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Rheological Properties Of Self-Consolidating Concrete Incorporating Natural And Industrial Pozzolans

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RHEOLOGICAL PROPERTIES OF SELF-CONSOLIDATING CONCRETE INCORPORATING NATURAL AND INDUSTRIAL POZZOLANS

by

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ABSTRACT

Rheological properties of Self-consolidating concrete incorporating natural and industrial pozzolans

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Self-consolidation concrete (SCC) is a latest version of high performance concrete with excellent workability and high resistance to segregation and bleeding. The main objective of this project is to study the rheological properties of SCC incorporating natural and industrial pozzolans (silica fume and metakaolin, respectively) as supplementary cementing materials (SCMs). Use of such pozzolanic materials in the development of environmentally friendly and cost effective SCC can lead to sustainable construction.

In this project eleven SCC mixtures are developed by incorporating different percentages of silica fume (SF) and metakaolin (MK) as replacement of cement. However, the water cement ratio of all SCC mixtures was kept constant. Mix designs of the developed concrete mixtures are optimized so that all mixtures satisfied the requirements of SCC in terms of fresh properties such as workability, stability, passing ability, bleeding and segregation resistance.

This study particularly concentrates on evaluation of the rheological properties such as viscosity and yield stress of developed silica fume and metakaolin based SCC mixtures. The influence of SF and MK dosages on viscosity and yield stress of SCC mixtures are evaluated. Correlations among fresh and rheological properties are developed and critically reviewed to make recommendations.

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Dedications

To my family

And

To those who support me towards success

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1. INTRODUCTION

1.1 Self-consolidating Concrete

Heavily congested reinforcement areas prove to be a problem when trying to pour concrete. Concrete is used mainly as building materials and is the largest consumer of natural resources such as water, sand, gravel and crushed rock. Portland cement is the commonly used binder for modern concrete mixtures. Due to high viscosity, the reinforcement sometimes is not fully encompassed by the concrete and therefore, a significant amount of vibration is required. Research has been conducted to improve these setbacks and to mitigate this issue. Self -consolidating concrete (SCC) has been developed to address this problem and to eliminate the need for vibration. SCC was created in the 1980's in Japan (Schutter et al. 2008). SCC is a new concrete technology known for its excellent deformability, high resistance to segregation and bleeding (Lachemi et al. 2005).

The basic requirement of SCC is to have high degree of flowability with no segregation and good cohesiveness. High flowability can easily be achieved by adding superplasticizer (SP) to the concrete. An easy way to avoid segregation due to the addition of SP is to increase the sand content and decreasing the coarse aggregate content.

The lack of knowledge regarding the in-situ properties and the structural performance of SCC members, has limited the widespread use of this material in practical applications. If the use of SCC is to evolve beyond the current prominence of being a concrete for highly congested members only, along with the development of cost-effective SCC, application and the structural performance involving the material should be explored. There is a need for more studies to develop SCC using different materials. There is an environmental need to use, natural materials (such as metakaloin) and industrial bye-products (such as silica fume) in the production of SCC. The development of such environmentally friendly SCC can lead to sustainable construction. Properly proportioned and placed SCC can result in both economic and technological benefits for the end user. The in-place cost savings, performance enhancements, or both, are the driving forces behind the use of SCC. Specifically, SCC can provide the following benefits (ACI.237 2007):

- Reduce labour and equipment,
- No need for vibration to ensure proper consolidation,
- Less need for screeding (finishing the concrete surface) operations,
- Enable the casting of concrete that develops the desired mechanical properties independent of the skill of the vibrating crew,
- Accelerate construction through higher rate of casting or placing and shorter construction duration,
- Facilitate and expedite the filling of highly reinforced sections and complex formwork while ensuring good construction quality. This can ensure better productivity; reduce the labour requirement and cost, or both
- Enable more flexibility in spreading placing points during casting. This can reduce the need for frequent movement of transit trucks and the need to move the pump lines to place concrete (possible reduction in the number of pumps, pump operators, and so

on). This greater flexibility in scheduling construction activities and procuring the required resources results in both time and resource savings,

- Reduce noise on the job site (especially critical in urban areas and for sections requiring heavy vibration consolidation),
- Reduce the need of vibration for construction typically requiring the use of heavy consolidation (such as fiber reinforced concrete and precast operations). In some cases, the use of noise-free or silent concrete can potentially extend construction hours in urban areas, enabling the scheduling of some construction activities during otherwise curfew periods to alleviate difficulties related to traffic conditions in urban areas,
- Reduce insurance premiums. Precasting facilities generating considerable noise pollution are sometimes required to pay premiums to national insurance agencies responsible for eventual treatment of hearing-impaired workers. Insurance premium reductions can partially offset the additional material cost of SCC, making it attractive for precast operations,
- Decrease employee injuries by facilitating a safer working environment,
- Permit more flexibility for detailing reinforcing bars. Avoid the need to bundle reinforcement to facilitate placement and consolidation.

1.2 Objectives and Scope

The objective of this study is to design and optimize SCC mixtures by incorporating natural and industrial pozzolans such as metakaolin and silica fume, respectively. The influence of silica fume and metakaolin on rheological parameters and the fresh properties of developed SCC mixtures have been studied. A series of trial concrete mixes are made to study the generation of flow behaviour as well as shear yield stress and plastic viscosity characteristics without segregation and bleeding of SCC. Correlations have been developed between rheological parameters and fresh properties of SCC mixtures. Such correlations can be used to predict the flow behaviour SCCs from their rheological parameters. With the help of such correlations, SCC mixes with desired properties can be achieved at an optimum cost and time. Over all, the interest of this project is to produce high performance SCC by incorporating natural and industrial pozzolans such as metakaolin and silica fume, respectively in order to contribute in sustainable development by means of reducing the use of the Portland cement.

2. LITERATURE REVIEW

Concrete is a construction material composed of cement (commonly Portland cement) as well as other supplementary cementitious materials (SCMs) (such as metakaolin, fly ash, silica fume and slag cement etc), aggregate (generally a coarse aggregate such as gravel, limestone, or granite, plus a fine aggregate such as sand), water, and chemical admixtures. Concrete solidifies and hardens after mixing with water and placement due to a chemical process known as hydration. The water reacts with the cement, which bonds the other components together, eventually creating a stone-like material. Concrete is used to make infrastructures such as pavements, buildings, motorways/roads, bridges/overpasses etc.

Concrete is used more than any other man-made material in the world. As of 2006, about 7 cubic kilometers of concrete are made each year—more than one cubic meter for every person on Earth. Concrete powers a US $35-billion industry which employs more than two million workers in the United States alone. More than 89,000 km of highways in America are paved with this material. The People's Republic of China currently consumes 40% of the world's cement/concrete production [http://wapedia.mobi/en/Concrete].

2.1 Self -Consolidating Concrete

Self-consolidating concrete (SCC) also known as self compacting concrete, is a highly flowable, non segregating concrete that can spread into place, fill the formwork and encapsulate the reinforcement without any mechanical consolidation. Although SCC is not expected to ever completely replace conventionally vibrated concrete, the use of the material in both the precast and ready mix markets in the UK, Europe and the rest of the world is expected to continue to increase as the experience and technology improve, the clients demand a higher quality finished product while the availability of skilled labor continues to decrease (Goodier 2003).

2.2 Methodology of developing SCC

Several different approaches have been used to develop SCC. One method to achieve self consolidating property is to increase significantly the amount of fine materials or mineral admixtures, for example fly ash (FA), ground granulated blast furnace slag (GGBFS), silica fume, limestone (LS) filler, volcanic ash (VA) or cement kiln dust (CKD) without changing the water content compared to common concrete [Khayat et al. 1997; Bui et al. 2002; Lachemi et al. 2003; Patel et al. 2004; Hossain and Lachemi 2004; European SCC Guidelines, 2005]. The use of such mineral admixtures can improve the slump flow and cohesiveness, reduce the segregation, lower the cost by replacing relatively costly cement, lower the heat of hydration, lower the permeability and lower the shrinkage and creep of SCC. Mineral admixtures can also exert beneficial effect on concrete for the improvement of interfacial transition zone [Gue et al. 2007]. GGBFS provides reactive fines with a low heat of hydration. A high proportion (more than 30 % of binder) of GGBFS may affect stability of SCC while slower setting can also increase the risk of segregation [European SCC Guidelines, 2005]. The high level of fineness and spherical shape of silica fume results in good cohesion and improved resistance to segregation when used in SCC.

However, silica fume is also very effective in reducing or eliminating bleeding and this can give rise to problems of rapid surface crusting. This could result in cold joints or surface defects if there are any breaks in concrete delivery and also the difficulty in finishing the top surface [European SCC Guidelines 2005].

One alternative approach to produce SCC consists of incorporating a viscosity modifying admixture (VMA) to enhance stability [Rols et al. 1999; Lachemi et al. 2004]. The use of VMA along with adequate concentration of super plasticizer (SP) can ensure high deformability and adequate workability leading to a good resistance to segregation.

To avoid segregation, SCC utilizes a limited aggregate content and superplasticizer as well as low water-to–powder ratio [Okamura and Ouchi 2003]. SCC performance is highly affected by the characteristics of the ingredient materials such as size, shape, surface area and grain size distribution of aggregates [Saak et al. 2002]. SCC may be classified into three types: the powder type, viscosity agent type and the combination type [EFNARC 2006]:

- In the powder type, SCC is characterized by the large amount of powder (all material < 0.15 mm), usually in the range of 550 to 650 kg/m^3. The powder provides the plastic viscosity and hence, the segregation resistance of the mix.
- In the viscosity type SCC, the powder content is lower (350 to 450 kg/m^3). The segregation resistance is mainly controlled by a VMA and the yield stress by the addition of SP.

- In the combination type SCC, the powder content varies from 450 to 550 kg/m^3 but in addition the rheology is also controlled by a VMA as well as an appropriate dosage of SP. The purpose of the addition of a VMA is to replace or limit the addition of fines, thus making a fresh concrete more cohesive [EFNARC 2006].

All types of cements can be used in the SCC production, but should develop a satisfactory interaction and compatibility with chemical additives, viscosity modifying admixtures and super plasticizers.

Super plasticizers improve workability and strength of concrete with reduced water-to-cement ratio (w/c). SPs are also often used when pozzolanic materials are added to concrete to improve strength. SPs have been manufactured from sulfonated naphthalene formaldehyde or sulfonated melamine formaldehyde. New products based on polycarboxylic ethers (PCE) are also developed. PCEs are not only chemically different from the older sulphonated melamine and naphthalene based products, but their action mechanism is also different, giving cement dispersion by steric stabilization, instead of electrostatic repulsion. This form of dispersion is more powerful in its effect and gives improved workability retention to the cementitious mix. Furthermore, the chemical structure of PCE allows for a greater degree of chemical modification than the older products, offering a range of performance that can be tailored to meet specific needs [Zhong et al. 2006]. Nephthalene and melamine super plasticizers are organic polymer. The long molecules wrap themselves around the cement particles, giving them a highly negative charge so that they repel each other [Khayat 1998]. The workability of SCC and performance of hardened concrete depend on the type of SP [Khayat and Hwang 2006].

There is no standard method for SCC mix design and many academic institutions and contracting companies have developed their own mix proportioning methods. Mix design often use volume as a key parameter because of the importance of the need to over fill the voids between the aggregate particles. Some methods try to fit available constituents to an optimized grading envelope. Another method is to evaluate and optimize the flow and stability of the paste and then the mortar fractions before the coarse aggregate is added and the whole SCC mix tested.

Sixty eight case studies on application of SCC (from 1993 to 2003 in different countries) have been analyzed with details [Domone 2006]. A clear majority (70 %) of cases used aggregate with a maximum size between 16 and 20 mm. The use of crushed rock or gravel aggregate seemed to depend on local availability. Approximately half the cases used a VMA in addition to super plasticizer and could therefore, be considered as a combined type of SCC. Limestone was the most common addition (41 % of the cases). Median value of the key mix proportions were coarse aggregate content of 31.2 % by volume, paste content of 34.8% by volume, powder content of 500 kg/m^3, water powder ratio of 0.34 weight and fine aggregate/mortar of 47.5 % by volume. In ninety percent of the cases, SCC with slump flow in the range of 600-750 mm was used while 80% had compressive strengths in excess of 40 MPa [Domone 2006].

2.3 Supplementary Cementing Material (SCMs)

SCMs used in conjunction with Portland cement contribute to the properties of fresh and hardened concrete through hydraulic, and pozzolanic activity or both. Silica fume and metakaolin are examples of SCM. A pozzolan is a finely divided siliceous or aluminosiliceous material and in presence of moisture, chemically reacts with the calcium hydroxide released by the hydration of Portland cement to form compound possessing cementing properties [Mehta 1983]. The practice of using SCM in concrete mixes has been growing in the whole would in recent years. The similarly between these materials are that these are generally by-products of other processes, and their judicious use provide solution that are environmentally-friendly and conserve energy [Mehta 1983]. Various industries are producing millions of tones of environment pollution. With proper quality control, large amount of these by-products can be incorporated into concrete, either in the form of blended Portland cement or as a mineral admixture. Pozzolanic materials can make concrete competitive, cost effective and durable over other construction materials [Mehta 1983].

Some of the common supplementary cementing materials are discussed in the following sections.

2.3.1 Metakaolin as Supplementary Cementing Material

Metakaolin (MK) is a pozzolanic material, which is typically dark grey or black. This makes it a more attractive choice when considering its colour-matching uses and application in other architectural projects [Wild et al 2001]. It is created from a natural, very abundant mineral (kaolin), and made based on the required applications in engineering. Kaolin is white, fine clay, traditionally being used as a product in the manufacturing of porcelain, as well as the coating of paper. Metakaolin is made under very controlled specifications in order to acquire a specific color, particle size, and level of purity. This allows for a higher quality of metakaolin, which in turn translates into a more effective and reactive pozzolanic activity. Metakaolin is obtained by calcinations of kaolintic clay at a temperature between 500° C and 800° C. The raw material input in the manufacture of metakaolin ($Al_2\ Si_2O_7$) is kaolin clay. Kaolin is a fine, white, clay mineral that has been traditionally used in the manufacture of porcelain. Kaoliniteis, the mineralogical term, is applicable to kaolin clays. Kaolinite defined as a common mineral hydrated aluminum di-silicate, is the most common constituent of kaolin. The meta prefix in the term is used to denote change. In the case of metakaolin, the change that is taking place is dehydroxylization, brought on by the application of heat over a defined period of time [Siddique and Klaus 2009].

Metakaolin finds its usage in many aspects of concrete [Siddique and Klaus 2009];

- High performance, high strength and lightweight concrete
- Precast concrete for architectural, civil, industrial, and structural purposes
- Fiber cement and ferrocement products

- Glass flber reinforced concrete
- Mortars, stuccos, repair material, pool plasters

Advantages of using metakaolin [Siddique and Klaus 2009]:

- Increased compressive and flexural strengths
- Reduced permeability
- Increased resistance to chemical attack
- Increased durability
- Reduced effects of alkali-silica reactivity(ASR)
- Reduced shrinkage due to particle packing, making concrete denser
- Enhanced workability and finishing of concrete
- Reduced potential for efflorescence
- Improved finishability, color & appearance

2.3.2 Silica fume as Supplementary Cementing Material

Silica fume (SF) is an industrial bye-product material that can be used as pozzolan [Rao 2001]. It 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. It rises as an oxidized vapor from 2000°C furnace, and then it cools [Mindess 2002].

Silica fume is non-crystalline form of SiO_2. One of the most beneficial uses for silica fume is in concrete. Because of its chemical (as a very reactive pozzolan) and physical (spherical shape and smaller size than cement) properties (Table 2.1), it plays a significant role in the transition zone. Inter facial transition zone (ITZ) is a thin layer between the bulk hydrated cement paste and the aggregate particles in concrete. ITZ is the weakest component in concrete, and is also the most permeable area. SF has the particle packing characteristic-ability to pack between the cement particles and can act as a lubricant. So, concrete containing silica fume can have very high strength and can be very durable [Kostmatka et al. 2002].

Table 2.1 Silica Fume [Kostmatka et al. 2002]

Silica Fume—Physical Properties	
Particle size (typical)	< 1 μ m
Bulk density, γ	
(as-produced)	130 to 430 kg/m^3
(slurry)	1320 to 1440 kg/m^3
(densified)	480 to 720 kg/m^3
Specific gravity	2.2 - 2.25
Surface area (BET)	13,000 to 30,000 m^2/kg

Effects of SF on freshly mixed concrete

Water demand increase when using SF (unless an additive of water reducer or SP is used). For some mixes of lean concrete, no increase in water demand if SF < 5 % is used. Concrete with SF shows a decreasing in bleeding and segregation. SF may or may not reduce the heat of hydration. SF can make concrete sticky (difficult to finish). SF aids pumpability of concrete. Air-entraining admixtures requirement increases with an increase in amount of SF in concrete. Concrete with SF may increase plastic shrinkage cracking because of its low bleeding. If silica fume concrete mixtures are given 7 days of continuous moist curing, there is no chance of cracking. Other methods of curing are used like fogging during placement, using an evaporation retarder during breaks in the placing sequence, and applying curing compound as soon as the surface texture has been completed [Mindess 2002].

Effects of SF on hardened concrete

By replacing a portion of cement used with SCM, more strength can be gained compared with an equal quantity of cement (C-S-H develops due to the following pozzolanic reaction:

The hydraulic reaction of cement component C_3S is

C_3S	+	H	→	C- S- H	+	CH
Tricalcium silicate		Water		Calcium silicate hydrate		Calcium hydroxide

While the principal reaction of SCM or SF is

CH + S + H → C- S- H [Kostmatka et al. 2002]

Especially when SF is used (fineness & higher surface area particles), high early strength develops between 3 and 28 days and it exceeds the strength of cement-only control concrete. SF is an expensive mineral material (10 times the cost of Portland cement), It is used as 5 – 15% of the cementing materials. SF can blend together with slag or fly ash in specific proportions to produce long-term high strength for high strength concrete. Concrete with SF and high-range water reducer and appropriate aggregate may reach a compressive strength up to 140 MPa [Mindess 2002].

SF as one of the SCM improves the durability of concrete through reduction of permeability decreasing pore size. The results of Rapid Chloride Permeability Test (RCPT) clearly indicate that silica fume was effective in reducing the RCP values regardless of the curing regimes applied (Table 2.2). Moreover, silica fume enhanced chloride resistance more than reducing w/c. This effect was confirmed by the diffusion tests [Kostmatka et al. 2002

Table 2.2 The results of Rapid Chloride Permeability test on silica fume[Kostmatka et al. ,2002]

Silica Fume	**RCP**	**Compressive Strength**
(by mass of cement)	coulombs	MPa
0%	> 3,000	35
7-10%	< 1,000	> 50
>10%	< 500	> 65

These values are typical for concrete containing about 600-650 lb/yd^3 of cement with a water-to-cementitious material ratio (w/cm) < 0.40. Use SF can cause reduction of expansion due to the alkali-silica reaction. This is due to the reduction in the alkali content and PH of the pore solution associated with the formation of C-S-H in pozzolanic reaction. Reduction of in chloride penetration (diffusion) to the concrete results an increase in electrical resistivity of the concrete, thereby, reduction of steel bars corrosion. SF increases chemical resistance of concrete. Generally, addition of SCM causes no effect on drying shrinkage, creep and soundness of concrete. SF improves the performance of shotcrete by reducing rebound loss of up to 50% and increasing one-pass thickness up to 300 mm [Kostmatka et al. , 2002].

Uses of silica fume in concrete structures

SF based high strength concrete is used in high-rise columns because of its higher modulus of elasticity. Use of high-strength concrete can save floor space, reduce the amount of reinforcing steel required, or both in parking structures, bridge decks and marine structures. In such structures, concrete is exposed to either deicing salt or to marine salts and also susceptible to chloride-induced corrosion. The protection mechanism for such cases is primarily by the reduction of the permeability of the concrete with the incorporation of SF. Silica fume can be used with Portland cement (PC) and fly ash for massive walls to reduce heat and to provide early strength for formwork removal. Silica fume is used in shotcrete as an excellent example of improvements in mechanical properties, durability, and constructability. Its higher bond strength improved cohesion to resist washout in tidal rehabilitation of piles and seawalls [Mindess 2002].

2.4 Benefits of Supplementary Cementing Materials

The supplementary cementing materials provide the following structural, economic and environmental benefits to concrete:

Structural

- The use of finely-divided particles tends to provide enhanced workability.
- Water requirement is reduced at a given consistency for materials that have low surface area.
- Ultimate strength, impermeability, and durability against chemicals is greatly increased.
- Thermal cracking resistance is improved because of the lower heat of hydration of cements, and increased tensile strain capacity.

Economic

- Portland cement is the most expensive part of the SCC mix, and can easily be replaced by supplementary cementing materials (SCM), which cost a fraction of the Portland cement.

Environmental

- CO_2 emissions are reduced (in comparison to Portland cement whose production releases one ton of emissions for every ton produced.
- Since SCMs (especially fly ash and silica fume) generally require little energy-intensive operations to be used, emissions are reduced as well.

