

**STUDY ON SEGREGATION AND
RHEOLOGY OF SELF COMPACTING
CONCRETE**

BY
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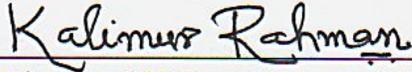
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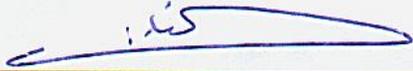
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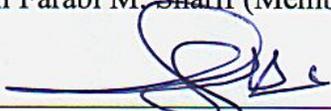
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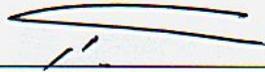
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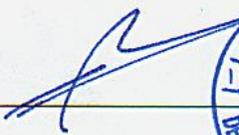

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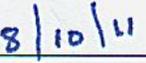

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Dedicated

to

My Beloved Parents

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THESIS ABSTRACT

Name MOHAMMAD ABDUL MALIK
Title STUDY ON SEGREGATION AND RHEOLOGY
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The durability of concrete structures is one of the most important parameters in concrete technology. Most of the durability problems arise from aggressive and harmful environmental factors and also because of improper compaction of concrete. Lately, a new type of concrete has been developed which is termed as 'Self Compacting Concrete' and which consolidates under its own weight without any need for external compaction or vibration. The two most important factors of SCC are its resistance to segregation and its flowability. Low segregation resistance induces blocking around reinforcement, high drying shrinkage, and leads to non-uniform compressive strength when the concrete hardens and consequently the durability is compromised.

The objective of this research, entitled '**Study on Segregation Resistance and Rheology of Self Compacting Concrete**', was to investigate the static and dynamic segregation resistance of SCC and to also study the rheological characteristics of SCC which play an important role in segregation and flowability, attributes that define the robustness of SCC.

A review of theoretical models that provide a basis of understanding of the fundamental mechanisms of static and dynamic segregation of SCC and rheology of SCC is carried out. A series of experiments are conducted using different SCC mixes to obtain the critical range of rheological parameters of yield stress and viscosity where segregation is minimized, yet the material retains its fluidity.

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THESIS ABSTRACT (ARABIC)

ملخص الرسالة

الاسم: محمد عبدالملك

عنوان الرسالة: دراسة خواص الانسيابية والانفصال في الخرسانة ذاتية الدمك

التخصص: الهندسة المدنية (إنشاءات)

تاريخ التخرج: أبريل ١٤٣٢

تعتبر قابلية الخرسانة على التحمل من اهم المعايير في صناعة الخرسانة. معظم مشاكل الخرسانة ناتجة الظروف البيئية القاسية بالاضافة الى سوء عملية دمك الخرسانة. في الأونة الأخيرة تم انتاج خرسانة سميت " الخرسانة ذات الدمك الذاتي" والتي تتم عملية دمكها عن طريق وزنها الذاتي ودون الحاجة الى الدمك الميكانيكي. تعتبر خاصيتي الانسيابية والمقدرة على مقاومة الانفصال من أهم الخواص للخرسانة ذات الدمك الذاتي. حيث أن ضعف مقاومة الانفصال لدى الخرسانة يؤدي الى التكتل عند حديد التسليح, ارتفاع الانكماش الجاف الذي يقود الى عدم تناسق مقاومة الخرسانة للضغط وبالتالي الى نقصان قدرتها على التحمل.

هذا المشروع البحثي المقترح سيتناول ظاهرة مقدرة الخرسانة ذاتية الدمك على مقاومة الانفصال والسيولة , وستناول البحث انفصال الخرسانة ذاتية الدمك الديناميكي والأستاتيكي وكذلك خواص السيولة لديها والتي تلعب دورا هاما في انفصال الخرسانة وانسيابيتها, سيتم تنفيذ هذا المشروع.

ويتم استعراض النماذج النظرية التي توفر أساسا لفهم الآليات الأساسية لفصل والدينامية من الخرسانة ذاتية الدمك الريولوجيا الخرسانة ذاتية الدمك من الخروج. وتجري سلسلة من التجارب باستخدام الخرسانة ذاتية الدمك مختلفة تمزج للحصول على مجموعة من المعلمات حرجة من التوتر الريولوجية المحصول واللزوجة، حيث يتم تصغير العزل، ومع ذلك فإن المواد سيولة تحتفظ بها.

ماجستير العلوم

جامعة الملك فهد للبترول والمعادن

الظهران ، المملكة العربية السعودية

CHAPTER 1

INTRODUCTION

1.1 Self Compacting Concrete

Reinforced concrete has proved to be an efficient and durable construction material since its inception due to its low-cost, eco-friendly characteristics, and excellent strength and stiffness properties combined with the ease of manufacture at the site. It is the most widely used construction material, more than any other material in the world. The present worldwide consumption of concrete is of the order of 10 billion tons yearly (Mehta and Monteiro, 2006)

In recent years, a lot of advancement has taken place in the construction industry. '*Self-compacting concrete (SCC)*' is one of the most remarkable developments in concrete technology. SCC is designed to flow under its own mass, resist segregation and meet the requirements of durability, formwork pressure and pump ability. Due to its better and more durable quality, dense and uniform surface

texture and higher strength characteristics, SCC may contribute to a significant improvement of the quality of concrete structures and open up new fields for the application of concrete for fast-track construction. The constituent materials used for the production of SCC are the same as those for conventionally vibrated normal concrete except that SCC contains lesser amount of aggregates and larger amount of powder (cement and filler particles smaller than 0.125 mm). Fly ash, glass filler, limestone powder, silica fume, etc are used as the filler materials and super plasticizers such as SSP 2000 (Scancem Chemicals AS) or ViscoCrete (Sika Norge AS) etc. are added.

