓ Reducing the noise pollution;
- ✓ Reduction of the time and cost for construction;
- ✓ Eliminating necessity for vibration;
- ✓ Facilitating constructibility and ensuring good structural performance;

For the concrete requiring a high flowability that can simply be accomplished by adding water reducing agent into concrete mixture. However, specific care has to be taken for proportioning such material to stay viscous during casting . An easy approach is followed by increasing the amount of fine aggregate in order to avoid segregation due to inclusion of superplasticizer. However, the reduction in aggregate capacity leads to the use of a high volume of cement, and it causes temperature rise and an increase in the cost. Another method is to incorporate a viscosity-changing mixture to develop stability (Bouzoubaa and Lachemi, 2001).

However, chemical mixtures cost a lot and employing these mixtures increase the total cost of the material. The increased cost can be balanced by saving in labor cost, but the utilization of admixtures like fly ash (FA) or ground granulated blast furnace slag (GGBFS) may affect workability of SCC mix without increasing the cost. Previous researches have shown that the use of FA and GGBFS in self-compacting concrete decreases the content of superplasticiser that is necessary to provide a similar workability as for concrete that is produced with Portland cement only (Gesoğlu and Özbay, 2007).

In addition, use of FA enchances the rheological characteristic and decrease formation of cracks due to internal heat of concrete as a result of hydration. Kim et al. (2007) investigates the properties of highly flowable concrete that contains fly ash. They determined that the level of replacement by 30% (40% for only one mixture) FA provided significant flowability and workability.

2.1.1 Benefits of SCC

Technologically advanced components in Self-Compacting Concrete (SCC) enable to create a mixture by offering numerous advantages. It provides following advantages for contractors and ready-mix producers and precast concrete fabricators (Hassan et al., 2012).

These parties require an increased understanding of SCC’s complex nature in order to have the benefits of SCC. Declines in skilled labor and quality control in the construction industry would make it more challenging for users. Consequently, developers should provide set procedures and methods for users to quantify the qualities of mix characteristics.

2.2 Fresh Properties of SCC

One of the important components of the performance of SCC is its workability. The filling ability of SCC, uniformity, homogeneity, segregation resistance, rheology and setting are the most notable fresh properties.

2.2.1 Flow Properties

Filling ability describes the capability of SCC to flow under its self weight and perfectly fill the formwork. Filling ability includes the concepts such as; how much the distance from the concrete can flow and discharge flow rate (deformation rate).

Concrete flow properties are characterized in order to describe the workability of SCC. Requirements for workability can change importantly depending on the process, even with in the scope of SCC. As such, many procedures are available to quantify various aspects of workability. Workability can be described in terms of particular field requirements or rheological properties (Khayat et al., 2004).

The workability needs for SCC are typically described in terms of three critical properties: passing ability, filling ability, and resistance to segregation (EFNARC, 2002).

Passing ability describes how SCC flows among congested reinforcing bars. Segregation resistance describes how concrete can remain uniform with respect to structure during placement and until setting. Various test methods are available to measure those fresh properties; however, there is no any single test to measure all of these properties at once. Given that these three features are interrelated, most tests indirectly monitor more than one property at a time (Tattersall, 1991).

Workability is defined in terms of static and dynamic stability (Dazcko, 2002; Assaad et al., 2003; Khayat et al., 2004). Dynamic stability describes the concrete performance during the casting process. It is related to energy input which may be from pumping, drop heights, agitation, or vibration and passing ability which is affected by member dimensions and reinforcement bar spacing. Static stability describes the concrete performance immediately after energy input from casting until setting. It is related to paste rheology, physical and size characteristics of the aggregates relative to the paste (Saak, 2000; Saak et al., 2001; Larrard, 1999). Other aspects of the workability of SCC are typically improved relative to conventionally placed concrete. In general, the pumpability and finishability of SCC are improved relative to conventionally placed concrete (Bury and Christensen, 2002). The formed surface finish is better because of the reduction in honeycombing and the quantity of bugholes (Martin, 2002). The retention of workability properties over time must be considered. Workability retention is not necessarily associated with setting time. For example, retarding admixtures can increase setting time while accelerating workability loss (Tattersall, 1991).

2.2. 2 Segregation Resistance

Resistance to segregation, is the ability of the concrete to remain uniform and cohesive throughout the entire construction process (mixing, transporting, handling, placing, casting, and etcetera). There should be minimum segregation of the aggregates (both fine and coarse) from the matrix and little bleeding. Bleeding is a special case of segregation in which 12 water moves upwards and separates from the mix. Some bleeding is normal for concrete, but excessive bleeding can lead to a decrease in strength, high porosity, and poor durability particularly at the surface. Stability is largely dependent on the cohesiveness and viscosity of the concrete mixture, and cohesiveness and viscosity can be increased by reducing the free water content and increasing the amount of fines. A reduction of free water content has been shown to improve stability while decreasing inter-particle friction among solid particles (Khayat and Monty, 1999).

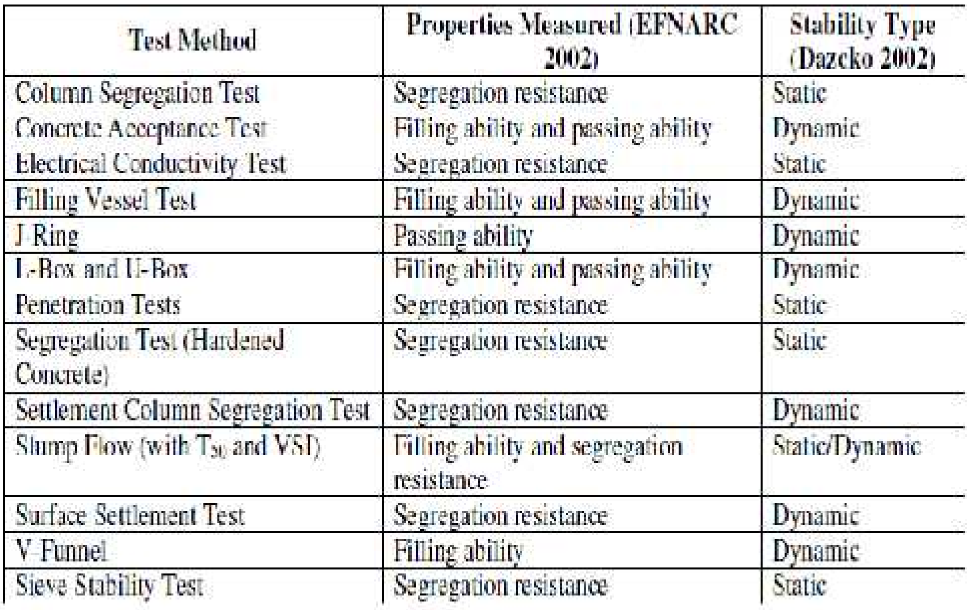
2.2. 3 Passing Ability

When the SCC has sufficient fluidity and resistance to segregation, then it would be more preferable. However, in the case of narrow passages and congested reinforcement, passing ability of SCC gains such importance that more careful mix design is required to achive a useful SCC to be used for construction (Tattersall, 1991).

2.2.4 Test Methods

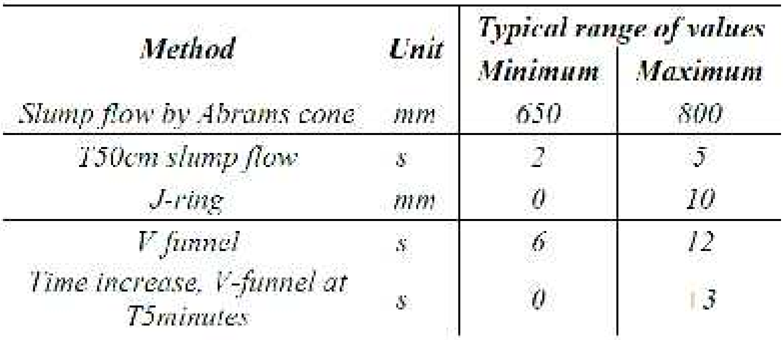
The available empirical workability test methods for SCC are categorized in Table 2.1 based on the property measured and the type of stability considered (static of dynamic). These test methods are described in alphabetical order in the following subsections. As well as the distinctions made in Table 2.1 between static and dynamic tests, it is also possible to indirectly measure static stability with certain dynamic stability tests. Concrete can be placed inside a dynamic stability test apparatus, such as the V-funnel or L-box, and allowed to rest for a specified period of time. The results for tests with and without the rest period are compared to determine if segregation occurred during the rest period. In the V-funnel, for example, the collection of coarse aggregate at the outlet of the funnel would result in an increased flow time or possibly a complete blockage. It must be cautioned that such delayed tests can also be affected by thixotropy and loss of workability (Dazcko, 2002**).**

Table 2.1 Test methods (EFNARC, 2005)



Test Method	Properties Measured (EFNARC 2002)	Stability Type (Dazcko 2002)
Column Segregation Test Concrete Acceptance Test Electrical Conductivity Test	Segregation resistance Filling ability and passing ability Segregation resistance	Static Dynamic Static
Filling Vessel Test	Filling ability and passing ability	Dynamic
J Ring	Passing ability	Dynamic
L-Box and U-Box Penetration Tests	Filling ability and passing ability Segregation resistance	Dynamic Static
Segregation Test (Hardened Concrete)	Segregation resistance	Static
Settlement Column Segregation Test	Segregation resistance	Dynamic
Slump Flow (with T_{50} and VSI)	Filling ability and segregation resistance	Static/Dynamic
Surface Settlement Test	Segregation resistance	Dynamic
V Funnel	Filling ability	Dynamic
Sieve Stability Test	Segregation resistance	Static

Table 2.2 Acceptance regions for SCC (EFNARC, 2005)



Method	*Unit*	*Typical range of values* *Minimum*	 *Maximum*
Slump flow by Abrams cone	*mm*	*650*	*800*
T50cm slump flow	*s*	*2*	*5*
J-ring	*mm*	*0*	*10*
V funnel	*s*	*6*	*12*
Time increase, V-funnel at T5minutes	*s*	*0*	*+3*

In evaluating empirical test methods, it must be remembered that empirical tests supply only an index of workability that may or may not be related to fundamental flow parameters. For example, in the study conducted by Ferraris et al. (2000), the results of the V-funnel and U-box tests were not correlated to yield stress or plastic viscosity measurements as determined with the IBB rheometer and the BTRHEOM rheometer. Nielsson and Wallevik (2003) found correlations between plastic viscosity and T_{50}, orimet flow time, V-funnel flow time, and L-box flow time and between yield stress and slump flow; however, the scatter was described as “significant”. Utsi et al. (2003) found that as long as only one rheological parameter was varied at a time, the rheological parameters measured with the BML viscometer were correlated to the results of the V-funnel and slump flow test; however, the scatter was high. Khayat et al. (2004) found that V-funnel results were a function of rhelogy of SCC. Many of the available empirical tests measure similar properties and, therefore, are correlated to each other to some degree. For example, Khayat et al. (2004) found correlations between the results of the U-box, L-box, V-funnel, and J-ring tests. Due to the lack of standardization of SCC test methods, the dimensions and details of the empirical test methods can vary within the literature. Dazcko (2003) listed dimensions of L-boxes, U-boxes, and J-rings reported by various researchers in the literature. Petersson et al. (2003) found that variations in the amount wall friction, which is affected by test geometry and the smoothness of wall material, can have a important influence on test results.