2.5 Fresh Properties of Self-consolidating Concrete

SCC fresh properties are characterized by its deformability and stability as well as its bleeding and segregation resistance. SCC remarks its capacity to flow homogeneously without segregation between ingredients or bleeding. The method for achieving self compact ability involves not only high deformability of paste or mortar, but also resistance to segregation between coarse aggregate and mortar when the concrete flows through the confined zone of reinforcing bars [Okamura and Ouchi 2003]. SCC should have static and dynamic stability without bleeding or surface settlement prior to stiffening [Bui et al. 2002; Khayat et al. 2004]. The lack of static stability can cause surface defects, including the presence of bleed channels. Bleeding and settlement can decline the quality of the interface between aggregate and cement paste with direct bearing on impermeability and hardened mechanical properties [Khayat and Guizani 1997]. SCC fresh properties are described in the following sections.

2.5.1 Deformability

Deformability can be defined as the ability of a SCC to flow in a heavily reinforced section and other restricted areas. Highly flow able SCC should have relatively low yield stress to ensure good deformability. Inter-particle friction between coarse aggregate, sand, and binder increases the internal resistance of flow, limiting the deformability and speed of flow of SCC [Khayat et al. 1999]. Such friction can be high when concrete flows through restricted spacing because of greater chances of collision between various solids. The deformability of SCC can be increased by increasing water to binder ratio (W/B), increasing the dosage of SP, and by incorporating very fine supplementary cementing materials (SCM) [Nanayakkara et al. 1988; Khayat et al. 1999]. Increase in the W/B can secure high deformability but it may affect the mechanical and durability properties of SCC in the long run. Increasing W/B can also reduce cohesiveness and can cause segregation that may leads to blockage during flow. Inter particle friction between binder grains can be reduce by using SP to disperse the cement grain. A high dosage of SP can however lead to segregation and blockage of the SCC flow [Bui et al. 2002; Khayat et al. 1999]. Very fine and glossy textured particle of SCM can reduce the inter-particle friction and lead to higher deformability.

2.5.2 Stability and Segregation

The stability of fresh concrete is characterized by its resistance to segregation, and bleeding and is affected by the mixture proportioning, aggregate shape and gradation, and the placement conditions. When a mixture does not possess an adequate level of stability, the cement paste may not be cohesive enough to retain individual aggregate particles in a homogenous suspension. This causes the concrete constituents to separate, thus resulting in a significant reduction in mechanical properties and durability [Khayat et al. 1999, Bui et al. 2002].

There are two kinds of segregation. The first is the separation of mortar from coarse aggregates and second is bleeding. Bleeding is defined as a phenomenon whose external manifestation is the appearance of water on the top surface after concrete has been placed but before it has set. Bleeding is the form of segregation where solids in suspension tend to move downward under the force of gravity. Bleeding occurs due to the inability of the constituent material to hold all the mixing water in a dispersed state. Some bleeding water reaches to the surface ; large amount of it gets trapped under large pieces of aggregate, and horizontal reinforcing bars, which effect the mechanical performance of concrete such as strength and bond [Bui et al. 2002].

Improper consistency, excessive amount of large particles in coarse aggregate with either too high or too low density, presence of fewer fines (due to low cement and sand contents or the use poorly graded sand) can cause segregation and bleeding in SCC. The concrete without mineral admixtures may suffer segregation and bleeding in concrete. Some of the measures that can be used to enhance the stability of fresh SCC are;

- The reduction in water-to-binder ratio (W/B)
- The increase of cementing material content such as fly ash, GGBFS and other fines
- The incorporation of viscosity modifying admixtures (VMA)

A large decrease in aggregate volume or an increase in water content can reduce the cohesiveness and lead to segregation. A relative high sand-to-total aggregate content of 42-52% is often used to enhance cohesiveness and reduce the risk of segregation and water dilution [Bui et al. 2002].

2.6 Rheology of Concrete

Concrete is a composite material, with aggregate, cement, and water as the main components. It is a concentrated suspension of solid particles (aggregates), in a viscous liquid (paste). Paste is not a homogeneous fluid and is composed of particles of cement and cementing materials grains in water [Ferraris 1999].

Normally there are two types of flow behavior: Newtonian fluid and non-Newtonian fluid. In the Newtonian fluid, the shear stress is proportional to the shear rate (shear strain rate) and at a given temperature; the viscosity remains constant at any shear rate. While in the non-Newtonian fluid, when the shear rate is varied, the shear stress doesn't vary in the same proportion and same direction. The viscosity of this fluid changes as the shear rate varies [Ferraris 2000].

The flow of paste, mortar, and concrete is assumed to follow the non-Newtonian equation of viscous flow, where viscosity of the fluid is the ratio of shear stress to shear rate (Shear strain rate).

2.6.1 Bingham and Other Models

Paste, mortar, and concrete are considered as non-Newtonian fluid. The most commonly used model for paste, mortar, and concrete is the Bingham model. This model requires two parameters, ie. yield stress and plastic viscosity. The yield stress is the stress above which the material becomes fluid. In other words, the yield stress corresponds to the intercept on the shear stress axis. The plastic viscosity is the measure of how easily the material will flow, once the yield stress is overcome. The plastic viscosity is the slope of shear stress-shear rate plot as per Binghham model shown in Fig. 2.1 [Ferraris,1999].

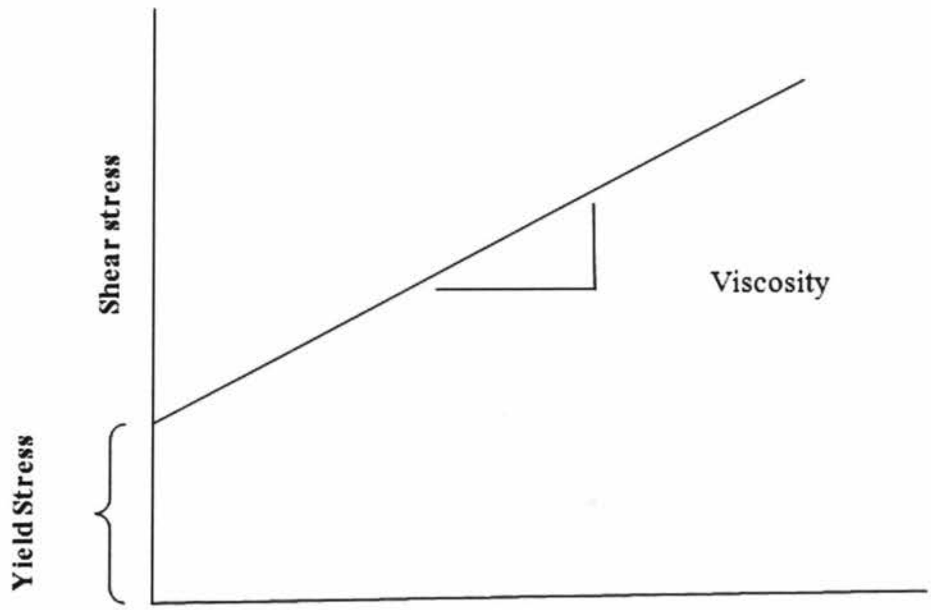


Fig 2.1: Bingham model for fluid (Ferraris, 1999).

The Bingham equation is represented as follows:

$$\tau = \tau_o + \eta\,\gamma \qquad (2.1)$$

Where,

τ = Shear stress $\quad$ η = Viscosity

τ_o = Yield stress $\quad$ γ = Shear rate

Table 2.3 shows other models compared to Bingham model relating shear stress and shear strain.

Table 2.3: Equations related to shear stress and shear strain (Ferraris, 1999).

Equation name	Equation
Newtonian	$\tau = \eta \gamma$
Bingham	$\tau = \tau_o + \eta \gamma$
Hurchel & Bulkley	$\tau = \tau_o + k \gamma^n$
Power	$\tau = A \gamma^n$
Vorn Berg	$\tau = \tau_o + B \sinh^{-1}(\gamma/C)$
Eyring	$\tau = a \gamma + B \sinh^{-1}(\gamma/C)$

Variable definitions:

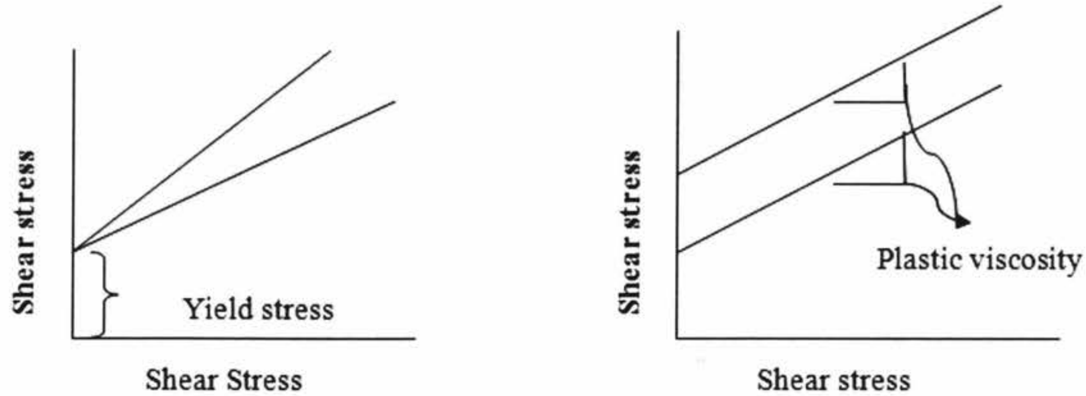
τ = Shear stress η = Viscosity

τ_o = Yield stress γ = Shear rate

A, a, B, C, K = constants

$n = 1$ Newtonian flow $n > 1$ Shear thickening $n < 1$ Shear thinning

The lower yield stress gives less resistance to start the flow of concrete. Higher viscosity prevents segregation but provides high resistance to the flow of concrete. It is important for SCC to have low yield stress and optimal viscosity to ensure enough flow and to prevent segregation [Saak et al. 2001]. The measurement of only one parameter (either yield stress or plastic viscosity) does not fully characterize SCC rheology. Fig. 2.2 shows how two concretes could have one identical parameter and a very different second parameter. These concretes may be very different in their flow behaviors. Therefore, it is important to use a test or combination of tests that will describe the concrete flow, by measuring both factors [Ferraris1999].



Same yield stress, different viscosity — Same viscosity, different yield stress

Fig 2.2: Concrete rheology for different flow behavior [Ferraris 1999].

2.6.2 Test apparatus for rheology

Tattersall rheometer is the first and most widely known instrument for measuring the rheological parameters of SCC. The apparatus consists of a bucket containing the concrete to be tested. A vane of special geometry, or spindle, is lowered into the sample. The resistance on the spindle due to the material against the rotation of spindle, ie. torque is measured. As the speed of rotation of the spindle is increased, a curve of the torque versus the speed is recorded. The graph obtained is linear; therefore the stress is extrapolated to the torque at zero speed to give the yield stress. The plastic viscosity is related to the slope of the curve [Ferraris 1999].

Tattersall gave the following equation:

$$T = (G / K)\ \tau_o + (G\ \eta)\ N \qquad (2.2)$$

Where

T = Torque; G = Constant obtained by calibration with non-Newtonian fluid

N = Speed of the impeller

τ_o = Yield stress

η = Viscosity

Tattersall designed the first instrument for measuring the two points rheology (yield stress and plastic viscosity) of concrete, after that, more instruments were developed with more or less the same principles [Ferraris 1999].Some of them are listed below:

- BML Viscometer
- IBB Concrete rheometer
- FHPCM rheometer
- Bertta apparatus
- BTRHEOM Rheometer

Apart from these (Tang et al. 2001) used commercially available Brookfield viscometer for rheological measurements of paste and mortar.

2.6.3 Rheological parameters and flow behavior of SCC

The rheological parameters of paste, mortar, and SCC are important to predict flow behavior of SCC [Wallevilk 2006]. Not much information is available on the correlation between the rheological parameters of paste/mortar and the flow behavior of SCC. The problem comes from the fact that the range of the particle size of binder and fine aggregate is very wide and difficulty in matching the testing conditions of rheology of paste/mortar and SCC. It is important to measure the rheology of paste/mortar in the same conditions that normally exist in concrete to achieve a reliable correlation [Schwartzentruber et al. 2006; Lacombe et al. 1999]. Tang et al. (2001) concluded that the fresh concrete made with mortar of low viscosity might cause aggregate segregation; whereas mortar with high viscosity might reduce the flowability. A mortar viscosity ranging from 3500 to 5500 mPa.s was found to be suitable for the production of SCC. The volumetric fraction of coarse aggregate was varied from 30 to 40% for their study.

2.7 Research related to rheological properties

The use of SCC is becoming widespread because of ongoing research (over the last decades) on its fresh/rheological, mechanical and durability properties. The growing use of SCC is leading to further research studies for developing cost effective alternatives to make SCC an economically feasible environment friendly construction material.

The most recent report related to SCC " ACI 238.1R (2008)" shows that the use of silica fume can improve workability when used at low replacement of the cement, but can reduce workability when added at higher replacement rates. Due to silica fume particles being significantly smaller than cement particles, a small volume of silica fume particles may enhance the powder particle size distribution, whereas a large volume of silica fume may result in worse powder particle size distribution. The report also discusses the slag cement effect on the workability which considers close to metakaolin effect. Slag cement generally improves workability; however, its effect can vary depending on the characteristics of the concrete mixture in which it is used.

Research from University of Sherbrook [Patit et al. 2007] had found significant influence of temperature and elapsed time on the rheological behaviour of self consolidating concrete. The change of the plastic viscosity and the yield stress with the elapsed time and temperature has to be precisely quantified in order to expect the variation of workability of cement-based materials. Table 2.4 shows experimental values of SCC viscosity with temperature.

Table 2.4 Experimental values for viscosity (Petit et al. 2007)

Mixtures	Temperature °C	Viscosity (Pa s)
SCC1	15	18.2
SCC2	20	18.65
SCC3	20	25.19
SCC4	20	41.9
SCC5	20	27.4

A number of studies on SCC have been conducted at Ryerson University and is still going on. In this section, a brief summary of some of the work already done on rheological properties of SCC at Ryerson University is discussed.

SCC was obtained with the incorporation of mineral admixtures (such as fly ash and slag) or viscosity-modifying admixtures (VMAs) [Bouzoubaa and Lachemi 2001; Hassan et al. 2008; Patel et al. 2004; Lachemi et al. 2004). When it comes to stabilizing the rheology of SCC, the use of VMA has proved very effective. A study by (Hossain et al., 2004) was conducted to investigate ways to reduce the use of high-range water-reducing admixtures (HRWR), while at the same time optimizing the utilization of fly ash. They formulated 21 statistically balanced concrete mixtures, and used four independent variables: total binder content (350-450kg/m^3), FA's percentage as cement replacement (30-60% by mass), and HRWRA's percentage (0.1-0.6% by mass), and water-to-binder ratio (0.33-0.45). They concluded that these additions were significant and had a positive influence on the SCC properties. During this study, the Box-Wilson central composite design (CCD) method was used. Fly ash has an excellent ability to reduce the HRWRA demand if a certain slump flow is required. Therefore, both the initial as well as the final setting times are dependent upon the percentages of FA and HRWRA. Higher percentages of these admixtures mean higher setting times. When the binder and HRWRA content were kept constant, the 28-day compressive strength began to decrease as the addition of fly ash increased. The statistical models and response charts that this study generated are essential tools in the mixture design of fly ash. One can use these models to predict the fresh, hardened, and durability properties of SCC mixes, and process the properties of multiple mixtures within a short time frame to conclude the most feasible mix for a certain scenario.

Another study conducted by Hossain et al. (2003) focused on the suitability of four new types of polysaccharide-based VMA for use in SCC mixes. First, to understand the rheological properties, preliminary investigations on mortar with various dosages of VMA was carried out. The study also looked at the influence and feasibility of the new types of VMAs. Soon after, a more comprehensive study was conducted on the SCC mixes to investigate their fresh and hardened properties based on the various tests, with differing dosages of VMAs. The SCC that is currently available on the market is costly simply due to the high price of VMAs and binder volume in the mixture. To overcome this, a cost-effective product is necessary to compete in the construction industry. Within this study SCC mixes that incorporated different types of VMAs were studied. These polysaccharide-based VMAs (suspended in water) were classified as A, B, C, and D. They had a specific gravity of 1.42, while a total solid content of about 81%. It was noted that a satisfactory SCC could be created by using a lesser content of one of these VMAs than the recommended dosage of commercial VMA. This, in turn, can help produce cost-effective SCC mixes for practical application.

3. EXPERIMENTAL INVESTIGATION

3.1 Introduction

Experiments were conducted at concrete and structural laboratories of Ryerson University to develop and evaluate the properties self consolidating concrete (SCC) mixtures incorporating metakaolin (MK) and silica fume (SF). In the first phase, tests were conducted to develop SCC mixtures and to assess fresh / workability properties (such as slump flow, slump flow time, L-box ratio, V-funnel time and segregation index of a range of concrete mixtures with different percentage of silica fume/metakaolin as replacement of cement. In the second phase, tests were conducted to determine hardened properties such as compressive and splitting tensile strengths of developed concrete mixtures. A total of twelve SCC mixtures were developed and evaluated in addition to a control SCC mixture without SF or MK.

3.2 Materials

The following sections discuss the materials and their properties used in this project. They are: cement, water, aggregate, super plasticizer, metakaolin and silica fume.

3.2.1 Cement

Type GU (General Use), hydraulic cement in compliance with CSA A3001-03 (Type 10 normal Portland cement) was used. Chemical, physical and strength properties of cement are shown in Table 3.1.

Table 3.1- Chemical and Physical Properties of Cement

Chemical Analysis (%)	**Cement**
Loss on ignition LOI	2.02
Silicon dioxide SiO_2	19.80
Aluminum Oxide Al_2O_3	5.51
Ferric Oxide Fe_2O_3	2.49
Calcium Oxide CaO	62.93
Magnesium Oxide MgO	2.43
Sulfur trioxide SO_3	4.50
Tricalcium silicate C_3S	52.26
Dicalcium silicate C_2S	17.37
Tricalcium aluminates C_3A	10.39
Tetra calcium aluminoferritte CaO	7.57
Total Alkali	1.00
Free lime CaO	0.79
Physical Analysis	**Cement**
Residue 45 um [%]	10.02
Blaine [m^2/kg]	410
Air content [%]	7.79
Initial set [mins.]	113
Compressive strength [MPa] 1 day	19.41
Compressive strength [MPa] 3 days	30.35
Compressive strength [MPa] 28 days	41.47

3.2.2 Water

Clean drinkable water with a temperature ranging between 22 and 24°C was used.

3.2.3 Aggregate

The grading of coarse and crushed fine aggregates was conducted according to ASTM C 136 and their grain size distributions are tabulated in Table 3.2.

Table 3.2- Sieve Analysis of Coarse and Fine Aggregate

Sieve #		3/8"	0.265 "	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
Opening (mm)		9.5	6.7	4.75	2.36	1.18	0.6	0.3	0.15	0.075
% of passing		100	99.8	96.5	82.8	69.8	51.8	22.1	6	1.5
Standard specifications	Min.	100		95	80	50	25	10		
	Max.	100		100	100	85	60	30	10	3

Table 3.3 shows the specific gravity, bulk density, moisture absorption, and surface moisture content of coarse and fine aggregates determined as per ASTM standards.

Table 3.3- Physical Tests of Coarse and Fine Aggregate

Test	**Coarse Aggregate**	**Fine Aggregate**
Dry loose bulk density, kg/m^3	1684	1730
Specific gravity (SSD), kKg/m^3	2671	2714
Specific gravity (Bulk). Kg/m^3	2638	2670
Moisture absorption. %	1.2	2.1
Fineness Modules		2.92

3.2.4 Super Plasticizer (SP)

PS-1466 from BASF Construction Chemicals (Master Builders) was used as SP. PS-1466 is based on polycarboxylate base and meets ASTM C 494/C 494 M requirements of Type A, water reducing; and Type F, high range water reducing, admixtures. Table 3.4 shows characteristics of PS-1466 as per the producer.

Table 3.4- Super Plasticizer PS-1466

Color	Brown
State	Liquid
Odor	No data
pH	2.7-6.5
Boiling point	100°C
Freeze Point	0° C
Specific Gravity	1.104-1.116

3.2.5 Metakaolin

Metakaolin can be used in combination with hydraulic cement for proportioning SCC mixtures. It should meet the requirements of ASTM C 618 or ASTM C 989. Metakaolin used for the development of SCC mixtures has the properties listed in Table 3.5.

Table 3.5- Chemical and Physical Properties of Metakaolin

Chemical Analysis (%)	Metakaolin
Silicon dioxide SiO_2	52.1
Aluminum Oxide Al_2O_3	41.0
Ferric Oxide Fe_2O_3	4.32
Calcium Oxide CaO	0.07
Magnesium Oxide MgO	0.19
Sodium Oxide Na_2O	0.26
Potassium Oxide K_2O	0.63
Loss on ignition	0.6
Specific surface area (m^2/Kg)	12,000

3.2.6 Silica Fume

Silica fume used in this project meets the requirements of ASTM C 1240. The chemical oxide composition of silica fume (wt %) is given in Table 3.6.