High flow ability and high segregation resistance of SCC are obtained by using:

- A larger quantity of fine particles, i.e., a limited aggregate content (coarse aggregate: 50% of the concrete volume and sand: 40% of the mortar volume).
- A low water/powder ratio (0.3-0.4); and
- A higher dosage super plasticizer and stabilizer.

Self-compacting concrete can be described as a high performance material which flows under its own weight without requiring vibrators to achieve consolidation by complete filling of the formwork even when access is hindered by narrow spaces between reinforcement bars.

The concept of self compacting concrete was first introduced in Japan in the 1980's. For several years beginning in 1983, the problem of the durability of concrete structures was a major topic of interest in Japan. An adequate compaction by skilled labor is required to obtain durable concrete structures. Studies to develop a solution

for this problem led to the development of self compacting concrete and was first reported in 1989(Okamura and Ouchi, 1999).

Since the development of self-compacting concrete in 1989, the use of self-compacting concrete in actual structures has gradually increased. The main reasons for the employment of self-compacting concrete can be summarized as follows:

- (1) It facilitates fast-track construction with minimal use of labor.
- (2) It assures good compaction in the structure: especially in zones of high reinforcement concentration where compaction by mechanical vibration is difficult to accomplish when using normal concrete.
- (3) Its use eliminates noise due to vibration, especially at concrete production plants.

Segregation of SCC is a major point of concern as when present, it can induce blocking around reinforcement, lead to high drying shrinkage and non-uniform compressive strength when the concrete hardens.

Segregation of self compacting concrete can occur either in a static form or in state of dynamic motion during the flow of concrete. Such segregation is highly undesirable because it would lead to layered material properties (modulus of elasticity, Poisson's ratio, shrinkage and creep) that in turn would lead to non-uniformity in strength and stresses resulting from internal restraint during volumetric changes (Shen, 2007).

This thesis focuses on the study of static and dynamic segregation in SCC as produced using local aggregates and admixtures in KSA through the use of mechanistic-

empirical models using principles of rheology and fluid dynamics.

Segregation is defined as the tendency for coarse aggregate to separate from the sand-cement mortar, and static segregation may occur in non-robust mixes from the time of casting until hardening of the SCC.

SCC is found to be more susceptible to changes than ordinary concrete because of presence of more ingredients, more complex mix design, and low yield stress and viscosity. Variations in properties (and robustness) are therefore associated to the specific effects of the ingredients on the rheological properties of the mixture, effects of the physical properties (i.e., size and specific density) of the aggregate, and the mixing history (Bonen et al., 2007).

1.2 Advantages of SCC

Self compacting concrete can be regarded as the most revolutionary development in the concrete industry in the recent decades. Though it was originally developed to overcome the shortage of skilled labor, it has now being used for both site and precast concrete work. It is proving to be beneficial both economically and environmentally because of a number of factors.

- i. Ease in placement
- ii. Uniform and complete consolidation,
- iii. Reduction in manpower,
- iv. Faster construction,

- v. Better surface finish
- vi. Increased durability
- vii. Greater bond strength
- viii. Reduced noise levels, due to absence of vibration and
- ix. Safe working environment.

1.3 Need for this Research

Since self compacting concrete is relatively new in Saudi Arabia, not much research has been done yet to study the conditions leading to segregation of SCC. There is a need to study the behavior of this newly developed concrete because of its innumerable advantages. SCC is more sensitive to segregation problems than is conventional concrete, so measurement of segregation and the effect of segregation on hardened properties of concrete need to be determined since the durability of concrete can be affected to a great extent due to segregation of concrete. Also, pumpability of SCC is a topic of great interest, in view of construction of high rise buildings. As SCC is pumped to higher elevations, pumping pressure can go up due to blockages in the pipeline and changes in rheological properties with increased temperature of the mix resulting from friction in the pipeline. Often, maximum size of aggregate is reduced in order to prevent blockage with increase in the pumping height. The rheological parameters of yield stress and plastic viscosity can be related to pumping. Highly viscous concrete is difficult to pump and place. So, a critical range of yield stress and plastic viscosity should be determined in which the concrete is flowable and

pumpable and does not segregate.

Hameed (2005) has carried out studies on mix design and durability of SCC. Raza (2006) has also conducted studies on self compacting concrete in Saudi Arabia using locally available materials and only Fly Ash as filler. Their work was mainly addressed at mix proportioning, flowability, strength and shrinkage characteristics of SCC. However, no work has been done to study the mechanisms leading to segregation of SCC and its effect on strength and flowability.

As self compacting concrete has a lot of advantages over conventional concrete, it is being used widely in the United States and also the rest of the world. SCC was used in construction of the Al-Turky Business Park, Dhahran, in which Riyadh aggregate was used. Also, SCC will be used for the proposed 'Al-Othman Tower' project in Khobar. It is also being used as a thin overlay on top of hardened concrete to render leaking reinforced concrete water tanks watertight. This new age concrete is gaining recognition in the Kingdom and its use will become more popular in the future.

This research involves experimental investigation on locally produced SCC using Silica Fume, Limestone Powder and Fly Ash as filler materials and focuses on mechanisms that lead to static & dynamic segregation which affect the durability and strength.

1.4 Objectives

The primary objective of this research was to determine the effect of different type of mineral admixture (filler), SCC rheology, aggregate gradation and volume fraction on flowability and segregation attributes of SCC.

In order to achieve the above objectives, experimental investigations were carried out on SCC with various mix designs produced locally by Saudi Ready Mix, a leading supplier of SCC in the Kingdom. The results of experimental studies will be helpful in suggesting guidelines for production of a robust self compacting concrete in the Kingdom.