2.2.5 L-Box and U-Box Tests

The L-box test provides a measurement of passing and filling ability. It has been used widely throughout the world and was selected by the European Testing SCC project as a reference test for passing ability. The L-box is similar to the U-box test. The L-box test was preferred for evaluation in this research because it is easier to visualize the flow of the concrete in the test especially any blocking behind the bars and the apparatus is easier to clean. The L-box test results are a function of both passing ability and filling ability because the extent to which concrete flows down the horizontal part of the box depends on the yield stress (filling ability) of the concrete and the extent of blocking caused by the row of bars (Bartos et al., 2002).

The L-box and U-box tests (Bartos et al., 2002; Kuriowa, 1993; EFNARC, 2002), which are shown in Figure 2.1, measure the filling and passing ability of SCC. In the case of the L-box, SCC is initially placed in the vertical part of the box. After that the gate is opened and SCC is allowed to flow through the reinforcement bars into the horizontal part of the L-box. The elapsed times for SCC required to reach the specified points 200 mm (T_{200}) and 400 mm (T_{400}) down the horizontal part of the L-box are measured. After the SCC stops flowing in the box, the levels of the SCC at the end of the horizontal part, H_2, and in the vertical section, H_1, are measured to compute the height ratio, H_2/H_1. Segregation resistance can be evaluated visually immediately after the test or the concrete can be allowed to harden and samples can be cut for further evaluation (Tanaka et al., 1993). For the U-box, concrete is filled into one side of the box, the gate is opened, and concrete is allowed to flow through a row of reinforcement bars and into the other half of the box.

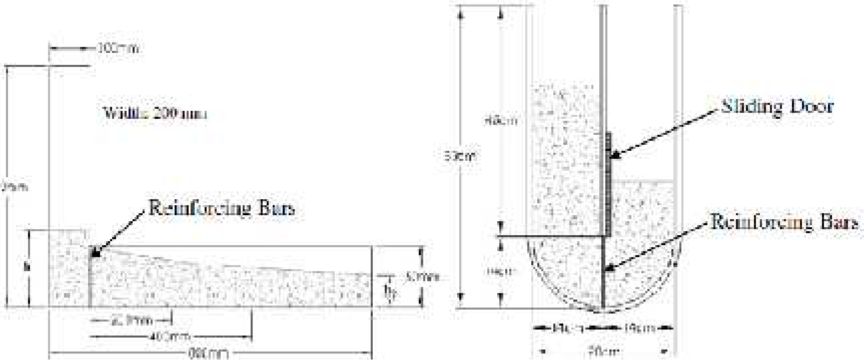


Figure 2.1 L box and U box apparatus (EFNARC, 2005)

Measurements are made of the time for concrete to cease flowing and of the heights on either side of the box. Khayat et al. (2004) found correlations between the results of the U-box and L-box tests; however, there was much scatter. The L-box was found to be preferable because it gives more information about filling ability. Further, the combination of L-box and slump flow tests was found to be preferable to a combination of J-ring and slump flow tests.The advantages and disadvantages of the L-box test are given below (Khayat et al., 2004).

The advantages of the L-box test include:

- The test supplies a visualization of how concrete will flow in the field,
- The amount of mass available to push concrete through the bars is more representative of field conditions than in the J-ring test, and
- The relationship between the test results and field performance is better established than for the J-ring test.

The disadvantages of the L-box test include:

- The test does not distinguish between passing ability and filling ability,
- The test apparatus is bulky, difficult to clean, and not well-suited for use in the field,
- The selection of rebar spacing is not well defined, and
- The volume of concrete required is greater than for the J-ring test.

2.2.6 Slump Flow Test (with T_{50} and Visual Stability Index)

The most commonly used test method for SCC is the slump flow test (Bartos et al., 2002; Kuroiwa et al., 1993; EFNARC, 2002). To conduct the test, a slump cone is located on a non-flexible and level non-absorbent plate. Then, it is filled with concrete without compaction. The slump cone can be placed in the conventional, upright orientation or inverted. The slump cone is removed up and the horizontal flow of the SCC and the time for the SCC to flow to a diameter of 500 mm (T_{500}) are measured. Emborg et al. (2003) has suggested measuring the time to flow to a diameter of 600 mm instead of 500 mm, for high fluidly mixtures. It is possible to evaluate the uniformity of the SCC qualitatively after carrying out the slump flow test. According the Khayat (1999), the lack of material separation during the slump flow test is not an assurance of stability during and after placement. Khayat et al. (2004) recommend using the VSI in conjunction with other tests for stability.The advantages and disadvantages of the slump flow test are given below (Bartos et al., 2002).

The advantages of the slump flow test include:

- The test provides an independent measurement of filling ability,
- The test is well-known, widely used, and simple to perform,
- The test is inexpensive and easily portable,
- The specimen size is small,
- The test is robust and repeatable,
- The spread is related to yield stress and T_{50} is related to plastic viscosity, and

- The test provides a visualization of concrete flow.

The disadvantages of the slump flow test include:

- The VSI is inadequate for ensuring segregation resistance,
- The test results do not reflect all aspects of filling ability and do not indicate the harshness of mixtures, and
- The test must be conducted on a flat base plate with no standing water.

2.2.7 V Funnel Test

The V-funnel test (EFNARC, 2002; Bartos et al., 2002), which is shown in Figure 2.2, is commonly used to observe the filling ability of SCC and can also be used to assess segregation resistance. To perform the test, the funnel is filled with SCC without compaction and the concrete is left undisturbed for 1 minute. Then, the gate at the bottom of the funnel is released and the elapsed time for all concrete to exit the funnel is recoded.

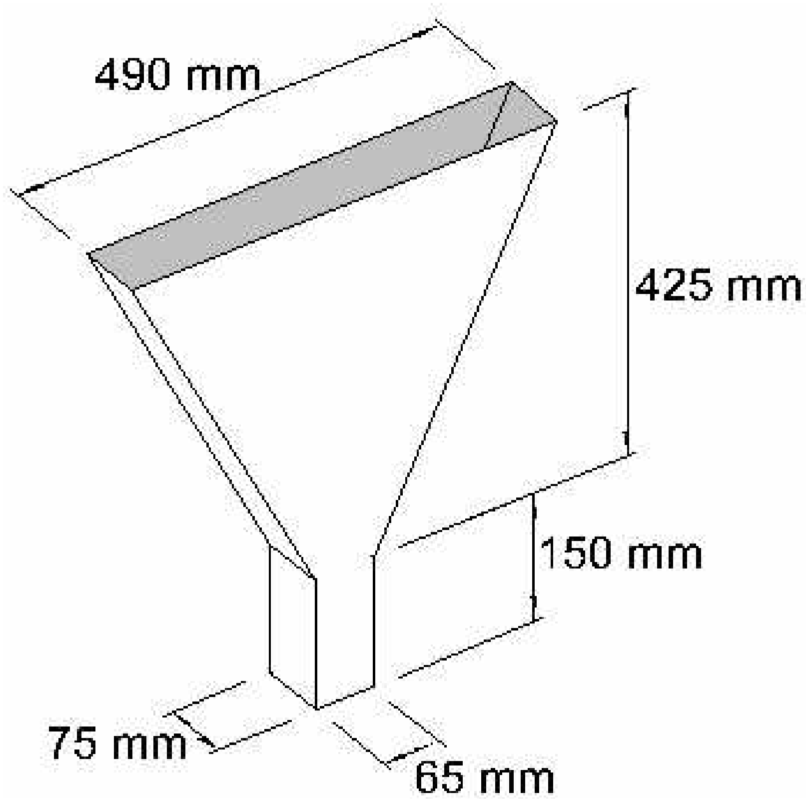


Figure 2.2 V funnel apparatus (EFNARC, 2005)

According to Khayat (1999), a long flow time can be used because of high viscosity, high interparticle friction, or blockage of flow by coarse aggregates. Likewise, Emborg et al. (2003) found that V-funnel results were related to concrete viscosity, passing ability, and segregation resistance. Therefore, the test results may not identify the true cause of a slow flow time. The opening size at the bottom is typically 75 x 75 mm or 75 x 65 mm. Emborg et al. (2003) has suggested using a 75 x 49 mm opening to increase the sensitivity of the measurement. In addition, a smaller version of the V-funnel is available for measurements of mortar or paste.

2.3 Effects of Admixtures on the Fresh Properties of 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 properties 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. Natural pozzolans, artificial pozzolans such as FA and SF and GGBFS are examples of such mineral admixtures (Erdoğan, 1997).

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 ranging 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 FA. The reason of such a decrease in permeability is that the CH liberated by the hydration of calcium silicate compound (C_2S and C_3S) reacts with pozzolans and leads to the formation of extra CSH which reduces the capillary pore spaces (Erdoğan, 1997).