Table 3.6- Chemical Properties of Silica Fume

Chemical Analysis (%)	Silica Fume
Silicon dioxide SiO_2	92.26
Aluminum Oxide Al_2O_3	0.89
Ferric Oxide Fe_2O_3	1.97
Calcium Oxide CaO	0.49
Magnesium Oxide MgO	0.96
Sodium Oxide Na_2O	0.42
Potassium Oxide K_2O	1.31
Sulphur Tri Oxide SO_3	0.33

3.3 Methodology

3.3.1 Mix Preparation

A mobile concrete mixer without hoper consisting of a smooth steel drum with two paddles operated by an electrical 4.0 hp motor was used (Fig. 3.1). A programmed Excel sheet for mix design was used to adjust and to calculate the amount of each of ingredients of concrete mixtures for each batch. The water requirement of the mix was carefully adjusted by balancing the water absorption of both coarse and fine aggregates.

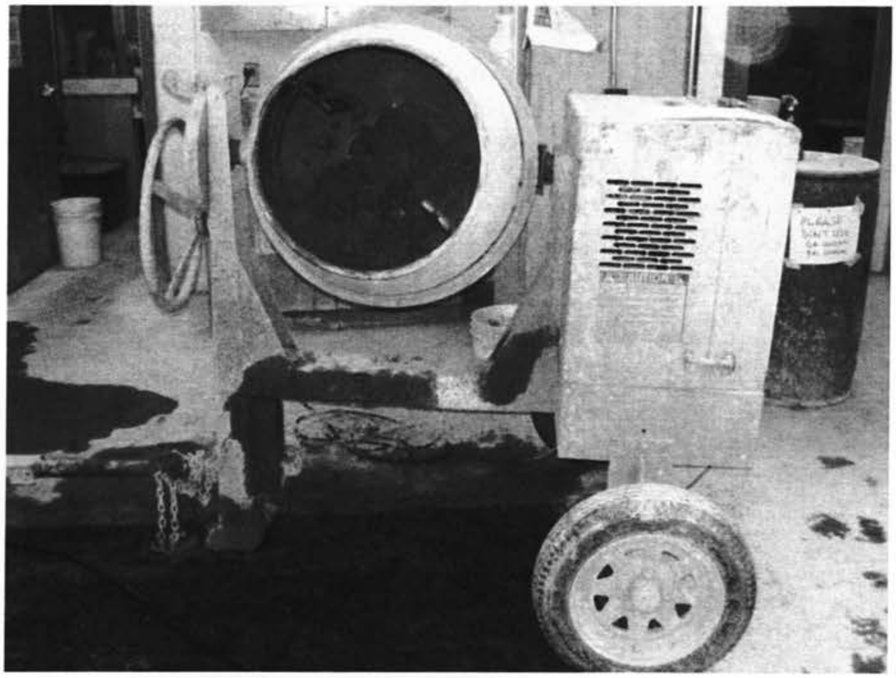


Fig. 3.1- Concrete Mixer

Before mixing, all required materials were prepared and weighed as per batch requirements. A small electrical scale was used to measure super plasticizer. All testing equipments to conduct slump flow, L-box, J ring and V funnel were prepared. The moulds for casting specimens such as prisms, cylinders and beams were also made ready.

3.3.2 Mixing Procedure

The mixing procedure involves the following steps:

1. After starting mixer, coarse and fine aggregate were added into drum and homogenized for 30 seconds.
2. Cement and SCM (SF or MK) were then added within 10 seconds of stopping period and then mixing continued for 30 seconds.
3. 60% of water mixed with super plasticizer was then distributed all over the mix and mixing continued for 30 seconds.
4. Remaining 40% of water mixed with super plasticizer was added and mixed for 60 seconds.
5. Stop and rest for 30 seconds.
6. Starting again the mixer and dispersion by hand gradually over concrete mix within 60 seconds.
7. Mixing continued for additional 120 seconds and then stopped.

3.3.3 Specimens

Immediately after concrete mixing, slump flow test followed by L-box, V funnel, and concrete rheology tests were conducted.

3.4 Fresh Property Tests

Workability tests included the determination of slump flow diameter (spread), slump flow time (T_{500}), L-box ratio, and V-funnel flow time.

3.4.1 Slump Flow

One of the most common tests performed to compare the lateral flow and the filling potentials of various SCC mixtures includes the slump flow test. Usually, the range of the slump flow is from (450-750 mm). In production, this test allows for the assessment of the consistency of the SCC and for determining its capacity to deform under its own weight. As outlined by the ACI Committee Report 237R-26, the difference from each batch should not be greater than 50 mm. It is normally the measure of the time it takes for the concrete to spread a distance of 500 mm, as well as the diameter of the concrete patty once it ceases to spread. Fig 3.2 shows the slump flow test performed during experimental program.

Fig 3.2- Slump Flow Test

Although not mandatory, the appendix of the ASTM C1611 / C1611M - 05 Standard Test Method for Slump Flow of Self-Consolidating Concrete outlines a procedure that can be used for the relative measurement of the properties of the SCC mix (such as its viscosity, stability, and flow rate). Calculations for the flow rate are carried out based on the duration of time it requires for the concrete to reach a diameter of 500 mm (T_{500}). The viscosity of the concrete also has a direct impact on its flow rate. As for its stability, a visual inspection and examination of the concrete can hint any segregation.

Conventionally, a slump test has been used to determine the plasticity of the fresh concrete. However, since that test is not suitable for the analysis of the fluidity of the SCC, a slump flow test is used. The slump flow test provides a measure of its flowability. The slump flow test, equipment-wise, is carried out similarly in the same manner as the slump test. The apparatus involved during the test include a regular slump cone, as well as a steel plate measuring 900 mm by 900 mm. These apparatus allow for the measurements of the two results of the test as mentioned above. The slump cone through which the concrete passes can be either used same up or inverted. Before commencing, the cone is raised, and without the use of any external forces or mechanical agitation such vibration or tamping, a sample of a fresh SSC mix is poured into the cone. Once through, the cone is lifted away and the concrete is left to spread without hindrance.

The time it takes to spread 500 mm is measured meanwhile. After the mix settles and the spreading stops, two perpendicular diameter measurements are taken of the concrete patty. It is important to note that if the two measurements have a difference of greater than 50 mm, the test is to be deemed invalid and is to be repeated. The average of the two, which is rounded to the nearest half inch, can be concluded as the slump flow. As mentioned earlier, slump flow rates between the ranges of 450-750 mm are acceptable, while the minimum value for classification as an SCC is 560 mm. Based on the test measurements, the SCC can then be classified as a Class 1, 2, or 3. As European Guidelines for self compacting concrete (EFNARC 2006) outlines, for an SCC mix to be recognized as Class 1, it must have a slump flow diameter of 550-650 mm, and the time it takes to spread 500 mm (T_{500}) of less or equal to two seconds. As for class 2, the slump flow diameter can be 600-750 mm, and T_{500} of greater or equal to two seconds. While EFNARC suggests the slump flow diameter of 760-850 mm for Class 3, no specification has been given for T_{500}.

3.4.2 L-Box

L-box test is an alternative to the J-ring test often used in developing SCC mixtures. It is also used to determine a concrete mixture's pass ability, fluidity, as well as the tendency to segregation. During this test, conditions that of the casting process are simulated as, under static pressure, the concrete is forced to flow through reinforced bars. The apparatus, L-box, is, simply a L-shaped device. It comprises of a "chimney" section and a "channel" section. The test performed is shown in Fig 3.3.

Fig 3.3- L-Box Test (http://www.geneq.com/catalog/en/l_box_fr.html)

Although there are no certain guidelines as outlined by the EFNARC, the time it takes for the SCC to reach 400 mm from three steel bars, T_{400} can be measured by using the height of the concrete in the chimney, h_1, and the height of the concrete in the channel section, h_2, though it has been used previously to estimate an SCC's flow velocity. Upon commencement, the vertical section, the chimney, of the L-box is filled with 12 liters of concrete, and left to rest for one minute. Next, the gate at the bottom of chimney is lifted and the concrete is left to flow through the reinforcing bars, similarly to the J-ring test.

The self-leveling characteristic of the concrete can be calculated using the ration h_2/h_1. As the EFNARC guidelines suggest, the limit should be between 0.8 and 1.0, where above 0.8 is considered to be a good passing ability.

3.4.3 V-Funnel Test

The V-funnel test is a test used to evaluate the fluidity of an SCC, as well as determine the ability of the mix to pass through constricted areas and change its path [Ozawa et al 1995]. Using the apparatus the time it takes for the SCC to flow through the V-funnel is measured. As outlined by EFNARC, the SCC can be classified as class 1 if the time it takes it takes is less than 8 seconds, whereas class 2 for 9 to 25 seconds. Fig 3.4 displays V-funnel test.

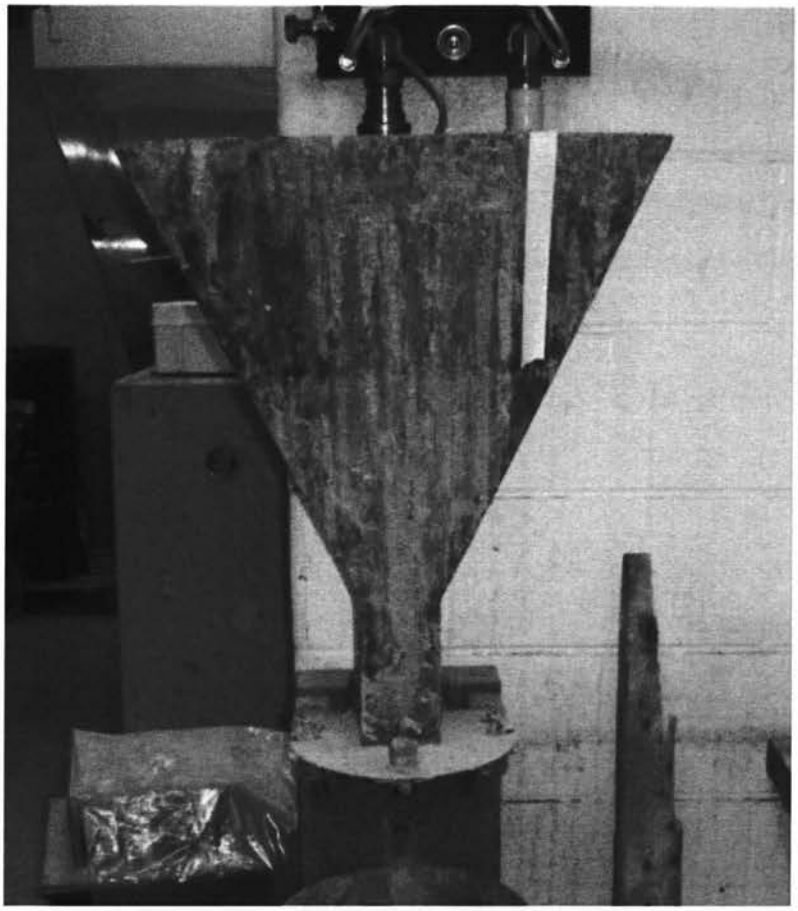


Fig 3.4- V-Funnel Test

3.5. Rheological Properties Tests

The rheology tests were done by using BML 4 viscometer. These tests were to obtain the plastic viscosity and yield stress values of SF and MK based SCC mixtures. The rheology tests were conducted immediately after mixing of the concrete in the mixer drum. The values of yield shear stress and plastic viscosity at a room temperature (25°C) for each of the concrete mixtures were obtained.

3.5.1 BML 4 Viscometer

This instrument measures SCC yield shear stress and plastic viscosity of the SCC is ConTec BML 4 viscometer Fig 3.5. This equipment was designed and made in Iceland by ConTec Ltd, a company specialized in rheology of concrete [Wallevik 2006].

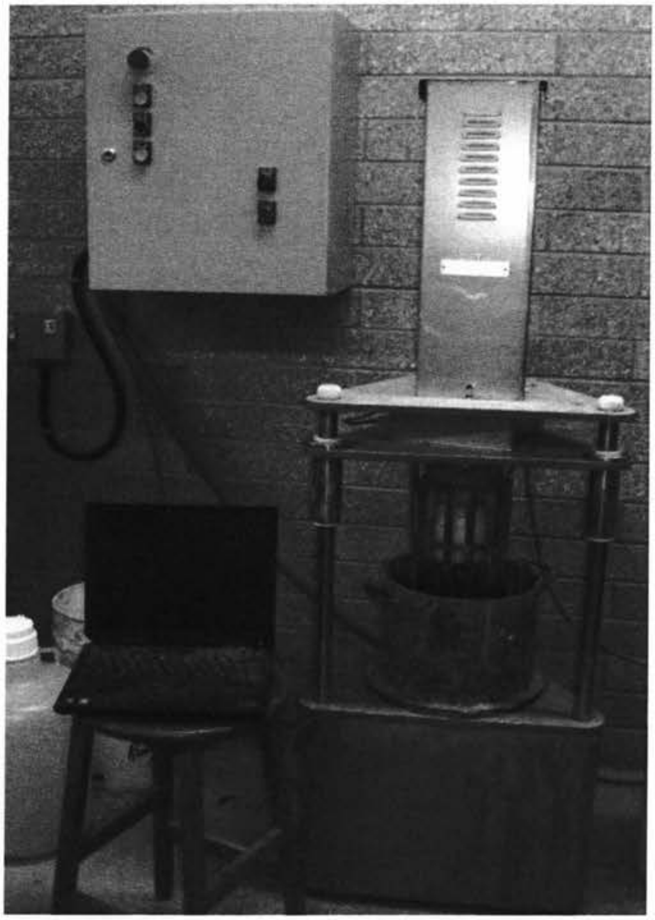


Figure 3.5 ConTek BML 4 Viscometer for SCC

3.5.2 Equipment Description

BML 4 viscometer has been currently used in many rheology researches. The apparatus is an automated computer-operated rheometer and uses the principle of a coaxial cylinder rheometer. The BML viscometer is used for the concrete with high workability (slump > 80mm) [Schutter et al. 2008].

The viscometer consists of a coaxial cylinder measuring system having an outer cylinder, the mix container, an inner cylinder unit and a top ring. The outer cylinder is mounted on a rotating disk on the instrument where guide ribs on the disk make sure that it is seated correctly. The inner cylinder, which registers the torsion-moment, is lowered into the outer cylinder by a hydraulic system. The inner cylinder is constructed as a two component unit, the bottom unit which is fixed at the mounting point of the inner cylinder and the upper unit which is free to rotate against a load cell which registers the torsion-moment. This arrangement of a two unit inner cylinder will virtually eliminate the effect of three-dimensional shearing at the bottom of the inner cylinder and therefore requires no special correction as to the bottom effect.

The viscometer is fully-automated, user-friendly and is controlled by computer and a software called Fresh-Win connected to viscometer by instrument cable, PC cable and interface box. The interface box is connected to a PC card on the left side of the laptop computer (Fig. 3.5).

A SCC standard measuring system C-200/1.3 was used for tests reported here, as per Table 3.7. The "C" stands for concrete and "200" is the diameter of the inner cylinder in millimeters while "1.3" presents the gap between outer and inner radius (Ro/Ri).

This coaxial cylinder measuring system consists of a top outer cylinder, the mix container, an inner cylinder unit with a pulp cylinder mounted at a top-ring

Table 3.7 SCC measuring system C-200/1.3

Measuring system	Inner radius (mm)	Outer radius (mm)	Effective height (mm)	Volume of testing material
C-200/1.3	100	131	150	~15 litres

4. RESULTS AND DISCUSSION

4.1 Introduction

In this chapter, test results covering fresh properties such as slump flow, flow time, and passing ability and rheological properties such as plastic viscosity and yield stress of SCC are described. A comparison between the characteristics of developed SCC with supplementary cementing materials (metakaolin and silica fume) will be described. Mix design details of developed SCC mixtures are presented. In addition, influence of SF and MK as replacement of cement on fresh and rheological properties of SCC mixtures is also described.

4.2 Details of Developed SCC Mixtures

A total of 11 SCC mixtures were developed by using SF and MK as supplementary cementing materials. Four SCC mixes were developed by using different proportion of SF (3, 5, 8 and 11% of cement replacement) and six SCC mixes were developed by using different proportion of MK (3, 5, 8, 11,15 and 20% of cement replacement) based on a control SCC mixtures (0% SF or MK). Tables 4.1 and 4.2 represent mix proportions of SCC mixtures with SF and MK, respectively, in addition to the control mix.

Table 4.1- Concrete Mix Proportion with Silica Fume

Component	0	3SF *	5SF	8SF	11SF
Silica Fume (%)	0	3	5	8	11
Silica Fume (kg/m^3)	0	13.50	22.50	36.00	49.50
Cement (kg / m^3)	450	436.50	427.50	414.00	400.50
Water (kg / m^3)	180	180	180	180	180
Water / binder	0.40	0.40	0.40	0.40	0.40
Sand (kg / m^3)	930	927.46	925.76	923.22	920.68
10 mm stone (kg / m^3)	900	897.54	895.50	893.44	890.98
Super plasticizer (L/m^3)	3.889	3.889	7.639	9.028	11.250

*Mix designation: SF represents silica fume and 3 represents % of SF

Table 4.2- Concrete Mix Proportion with Metakaolin

Component	0	3MK *	5MK	8MK	11MK	15MK	20MK
Metakaolin (%)	0	3	5	8	11	15	20
Metakaolin (kg / m^3)	0	13.50	22.50	36.00	49.50	67.50	90.00
Cement (kg / m^3)	450	436.50	427.50	414.00	400.50	382.50	360.00
Water (kg / m^3)	180	180	180	180	180	180	180
Water / binder	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Sand (kg / m^3)	930	928.64	927.74	926.38	925.02	923.21	920.96
10 mm stone (kg / m^3)	900	898.68	897.81	896.50	895.18	893.43	891.25
Super plasticizer (L/m^3)	3.889	3.889	4.861	4.861	5.556	6.250	11.250

*Mix designation: MK represents metakaolin and 3 represents % of MK

4.3 Fresh Properties

The results of slump flow (spread), slump flow time, L-box, penetration test, and V-funnel flow time are summarized in Table 4.3. The following table presents the findings based on the various fresh properties tests conducted.

Table 4.3- Results of Fresh Properties Tests

Mix No	Mix Designation	Slump Flow		V-funnel	L-box		
Mix No.	**SCM %**	**Final Dia (mm)**	**T_{50} (sec)**	**Time (sec)**	**T20 (sec)**	**T_{40} (sec)**	**h_2/h_1**
1	0	640±0	4.0	9.50	2.5	3.5	1.00
2	3SF	660±10	3.0	6.00	1.5	2.5	0.84
3	5SF	650±0	3.0	6.50	1.5	2.0	0.84
4	8SF	640±0	3.0	7.00	1.5	3.0	0.84
5	11SF	650±0	3.0	7.50	2.0	3.0	1.00
6	3 MK	650±10	4.0	8.00	2.0	3.5	0.91
7	5 MK	650±10	4.0	10.00	2.0	4.0	0.84
8	8 MK	640±10	4.0	10.00	2.0	3.5	0.84
9	11 MK	650±10	4.0	10.00	2.0	3.5	0.84
10	15 MK	650±10	4.0	11.00	2.5	4.5	0.91
11	20 MK	650±0	4.5	12.00	2.5	4.0	0.88

4.3.1 Slump Flow Test Results

All the SCC mixes were developed to have a slump flow of 650±10 mm. All mixes satisfy the criteria for SCC in terms of slump flow as per EFNARC. As shown in Figure 4.1, for constant dosage of SP, the SCC mix with a 3% silica fume concentration had the largest slump flow diameter, which suggests its high flow ability. In general, slump flow increased with the increase of SF (Table 4.3, Fig. 4.1). Higher dosages of SP was needed to keep slump flow of MK-based SCC mixtures at 650 mm, that suggested the decrease of slump flow with the increase of percentage % of metakaolin.

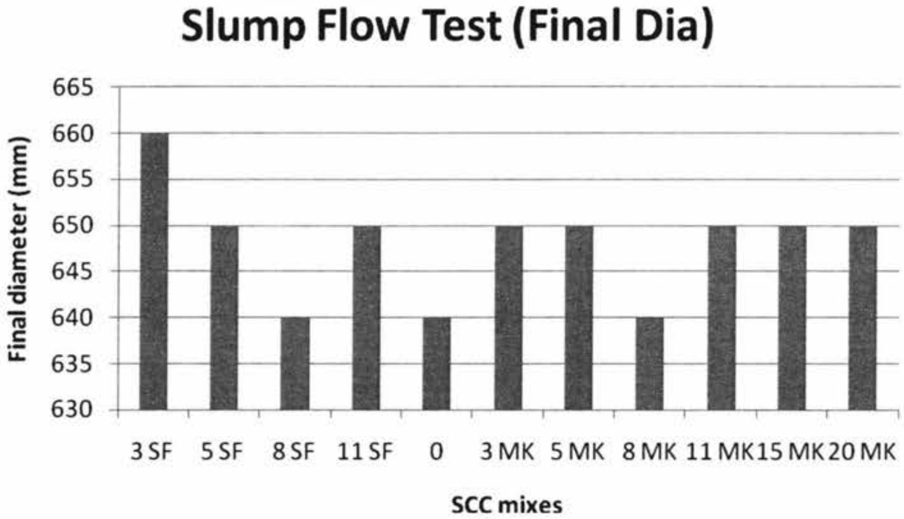


Figure 4.1 – Slump Flow of Various Mix Proportion

The pattern, as seen in figure 4.2, seems very uniform. Mixes with silica fume reached a distance of 500 mm within 3 seconds, while the mixtures with metakaolin lagged behind at around 4 seconds although they had more or less similar slump flow. Based on this chart, silica fume clearly increases the workability of SCC, while metakaolin addition seems to have increased the viscosity and cohesiveness.