The following investigations have been carried out on selected SCC in order to meet the above stipulated objectives:

1. Experimental investigation of the conventional flow and strength properties of concrete.
2. Determination of rheological parameters of yield stress, viscosity and thixotropy of SCC for different mixes.
3. Experimental study of static segregation of SCC by the following tests
 - i. Hardened VSI
 - ii. Segregation Probe
4. Investigation of dynamic segregation of SCC using Flow Trough Method.
5. Development of guidelines for production of robust SCC.

1.5 Workplan

The research work was conducted in the following five phases.

The first included a comprehensive literature survey in the following areas:

- 1) Characteristics & properties of SCC.
- 2) Testing methods for SCC.
- 3) Review of segregation mechanisms and modeling.
- 4) Review of rheological models governing flow of SCC.

The second phase involved fabrication and calibration of the equipment. The segregation probe and flow trough were fabricated to measure the static and dynamic segregation respectively.

In the third phase, trial mixes were conducted to select suitable mix designs of SCC based on low segregation and acceptable flow properties. Nine mix designs were made by varying the amount of Silica Fume, Limestone powder and Fly ash. Water/powder ratio was kept constant at 0.3.

In the fourth phase, the SCC mixes were tested for self-compactibility, static segregation, dynamic segregation and rheology. Compressive strength was tested at 7 days and 28 days. The fifth phase, involved the analysis of experimental data.

CHAPTER 2

LITERATURE SURVEY

2.1 Background of Self Compacting Concrete

Colleparidi (2003) describes self compacting concrete as a special type of concrete mixture, characterized by high resistance to segregation under appropriate conditions that can be cast without compaction or vibration. With the advent of super plasticizers, self compacting concretes with slump levels up to 250 mm were manufactured with no or negligible bleeding, provided that an adequate cement factor was used, that is at least 350 kg/m³.

The necessity of this type of concrete was proposed by Okamura in 1986. Studies to develop self-compacting concrete, including a fundamental study on the workability of concrete, were carried out by (Ozawa et al., 1989) at the University of Tokyo.

2.2 Fresh Properties of SCC

According to Bartos (2000), Self Compacting Concrete must possess the following key properties at required levels:

A Filling ability: This is the ability of the SCC to flow into all spaces within the formwork under its own weight.

B Passing ability: This is the ability of the SCC to flow through tight openings such as spaces between steel reinforcing bars, under its own weight.

C Resistance to segregation: The SCC must meet the required levels of properties A & B whilst its composition remains uniform throughout the process of transport and placing.

Table 2-1: Acceptance Criteria of Self-Compacting Concrete

	Test Method	Unit	Minimum	Maximum
1	Slump Flow	mm	650	800
2	T-50	sec	2	5
3	V-Funnel	sec	6	12
4	L-Box	(h_2/h_1)	0.8	1
5	J-Ring	mm	0	100

2.3 Mix Design of Self Compacting Concrete

Generally, there is no standard method for mix design for SCC. Mix design is often based on using volume as a key parameter because of the necessity to overfill the voids between 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 first and mortar fractions before the coarse aggregate is added to the whole SCC mix.

The mix design is generally based on following approach:

- 1) Water demand is evaluated and flow and stability of paste is optimized.
- 2) Appropriate amount of coarse aggregate is selected.
- 3) Proportion of sand and dosage of admixture is set to give the required robustness.
- 4) The sensitivity is tested for small variations in quantities.
- 5) Fresh SCC is produced in the laboratory and the required tests are performed.
- 6) Properties of SCC are tested in the hardened state.

Table 2-2 : Typical Range of SCC Mix Composition (EFCA, 2005)

Constituent	Typical range by mass (kg/m ³)	Typical range by litres (litres/m ³)
Powder (Cement+filler)	380-600	
Paste		300-380
Water	150-210	150-210
Coarse Aggregate	750-1000	270-360
Fine Aggregate (Sand)	Content balances the volume of the other constituents, typically 48-55% of total aggregate weight.	
Water/Powder ratio by Vol		0.85-1.0

These ranges serve as general guidelines for designing an SCC mix depending on the requirements of flowability and passing ability. A designer is at liberty to tailor the mix by adjusting the weight of the constituents. Superplasticizer requirement varies depending on the type of filler used. Cyr et al., (2000) have shown that different superplasticizers and mineral admixtures affect the rheological properties differently. The shear thickening is increased in the presence of metakaolin, ground quartz and fly ash have no effect on it, whereas silica fume reduces it.

(Kim et al., 1998) have determined the material properties of Self Compacting Concrete and compared with normal concrete. They used five types of Self Flowing Concretes with fly ash as admixture, sulfonate naphthalene formaldehyde condensate as super plasticizer and three types of normal concrete. Based on the experimental

results of fresh concrete it was concluded that the self flowing concrete has sufficient flowability and workability to obtain the self compactable performance. The suggested critical volume ratio of coarse aggregate-to-concrete for enough flow ability and workability exists between 0.31 and 0.35.

They observed the effect of fly ash on the compressive strength of self flowing concrete and found the rate of increase of the compressive strength of self flowing concrete is lower than that of ordinary concrete at early stages, but at late ages the rate of increase of the strength of self flowing concrete is higher than that of ordinary concrete. At the same time compressive strength, the splitting tensile strength of self flowing concrete is almost identical with that of ordinary concrete.