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. Among them, brick powder was discovered to have pozzolanic properties (Corinaldesi et al., 2002). Therefore, brick powder obtained as a byproduct of a brick factory can be used as an artificial pozzolan in concrete production.

Other popular mineral admixture for cement replacement is metakaolin (MK) which is produced by a series of controlled processes and known to have pozzolanic properties (Dunster et al., 1993). According to the study about MK conducted by Batis et al. (2004), it was concluded that metakaolin provides improvement of the compressive strength and the 10% addition results in the best contribution to the strength development. The benefication of metakaolin, either as a sand replacement up to 20%, or as a cement replacement up to 10% also improved the corrosion behavior of mortar specimens. Higher percentages of metakaolin, however, decreased the corrosion resistance (Batis et al., 2004).

As explained earlier, chemical admixtures such as superplasticizer (SP) and viscosity modifying admixture (VMA) are important materials benefited for the SCC production. Therefore, effects of these chemical admixtures on the properties of SCCs have been investigated by other researchers (Sakata et al., 2003). In a research conducted by Golasweski and Swabowski (2002), mortars with different type and amount of superplasticiser with various type of cements indicated obvious differences in rheological properties of SCMs. The research revealed that polycarboxylate ester (PE) and polycarboxylate acid (PA) type superplasticizers were very influential when compared to naphthalene sulphate acid (NSA) superplasticizers. If they were used in the same dosage, these two super-plasticizers could produce 13 mortars with significantly lower yield stress and reduced the workability loss.

In another study by Lachemi et al. (2002), the effect of VMAs on the properties of cement pastes was investigated. They used five different types of VMA as a chemical admixture for making the cement pastes. Various tests were conducted to measure the fresh properties, such as fluidity, segregation, and washout resistance. Using a SP of 0.25% together with VMAs, they showed that there was a rise in the slump flow diameter of the freshly poured paste prepared with the VMAs compared to the mix prepared with the SP alone. The range of mini slump test was 127 and 132 mm for VMA pastes, while 116 mm in the control paste (0% VMA). It was concluded that combining convenient amount of SP and VMA could produce high-performance cement pastes with high fluidity and moderate cohesiveness to enhance water retention and lower water dilution.

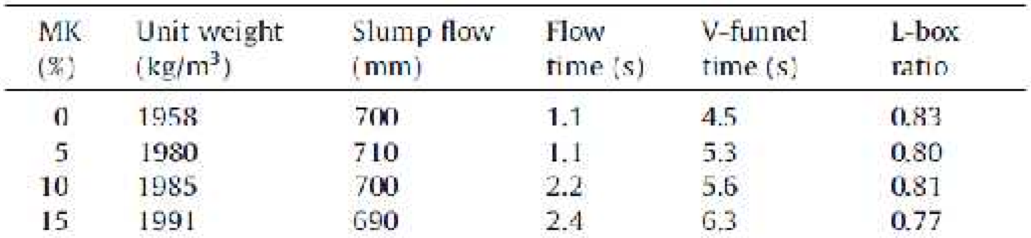
It may be expected that, for the same water-powder w/p ratio, increasing the volume of fine particles such as mineral admixtures will result in a reduction in the workability of concrete. The reason is the increase in water requirement due to an increase in the surface area of particles. However, it is also commonly known that the shape of mineral admixture is also an important factor for the workability characteristic concrete. For example it is reported that for the same workability the round and spherical geometry of fly ash particles generally help to decrease the water requirement of concrete mixture (Erdoğan, 1997).

In a study conducted by Ferraris et al. (2000) the effect of FA on the rheological features of cement paste were studied. The fly-ash with mean particle size 3.1m was term as ultra fine fly-ash (UFFA). It was concluded that substitution level of cement with UFFA results in a decrease in high range water reducer dosage at given yield stress and viscosity. Bosiljkov (2003) also indicated that the deformability of the paste could be significantly increased through finer and better graded limestone dust. Bosiljkov (2003) concluded that if a high amount of filler was included to the SCC mixture, the desired self-compacting properties could be obtained at a lower water/ (cement + filler) ratio, and it also seemed that the addition of filler enhanced the 28-day compressive strength of concrete mixes due to the filler effect and improved fine-particle packing.

Another research on the fresh properties of mortar conducted by Domone and Jin (1999) included four different types of SPs, various combinations of powder, including PC, GGBFS, pulverized fuel ash, and limestone powder. The rheological properties that were determined included spread, V-funnel flow time, yield stress and plastic viscosity. It was concluded that the workability retention was depended on a combination of parameters, including the powder composition and the dosage and type of SP, and ternary blends of powder. An adverse effect of replacing the Portland cement with mineral admixture was the increase in setting times of mixture. One study by Vu et al. (2001) indicated the effect of calcined kaolinite on setting time of Portland cement. They concluded that the addition of calcined kaolinite to PC resulted in an increases in the normal consistency of blended PC mixture. Blending Portland cement by 10-20% calcined kaolin by weight did not significantly alter the initial and final setting however, exceeding this range caused a significant increase in the observed setting time.

In a study by Karahan et al. (2011), there were four mixtures that containing 0%, 5%, 10% and 15% metakaolin content as a partial binder substitution. It was reported that increases in metakaolin content made the filling and passing ability of SCLC worse and by the inclusion of MK no positive influence on the strength properties on SCCs was observed. The fresh properties of SCCs obtained by Karahan et al. (2011) are shown in Table 2.3

Table 2.3 Fresh properties of SCCs (Karahan et al., 2011)



MK (%)	Unit weight (kg/m^3)	Slump flow (mm)	Flow time (s)	V-funnel time (s)	L-box ratio
0	1958	700	1.1	4.5	0.83
5	1980	710	1.1	5.3	0.80
10	1985	700	2.2	5.6	0.81
15	1991	690	2.4	6.3	0.77

The fresh properties of SCCs for several mixes produced by Uysal and Sumer (2010), are given in Figures 2.3 and 2.4 According to Uysal and Sumer (2010) FA and GGBFS considerable improved fresh properties and compressive strength of SCC mixtures. The best resistance to sulphate attacks was obtained for the mix with 40% GGBFS with 60% PC. In mineral admixtures, the best performance has been obtained for FA series as workability properties. In general, the use of mineral admixtures enchanced the workability properties of SCC importantly. The researchers reported that workability characteristics of SCC mixes as slump flow, T_{50}

time, V-funnel flow time and L-box height ratio tests used, it can be observed that all SCC mixtures have stayed in target range for each test except V-funnel time (Uysal et al., 2011).

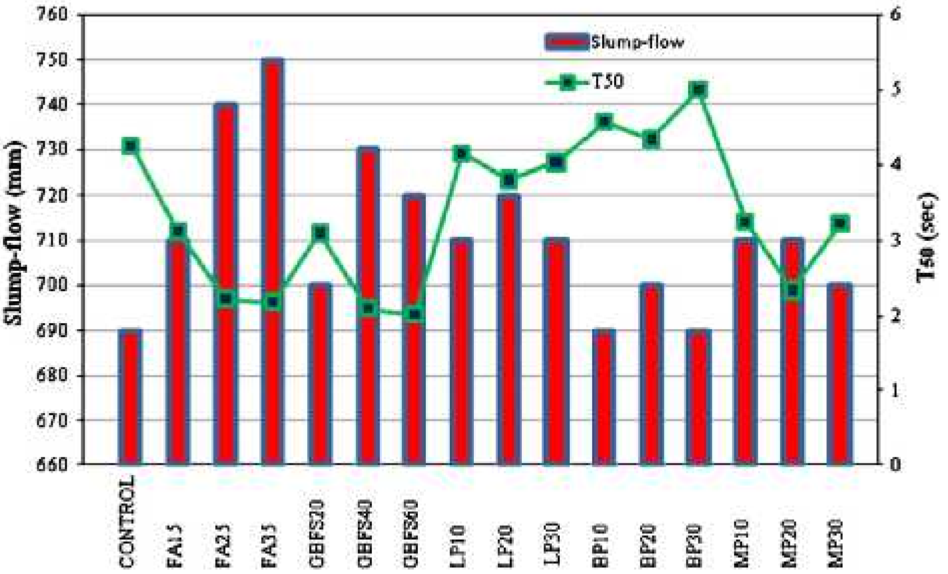


Figure 2.3 Slump-flow and T_{50} time of SCC mixtures (Uysal et al., 2011)

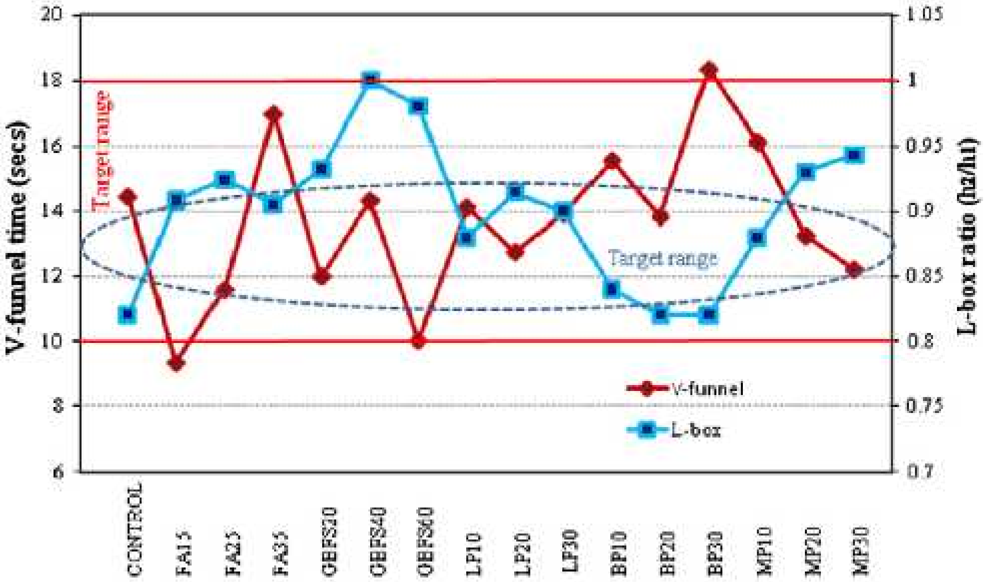


Figure 2.4 V-funnel time and L-box ratio of SCC mixtures (Uysal et al., 2011)