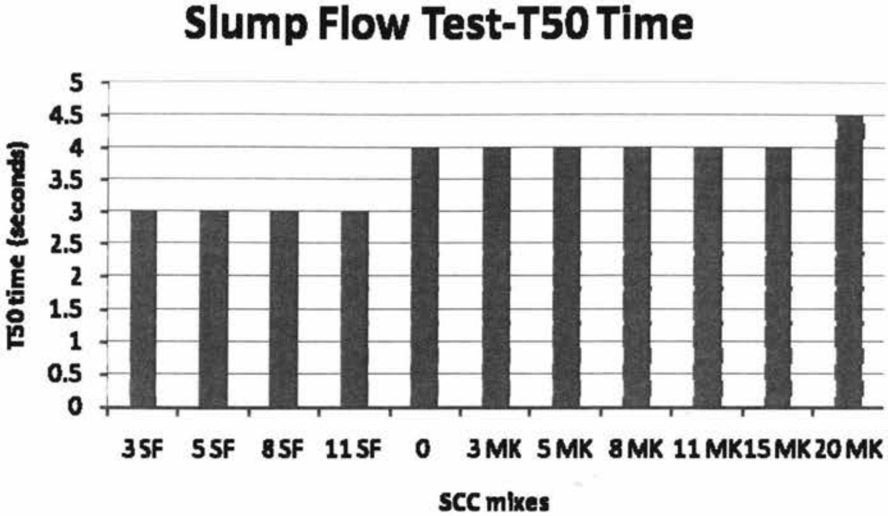


Figure 4.2 – Slump Flow T_{50}

4.3.2 L-Box Test Results

As evident in Table 4.3 , the results of the T_{20} and T_{40} (times to reach 200mm and 400 mm in horizontal part of the L-box, respectively) present a similar influence of SF and MK on flow ability as observed in slump flow test. In the T_{20} test, for the silica fume SCC mixes, the time for most of the mixes was 1.5 seconds, with 11% SF at 2 seconds. Similarly, the time for most of the metakaolin mixes was 2 seconds. The 15% and 20% MK once again took the longest time of all the metakaolin mixes. As for the T_{40} test, the 3% and 5% silica fume had the lowest time, followed by 8% and 11% SF. In the metakaolin category, 8% and 11% were the quickest, followed by 5% and 20%, with 15% MK being the slowest of all once again, not surprisingly.

It is clear from the results that all mixes had a L-box ratio of above 0.8 (Table 4.3). The minimum required L-box ratio for a SCC mixture is 0.8 [European SCC Guidelines 2005], so all concrete mixtures satisfy the requirement of SCC. If the SCC flows as freely as water, it will be completely horizontal and the L-box ratio will be equal to 1.0. Therefore, the nearer this ratio is to 1.0, the better the flow potential of the SCC mixture. This is an indication of passing ability, or the degree to which the passage of SCC through the bars is restricted.

4.3.3 V-Funnel Test Results

Table 4.3 shows the results of the V-funnel flow time. The 3% SF mix showed the lowest time. The pattern for the metakaolin mixes seems to be that as the concentration of MK rises, the time increases with the increase of metakaolin (that exhibits higher viscosity and lower passing ability). The mixes with silica fume, in general, on the other hand, have low times compared to the metakaolin mixes. A maximum flow time of 12s was observed that is within the specified maximum 12s for a SCC mixture.

4.4 Rheological Properties

The rheological parameters such as plastic viscosity and yield stress are presented. Table 4.4 also the rheological properties parameters, slump flow, and SP content of the MK based mixtures. Table 4.5 shows the rheological properties parameters, slump flow, and SP content of the SF based mixtures.

Table 4.4- Results of Rheological Properties of MK based mixtures

Component	HRWR (ml/M3)	Viscosity (Pa.s)	Slump Flow			Yield Stress (Pa.)	Yield Stress at 650 mm Slump flow	Viscosity at 650 mm slump flow
			Dia. mm	T500 sec	T total sec			
0	3750	16.87	500	3.4		48.54	13.78	15.3
	5000	14.22	700	4.5	10.8	10.54		
	4666	15.16	640	5	21.9	13.78		
3MK	2308	28.19	470		5.6	76.32	16.49	19
	3462	22.49	600	3	16.5	21.13		
	3846	20.5	630	2.4	20.5	18.71		
5MK	1538	30.7	325		2.9		16.56	21
	3462	25.65	580	3.2	19	29.75		
	4000	22.34	630	2.8	23.5	18.09		
8MK	3462	26.5	560	3	8.8	35.11	16.93	21.5
	4000	25.2	610	3.2	15.8	22.06		
	4385	20.56	660	2.6	25.5	15.79		
11MK	2937	31.29	510	5	8.9	55	18.24	22.5
	3986	21.62	660	3.5	25.8	16.1		
	4615	19.1	690	3.1	33	15.2		
15MK	3846	31.1	570	3.9	11.4	39.76	18.62	28
	4385	29.83	620	3.8	24.7	22.34		
	4615	25.91	680	3.7	36.1	16.1		
20MK	3077	32.78	350		3		20.13	34.5
	3846	36.64	550	3.7	8.3	47.31		
	4769	34.06	675	3.8	39.5	15.14		

Table 4.5- Results of Rheological Properties Tests of SF based Mixtures

Compone nt	HRWR (ml/M3)	Viscosity	Slump Flow			Yield Stress (Pa.)	Yield Stress at 650 mm slump flow	Viscosity at 650 mm slump flow
			Dia. mm	T500	T total sec			
0	3750	16.87	500	3.4		48.54	13.78	15.3
	5000	14.22	700	4.5	10.8	10.54		
	4666	15.16	640	5	21.9	13.78		
3SF	5000	13.89	665	3.5	6.9	11.87	12.15	14.78
	4166	15.24	600	5	22.5	20.65		
	4666	14.82	650	4	27.9	12.15		
5SF	8000	15.21	600	7	11	20.54	11.51	14.48
	8800	14.29	650	4.5	19	11.73		
	7857	14.68	650	5.5	26.1	11.29		
8SF	13000	14.34	650	4.5		15.68	15.68	14.34
					13.7			
					22.6			
11SF	3333	18.55	650	3.5	12.4	20.58	20.58	18.55
					16.6			
					23.5			

4.5 Discussion on Rheological and fresh properties of Metakaolin based SCC Mixtures

Influence of metakolin on rheological/fresh properties and correlations

A good correlation (Eq. 4.1) with a correlation coefficient (R^2) of 0.9281 is found to exist between the yield stress and metakaolin percentage (Fig. 4.3). Yield stress of concrete increases with the increase of MK percentage. This is an important finding for this research and it confirms that SCC with high volume of MK has higher yield stress.

$$\text{Yield stress} = 14.825e^{0.0166\,(MK\,\%)} \quad \text{(Correlation coefficient, } R^2 = 0.9281) \qquad (4.1)$$

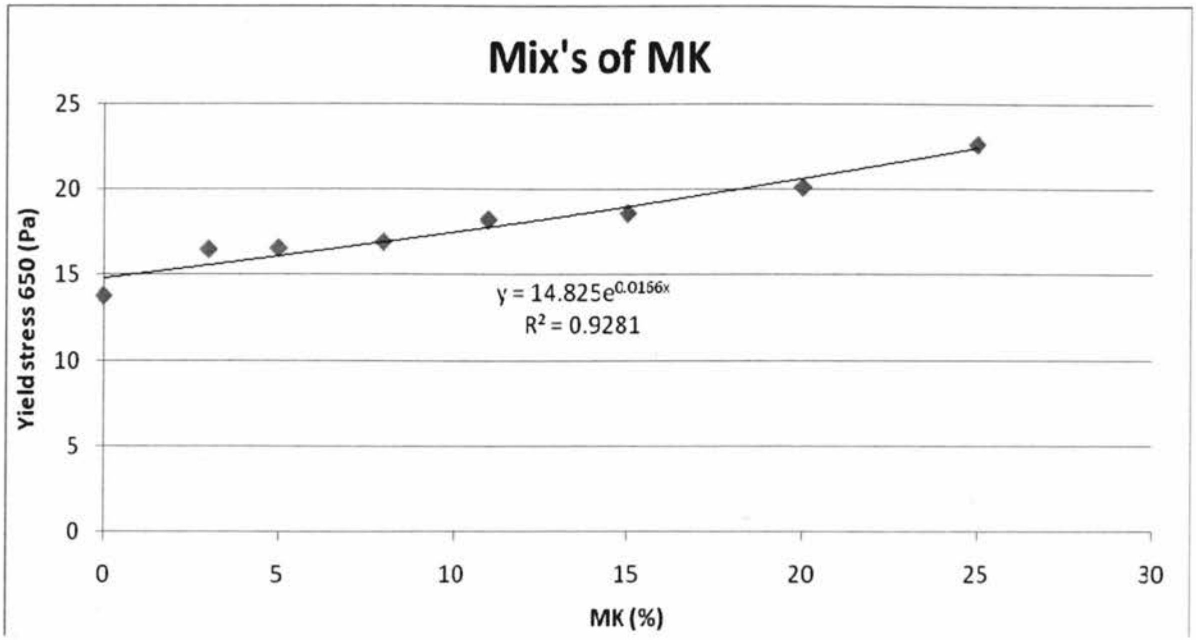


Fig 4.3: Relation between the yield stress and metakaolin percentage

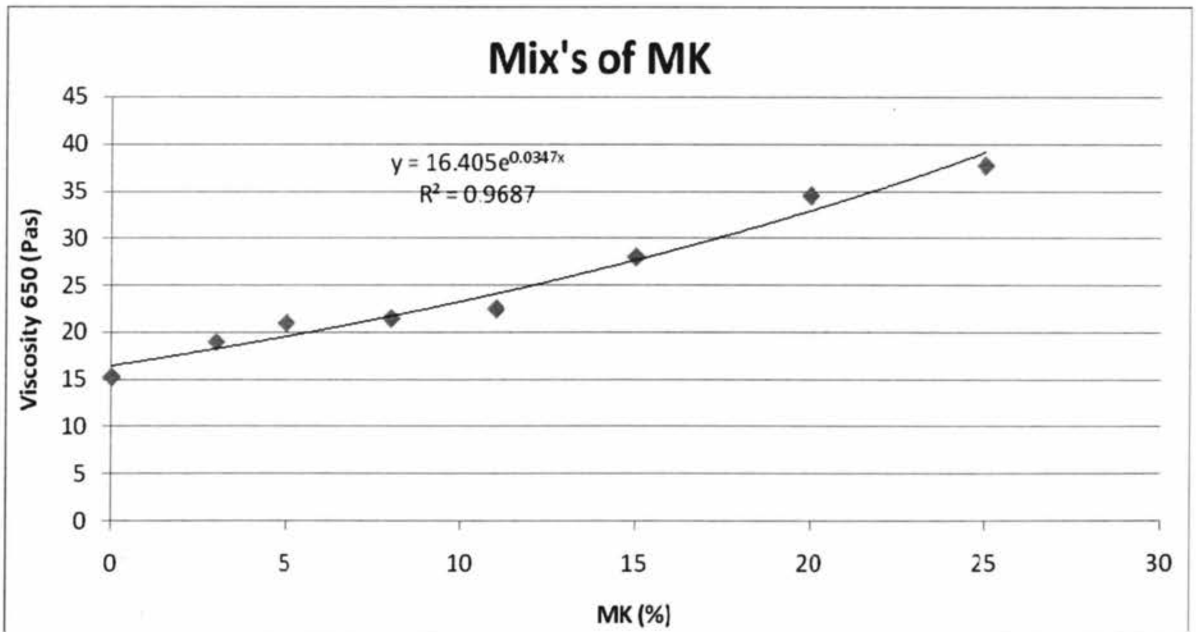


Fig 4.4: Relation between the viscosity of concrete and metakaolin percentage

A high value of correlation coefficient (R^2) in Eq. 4.2 represents a good correlation between the viscosity of concrete and metakaolin percentage. It is noted that the viscosity increases with the increase of MK percentage (Fig. 4.4). This finding is important as it leads to the controlled use of high volume of MK in SCC. Higher volume of MK produces higher viscosity which may significantly affect the flowability and workability of SCC mixtures.

$$\text{Viscosity} = 16.405e^{0.0347\,(MK\,\%)} \quad \text{(Correlation coefficient, } R^2 = 0.9687) \qquad (4.2)$$

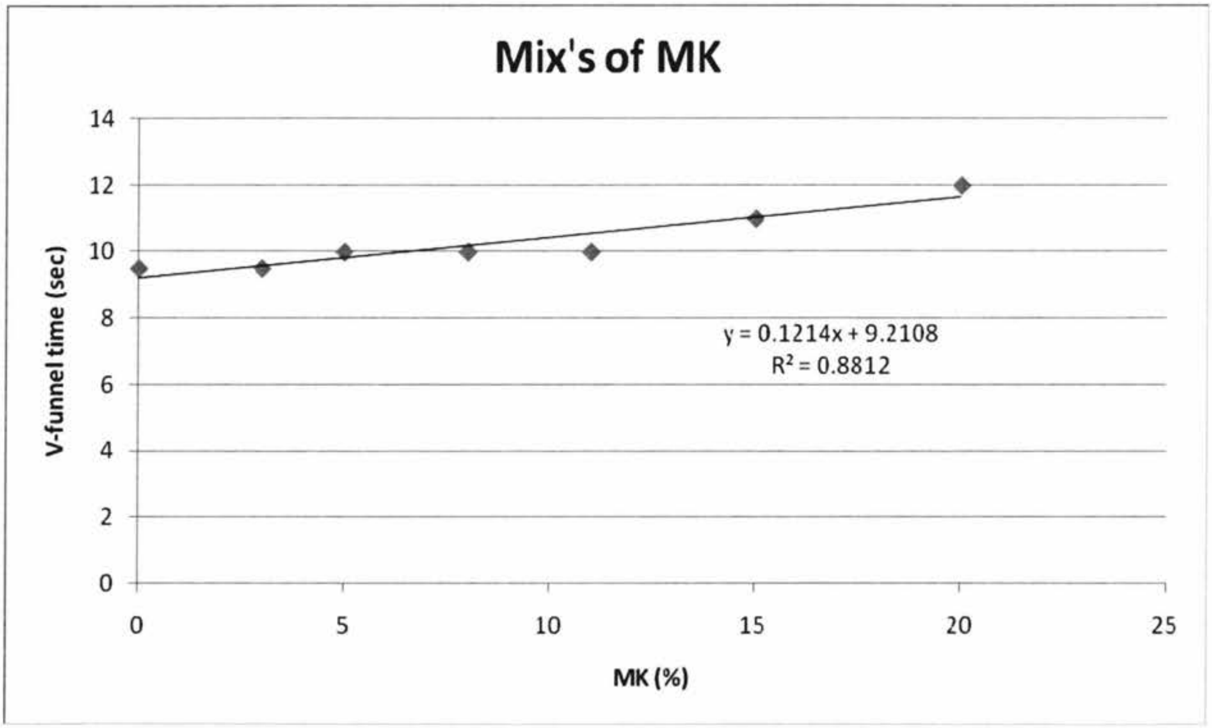


Fig 4.5: Relation between the V-funnel flow time and MK percentage

V-funnel flow time increases with the increase of MK percentage (Fig. 4.5). Equation 4.3 shows a good linear relation between V-funnel time and MK percentage of SCC mixtures. Hence, the use of higher MK percentage would result in less workability of SCC mixtures.

$$\text{V-funnel time} = 0.1214(MK\,\%) + 9.2108 \text{ (Correlation coefficient, } R^2 = 0.8812) \; (4.3)$$

Correlations among fresh properties

It is noted from Fig.4.6 that the time of 500 mm (T_{500}) slump flow seems to decrease with the increase of total slump flow diameter. However, the average values indicate a very small decrease. The correlation coefficient of 0.007 indicates no correlation between T_{500} and the total slump flow diameter for metakaolin based SCC mixtures.

$$T_{500} = 10.305(\text{Slump flow})^{-0.169}; \quad (\text{Correlation coefficient, } R^2 = 0.0073) \quad (4.4)$$

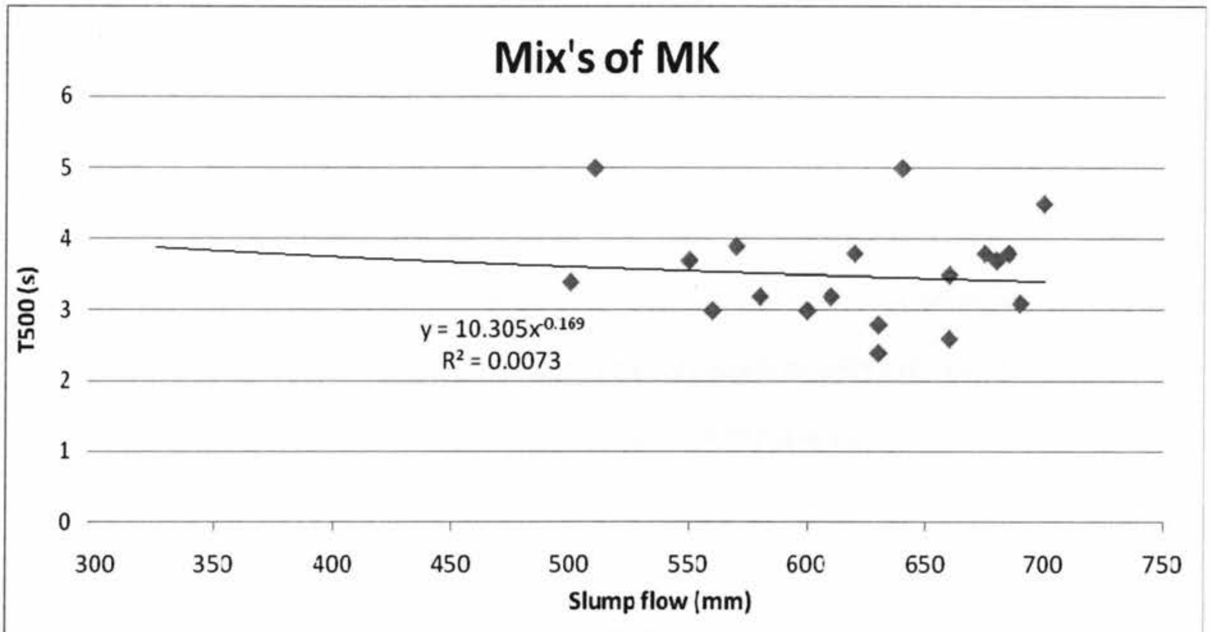


Fig. 4.6: Relation between T_{500} and the total slump flow diameter metakaolin based SCC

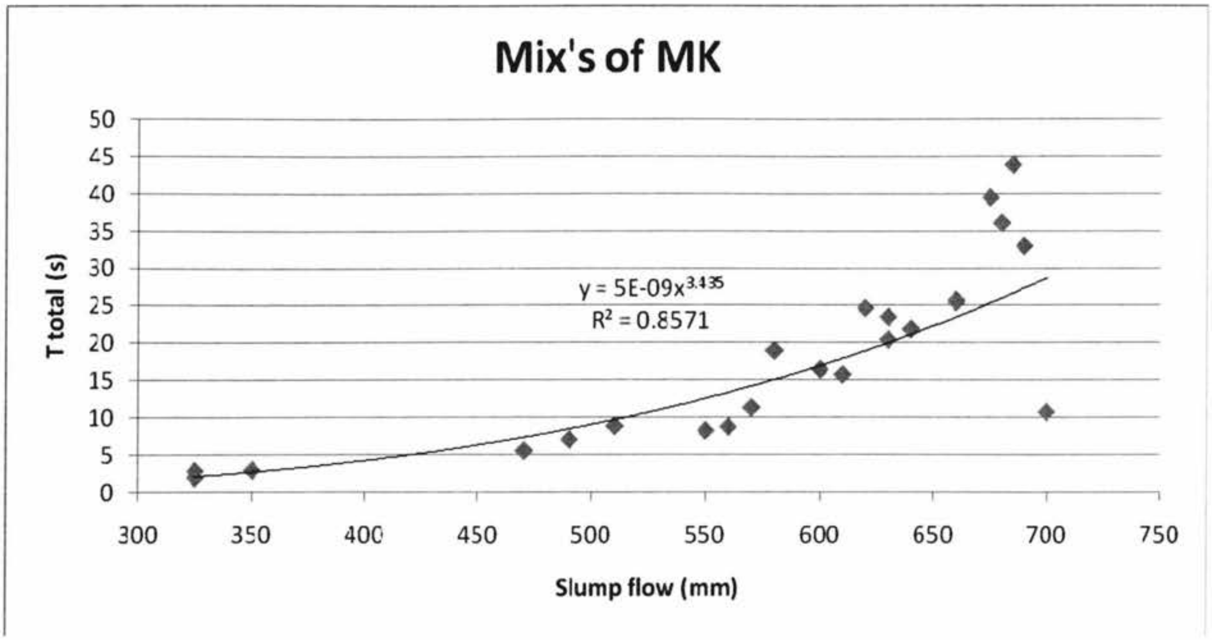


Fig 4.7: Relation between total slump flow time (T) and total slump flow diameter for metakaolin based SCC

A good correlation between slump flow and total slump flow time (T_{total}) exists for the all the MK based SCC mixtures (Fig. 4.7 and Eq. 4.5).

$$T_{total} = 5E\text{-}09(\text{Slump flow})^{3.435} \quad \text{(Correlation coefficient, } R^2 = 0.857) \qquad (4.5)$$

The relation shows a non-linear correlation where T_{total} increases with the increase of slump flow (SF).