The theory proposed by Saak et., al(2001) suggests that aggregate segregation is governed by the yield stress, viscosity and density of the cement paste matrix. A common methodology for design of concrete is to divide concrete into two constituents: coarse aggregates and mortar. The rheology of the mortar is then adjusted to have self-flowing concrete by incorporating a variety of mineral additives, plasticizers and thickeners. Another approach is to optimize particle size distribution of the binder (like cement, silica fume, limestone, dust, etc.) and of the fine and coarse aggregates based on packing considerations. Based on previous studies, it is unclear if high packing density alone should be used as design criteria for producing highly flow able concrete. The physical properties of the particles on the rheology of the cement paste show that the interparticle separation (IPS) should be used along with particle packing density as the rheological design parameters. IPS is controlled by the particle size distribution of the aggregates and volume percent binder (that is the cement paste

matrix). For a given particle size distribution of aggregate, the amount of binder must be sufficient enough to fill the interstitial voids between aggregates and produce the desired IPS. The guidelines suggested by various authors for producing SCC are:

Table 2-3: Guidelines for Producing SCC

Author	V_c/V_{agg}	V_f/V_{agg}	V_b/V_s	$(V_b+V_f)/V_{agg}$
Okamura	0.64	0.36	0.22	0.64
Yurgui et al	0.54	0.46	0.24	0.78
Ambrose, Rols, and Pera	0.44	0.56	0.18	0.78

V_c = Volume of coarse aggregate

V_f = Volume of fine aggregate

V_{agg} = Volume of total aggregate

V_b = Volume of binder(solids)

V_s = Volume of total solids (aggregates + binder)

The theory proposes that the rheology of the cement paste matrix largely dictates the segregation resistance and workability of fresh concrete, for a given particle size distribution and volume fraction of aggregate. Fine aggregate particles segregate at a lower yield stress and viscosity than the larger coarse aggregate particles. A minimum paste yield stress and viscosity is necessary to avoid segregation under static and dynamic conditions, respectively. But, if the yield stress or viscosity is too high, the

particles will never segregate; however, the material will have poor workability and flow ability. The rheology of concrete is optimized at a certain cement paste yield stress and viscosity just high enough to avoid segregation. Segregation resistance, however, is optimized for SCC at the highest yield stress and viscosity within the SFZ.

Based on the experimental results, it has been shown that, paste containing silica fume and cellulose has a greater segregation resistance along with the desired workability in comparison to paste containing only cement.

More recent research has shown that SCC can be produced using recyclable industrial by-products like silica fume, flyash and limestone powder by partially replacing cement. Bhattacharya et al.,(2008) have investigated the effects of using limestone powder, fly ash and silica fume on the fresh and hardened properties of SCC. Selvamony et al.,(2010) performed experimental investigations on the use of LSP, SF, quarry dust and clinkers on the performance of SCC. It was observed that use of SF significantly increased the dosage of superplasticizer. LSP improved the workability of SCC whereas when used along with quarry dust, it had adverse affects on the mechanical properties of SCC. Turkel and Kandemir (2010) have also reported the effect of using FA and LSP on the performance of SCC. Results show that properties of SCC are greatly affected by incorporation of mineral admixtures.

Douglas et al.,(2005) have showed that the structural buildup and thixotropy are also related to the superplasticizer content, rest time and mixing energy.

2.4 Rheology

Rheology is the science dealing with deformation of flow of material under stress (Mindess et al., 2002). Although rheology is concerned with the flow and deformation of matter- including liquids, solids, and gases- the term rheology is mainly used to refer to the study of liquids. Elasticity is not typically considered in the formal study of rheology. When defining a liquid, it is useful to make a distinction between an elastic solid and a viscous liquid. If a constant stress is applied to an elastic solid, the material will undergo a finite deformation; this deformation is recovered upon removal of the load.

In contrast to an elastic solid, a viscous liquid deforms continuously due to an applied shear stress for as long as the shear stress is applied; this deformation will not be recovered once the load is removed. The two-dimensional case for the flow of a liquid between two parallel plates of sufficient length such that end effects can be ignored is shown in Figure 2-1. If a shear force (F) is applied, a velocity gradient (V) is induced in the liquid.

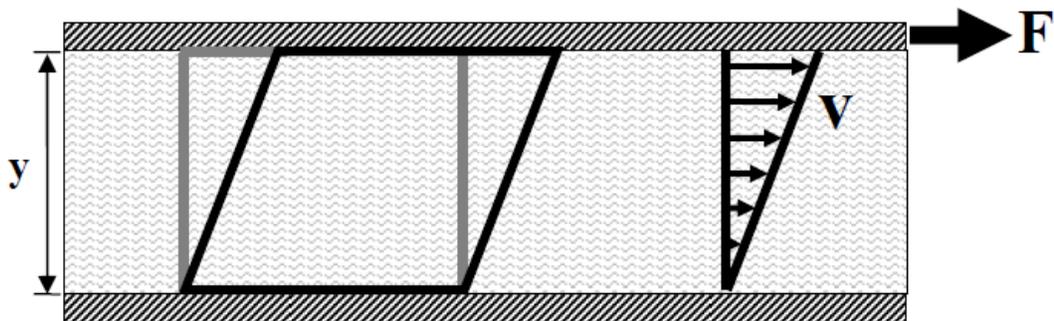


Figure 2-1: Two-Dimensional Representation of Viscous Flow (Kohler, 2004)

In viscous flow, the shear stress and the time rate at which the shear stress is applied are related-the faster the fluid is sheared the greater the shear stress that is required. For the case of constant flow, the shear stress τ , is related to the shear rate $\dot{\gamma}$, by the coefficient of viscosity, η :

$$\tau = \eta \dot{\gamma} \quad (2-1)$$

However, the distinction between a solid and a liquid is not as clear as it seems. Certain inelastic solid materials can undergo irrevocable deformations over a certain range of strains. Similarly, viscous fluids may behave as elastic solids at very low shear strains. A viscoelastic material exhibits both a viscous and elastic response under a constant stress. Thus, from a rheological point of view, it is important to consider the relevant type of behavior under a particular loading of a given material. Further, it has been argued that given sufficient time, all materials tend to flow (Barnes, 1999).