2.4 Effect of Metakaolin on the Fresh Properties of SCC

The production of SCC mainly includes use of additional cementitious materials (SCMs) like FA, slag and/or SF. SF is considered one of the most effective and commonly used SCMs that highly increase the mechanical properties and considerably reduce the permeability of concrete. Nevertheless, adding SF to SCC is a limited practice because it is difficult to obtain the desired workability in SCC. Research on the workability of conventional concrete incorporating metakaolin (MK) yielded various results: in some cases, there was deterioration of workability, while in others there was either no effect or an enhanced workability when adding MK to concrete. However, it is generally admitted that MK has tendency of negative effect on the workability of conventional concrete but demonstrates better workability than concrete containing SF. Caldarone et al. (1994) reported that the concrete with MK necessiates 25 to 35% less superplasticiser than concrete with SF to obtain a comparable slump of 120 to 180 mm. The decrease in HRWRA demand in MK concrete caused a less sticky consistency and better finish than SF concrete to happen. It was shown by Ding and Li (1999) that MK provided a much better workability than SF for the same mix design parameters. Concrete mix with 5 to 10% MK had somewhat higher slump than the control mixture. Even when level of the replacement of MK was raised to 15%, the slump was only reduced by approximately 10%. For SF concrete, the slump value illustrated only a negligible decrease at the replacement level of 5% and then reduced almost linearly with a rise of SF replacement to 15%.

The fresh qualities of MK concrete with a content of Type I and II cements were also tested by Balaguru (2001). The addition of MK resulted in either no influence or a slight increase in slump for Type I cement. In the case of Type II cement, MK decreased the slump slightly with a more noticed decrease in high-strength concrete (Balaguru, 2001).

An SCC mixture should have a low yield stress to guarantee good flowability and high deformation. However, the yield value should not be very low, or else, segregation may take place due to static conditions. In general, the optimum yield value of SCC is a complex function of the formwork thickness and the density of reinforcement. However, a range of 20 to 60 Pa yield value was found to be sufficient for a proper SCC mixture (Balaguru, 2001).

Mouret and Cyr (2003) reported the rheological behavior of cement paste that includes MK and SF to make an evaluation of their utilization potential for SCC. It was observed that MK improved the viscosity of cement paste which is useful for SCC because it slows down the seperation of particles and improves the dispersion of solids in the plastic state. In addition, SF reduces the viscous behaivour and increases the HRWRA demand.

Another research on the fresh properties of SCC conducted by Hassan et al. (2012), the following conclusions presented in Figures 2.5 and 2.6.

The inclusion of MK increased the amount of HRWRA in SCC mixtures. Replacement of cement by 25% MK in the SCC mixture with a 25.6 in. (650 mm) slump flow diameter rised the amount of HRWRA by 27%.

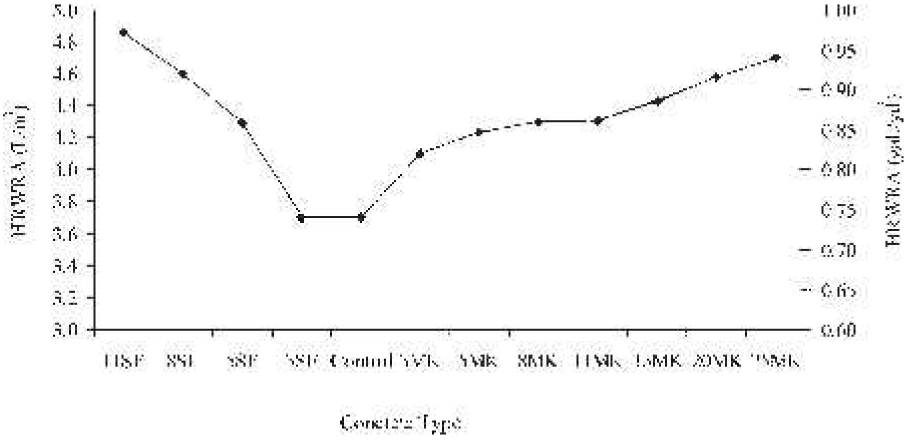


Figure 2.5 HRWRA demand at 25.6 in. (650 mm) slump flow diameter (Hassan et al., 2012)

The plastic viscosity that was raised as the replacement of MK was increased in SCC mixtures. The replacement of cement by 25% MK caused the viscosity of the control mixture to increase by 2.4 times.

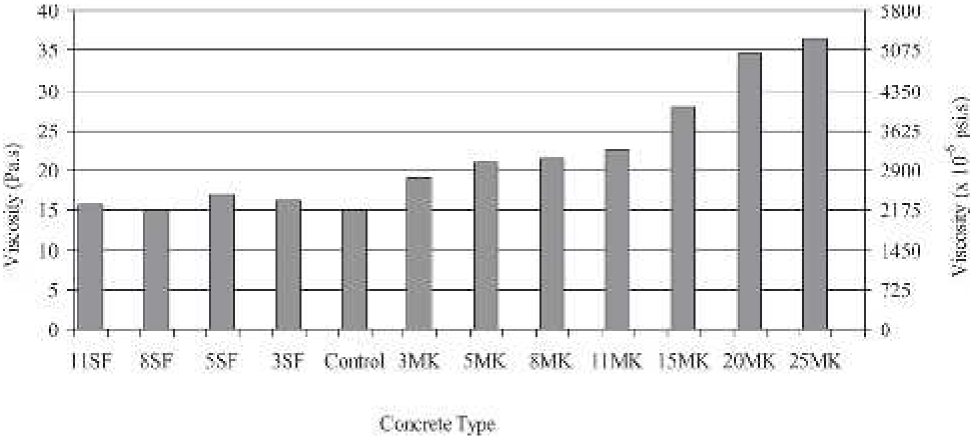
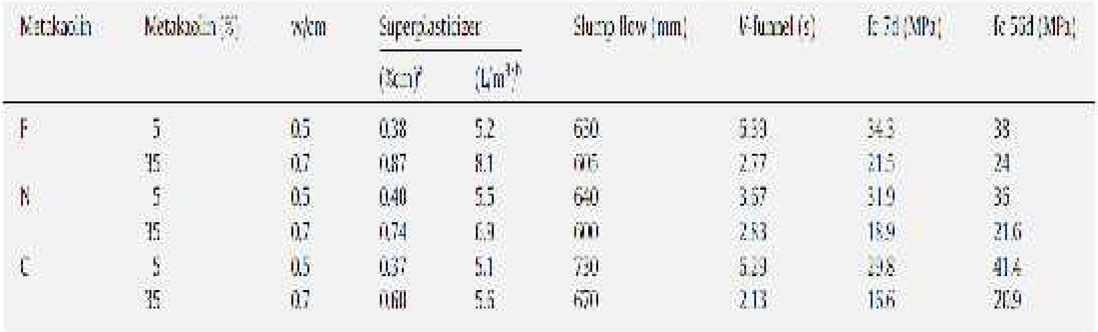


Figure 2.6 Viscosity at 25.6 in. (650 mm) slump-flow diameter (Hassan et.al., 2012)

Melo and Carneiro (2008) examined the impact of content and finesses of MK in self-consolidating concrete material. MK was utilized at three different finesses (fine, normal and coarse) and at 5% and 35% of replacement with cement mass in their study. According to the results reported, the conclusion was drawn that in spite of the MK finesses, as the amount was raised, the need for more superplasticizer was increased, as well; this was seen in both the pastes and concretes. An increase in the volume of paste increased the workability of the mixtures, and reduced the demand for superplasticizer. It is significant to draw the attention to the fact that, despite this enhancement of the fresh properties, the paste volume should be just the amount necessary to fill the voids among the grains, and still enough to involve them through a layer that makes rolling easier. The results obtained from the study conducted by Melo and Carneiro (2008) are shown in Table 2.4.

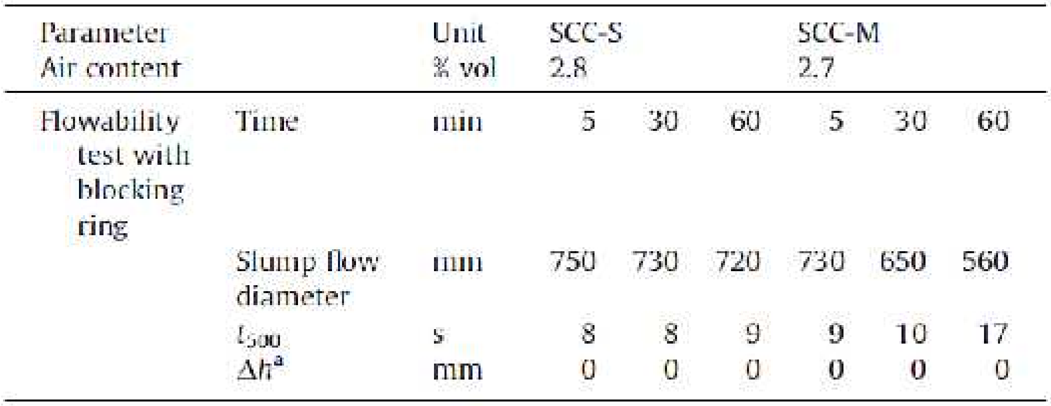
Table 2.4 Results of tests in concretes (Melo and Carneiro, 2008)



Metakaolin	Metakaolin (%)	w/cm	Superplasticizer		Slump flow (mm)	V-funnel (s)	fc 7d (MPa)	fc 56d (MPa)
			(%cm)^a	(L/m^3)^b				
F	5	0.5	0.38	5.2	630	5.39	34.3	38
	35	0.7	0.87	8.1	605	2.77	21.5	24
N	5	0.5	0.40	5.5	640	3.57	31.9	36
	35	0.7	0.74	6.9	600	2.83	18.9	21.6
C	5	0.5	0.37	5.1	730	5.29	29.8	41.4
	35	0.7	0.60	5.5	670	2.13	15.6	20.9