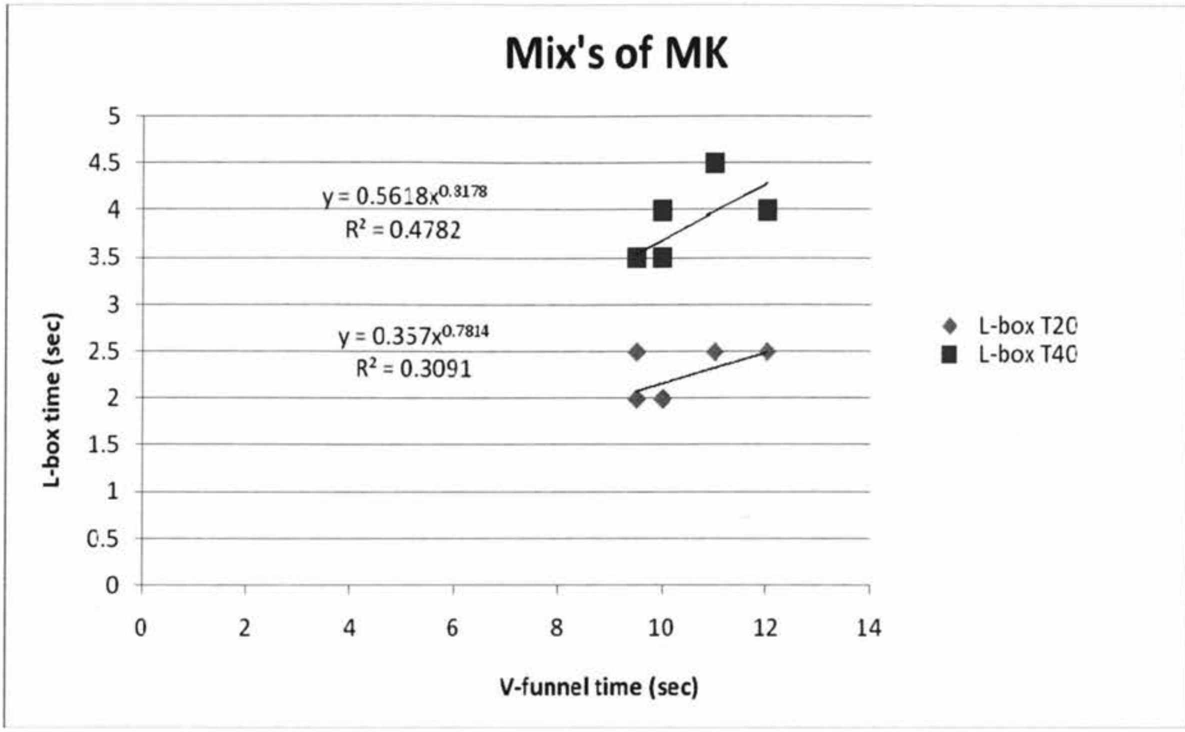


Fig 4.8: Relation between the L-box time and V-funnel time of MK based SCC mixtures

Although L-box time increases with the increase of V-funnel flow time of MK-based SCC mixtures (Fig. 4.8). No good correlation is found to exist between them due to scatter of the limited data. Equations 4.6 and 4.7 with lower values of correlation coefficients confirms the fact.

L-box time (T40) = 0.5618(V-funnel) $^{0.8178}$ (Correlation coefficient, $R^2 = 0.4782$) (4.6)
L-box time (T20) = 0.357(V-funnel) $^{0.7814}$ (Correlation coefficient, $R^2 = 0.3091$) (4.7)

Correlations between fresh and rheological properties

Fig. 4.9 shows that yield stress decreases with the increase of viscosity. Good correlation (Eq. 4.8) exists between the yield stress and the total slump flow diameter of MK based SCC mixtures.

$$\text{Yield stress} = 2962.6e^{-0.008(\text{Slump flow})} \quad (\text{Correlation coefficient, } R^2 = 0.9345) \qquad (4.8)$$

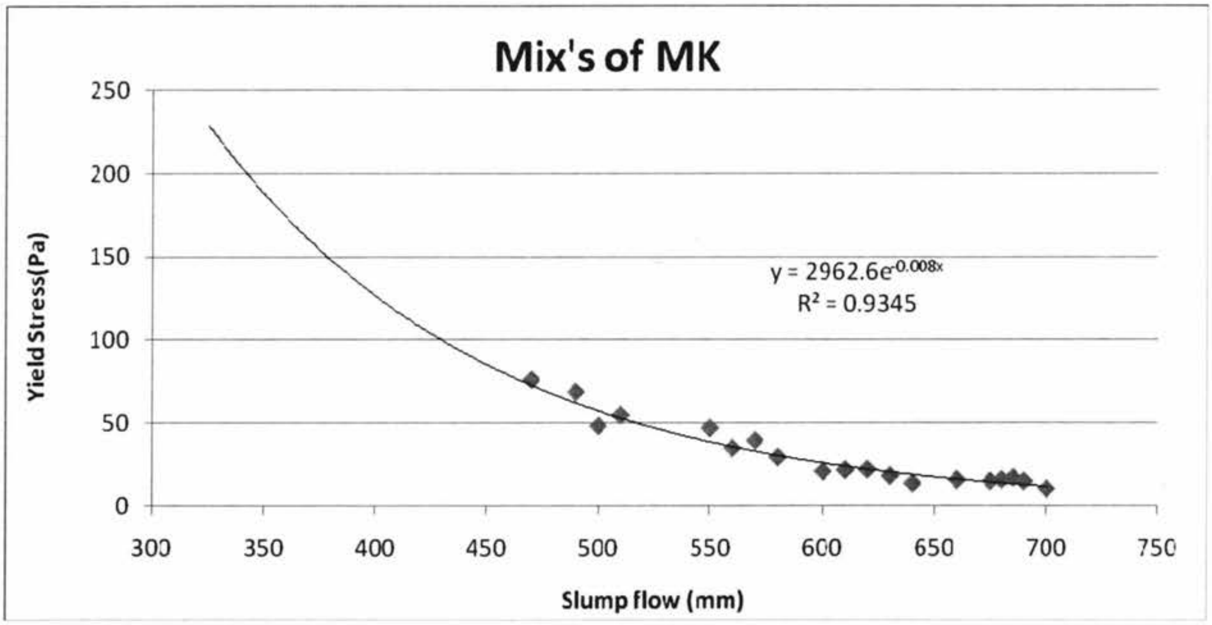


Fig 4.9: Relation between the yield stress and the total slump flow MK based SCC mixtures

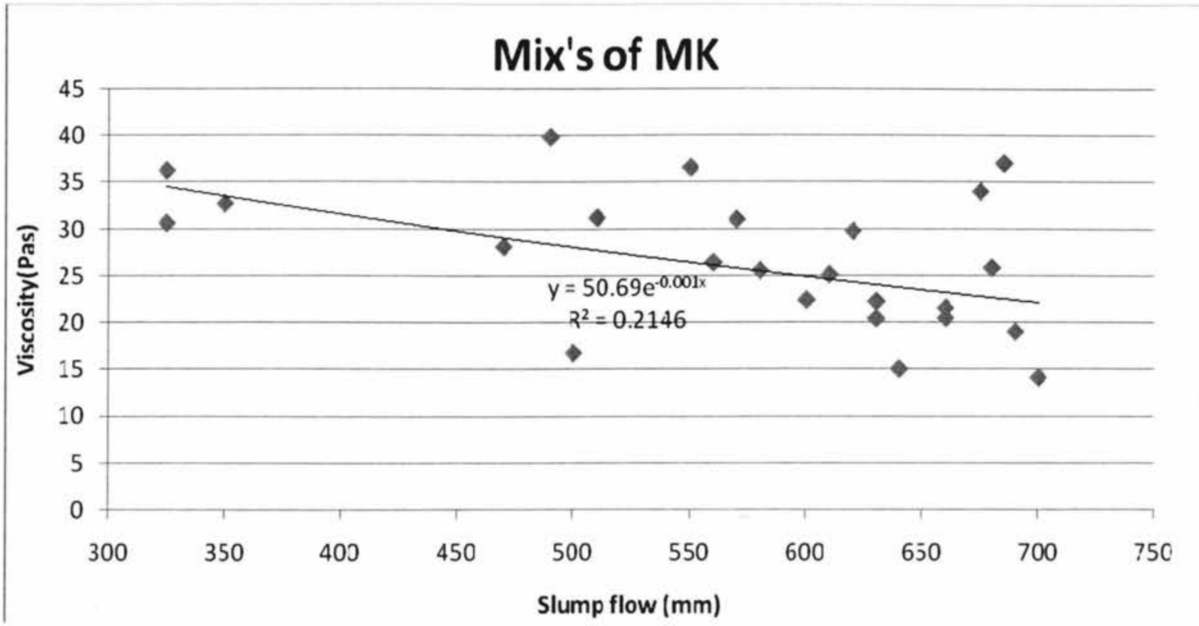


Fig 4.10: Relation between the viscosity and slump flow diameter of MK-based SCC

From Fig 4.10, it is evident that the viscosity decreases with the increase of slump flow. No good correlation exists between the yield stress and the slump flow diameter of MK-based SCC mixtures. However, correlation equation 4.9 suggests a general trend of decrease of viscosity with an increase of slump flow.

$$\text{Viscosity} = 50.69e^{-0.001(\text{Slump flow})} \quad (R^2 = 0.9345) \qquad (4.9)$$

As per Fig. 4.11, V-funnel time increases with the increase of yield stress of SCC, as expected. The relation between V-funnel time and yield stress is fairly good with a correlation coefficient of 0.7122.

$$\text{V-funnel} = 0.3797(\text{Yield stress}) + 3.736 \ (R^2 = 0.7122) \qquad (4.10)$$

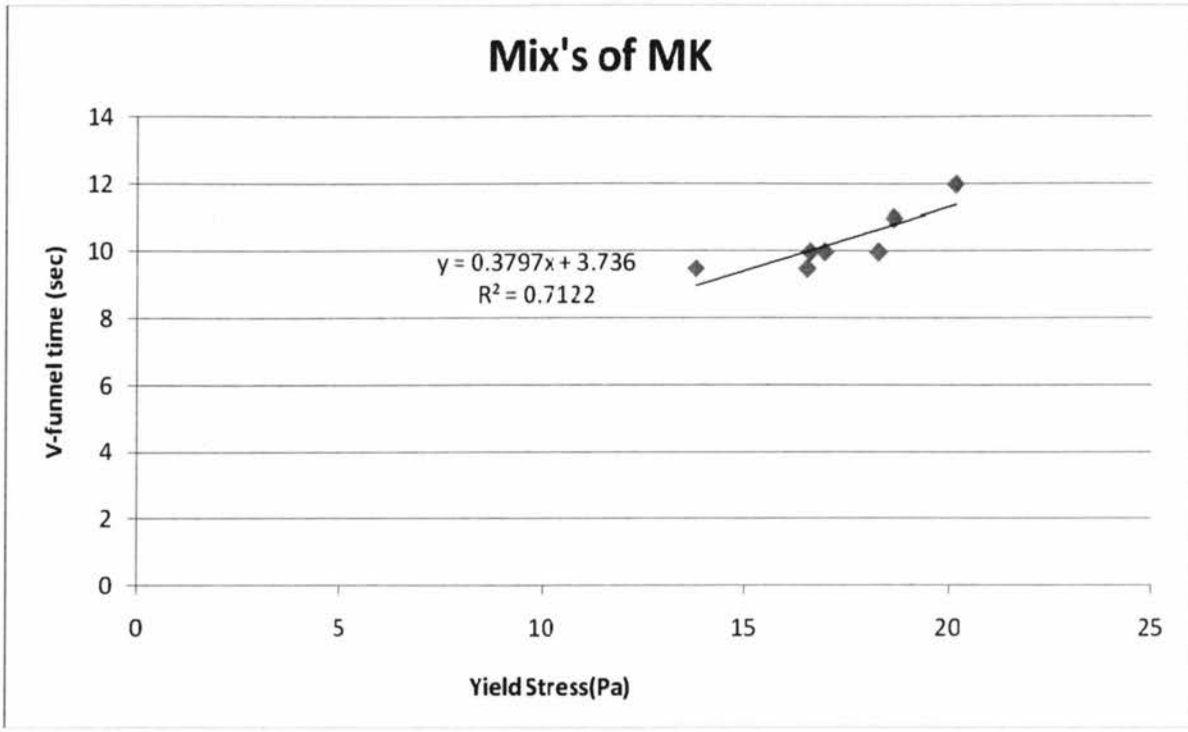


Fig 4.11: Relation between the v-funnel time and the yield stress of MK-based SCCs

Fig. 4.12 shows that the V-funnel flow time increases with the increase of viscosity of MK-based SCC mixtures. An excellent linear correlation exists between (Eq. 4.11) with good correlation coefficient of 0.9599. The V-funnel time can be predicted from the viscosity of MK-based SCC mixtures.

$$\text{V-funnel} = 0.1407(\text{Viscosity}) + 7.0334 \quad (R^2 = 0.9599) \quad (4.11)$$

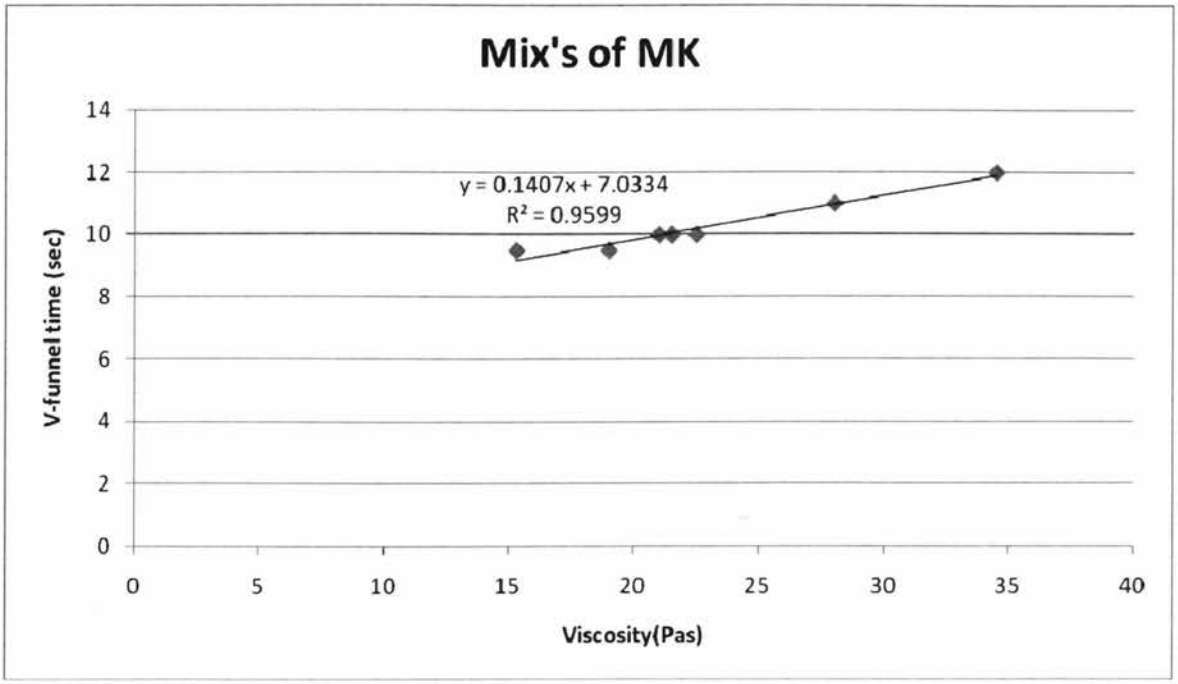


Fig 4.12: Relation between the v-funnel time and viscosity of concrete containing mitakaolin

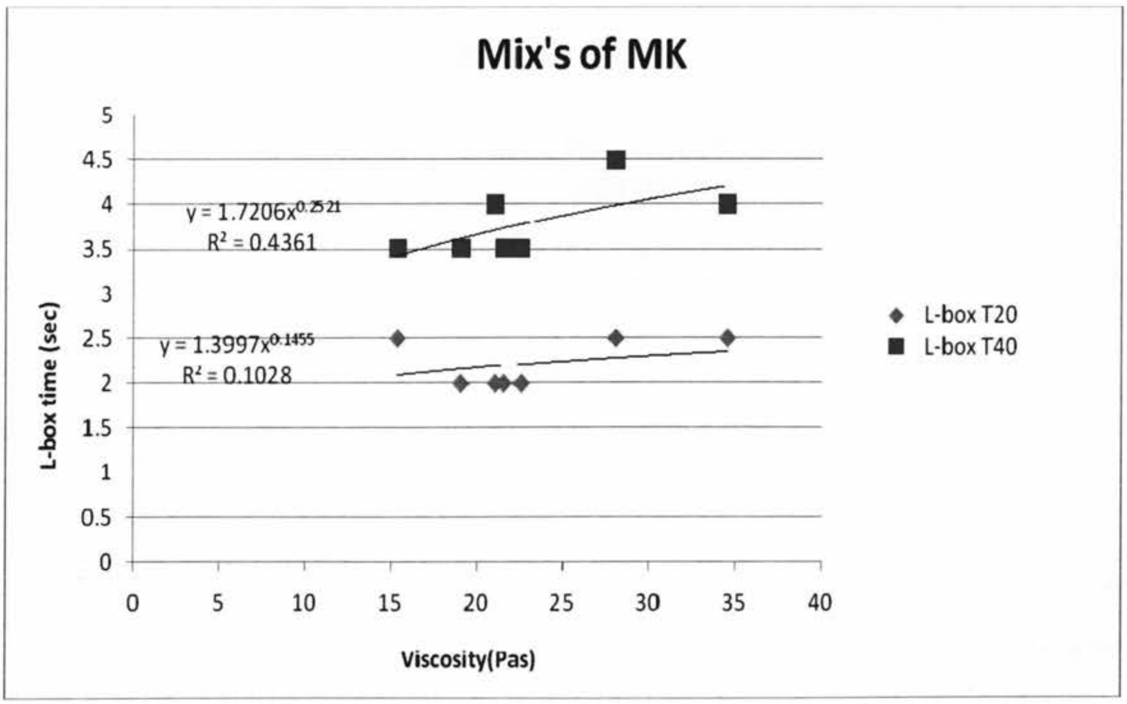


Fig 4.13: Relation between the L-box time and viscosity of MK-based SCC mixtures

Although L-box time increases with the increase of viscosity of SCC mixtures, no correlation is found to exist between them (Fig. 4.13). Equations 4.12 and 4.13with lower values of correlation coefficients confirms the fact.

$$\text{L-box time (T40)} = 1.7206(\text{Viscosity})^{0.2521} \qquad (R^2 = 0.4361) \qquad (4.12)$$

$$\text{L-box time (T20)} = 1.3997(\text{Viscosity})^{0.1455} \qquad (R^2 = 0.1028) \qquad (4.13)$$

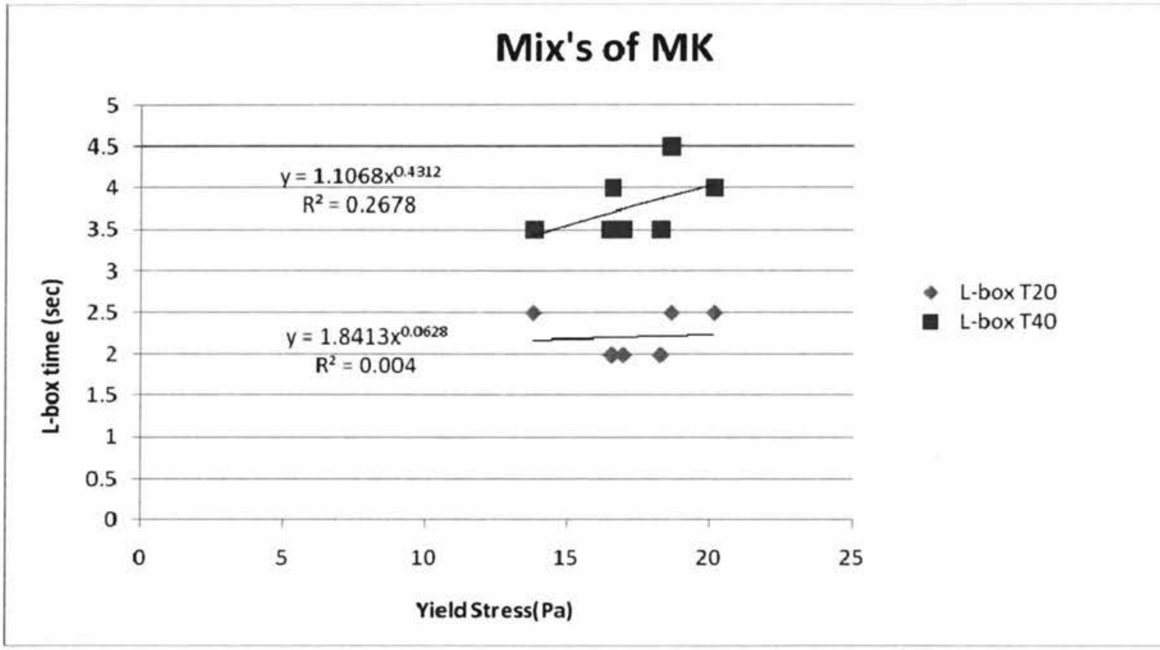


Fig 4.14: Relation between the L-box time and yield stress of concrete containing metakaolin