2.5 Constitutive Equations of Fluid Flow

Equation (2-1) represents one combination of shear stress and shear rate during steady flow; however, it is important to know the flow properties over a range of shear stresses and shear rates while measuring the rheology of a material. The relationship between shear stress and shear rate is represented graphically by a flow curve. Fluids may be described by their flow curves. Various models-or constitutive equations- have been developed to idealize flow curves. Six of the most common relationships associated with concrete are as shown in Figure 2-2.

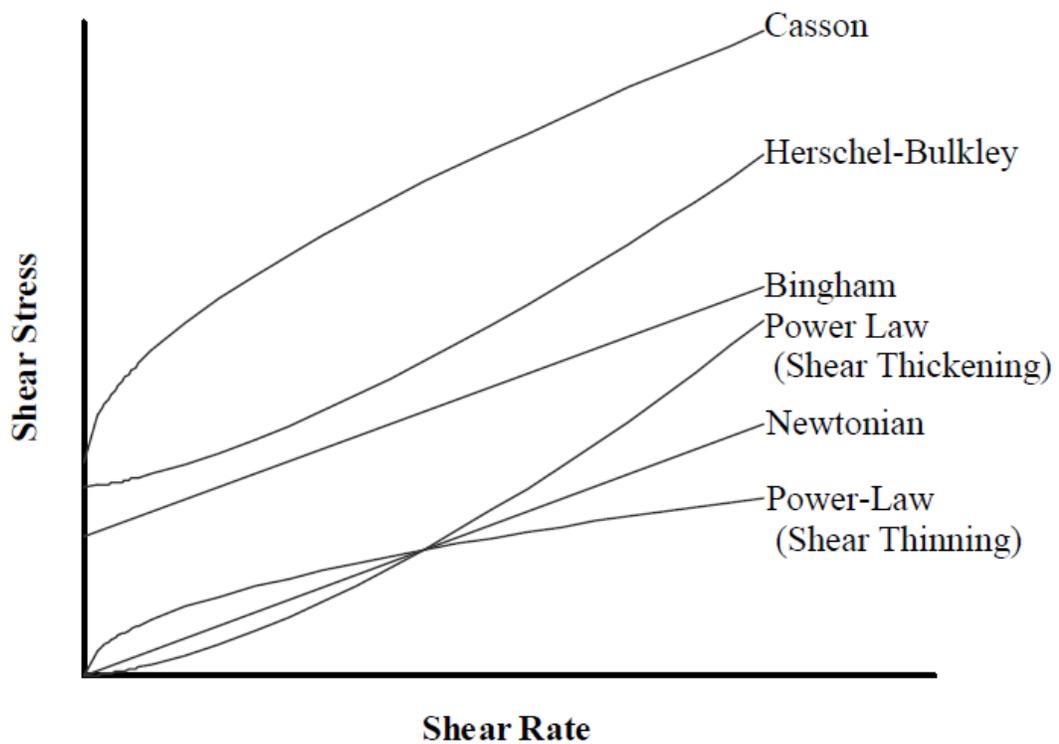


Figure 2-2: Basic Constitutive Relationships for Flow

The most basic constitutive equation is for a Newtonian fluid, where the shear stress is related to shear rate linearly as shown in Equation (2-1), and applies for the entire

range of shear rates, thereby the viscosity of the material remains constant.

The Newtonian model represents the basic fluid flow, and fails to represent adequately the flow response of most fluids, including many concrete mixtures, as the Newtonian model assumes that the flow curve intercepts the shear stress axis at the origin. But, in reality most fluids do not behave linearly. Many fluids possess some minimum stress—namely, a yield stress that must be exceeded for the flow to start. The practical observation of the yield stress can be seen in the slump test. When the slump cone is removed, the stress induced by gravity is sufficient to exceed the yield stress. As a result, the concrete flows briefly for some distance and when the stress induced by gravity becomes less than the yield stress, it ceases to flow. Materials exhibiting such kind of behavior are considered to be viscoplastic materials.

The Bingham Model is the most commonly used model for defining the flow of concrete mixtures. It assumes a linear relationship between shear stress and shear rate and accounts for an initial yield stress, defining the flow behavior of concrete mixtures more closely than other models.

$$\tau = \tau_0 + \mu\dot{\gamma} \quad (2-2)$$

where τ - shear stress applied to the material

τ_0 - dynamic yield stress (Pa)

μ - plastic viscosity (Pa-s)

$\dot{\gamma}$ - rate of shear (1/s)

This model requires the determination of two parameters i.e the dynamic yield stress and the plastic viscosity. The dynamic yield stress is the stress above which the material remains fluid, and corresponds to the intercept on the shear stress axis. The plastic viscosity describes the ease with which the material can flow.