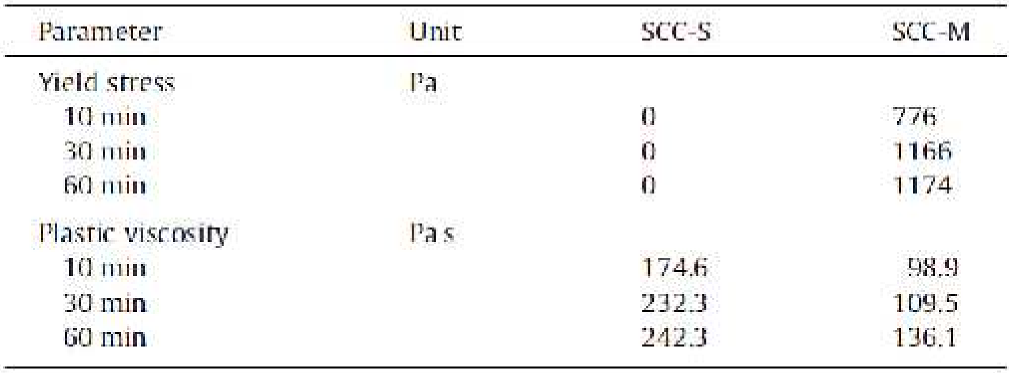
The qualities of self-compacting concrete mixtures containing metakaolin (SCC-M) and blast furnace slag (SCC-S) were examined in t study performed by Vejmelkova et al. (2010). The SCC-M mixture containing metakaolin exhibited smaller slump flow diameter and longer time of flowing as compared with SCC-S (Table 2.5). The rheological characteristics of SCC mix with MK are determined by yield stress and relatively low viscosity while the mix GGBFS has zero yield stress and higher viscosity. The rheological properties of studied SCC are presented in Table 2.6. The compressive strength of SCC with metakaolin rises very fastly during the first hardening period and remains higher to a great extent when compared with the mixture with blast furnace slag up to 90 days (Table 2.7).

Table 2.5 Results of testing fresh SCC mixtures (Vejmelkova et al., 2010)



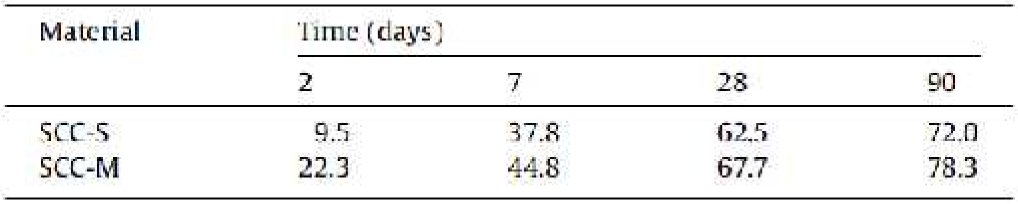
Parameter		Unit	SCC-S			SCC-M		
Air content		% vol	2.8			2.7		
Flowability test with blocking ring	Time	min	5	30	60	5	30	60
	Slump flow diameter	mm	750	730	720	730	650	560
	t_{500}	s	8	8	9	9	10	17
	Δh^a	mm	0	0	0	0	0	0

Table 2.6 Rheological properties of fresh SCC mixtures (Vejmelkova et al., 2010)



Parameter	Unit	SCC-S	SCC-M
Yield stress	Pa		
10 min		0	776
30 min		0	1166
60 min		0	1174
Plastic viscosity	Pa s		
10 min		174.6	98.9
30 min		232.3	109.5
60 min		242.3	136.1

Table 2.7 Compressive strength (MPa) (Vejmelkova et al., 2010)



Material	Time (days)			
	2	7	28	90
SCC-S	9.5	37.8	62.5	72.0
SCC-M	22.3	44.8	67.7	78.3

2.5 Measuring Rheological Properties

Rheometers are used to measure the rhelogy related characteristics of concrete. Coaxial-type rheometers with two cylinders are used in the experiment. Concrete mixture is poured into the gap between the inner cylinder and the outer cylinder up to a specified height. Then the outer cylinder is rotated in varying speed and the torque on the inner cylinder is measured. Then the graph of the variation on the torque of the inner cylinder with the rotational speed is plotted. Plastic viscosity and the shear stress are calculated by using the gradient and the intercept of the graph. Results can be expressed in relative units (torque vs. speed) or absolute units (shear stress vs. shear rate). Rheometers must be uniquely designed for concrete (primarily due to large aggregate size).Figure 2.7 shows typical rheometer geometry (Koehler, 2004).

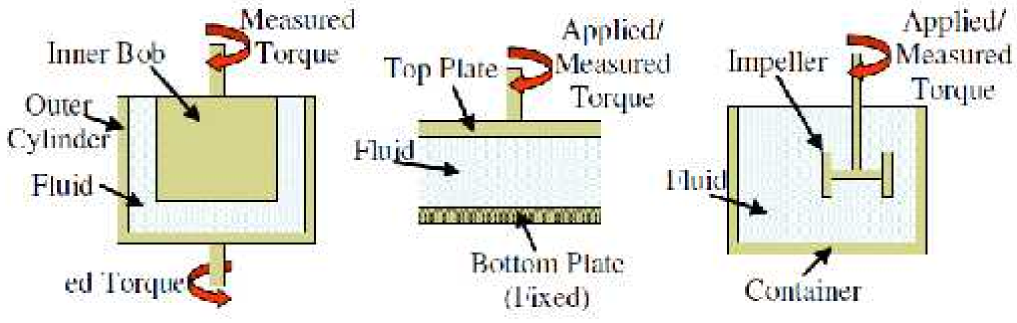


Figure 2.7 Typical rheometer geometry configurations (Koehler, 2004)

CHAPTER 3

EXPERIMENTAL DETAILS

3.1 Materials

A local kaolin obtained from a quarry located in Balıkesir city, Turkey, was utilized. Following a proper heat treatment reported in the previous study of Güneyisi et al. (2012), calcined impure kaolin (CK) was obtained to be used as a mineral admixture for the production of SCC. The chemical and some physical properties of CK are given in Table 3.1. The kaolin was calcined for 3 hours in a muffle furnace. The calcination process and microstructural characterization were described by details in the study of Güneyisi et al. (2012).

The commercially available metakaolin (MK) utilized in the experimental study is a white powder with a Dr Lange whiteness value of 87. The specific gravity is 2.60 and specific surface area (Nitrogen BET surface area) of 18000 m^2/g. Physical and chemical properties of MK used in this study are also given in Table 3.1. The origin of the MK is from Czech Republic.

CEM I 42.5 R type PC with a specific gravity of 3.13 and Blaine fineness of 338 m^2/kg was utilized for the production of SCCs. The chemical composition and some physical properties of the cement is shown in Table 3.1.

Table 3.1 Some physical and chemical properties of Portland cement (PC), calcined impure kaolin (CK), and high reactivity metakaolin (MK)

	Item	PC	CK	MK
Chemical properties	CaO (%)	63.60	2.22	0.5
	SiO_2 (%)	19.49	69.78	53
	Al_2O_3 (%)	4.54	24.16	43
	Fe_2O_3 (%)	3.38	0.69	1.2
	MgO (%)	2.63	0.89	0.4
	TiO_2 (%)	-	0.49	0.8
	LOI (%)	2.99	0.73	0.4
Physical properties	Specific gravity	3.13	2.60	2.60
	Fineness (m^2/g)	338*	7340**	18000**

* Blaine fineness, **BET nitrogen adsorption method

Crushed limestone aggregate was obtained from local sources was used as both coarse and fine aggregate. The aggregate grading was adjusted so that the grading is as close to Fuller's curve as possible. The aggregate grading is shown in Figure 3.1. Moreover, some physical properties of the crushed limestone aggregates and their fineness values are given in Table 3.2.

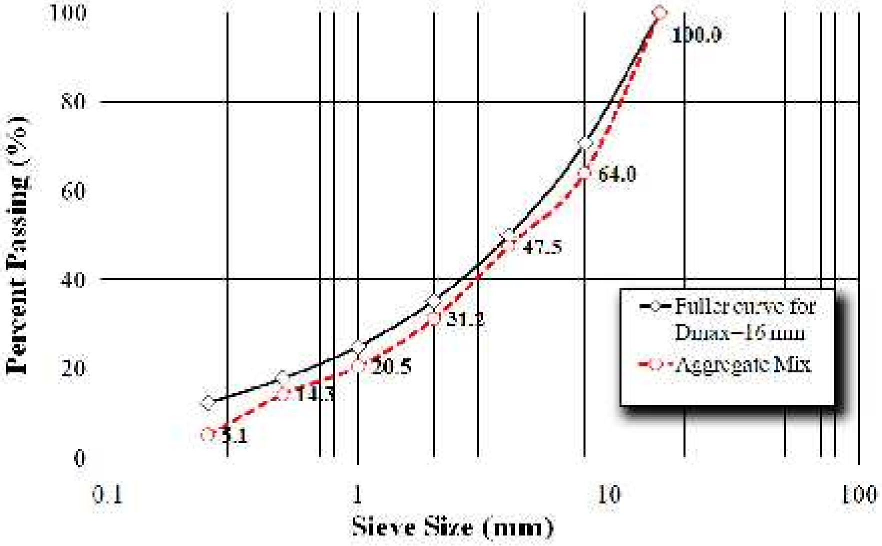


Figure 3.1 Grading of the aggregate mixture

Table 3.2. Some physical properties of aggregates

Property	Fine aggregate	Coarse aggregate
Fineness modulus	3.38	5.68
Specific gravity	2.45	2.72
Water absorption (%)	0.95	0.45

A high range water reducing admixture (HRWRA) with a specific gravity of 1.07 and pH value of 5.7 was used in all SCC mixtures. HRWRA used in this study is polycarboxylic ether type water reducing admixture commonly used in SCC production.