Good correlation was not found between L-box time and yield stress of MK-based SCC mixtures. Equations 4.14and 4.15 with lower values of correlation coefficients confirms the fact. L-box time increases with the increase of yield stress of MK-based SCC mixtures as more shear stress has to continue to flow (Fig. 4.14).

$$\text{L-box time (T40)} = 1.1068(\text{Yield stress})^{0.4312} \qquad (R^2 = 0.2678) \qquad (4.14)$$

$$\text{L-box time (T20)} = 1.8413(\text{Yield stress})^{0.0628} \qquad (R^2 = 0.2678) \qquad (4.15)$$

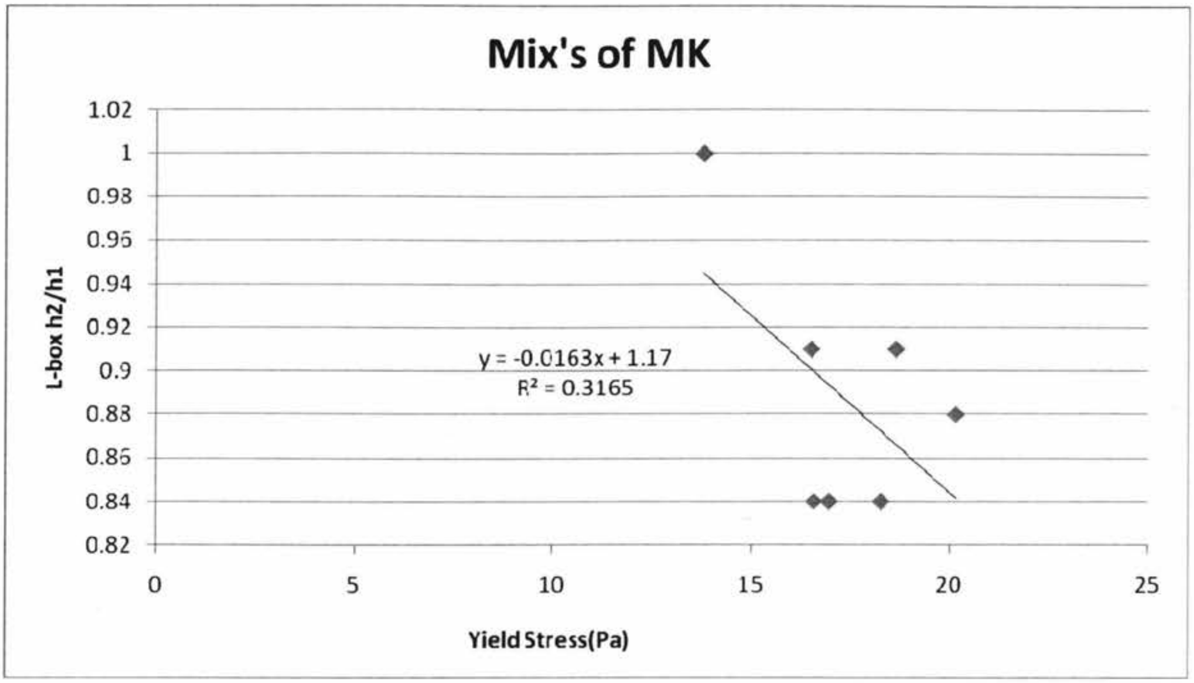


Fig 4.15: Relation between the L-box ratio (h2/h1) and yield stress of MK-based SCC

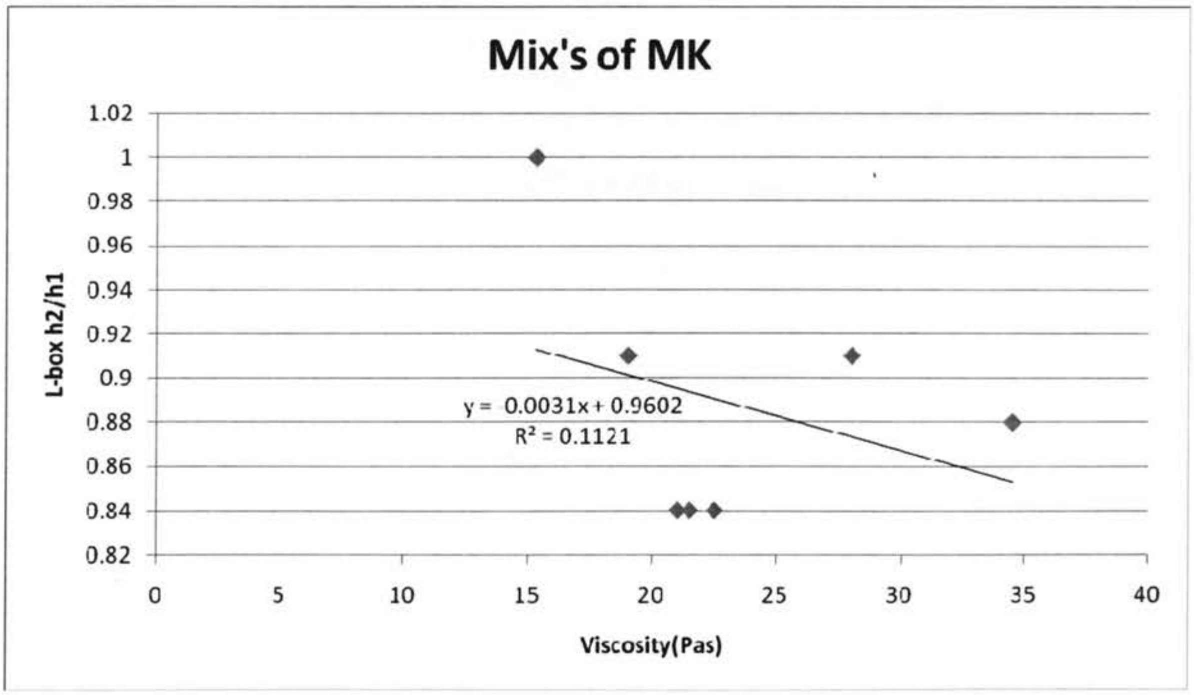


Fig 4.16: Relation between the L-box ratio (h2/h1) and viscosity of MK-based SCC

L-box ratio decreases with the increase of yield stress and viscosity of MK-based SCC mixtures (Figs. 4.15 and 4.16). Equations 4.16 and 4.17 with lower value of correlation coefficients confirm the poor correlation t between L-box ratio and yield stress or viscosity, respectively.

$$\text{L - box (h2/h1)} = -0.0163(\text{Yield stress}) + 1.17 \quad (R^2 = 0.3165) \qquad (4.16)$$

$$\text{L-box (h2/h1)} = -0.0031(\text{Viscosity}) + 0.9602 \quad (R^2 = 0.1125) \qquad (4.17)$$

4.6 Discussion on Rheological and fresh properties of silica fume based SCC mixtures

Influence of silica fume on rheological/fresh properties and correlations

Equation 4.18 shows an excellent polynomial correlation between the yield stress and silica fume percentage. Results show that the yield stress of SF-based SCC mixtures decreases with the increase of SF percentage of up to 6%. Beyond 6%, yield stress increases with the increase of SF (Fig. 4.17). This is in agreement with the findings presented in ACI 238.1R (2008). This is considered as one of the important findings of this research project.

$$\text{Yield stress} = 0.157\,(\text{SF\%})^2 - 1.099(\text{SF\%}) + 13.75 \quad (R^2 = 0.981) \qquad (4.18)$$

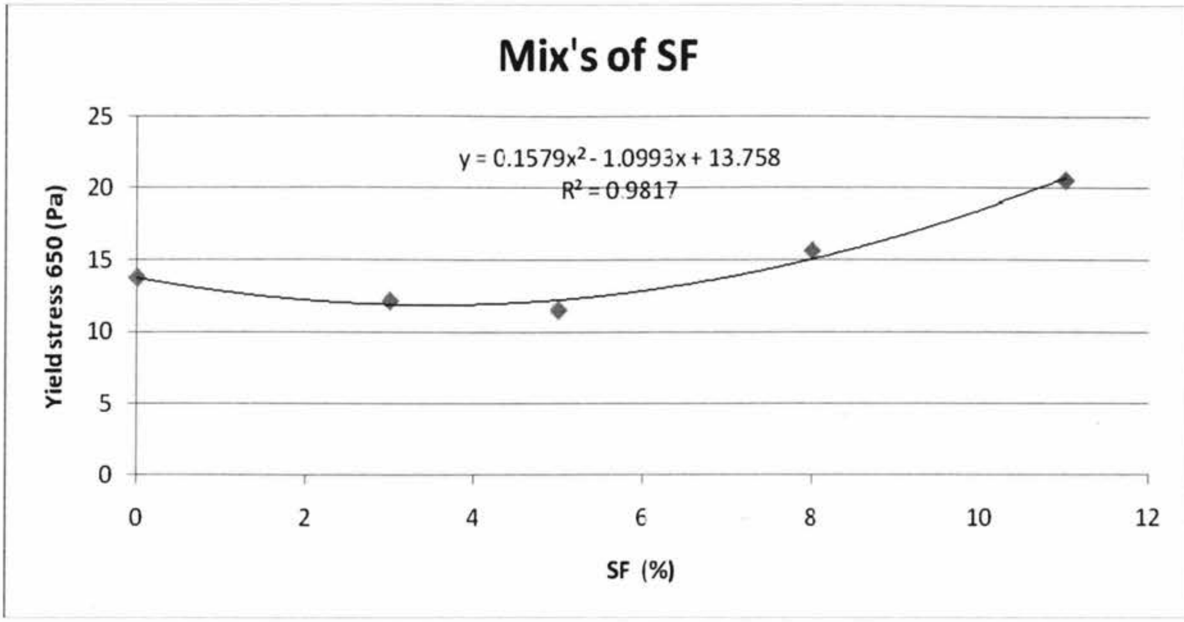


Fig 4.17: Relation between the yield stress and silica fume percentage of SF-based SCC

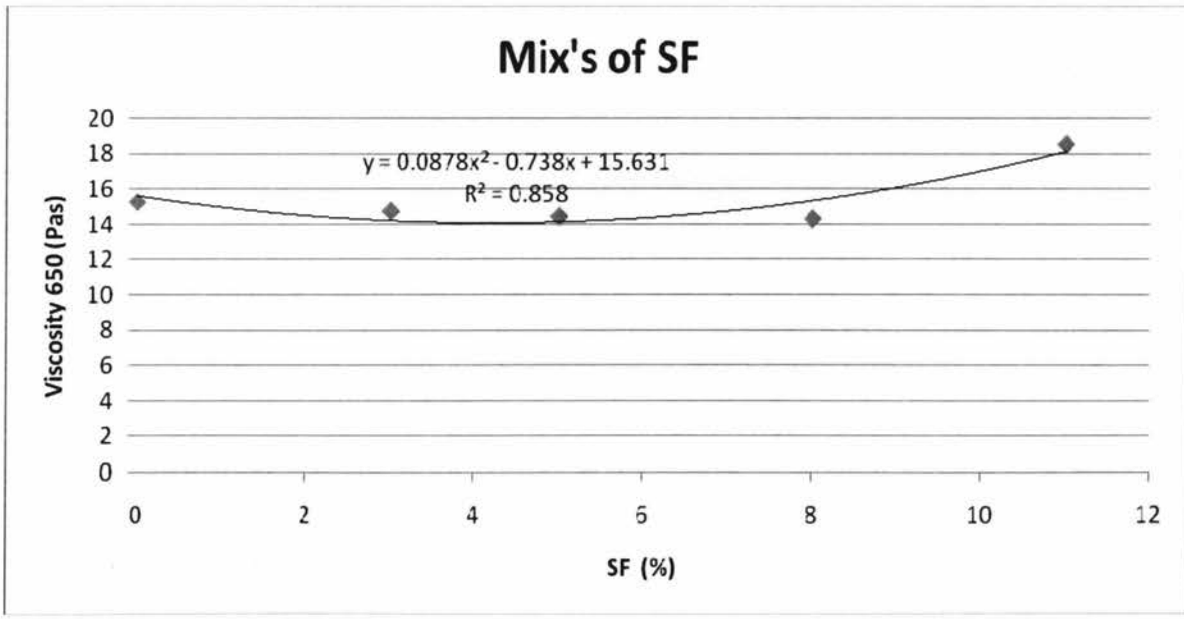


Fig 4.18: Relation between the viscosity and silica fume percentage of SF-based SCC

Results show that the viscosity of SF-based SCC mixtures decreases with the increase of SF percentage of up to 9%. Beyond 9%, viscosity increases with the increase of SF (Fig. 4.18). This is in agreement with the findings presented in ACI 238.1R (2008). This is also considered as one of the important findings of this research. Equation 4.19 shows an excellent polynomial correlation between the yield stress and silica fume percentage.

$$\text{Viscosity} = 0.087(\text{SF\%})^2 - 0.738(\text{SF\%}) + 15.63 \quad (R^2 = 0.981) \quad (4.19)$$

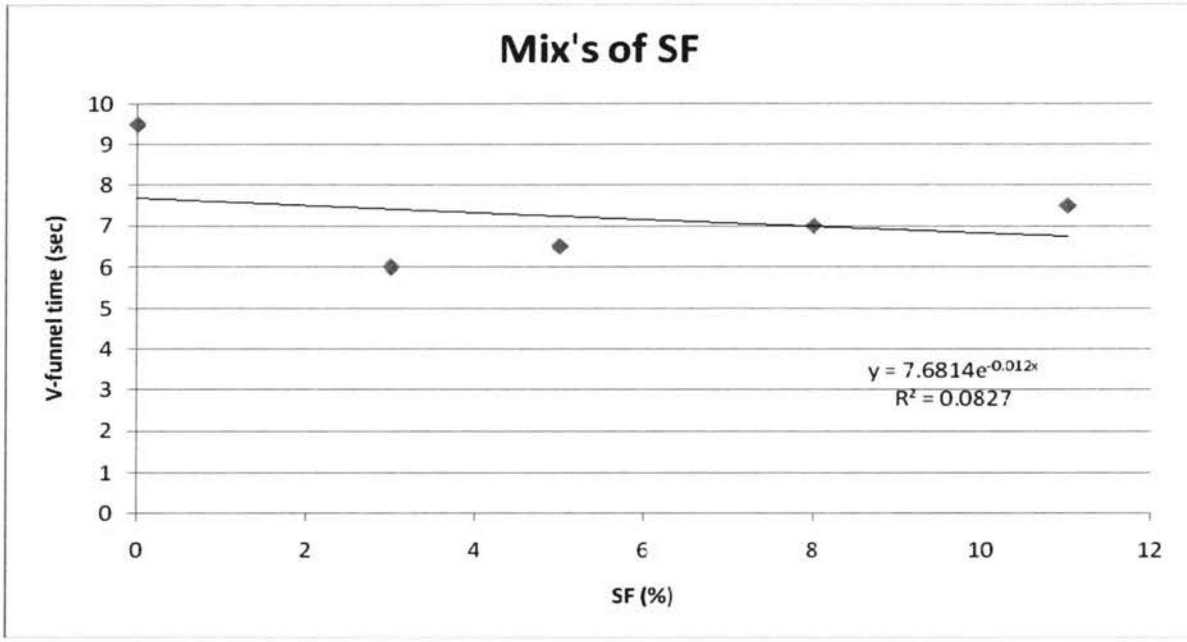


Fig 4.19: Relation between V-funnel flow time and silica fume percentage of SF-based SCC

V-funnel flow time seems to decrease with the increase of SF percentage up to 3% and beyond 3%, V-funnel flow time increases with the increase SF (Fig. 4.19). Equation 4.20 shows a linear relation between V-funnel time and SF percentage of SCC mixtures with low correlation coefficient.

$$\text{V-funnel time} = 7.681e^{-0.01\,(\text{SF\%})} \quad (R^2 = 0.0827) \quad (4.20)$$

Correlations among fresh properties

It is noted from Fig.4.20 that the T_{500} (time for 500 mm slump flow) decreases with the increase of the total slump flow diameter. The correlation coefficient of 0.011 is very small which indicate no correlation between T_{500} and the total slump flow diameter (Eq. 4.21).

$$T_{500} = 0.784\ (\text{slump flow})^{0.270} \qquad (R^2 = 0.011) \qquad (4.21)$$

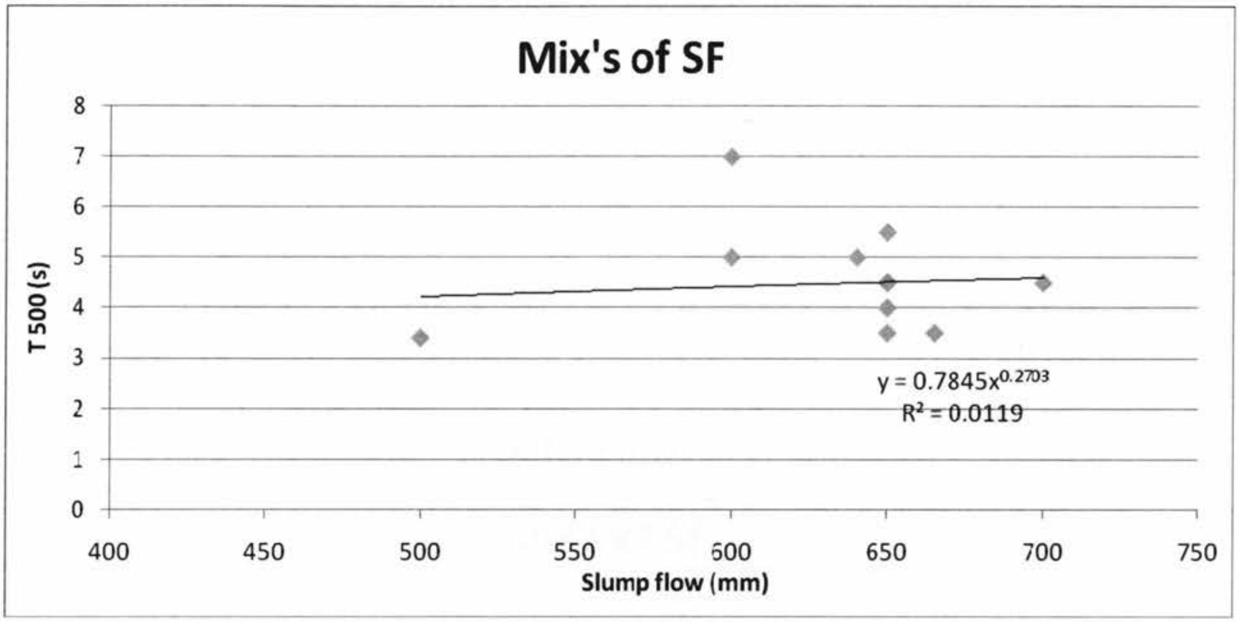


Fig 4.20: Relation between the T_{500} and slump flow diameter of SF-based SCC

Although trend shows a decrease of total slump flow time (T_{total}) with an increase of total slump flow (Fig. 4.21), no reliable correlation ($R^2 = 0.074$) exists (Eq. 4.22).

$$\text{Time total} = 8E{+}08\ (\text{slump flow})^{-2.74} \qquad (R^2 = 0.074) \qquad (4.22)$$