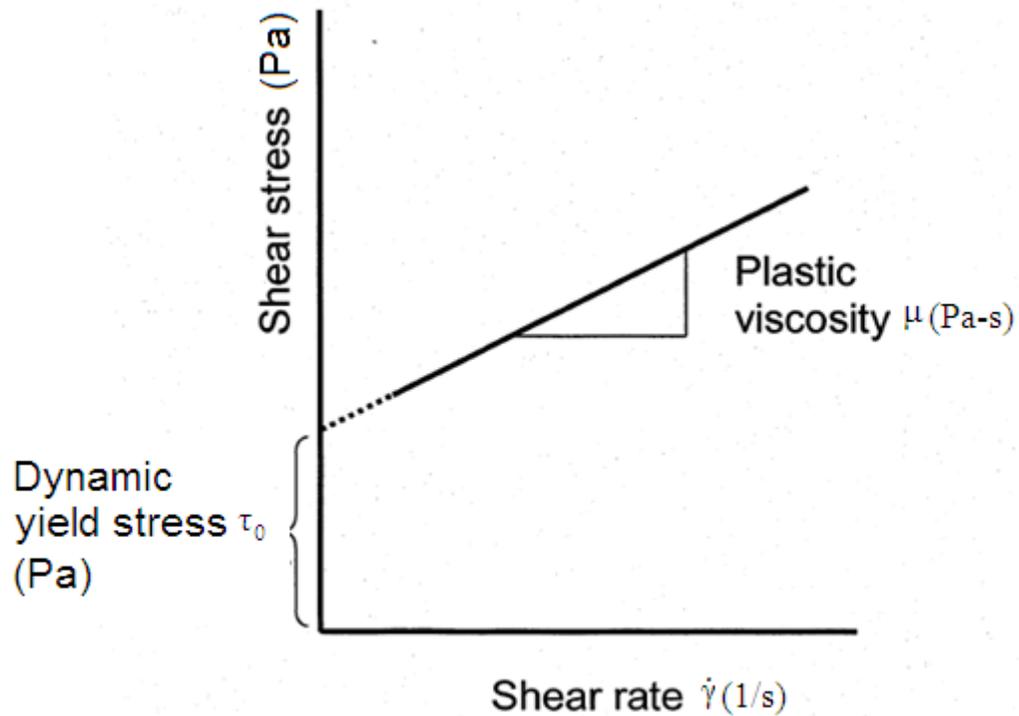


Figure 2-3: Bingham Model showing plastic viscosity and dynamic yield stress

The concrete is a very complex material due to several reasons. It involves a wide range of particle sizes. Concrete is a suspension of fine and coarse aggregates in cement paste, which is, in turn, a concentrated suspension of cement particles in water. It is a time-dependant material since irreversible chemical reactions take place due to hydration and the properties change. The area of concrete rheology has been widely studied and can be very useful in scientifically defining concrete workability Erdogan (2005).

Fluid Rheology is an established science that is directly applicable to the workability of fresh concrete. Yield stress represents a minimum force required to start the concrete to flow. For normal concrete, vibration is that force. Plastic viscosity can be described as the resistance to flow, or the stiffness of fresh concrete.

SCC has lower yield stress than conventional concrete which makes it easily flowable. Figure 2-4 compares flow curves of conventional concrete with different SCC mixtures. The conventional concrete has a high dynamic yield stress, thus it requires additional energy in the form of vibration for consolidation after it is placed in forms.

The SCC mixtures have low dynamic yield stress and consolidate under self-weight, but the rheological properties differ depending on the viscosity. The SCC with a high plastic viscosity will be sticky and difficult to finish, whereas the mix with low plastic viscosity will be prone to segregation. Thus, by using different mixture proportions and admixtures, an optimum balance between ease of flow and resistance to segregation has to be achieved for satisfactory performance.

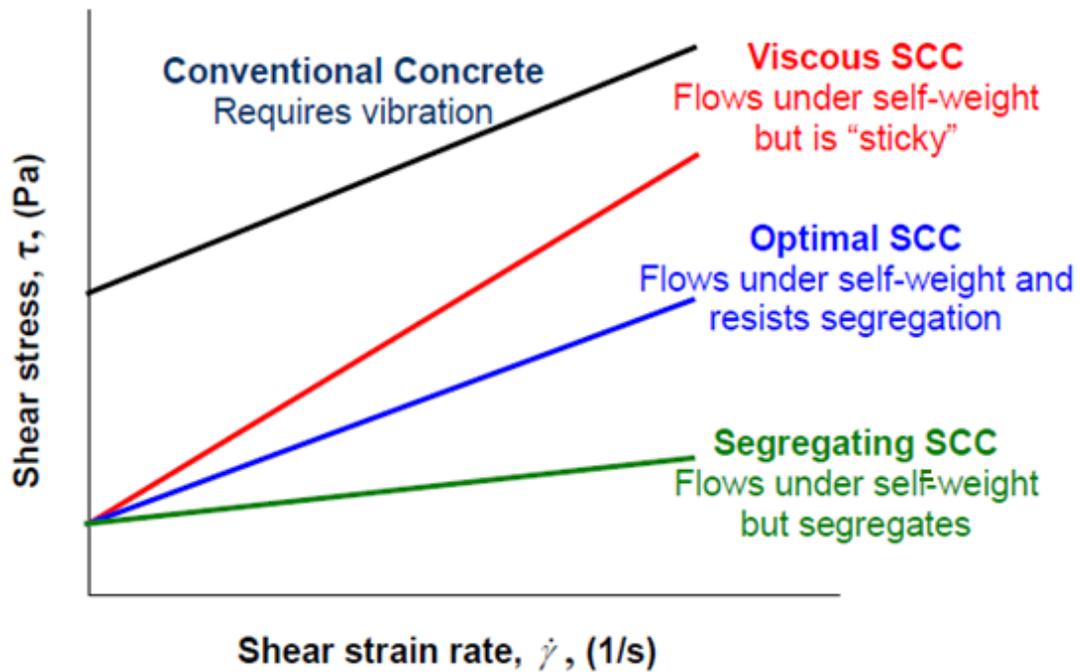


Figure 2-4: Concrete Flow Curves

Fresh SCC behavior cannot be fully understood without understanding its rheology. The placement, pumping, spreading and compaction of any type of concrete depends on its rheology. By knowing the science of rheology, it is becoming possible to predict fresh properties, select materials and model processes to achieve the required performance.