3.2 Concrete Mixture

SCC mixtures were produced having water/binder ratio of 0.35 and total binder content of 520 kg/m^3. In the production of SCCs, binary blends of PC and thermally treated kaolins (MK or CK) were utilized. The replacement levels assigned for MK or CK are 0%, 5%, and 10% for SCC mixtures. Designation of the mixtures was based on the replacement level of MK or CK. For example, 5CK means SCC mixture containing 5% CK. Details of the mix proportions of SCCs are given in Table 3.3. The concretes were designed to provide a slump flow diameter of 700±20 mm. This was achived by using HRWRA at varying amounts.

Table 3.3 Mix proportions of control and mineral admixed self compacting concretes

	Plain	MK concretes		CK concretes	
Material (kg/m^3)	Control	5%	10%	5%	10%
Cement	550.0	522.5	495.0	522.5	495.0
MK or CK	0.0	27.5	55.0	27.5	55.0
Water	192.5	192.5	192.5	192.5	192.5
Coarse aggregate	790.9	787.4	783.4	787.4	783.4
Sand	750.6	747.2	743.5	747.2	743.5
HRWRA	7.43	8.25	9.35	8.25	9.35

3.3 Concrete Casting

In order to provide homogeneity and uniformity in all SCC mixtures a thorough mixing procedure which covers a systematic sequence and certain durations of various mixing stages should be followed. In this experimental study, the first stage of the batching sequence starts with preparing a homogenous mix of the coarse and fine aggregates blended for 30 s in a rotary planetary mixer with capacity about 50 liter. About half of the mixing water is then added into the mixer and continues to mix the aggregates for another one minute. Afterwards the cement and mineral admixtures were added and the mixing was restarted for another minute. Finally, the HRWRA with remaining water was added, and the concrete was mixed for two minutes and then left for one minute to rest. After that, the concrete was mixed for additional one minute to complete the mixing sequence.

3.4 Test Methods

3.4.1 Fresh Properties

Slump flow, V-funnel, L-box, and ICAR rheometer were used to test the workability, passing ability, and viscosity of SCCs. Workability of the cocretes was adjusted via the slump flow test such that slump flow diameters of all of the mixtures were designed to be in the range of 700 ± 20 mm so as to satisfy the EFNARC (European Federation for Specialist Construction Chemicals and Concrete Systems) limitation. Flowability of the mixtures was observed through the V-funnel test. L-box test was carried out as an indication of passing ability, or the degree to which the passage of concrete through the bars is restricted. Slump flow, L-box, and V-funnel tests were performed according to the procedure recommended by EFNARC committee In accordance with EFNARC specifications, three typical slump flow classes for the range of applications have been identified. The upper and lower limits of the classes specified in EFNARC are shown in Table 3.4. Figures 3.2 and 3.4 demostrate the measurement of the fresh properties of SCCs.

Table 3.4 Slump flow, viscosity, and passing ability classes with respect to EFNARC (EFNARC, 2005)

Slump flow classes	Slump flow diameter [mm]	
SF1	550-650	
SF2	660-750	
SF3	760-850	
Viscosity classes	T_{50cm} [s]	V-funnel time [s]
VS1/VF1	≤2	≤8
VS2/VF2	>2	9 to 25
Passing ability classes	No. of rebar	
PA1	≥0.8 with two rebar	
PA2	≥0.8 with three rebar	

Figure 3.2 Photographic demonstration of measurement of slump flow diameter

Figure 3.3 Photographic view of V-funnel flow time measurement

Figure 3.4 Photographic view of L-box apparatus and testing procedure

Characterization of rheology was achieved by ICAR rheometer as shown Figure 3.5. To this aim, the fresh SCC was poured into container of the rheometer and filled up to a height of 300 mm. Four-bladed vane having 125 mm diameter and 125 mm height was immersed into the centre of fresh concrete and rotated at a series of specific speeds. The gap distance is 87.5 mm above and below the vane. The ICAR rheometer was utilized to monitor the flow curve which consists of the following inputs: breakdown speed and time, number of points, time per point, initial speed, and final speed for each of the fresh concrete mixtures. The first rotation speed is 0.5 rps for a breakdown period of 20 s. Torque measurements were then recorded for seven speeds ranging in descending order from 0.5 rps to 0.05 rps. For analyzing rheological parameters of the fresh concrete properties, Eqn. (3.1) was used for drawing the flow curves in relative units.

$$T=Y+VN \tag{3.1}$$

Figure 3.5 Photographic view of ICAR rheometer device including vane, and the main dimensions (all dimensions are in mm)

Where V is denoted as the slope of the line (Nm.s) related to plastic viscosity, Y intercept of the line with the torque axis (Nm) which is related to yield stress and T is the torque axis (Koehler and Fowler, 2004).

To determine the plastic viscosity analytically in fundamental units, the resultant data were evaluated based on the Bingham model (Eqn. 3.2), where by a straight line was fitted to the plot of torque τ (Pa), versus rotation speed, (rad/s). The intercept, τo (Pa), and the slope, μ (Pa.s), of this line were considered to be related to yield stress and plastic viscosity, correspondingly.

$$\tau = \tau_0 + \mu\gamma' \tag{3.2}$$

Where τ is shear stress (Pa), τ_o is yield stress (Pa), μ is plastic viscosity (Pa s), and γ' is shear rate (rotation speed) (1/s). Due to the thixotropy and loss of workability of the fresh concrete, the parameters in the Bingham equation, particularly yield stress and viscosity are not constant in time (Wallevik, 2003; Roussel, 2005; Roussel, 2006). Moreover, the apparent viscosity increases by increasing shear rate, which is due to the preferential orientation of the particles resulting in the more rapid increase of the shear stress than the shear rate (Roussel, 2006; Douglas, 2004).

The hardened concrete were tested for the compressive strength and ultrasonic pulse velocity (UPV). Compressive strength of SCCs was tested according to ASTM C 39 using a 3000 kN capacity testing device. The test was performed on three cube specimens with 150x150x150 mm dimension at 28 days of curing. The average of three specimens was reported as 28 day compressive strength. The cubes were also utilized for computing the ultrasonic pulse velocity according to ASTM C597. For this, a commercial UPV measurement devise was used.

CHAPTER 4

EXPERIMENTAL RESULT AND DISCUSSIONS

4.1 Fresh Properties

EFNARC (2005) specifies that the filling ability and stability of fresh SCC may be interpreted by four critical factor which are, viscosity, flowability, segregation resistance, passing ability. Once the requirements for flowability, passing ability and segregation resistance are fulfilled, then the concrete can be classified as SCC. Satisfaction of these criteria is necessary to provide ease of flow and homogeneity of SCC. Assessment of the fresh properties of SCCs produced in this study was carried out according to the limitations specified by EFNARC (2005). The limiting values for the critical fresh properties are given in Table 3.4 of section 3.4 testing methods.

In this study, in order to keep the slump flow diameters fixed for all of the mixtures within the range of 700±20 mm, trial batches were produced to determine the amount of HRWRA for each mixture. As shown in Table 3.3, it was noticed that using CK or MK in the mixtures caused an increase in the amount of HRWRA to achieve the target slump flow diameter. For the same replacement levels, same amount of HRWRA was used for SCCs. Owing to very high fineness values of MK and CK compared to PC, increasing the amount resulted an increase in the dosage of HRWRA.

Figures 4.1 and 4.2 indicate slump flow (T_{50cm}) and V-funnel flow times, respectively, so as to illustrate the viscosity class of SCCs according to EFNARC. It can be observed that all of the SCCs, except 10% MK incorporating one, conformed VS2/VF2 class in terms of both slump flow and V-funnel flow times. According to EFNARC (European Federation for Specialist Construction Chemicals & Concrete Systems, 2005), such concretes conforming to VS2/VF2 may be applied to construction of various normal structural members. However, due to high specific surface area of MK (18000 m^2/g), utilization of 10% caused a negative effect prolonging the flow times. However, in the study of (Güneyisi et al., 2010), 10% MK incorporation resulted in 6 s and 20 s of flow times for T_{50cm} and V-funnel tests, respectively. This may be due to relatively lower fineness of MK used in that study (12000 m^2/g) as well as other mix parameters.