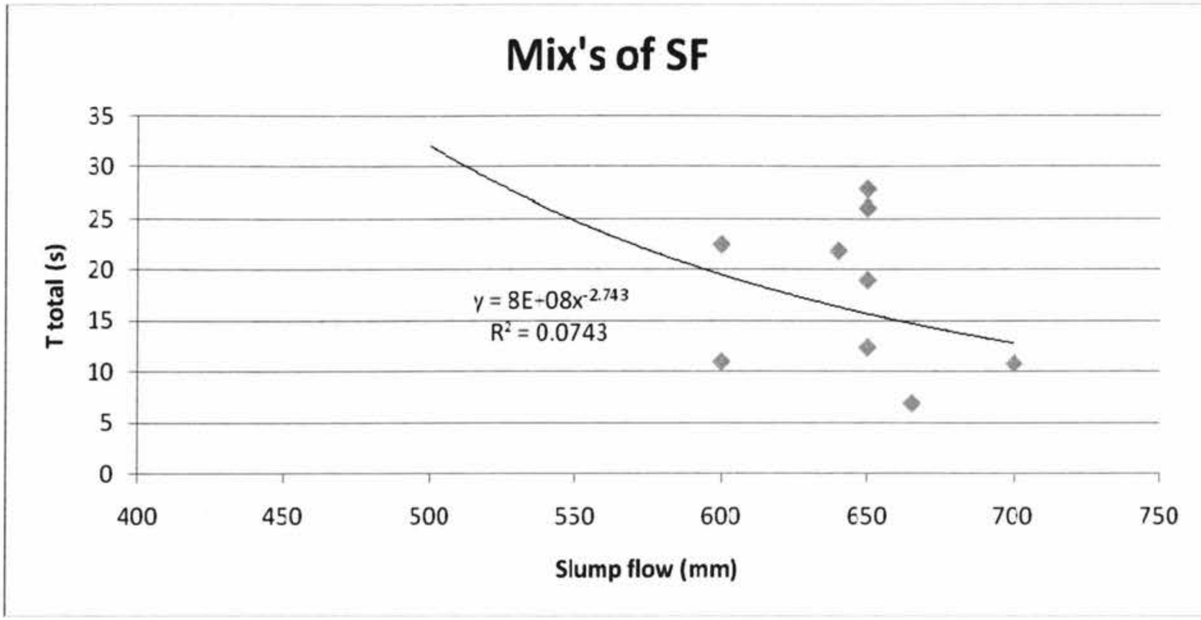


Fig 4.21: Relation between total slump flow time and total slump flow diameter of SF-SCC

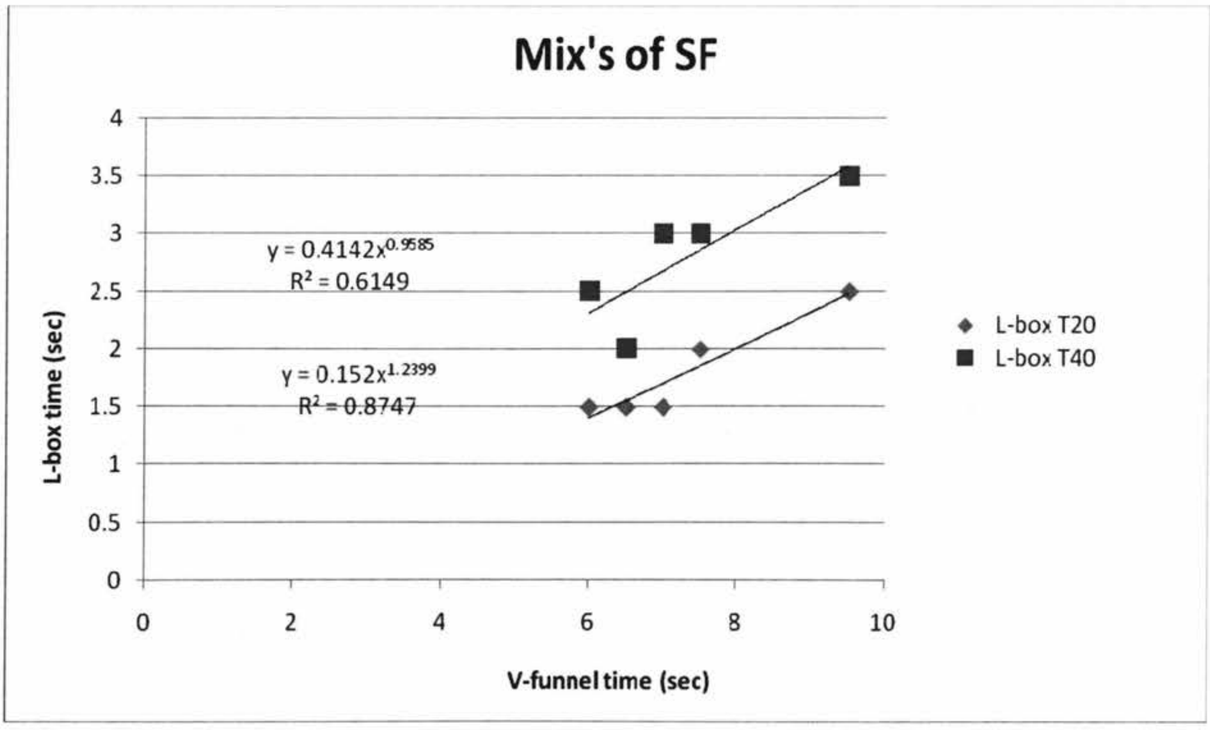


Fig 4.22: Relation between the L-box time and V-funnel time of SF-based SCC

L-box time increases with the increase of V-funnel flow time of SF-based SCC mixtures (Fig. 4.22). A reasonable correlation is found to exist between them. Equations 4.23 and 4.24 with correlation coefficients confirm the fact.

$$\text{L-box time} = 0.414\text{V-funnel}^{0.958} \quad (R^2 = 0.614) \tag{4.23}$$

$$\text{L-box time} = 0.152\text{V-funnel}^{1.239} \quad (R^2 = 0.874) \tag{4.24}$$

Correlations between fresh and rheological properties

From Fig 4.23, it is evident that the yield stress of SF-based SCC mixtures decrease with the increase of SF percentage. Excellent nonlinear correlation exists between yield stress and slump flow of SF-based SCCs (Eq. 4.25).

$$\text{Yield stress} = 3E+14\ (\text{Slump flow})^{-4.72} \quad (R^2 = 0.863) \tag{4.25}$$

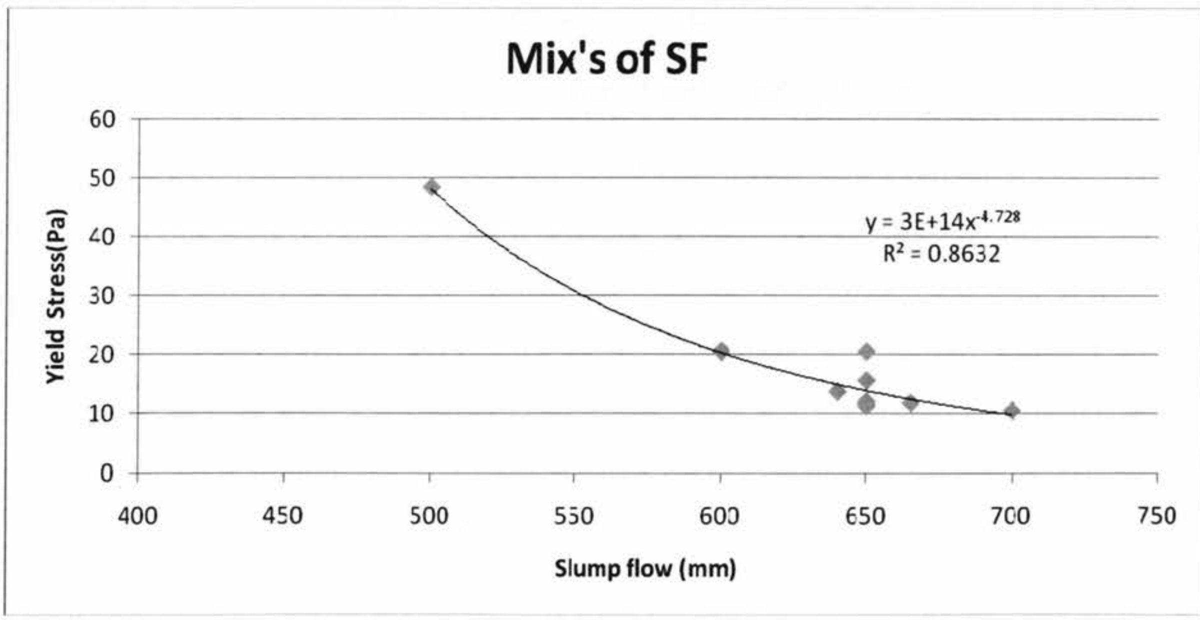


Fig 4.23: Relation between yield stress and total slump flow diameter of SF-based SCC

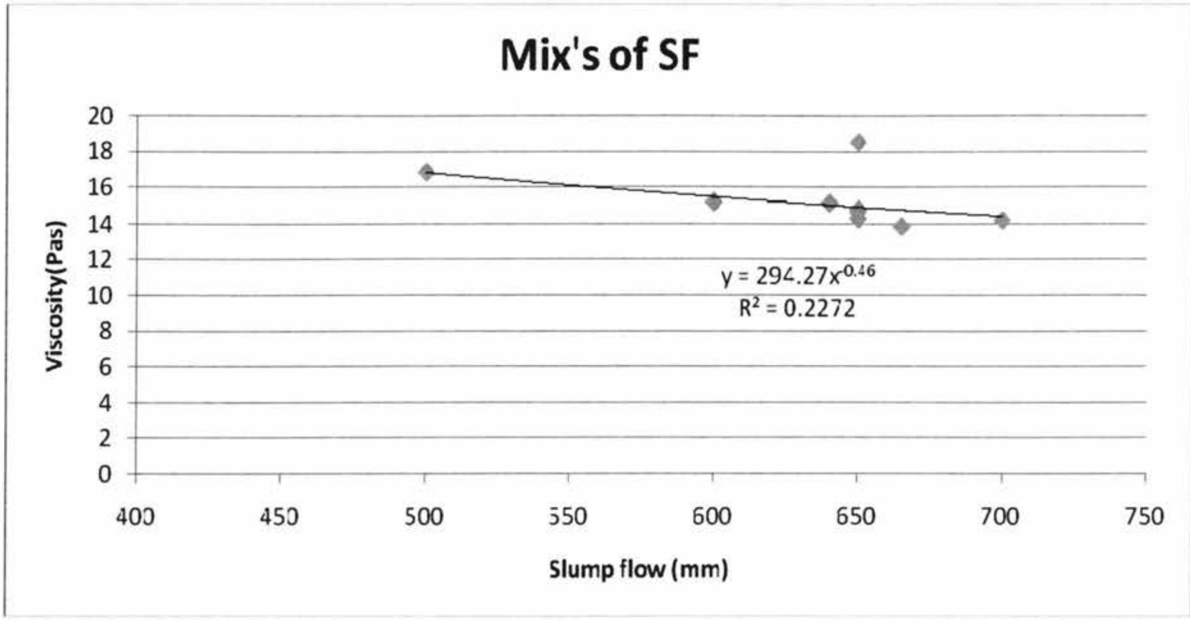


Fig 4.24: Relation between the viscosity and the total slump flow diameter of SF-based SCC

From Fig 4.24, it is evident that the viscosity decreases with the increase of slump flow. Good correlation does not exist between the yield stress and the slump flow diameter of SF-based SCC mixtures (possibly due to the deviation of one data point). However, correlation equation 4.26 suggests a trend of decrease of viscosity with an increase of slump flow.

$$\text{Viscosity} = 294.2\ (\text{slump flow})^{-0.46} \qquad (R^2 = 0.227) \qquad (4.26)$$

Due to scatter of the data, no correlation (Eq. 4.27) is found to exist between the V-funnel time and the yield stress of the SF-based SCC (Fig. 25).

$$\text{V- Funnel time} = 0.222\text{Yield stress} + 4.320 \qquad (R^2 = 0.072) \qquad (4.27)$$

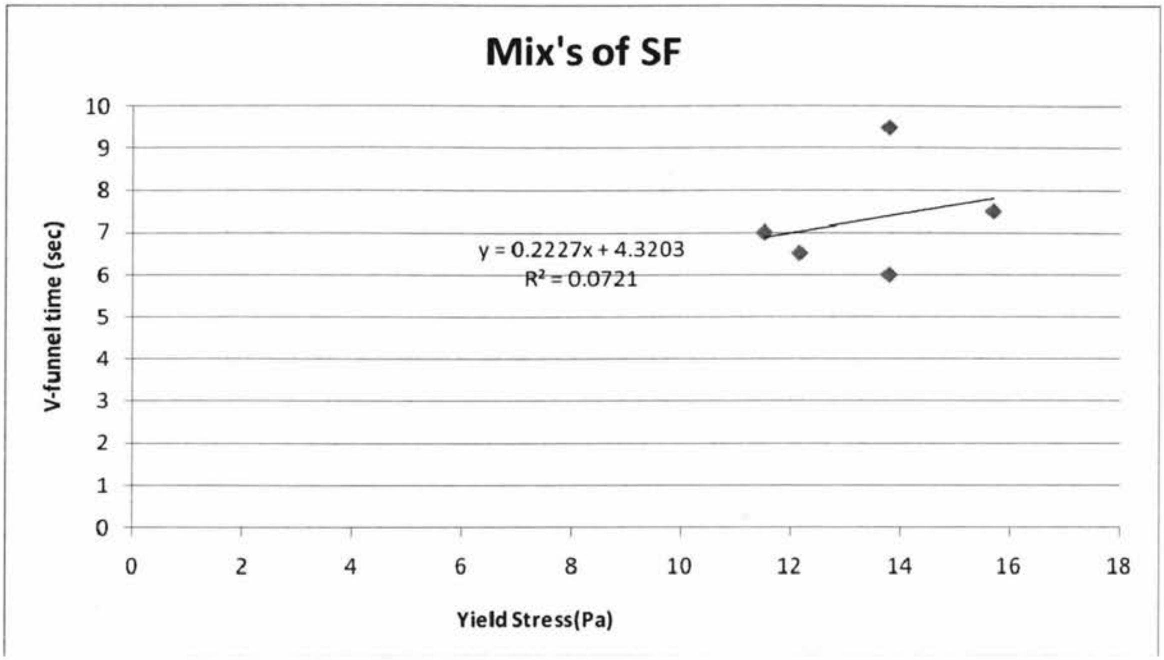


Fig 4.25: Relation between the V-funnel time and the yield stress of SF-based SCC

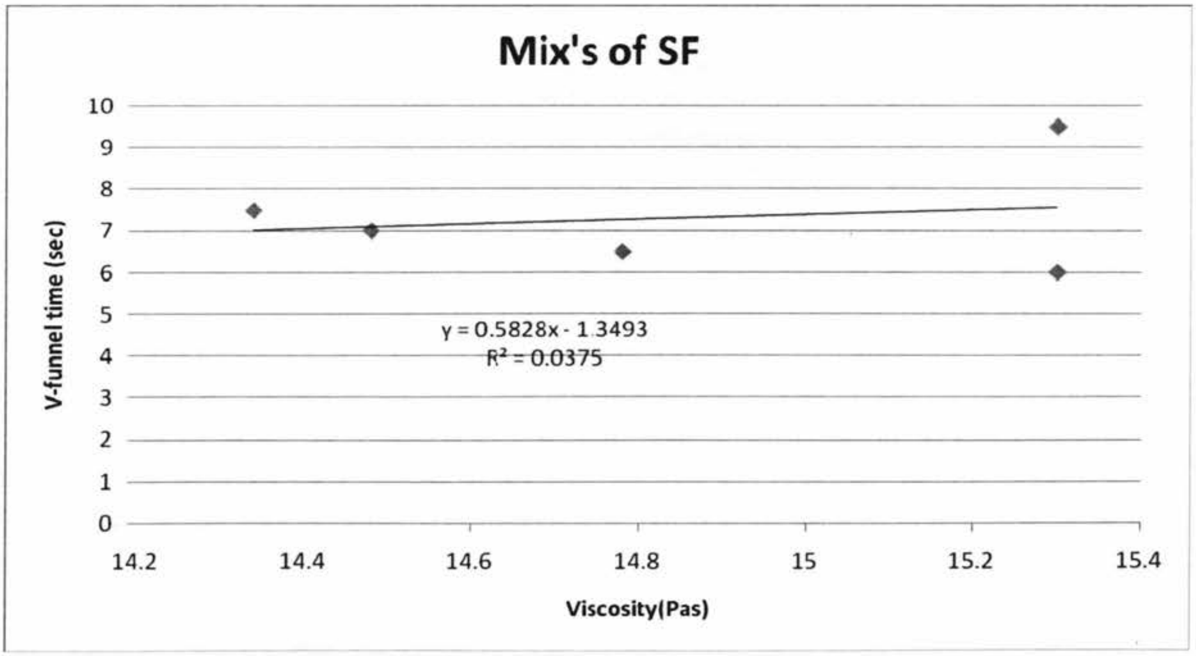


Fig 4.26: Relation between the v-funnel time and viscosity of concrete containing silica fume

Trend from the most of the data points, it is fond that the V-funnel time decreases with the increase of viscosity (Fig. 4.26). Good correlation is not found between the V-funnel time and the viscosity of the SF-based SCC possibly due to one data point.

V-Funnel= 0.582 (Viscosity) $^{-1.349}$ (R^2 = 0.0375) (4.28)

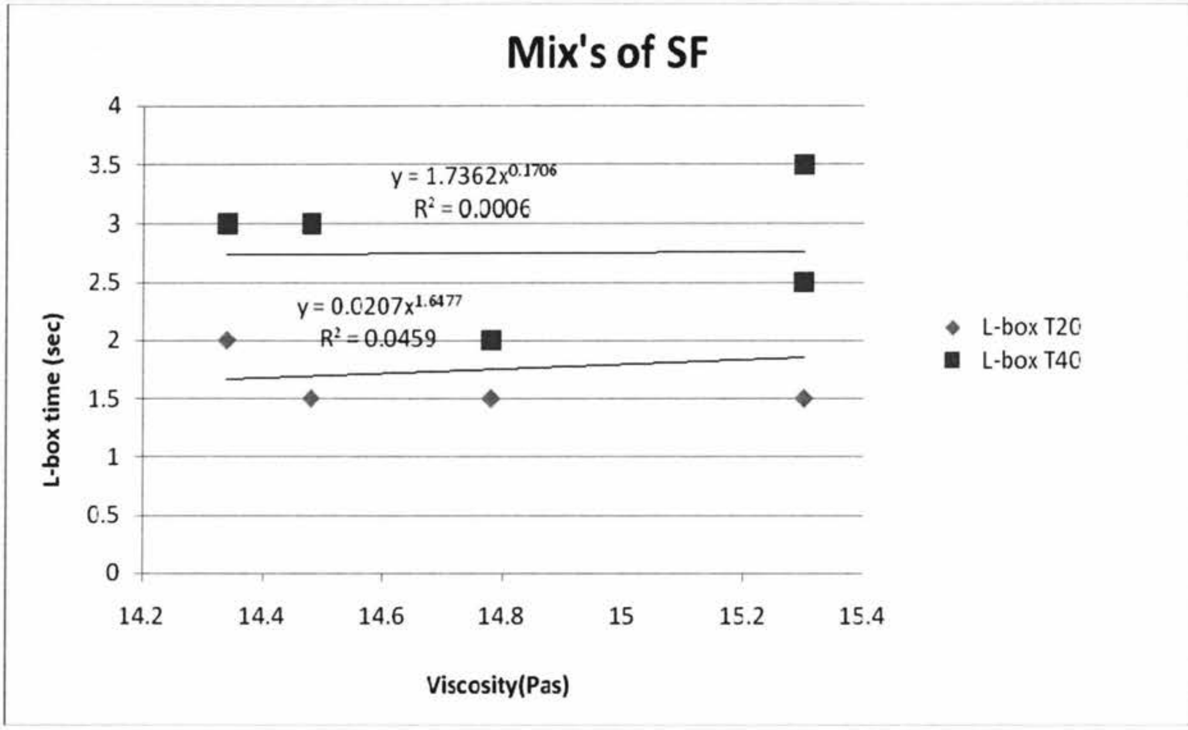


Fig 4.27: Relation between the L-box time and viscosity of concrete containing silica fume

Although L-box time decreases with the increase of viscosity of SF-based SCC mixtures, no correlation is found to exist between them. Equations 4.29 and 4.30 with lower values of correlation coefficients confirm the fact.