SCC has been developed in a wide range of compositions using various materials. The dark grey region in Figure 2-5 represents the target area of SCC concerning the yield stress and plastic viscosity, which is the result of measurement conducted with the BML-Viscometer (Nielsson and Wallevik, 2003). It is also reported that the Bingham Model best describes the flow behavior of SCC.

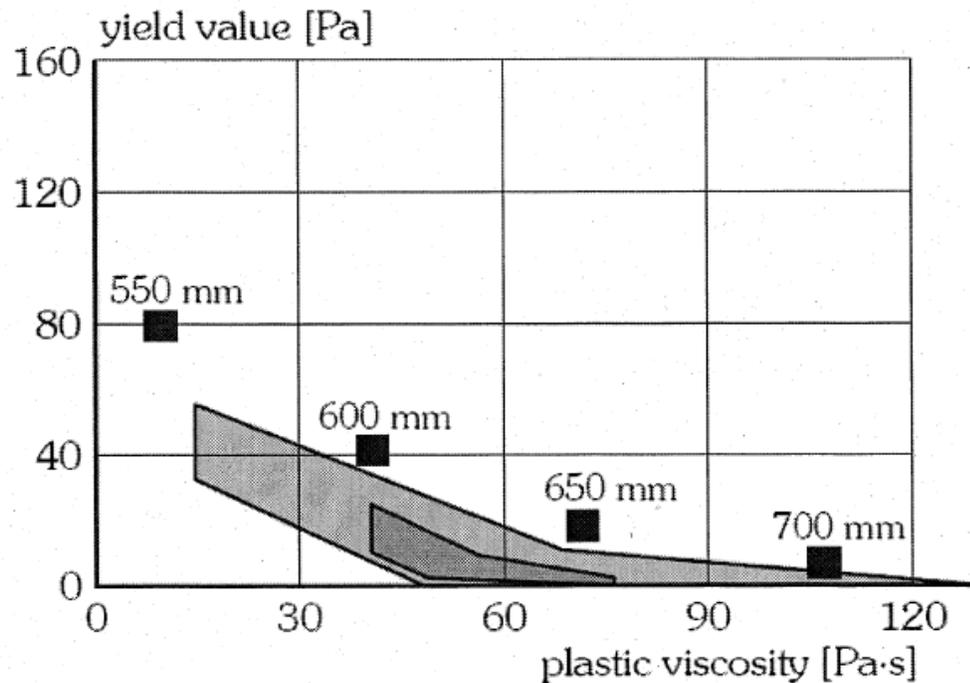


Figure 2-5: Range for SCC and Recommended Slump Flow

2.6 Factors Affecting Rheology of Concrete

Workability and other flow properties like passing ability and pumpability are related to the rheology of fresh concrete, which requires at least two parameters, such as Bingham Parameters, for adequate description of flow. The principal factors influencing the rheological parameters of concrete are : the composition of concrete, including the chemical and mineral admixture dosage/type, the gradation/shape/type of aggregates, the water content and the cement characteristics (Banfill, 2003).

The same mix proportion may result in different flow properties if secondary factors are not considered. These are: mixer type-pan, truck (these may induce different levels of deflocculation and air entrainment); mixing sequence, mixing duration and

temperature (Ferraris et al., 2001).

SCC varies in properties, applications and design methods. Table 2-4 shows an estimation of typical SCC powder, water and rheological parameters (Nielsson and Wallevik, 2003) for various countries around the world.

Table 2-4: Estimate of Typical SCC Rheological Parameters from Various Countries

Country	Powder(kg/m³)	Water(kg/m³)	Dynamic Yield Stress τ_0 (Pa)	Plastic Viscosity μ (Pa-s)
Sweden	>550	180	0-30	50-100
Netherlands	>550	190	0-10	60-120
Japan	>550	170	0-30	50-120
France	-	-	0-10	>60
Switzerland	<450	200	0-50	10-20
Norway	<450	170	10-50	30-45
Iceland	<450	180	10-50	20-40
Denmark	<400	160	30-60	<40
UK	>500	210	10-50	50-80
Germany	>500	180	0-10	60-90
US	>500	190	0-20	40-120

2.7 Thixotropy of SCC

The measured flow curve often depends on the shear history of the sample. A thixotropic material experiences a reversible, time-dependent decrease in viscosity when subjected to constant shearing whereas an anti-thixotropic, or rheopatic, material experiences an increase in viscosity (Hackley and Ferraris, 2001). Depending on the material, the time-dependence of flow properties can influence readings for time periods ranging from seconds to days. Figure 2-6 depicts the effects of thixotropy for a test where the shear rate is gradually increased from zero to a maximum value and then decreased to zero.