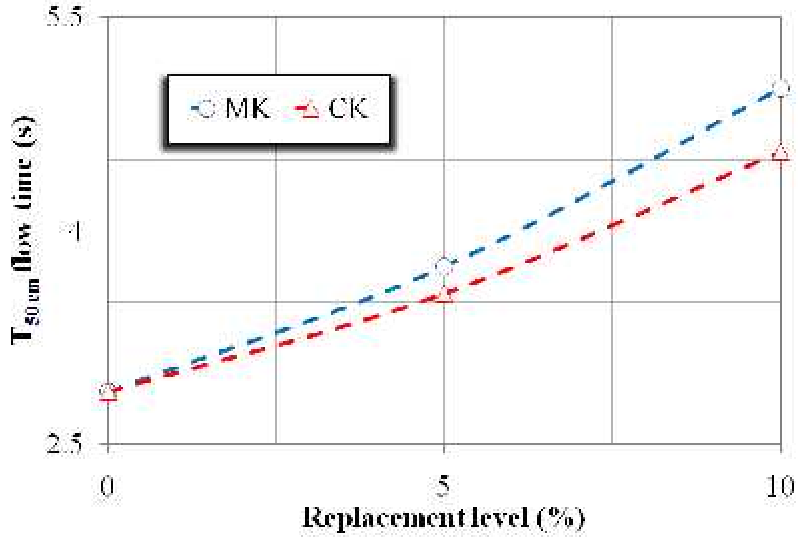


Figure 4.1 Effect of MK and CK on the slump flow times of SCCs

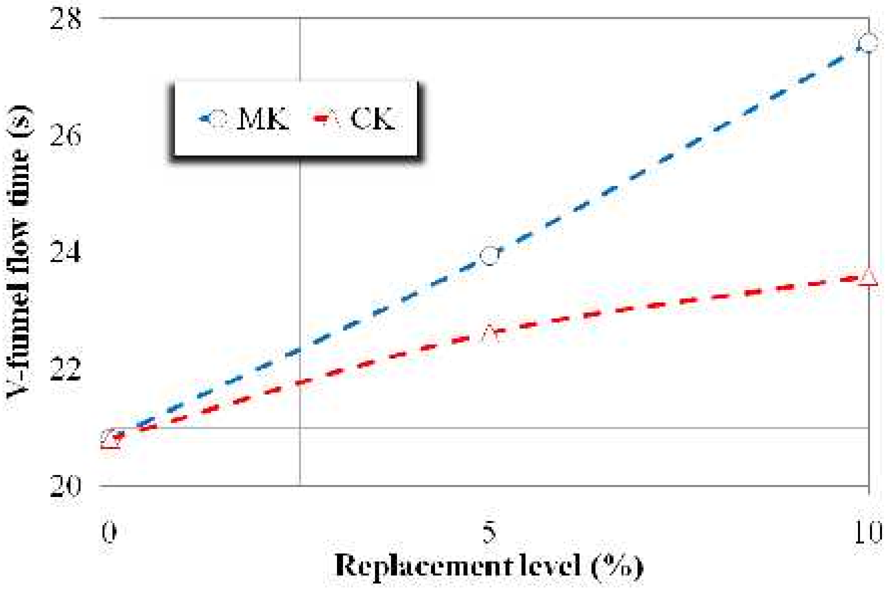


Figure 4.2 Effect of MK and CK on the slump flow times of SCCs

Variation of the L-box height ratio (h_2/h_1) is given in Figure 4.3 to evaluate the passing ability properties considering the recommendations in Table 3.4. Test results showed that the L-box height ratios ranged from 0.73 to 0.98 depending mainly on type and replacement level of mineral admixture. According to the specifications given by EFNARC (2005), the SCCs with L-box height ratio between 0.8 and 1.0 is classified as PA2 in terms of passing ability (Table 3.4). Therefore, the concretes without mineral admixture or with 5% MK or CK satisfied the EFNARC (2005) limitation. Incorporating 10% MK or CK, however, decreased the h_2/h_1 ratio such that close values of L-box height ratios of 0.76 and 0.73 were obtained for SCCs incorporating CK and MK, respectively.

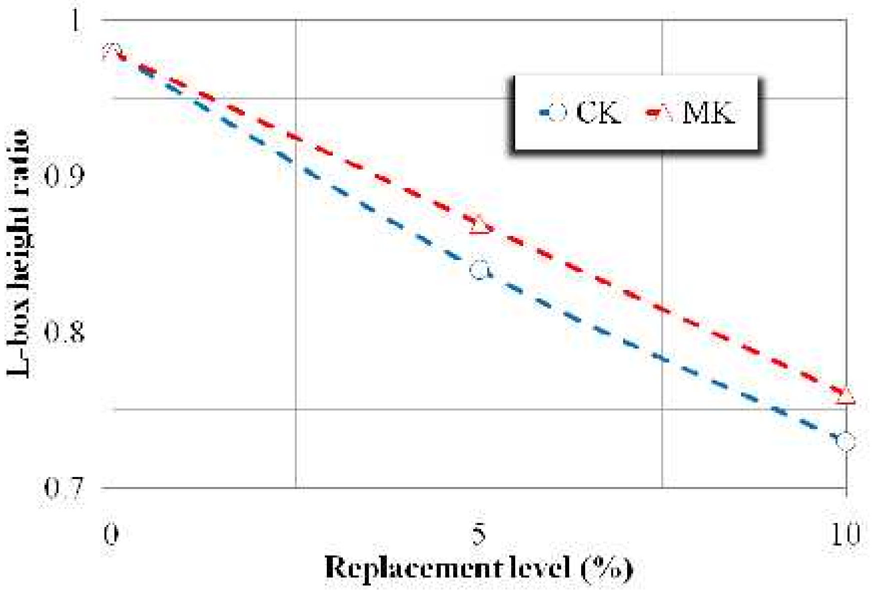


Figure 4.3 Effect of MK and CK on L box height ratio of SCCs

Yield stress and viscosity are the most critical rheological parameters for concretes, particularly for SCCs. In order to ensure a high flowing ability as well as a good de-airing of the SCC, a low yield stress and moderate viscosity are required. Koehler (2009) specifies that self-compacting concrete has far lower yield stress value than conventional concrete. Considerably lower yield (near to zero) stress allows concrete to flow freely. Moreover, having similar plastic viscosity to that of normal concrete, SCC gains segregation resistance. SCC mixture should be designed to have neither too low nor too high plastic viscosity. Because, when SCC has too low plastic viscosity there is risk of segregation, while in case plastic viscosity is too high concrete is sticky and difficult to pump and place (Koehler, 2009).

The flow curves of SCCs are given in Figure 4.4. The data used for plotting the graphs were obtained from ICAR rheometer in terms of rotational speed (V) in revolution-per-second and torque (T) in Newton-metre. V and T represent the shear strain rate and shear stress, respectively. It was found out that increasing the amount of mineral admixture leaded to steeper slope of the curves for both SCCs incorporating MK and CK. However this shift is more for MK concretes than CK ones. At the rotational speed of 0.1, the torque was almost same for control CK5 and CK10 SCC. However, as the rotational speed increased the difference between the values of the torque become more obvious.

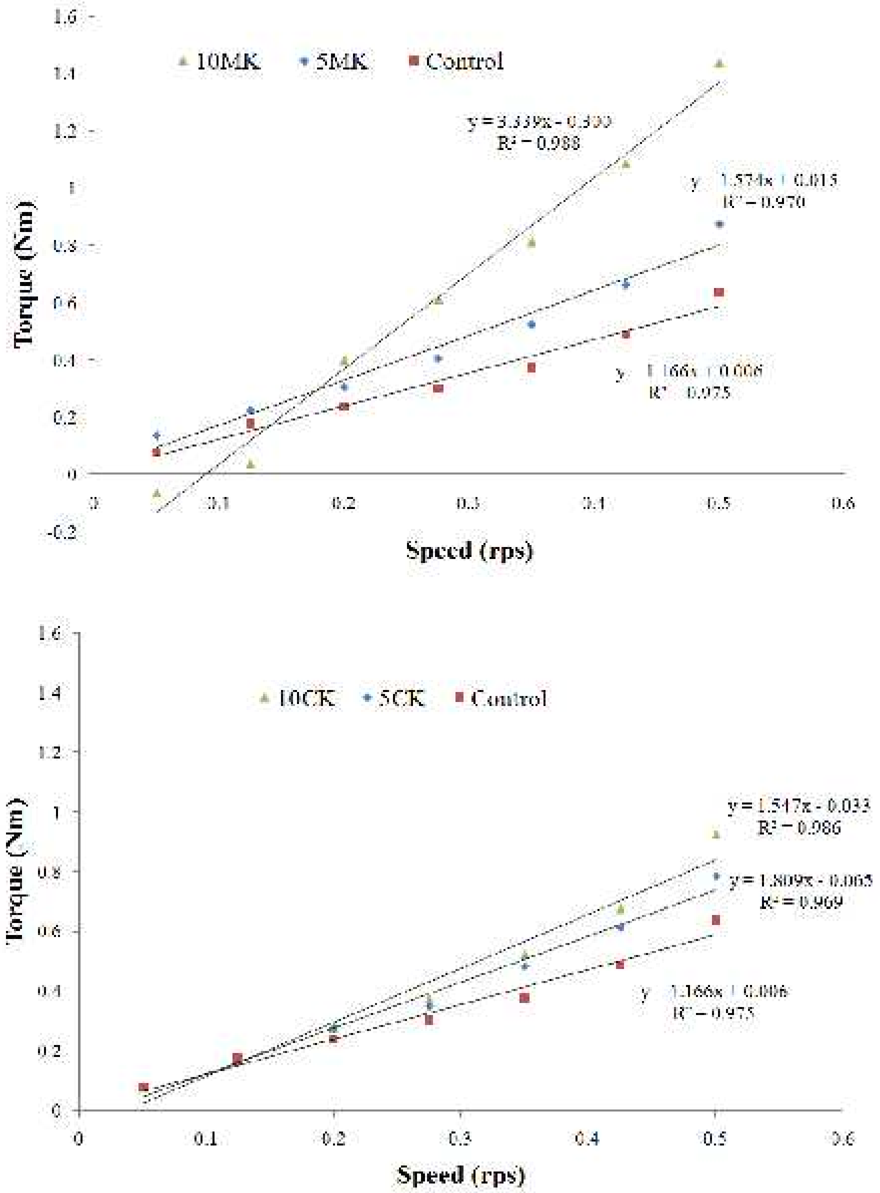


Figure 4.4 Flow curves for a) control vs. MK incorporated SCCs, b) control vs. CK incorporated SCCs

When T values are converted to shear stress (τ) and rotational speed is converted to shear rate (γ), then the plastic viscosity can be calculated using Bingham model. The plastic viscosity values are demonstrated in Figure 4.5. As seen in Figure 4.5, increasing the replacement of mineral admixture resulted in increase in the plastic viscosity and provided the concretes to be less susceptible to segregation. The highest plastic viscosity of 55.1 Pa.s was calculated for 10MK SCC while the lowest was observed to be 23.9 Pa.s for control SCC. It was also noticed that increasing the amount of MK resulted in increase with an ascending slope whereas a descending tendency was observed for CK incorporated ones. Since SCCs had very low yield stress they may be ignored. Feys et al. (2009) and Nielsson et al. (2003) reported that the yield stress values below 10 Pa could be negligible. The yield stress values of SCCs in this study were all below 10 Pa and there was no distinguishable trend since the slump flow diameter had been kept constant (700±20 mm) for all of the concretes.