L-box time (T40) = 1.736(Viscosity) $^{0.170}$ (R^2 = 0.0375) (4.29)

L-box time (T20) = 0.0207(Viscosity) $^{1.6477}$ (R^2 = 0.0459) (4.30)

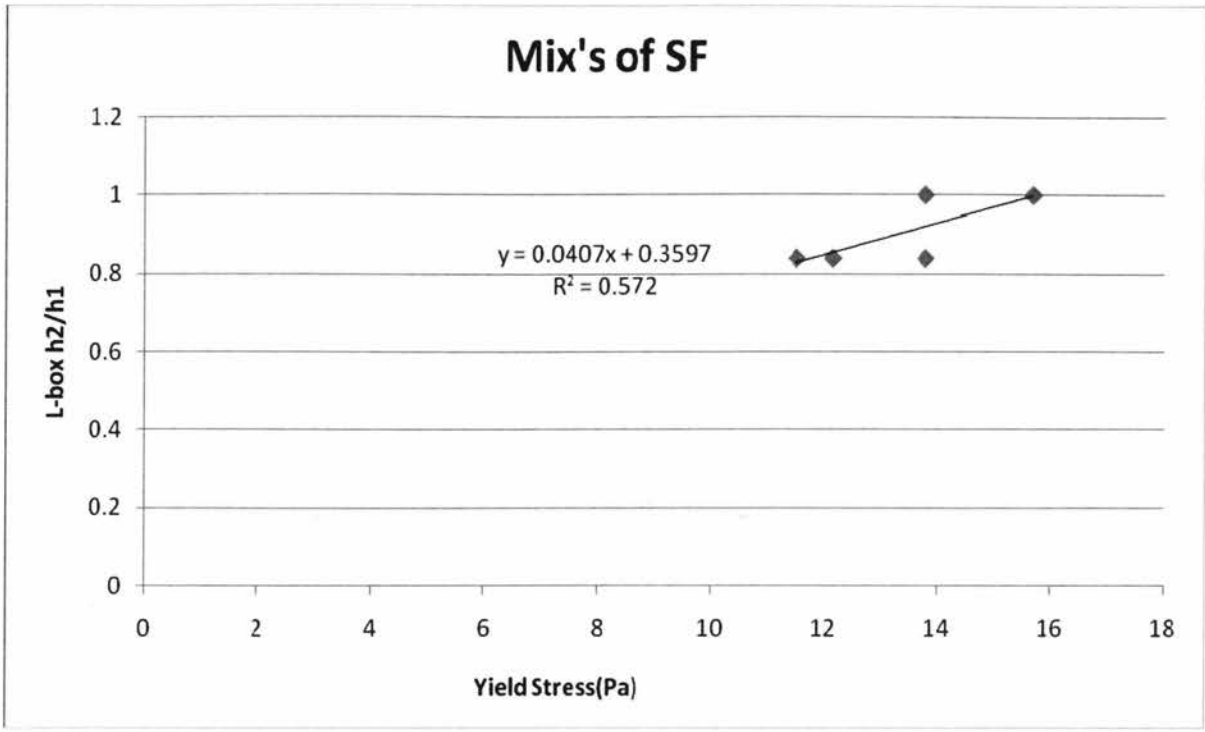


Fig 4.28: Relation between the L-box ratio (h2/h1) and yield stress of SF-based SCC

Trend shows an increase in L-box ratio with the increase of yield stress of SF-based SCC mixtures (Fig. 4.28). On the other hand, no trend can be established between L-box ratio and viscosity (Fig. 4.29). Equations 4.31 and 4.32 with lower values of correlation coefficients confirm the poor correlation t between L-box ratio and yield stress or viscosity, respectively.

$$\text{L-box ratio (h2/h1)} = 0.040\ (\text{Yield stress}) + 0.359 \quad (R^2 = 0.572) \qquad (4.31)$$

$$\text{L-box ratio (h2/h1)} = -0.007\ (\text{Viscosity}) + 1.021 \quad (R^2 = 0.001) \qquad (4.32)$$

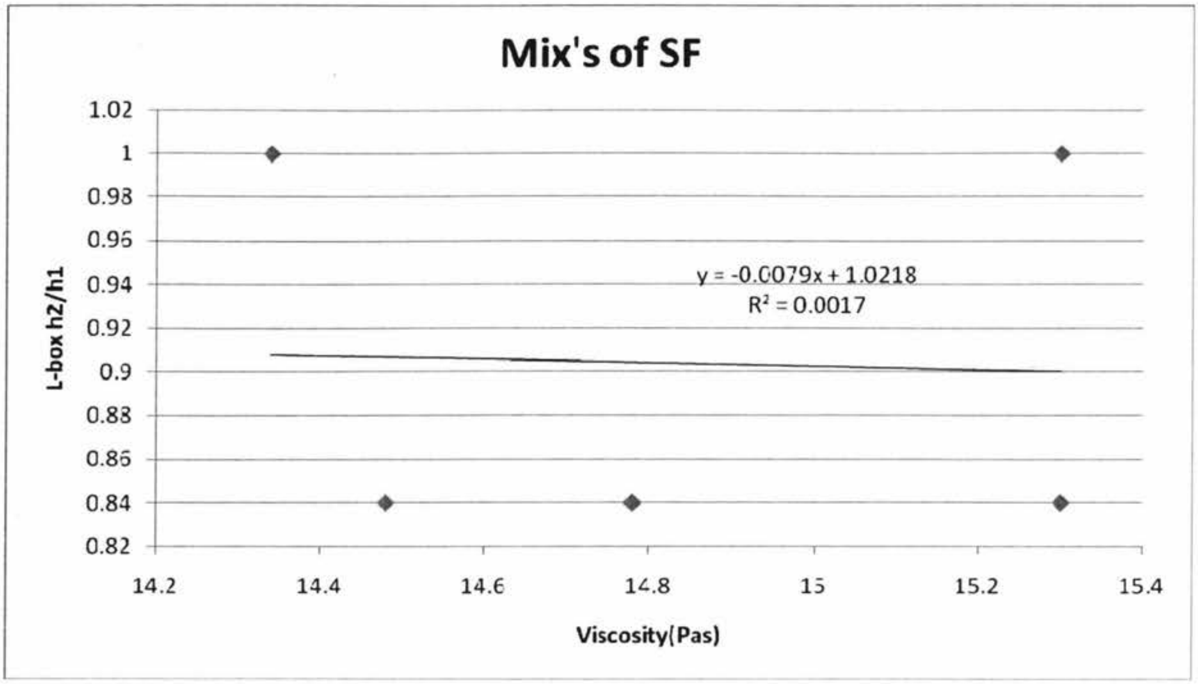


Fig 4.29: Relation between the L-box ratio and viscosity of SF-based SCC

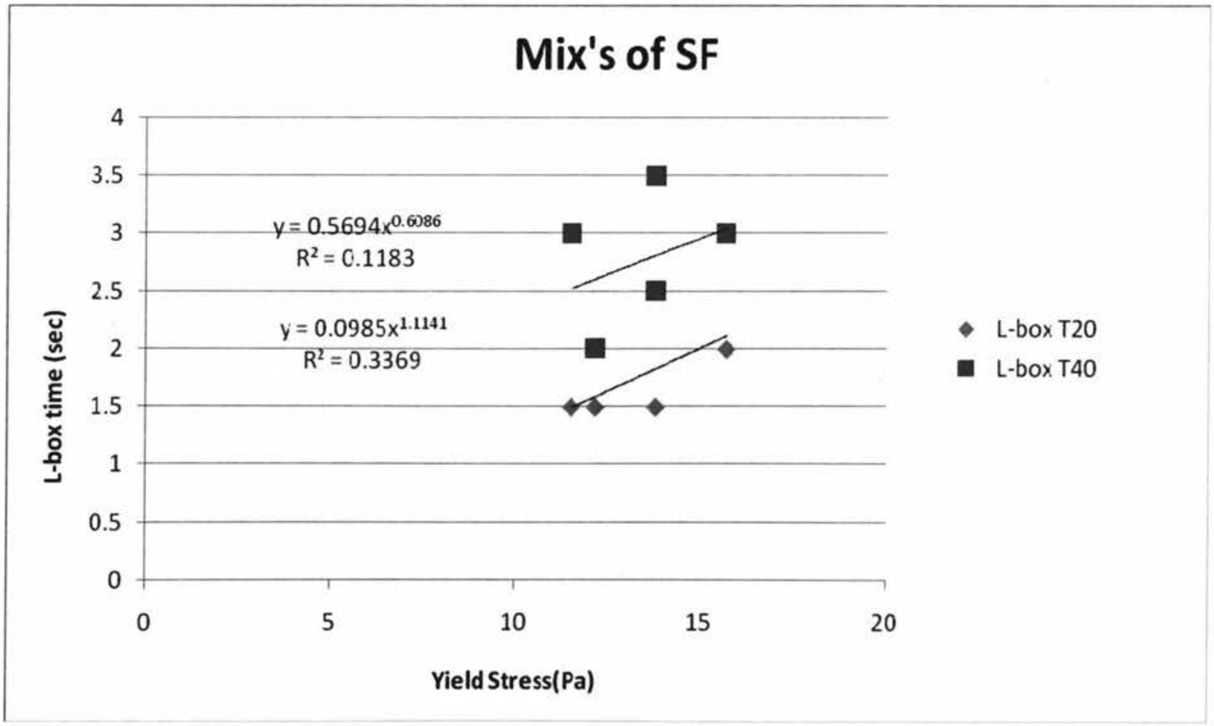


Fig 4.30: Relation between the L-box times and yield stress of SF-based SCC

Good correlation does not exist between L-box times and yield stress of MK-based SCC mixtures. Equations 4.33 and 4.34 with lower values of correlation coefficients confirm the fact. L-box time increases with the increase of yield stress of SF-based SCC mixtures (Fig. 4.30).

$$\text{L-box time (T40)} = 0.569\text{Yield stress}^{0.608} \quad (R^2 = 0.118) \tag{4.33}$$

$$\text{L-box time (T20)} = 0.098 \text{ Yield stress}^{01.114} \quad (R^2 = 0.0336) \tag{4.34}$$

5. CONCLUSIONS & RECOMMENDATIONS

5.1 Introduction

The purpose of this project was to develop self-consolidating concrete (SCC) by incorporating two supplementary cementing materials including metakaolin (MK) and silica fume (SF) at different percentages. 11 SCC mixtures were developed by incorporating 3%, 5%, 8%, and 11% of SF as well as 3%, 5%, 8%, 11%, 15%, and 20% of MK based on a control SCC mixture. Fresh properties of all 11 SCC mixtures including the control SCC were evaluated using slump flow, slump flow time, L-box, and V-funnel flow time tests as per standard specifications. In addition, the rheological properties such as plastic viscosity and yield stress of SF and MK-based SCC mixtures were evaluated using a viscometer. Effect of SF and MK on fresh and rheological properties of SCC mixtures were evaluated. Correlations among fresh properties as well as between fresh and rheological properties were derived.

5.2 Fresh Properties

Silica fume addition clearly increased the workability of SCCs while metakaolin addition had a tendency to reduce workability due to increased viscosity/cohesiveness of the mix. Higher dosages of superplasticizer (SP) was needed to keep slump flow of MK-based SCC mixtures at 650 mm which suggested the decrease of slump flow with the increase of percentage % of metakaolin.

Developed SF and MK-based SCC mixtures exhibited good ability to flow through the rebar of the L-box test. Desired L-box ratio (h2/h1) should be > 0.8 for SCC mixes. L-box ratio s for all developed SCCs were greater than 0.8 and there were no blockage of flow for all mixtures. Based on slump flow, L-box, and V funnel tests, the self-consolidating properties for all developed SF and MK-based SCC mixtures were considered satisfactory.

5.3 Rheological Properties

The rheological test results of both silica fume and metakaolin based SCC mixtures show that each of the supplementary cementing material has its own benefit. The use higher metakaolin percentage provides higher yield stress and higher viscosity. The higher viscosity due to addition MK can affect the workability (by reducing flowability) and at the same time it has the beneficial effect of reducing bleeding and segregation. Visual observation revealed no segregation of developed MK based SCC mixtures.

As a concept of the SCC the less viscosity is better workability, then better use for the application of SCC; however, the limitation of the lesser viscosity is to keep the SCC without segregation. Or add VMA to prevent the segregation in case of low viscosity. In this project we did not noted any virtual segregation and it was not part of this project to add VMA.

Use of silica fume percentage up to 5% lowered the viscosity of SCC mixtures while viscosity increased when SF addition was more than 5%. On the other hand, yield stress decreased with the increase of SF percentage up to 8%. The yield stress of SCC mixtures showed a significant increase when SF percentage was 8% or more. Considering the rheological parameters of SCC mixtures, the optimum percentage of SF was found to be 11%.

The rheological test results showed superior performance of metakaolin in enhancing rheological properties (increasing both viscosity and yield stress) of SCC compared to silica fume. Among different replacement levels, the use of metakaolin at the replacement level of 20% performed the best - which resulted in the highest yield stress over the control SCC mixture. In general, all SCC mixtures made by incorporating various proportions of SF and MK satisfied the criteria for SCC and hence, can be recommended for use in practical construction.

Correlations are found to exist between fresh and rheological properties of SF and MK based SCC mixtures. Developed correlation equations can be used as a tool to predict fresh properties from rheological parameters of SCC mixtures.

5.4 Recommendations for Future Research

A preliminary investigation is conducted to develop SCC mixtures by incorporating metakaolin and silica fume as supplementary cementing materials (SCM). More investigations are needed and future research studies should be conducted to obtain the following:

- In spite of having some good correlation equations among various fresh and rheological properties in this project, more investigations are needed in this direction to check the validity of these correlations
- Do more tests for each percentage of SCM by changing SP percentage to obtain different slump flow, then build relationship between fresh and rheological parameter

6. REFERENCES

6.1 Web Sites

http://www.geneq.com/catalog/en/l_box_fr.html, Access dated 16-11-2009

http://wapedia.mobi/en/Concrete, Access dated 18-10-2009.

6.2 References

American Concrete Institute Committee 237 (2007), "Self Consolidating Concrete" ACI, Farmington Hills, MI 48331, 30p.

American Concrete Institute, Committee 238.1R (2008)."Report on Measurements of Workability and Rheology of Fresh Concrete" PCA Library, 5420 Old Orchard Road, Skokie, IL, USA.

Brzev, S. and Pao, P. (2006) Reinforced Concrete Design: A Practical Approach. Toronto: Pearson Education Canada.

Bui, V.K., Akkaya, Y., and Shah S.P (2002) "Rheological Model for Self -consolidating Concrete," ACI Materials Journal, 99(6) 549-559.

CSA CAN3-A23.3 (2004), "Design of concrete structures" Canadian Standards Association, Rexdale, Ontario.

Domone, P.L. (2006), "Self-compacting Concrete: An Analysis of 11 Years of Case Studies," Cement & Concrete Composites, 28 (2) 197-208.

EFNARC (2006), "European Federation for Specialist Construction Chemicals and Concrete Systems, Guidelines for Viscosity Modifying Admixtures for Concrete," 11p, (www.efnarc.org/publications.html).

Ferraris C (1999), "Measurement of the Rheological Properties of High Performance Concrete:State of the Art Report", National Institute of Standards and Technology, Gaithersburg, MD 20899-0001.

Ferraris C.F, Brower L,Ozyildirim C, Daczko J (2000), "Workability of Self-Compacting Concrete" The economical solution for durable bridge & transportation structures, International symposium on HPC proceedings, PCI/FHWA/FIB, September 25-27, 2000, Orlando, Florida, 398 – 407.

Goodier, C.I. (2003), "Development of Self-compacting Concrete," Proceedings of the Institution of Civil Engineering: Structures and Building, 156(4) 405-414, Publisher: Thomas Telford Services Ltd.

Hassan, A.A.A., Hossain, K.M.A. and Lachemi, M. (2008), "Behaviour of full-scale self-consolidating concrete beams in shear," Cement & Concrete Composites, 30 (7) 588-596.

Hossain, K.M.A., and Lachemi, M. (2004), "Corrosion Resistance and Chloride Diffusivity of Volcanic Ash Blended Cement Mortar," Cement and Concrete Research, 34(4) 695-702.

Hossain, K.M.A., and Lachemi, M. (2004), "Use of Volcanic Debris and Industrial Wastes in the Development of Self-consolidation Concrete for Sustainable Construction," Structural Specialty Conference of the Canadian Society for Civil Engineering, Saskatoon, Canada, June 2-5.

Khayat K.H, and Assaad J (2002), "Air-Void Stability in Self-Consolidating Concrete" ACI Materials Journal, 99 (4) 408-416.

Khayat K.H, Ghezal A, and Hadriche M.S (1999), "Factorial design models for proportioning self-consolidating concrete", Materials and Structures, 32 (9) 679-686.

Khayat K.H, Yahia A, and Sonebi M (1999), "Applications of statistical models for proportioning underwater concrete," ACI Materials Journal, 96 (6) 634 - 640.

Khayat K.H. and Hwang S.D. (2006), "Effect of High Range Water Reducing Admixture Type on Performance of Self-consolidating Concrete" SP239-13 ACI Special Publication, 239(13) 185-200.

Khayat K.H. Assaad, J, and Daczko J (2004), "Comparison of Field-Oriented Test Method to Assess Dynamic Stability of Self-consolidating Concrete", ACI Materials Journal, 101 (2) 168-176.

Khayat K.H. Manai, K, and Trudel, A. (1997), "In Situ Mechanical Properties of Wall Elements using Self-consolidating Concrete", ACI Materials Journal, 94(6) 491-500.

Khayat, K.H. (1998), "Viscosity-Enhancing Admixtures for Cement based materials an overview," Cement and Concrete Composites, 20(2) 171-188.

Kosmatka SH, Kerkhoff B, William C., Norman F. and McGrath RJ (2002), "Design and Control of Concrete Mixtures", Seventh Canadian Edition (2002), Cement Association of Canada, Ontario.

Lachemi M, Hossain K.M.A, Lambros V., Nkinamubanzi P, and Bouzoubaa N (2004), "Performance of New Viscosity Modifying Admixtures in Enhancing the Rheological Properties of Cement Paste", Cement and Concrete Research, 34 (2)185-193.

Lachemi M, Hossain K.M.A, Pater R, Shahata M, Bouzoubaa N (2007), "Influence of Paste/Mortar Rheology on the Flow Characteristics of High-Volume Fly Ash Self-Consolidating Concrete", Magazine of Concrete Research, 59 (2) 1-12 .

Lachemi M, Hossain K.M.A and Lambros V. (2005),"Shear resistance of self-consolidating concrete beams- experimental investigation," Can. J. Civil Eng: 32(6) 1103-1113.

Lachemi, M, Hossain, KMA, Lambros VB, Nkinamubanzi, P.-C. and Bouzoubaa, N (2004), "Self-Consolidating Concrete Incorporating New Viscosity Modifying Admixtures" Cement and Concrete Research, 34 (6) 917–926.

Lacombe P, Beaupre D, and Pouliot N. (1999), "Rheology and bonding characteristics of Self-leveling concrete as a repair material," Materials and Structures, 32 (8) 593-600.

Mehta, P.K (1983),"Pozzolanic and Cementitious byproducts as Mineral Admixtures for Concrete-A Critical Review", ACI SP 79-1, Edited by V.M. Malhotra..

Mindess S, Young J.F, Darwin D (2002), "Concrete", Second Edition, Toronto.

Nanayakkara A, Ozawa K, and Maekawa K (1998), "Flow and segregation of fresh concrete in tapered pipes", Proceedings, 3rd International symposium on liquid – solid flows, ASME, FED- 75, 139-144

Okamura, H, and Ouchi M (2003), "Self compacting Concrete", Journal of Advanced Concrete Technology, Japan Concrete Institute, 1(1) 5-15.

Ozawa K, Sakata N, and Okamura H (1995), "Evaluation of self-compactibility of fresh concrete using the funnel test", Proceeding of JSCE, 25, 59-75.

Patel, R., Hossain, K.M.A., Shehata, M., Bouzoubaa and Lachemi, M. (2004), "Development of Statistical Models for Mixture Design of High Volume Fly-Ash Self- consolidating Concrete" ACI Materials Journal, 101(4) 294-302.

Petit J.Y, Wirquin E, Vanhove Y, Khayat K (2007), "Yield Stress and Viscosity Equations for Mortars and Self-Consolidating Concrete" Cement and Concrete Research, 37(5), 655–670.

Rao G (2001),"Influence of Silica Fume on Long-term Strength of Mortars Containing different aggregate fractions", Cement and Concrete Research, 31 (1), 7-12.

Rols, S., Ambroise, J., and Pera, J. (1999), "Effects of Different Viscosity Agents on the Properties of Self Leveling Concrete", Cement and Concrete Research, 29(2) 261-266.

Saak A.W, Jeninings H.M and Shah S.P (2001), "New Methodology for designing Self-Compacting Concrete" ACI Materials Journal, 98 (6) 429-436.

Saak, A.W., Jennings, H.M., and Shah, S.P. (2002), "New Methodology for Designing Self-compacting Concrete" ACI Materials Journal, 99(5) 509-512.

Schutter G., Bartos P., Domone P. and Gibbs J. (2008), "Self Compacting Concrete", Whittles Publishing, Dunbeath, UK.

Schwartzentruber L, Roy L and J. Cordin J (2006), "Rheological Behaviour of Fresh Cement Pastes Formulated From a Self Compacting Concrete (SCC)" Cement and Concrete Research, 36 (7) 1203–1213.

Siddique R and Klaus J (2009),"Influence of Metakaolin on the properties of Mortar and Concrete: A review", Applied Clay Science, 43, 392-400.

Tang C, Yen T, Chang C, and Chen K (2001), "Optimizing Mixture Proportions for Flowable High-Performance Concrete via Rheology Tests, ACI Materials Journal, 98(6) 493-502.

Wallevilk J.E (2006), "Relationships between Bingham parameter and slump", Cement and Concrete Research, 36(3) 501-509.

Wild, S., Sabir, B.B., and Bai, J. (2001), "Metakaolin and Calcined Clays as Pozzoloans for Concrete", a Review, Cement & Concrete Composites, 23 (6) 441-454.

Zhong, S.Y., Bao M.X., and Xue, M. (2006), "Rheologic parameters of Self-compacted Concrete with Poly Carboxylate Superplasticizer," Journal of Building Materials, 9(5) 521-526.