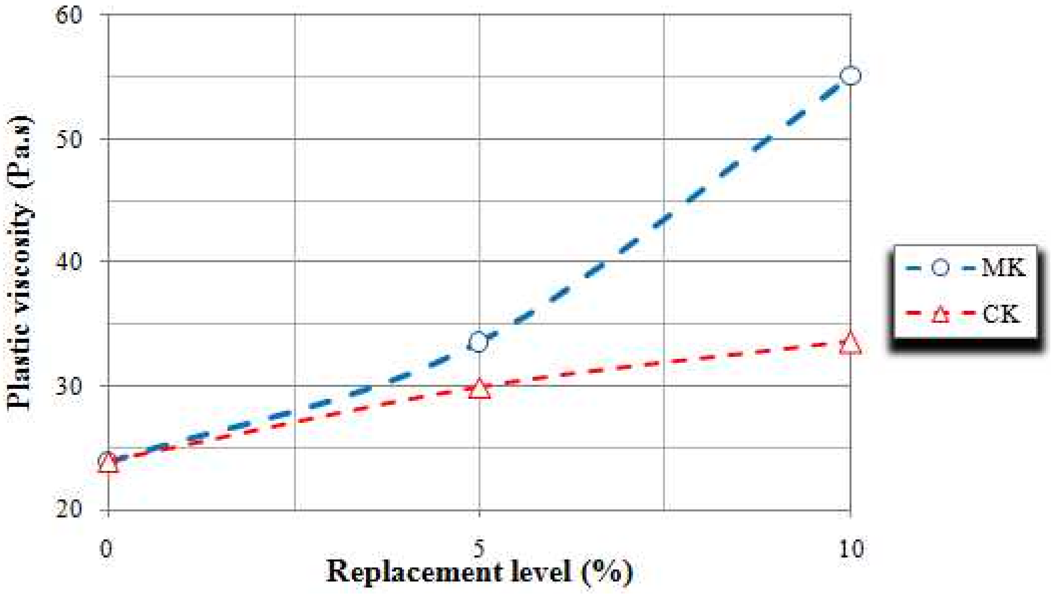


Figure 4.5 Plastic viscosity of SCCs

4.2 Compressive Strength and Ultrasonic Pulse Velocity (UPV)

Effect of MK and CK on 28 day compressive strength and UPV of SCCs are depicted in Figures 4.6 and 4.7, respectively. Moreover, Figure 4.8 indicates the correlation between compressive strength and UPV values. As seen in Figure 4.6, utilization of MK and CK had positive effect in the enhancement of compressive strength. Mineral admixtures provided 10.5% and 3.0% increase in compressive strength for 5% replacement level MK and CK, respectively. While 14.4% and 8.0% increase were observed for 10% replacement level of MK and CK, respectively. The enhancement in compressive strength of concrete is due to both microfilling and secondary hydration of mineral admixture with Portlandite (Siddique et al., 2009; Badogiannis et al., 2005; Shvarzman et al., 2003; Chandrasekhar, 2006; Mermerdaş et al., 2013; Güneyisi et al., 2013; Nadeem et al., 2013; Mermerdaş et al., 2012). Moreover, in the study of Mermerdaş et al., it was reported that calcined crude kaolins might be as effective as metakaolin in terms of strength development of the concretes.

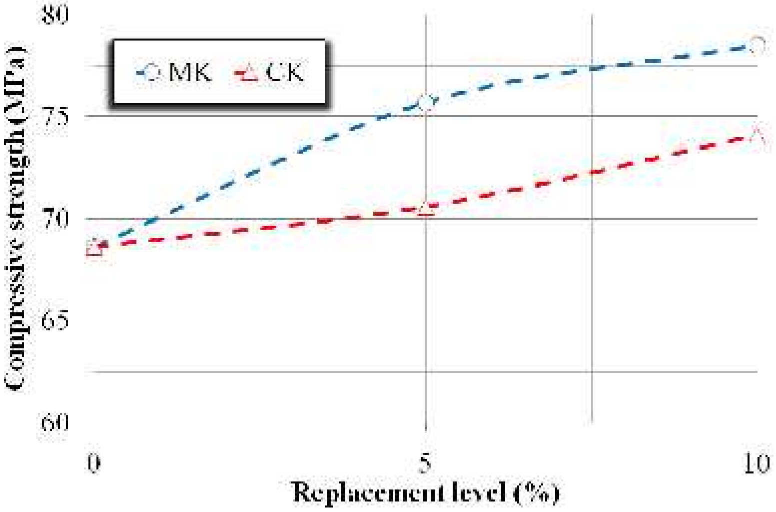


Figure 4.6 Effect of MK and CK on 28 day compressive strength of concretes

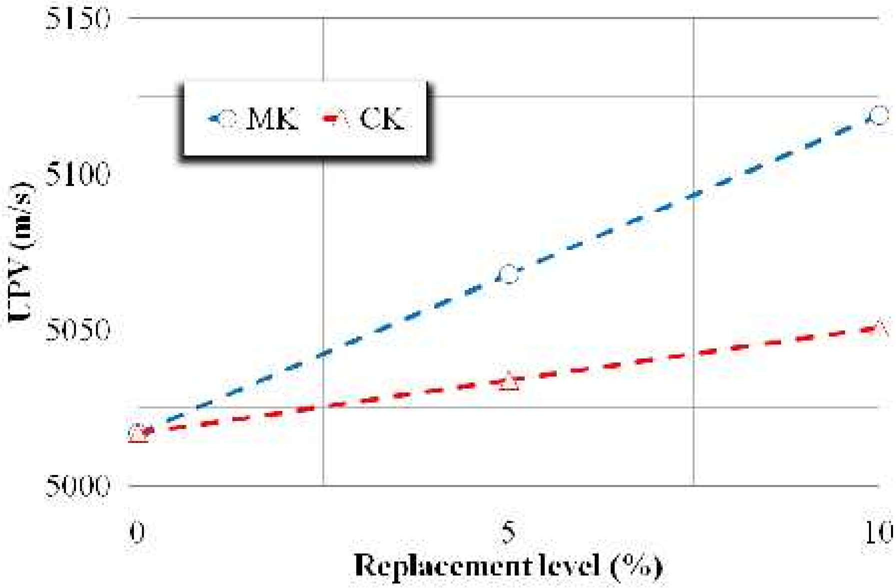


Figure 4.7 Effect of MK and CK on 28 day ultrasonic pulse velocity (UPV) of concretes

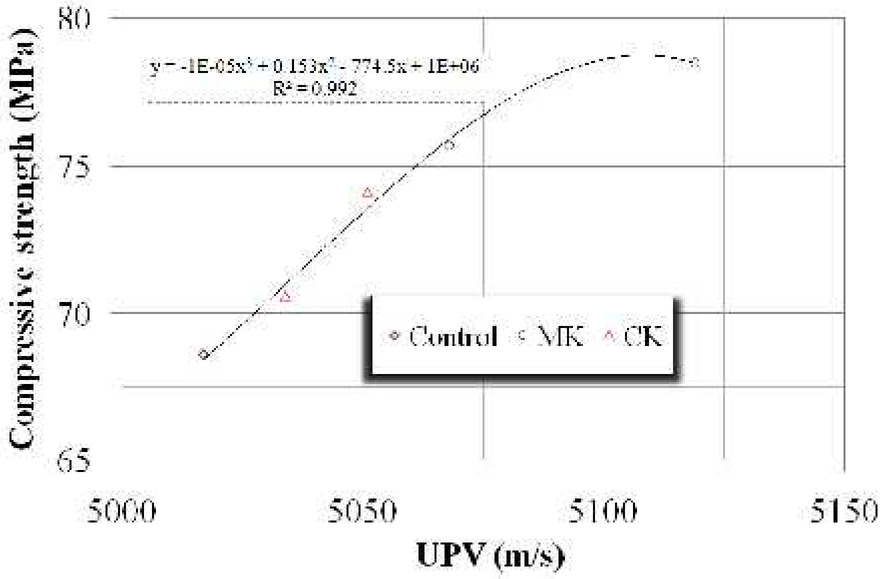


Figure 4.8 Correlation between compressive strength and UPV values of the concretes

Being a non-destructive testing method of concrete, UPV provides a relative comparison about the quality and density of concrete. The higher the rate of pulse wave, the denser the concrete is. As observed from Figure 4.7, the range of the variation of UPV values are very narrow. However, there is a clear trend indicating the increase of UPV values with the increase in the amount of mineral admixture. Furthermore, there is a strong correlation between compressive strength and UPV values as shown in Figure 10. A polynomial correlation with R^2=0.99 were obtained. The higher the UPV value, the higher the compressive strength was observed. This indicates that the inclusion of mineral admixtures provided improvement in pore structure and hence led to increase in compressive strength.

CHAPTER 5

CONCLUSIONS

The following conclusions mıght be drawn from the findings presented in this experimental study:

- It was observed thet SCCs with proper workability characteristics could be produced using calcined impure kaolin. All of the SCCs had T_{50cm} slump flow times ranging between 2.8 and 5.0 s, depending on type and amount of the mineral admixture. Considering V-funnel flow time, only 10MK was out of the limitations of EFNARC. Although 10% replacement level of MK seemed to deteriorate the workability properties according to the EFNARC specifications, by adjusting mix design parameters higher levels of replacement can be utilized to stay with in the EFNARC specifications.
- L-box height ratios of control and 5% mineral admixture incorporating SCCs were higher than 0.8 while 10% replacement level caused significant reduction in these ratios. Higher specific surface area of MK was dominant factor for the variations in the workability properties.
- Yield stress of SCCs were observed to be insignificant (less than 10 Pa), however, plastic viscosity of SCC were apparently increased with the inclusion of mineral admixture. Particularly, increasing amount of MK

- proved to be more effective in increasing the plastic viscosity than CK did. Although, increasing the plastic viscosity may be beneficial for segregation resistance, shear thickening may result in difficulties in constructional applications.
- The calcined kaolin which was obtained from non-purified Turkish kaolin, yielded similar behavior to that of the commercial metakaolin, in terms of 28 day compressive strength of SCCs. However, MK incorporated SCCs revealed higher level of enhancement than that of CK incorporating ones.
- The UPV values of CK and MK modified SCCs, at 28 days, was proved to be comparatively better than control concrete. Moreover, a strong relation between UPV and compressive strength of SCCs was observed.

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