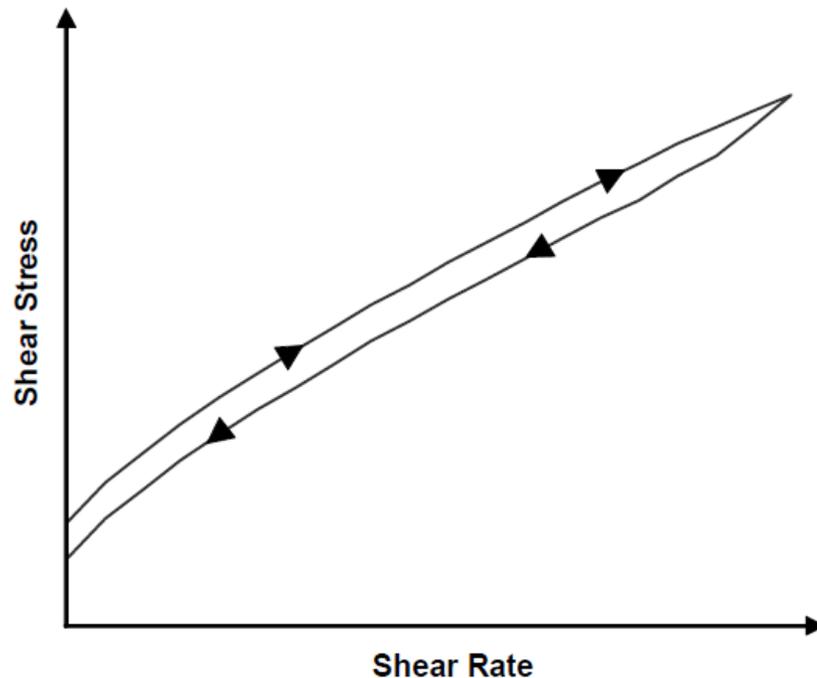


Figure 2-6: Thixotropy (ICAR,2008)

The area between the up and down curves depends partly on the material and the amount of time for the reading of each shear point-longer readings allow for a more pronounced thixotropic effect-and should not be taken as a representation of the degree of thixotropy.

The self compacting concrete exhibits thixotropic behaviour, meaning the apparent viscosity decreases over time at a constant shear rate and eventually steadies out to a constant value (Barnes, 1997).

Roussel (2004) has conducted study on steady and transient behavior of fresh cement pastes and has proposed a thixotropic model to predict the shear stress, where the apparent viscosity is a function of the structure parameter λ or “degree of jamming”.

$$\tau = \mu_0(1 + \lambda^n)\dot{\gamma} \quad (2-3)$$

$$\frac{\partial \lambda}{\partial t} = \left(\frac{1}{T} \right) - \alpha \lambda \dot{\gamma} \quad (2-4)$$

Where μ_0 is the viscosity at infinite shear rate when λ tends towards zero, n is a constant positive parameter, $1/T$ is the flocculation term and $\alpha \lambda \dot{\gamma}$ is associated with the deflocculation rate. The model predicts flocculation at rest, deflocculation under an applied strain rate (constant or variable in time) and describes steady state as equilibrium between deflocculation and flocculation phenomena. However, it is not able to predict quantitatively the structuration state for resting time longer than 1 minute.

Roussel (2006) has proposed a model to determine the thixotropy of fresh concrete.

The general form of the model is

$$\tau = (1 + \lambda)\tau_0 + k\dot{\gamma}^n \quad (2-5)$$

$$\frac{\partial \lambda}{\partial t} = \frac{1}{T\lambda^m} - \alpha\lambda\dot{\gamma} \quad (2-6)$$

where λ is the flocculation state of the material and T, m and α are thixotropy parameters. The simplified version of the model assumes that the Bingham model is sufficient for the description of the steady state flow of fresh concrete: $n=1$, $k= \mu$ (plastic viscosity). It also assumes that the yield stress at rest increases as a linear function of time: $m=0$. This reduces the model to the form

$$\tau = (1 + \lambda)\tau_0 + \mu\dot{\gamma} \quad (2-7)$$

$$\frac{\partial \lambda}{\partial t} = \frac{1}{T} - \alpha\lambda\dot{\gamma} \quad (2-8)$$

where the four thixotropy parameters have to be identified. It is also assumed that the characteristic time of flocculation (T) is long compared to the characteristic time of deflocculation. So,

$$\frac{\partial \lambda}{\partial t} \approx -\alpha\lambda\dot{\gamma} \quad (2-9)$$

On integration,

$$\lambda = \lambda_0 e^{-\alpha\dot{\gamma}t} \quad (2-10)$$

$$\tau = (1 + \lambda_0 e^{-\alpha\dot{\gamma}t})\tau_0 + \mu\dot{\gamma} \quad (2-11)$$

At rest, $(\dot{\gamma} = 0)$

On solving Equation (2-8), we obtain,

$$\lambda_0 = \frac{t}{T}$$

Therefore the increase in the static yield stress at rest is given by,

$$\tau_0(t) = (1 + \lambda_0)\tau_0 = \tau_0 + \tau_0\left(\frac{t}{T}\right) = \tau_0 + A_{\text{thix}} t \quad (2-12)$$

$$\text{with } A_{\text{thix}} = \frac{\tau_0}{T} \quad (2-13)$$

A classification of SCC according to their flocculation rate A_{thix} was proposed.

Table 2-5 : Classification of SCC

Flocculation rate A_{thix}(Pa/s)	SCC type
Less than 0.1	Non-Thixotropic SCC
Between 0.1 and 0.5	Thixotropic SCC
Higher than 0.5	Highly Thixotropic SCC

Roussel (2007) introduces the concept of rheology of fresh concrete and its relation with the casting processes. Measurements of the rheological properties of fresh concrete (yield stress and viscosity) and its relation with the casting processes have been studied. The ability to predict whether a given concrete will correctly fill a formwork without segregation can be done by studying the rheological parameters. The extremely fluid SCC also encounters problems because of formwork and reinforcement configurations. Fresh cementitious materials are like fluids with a yield stress, which is the minimum shear stress for flow to occur (Roussel, 2009). The behavior of fresh concrete is often approximated by a yield stress model of the

following general form:

$$\dot{\gamma} = 0 \quad \text{when} \quad \tau < \tau_0$$

$$\dot{\gamma} \neq 0 \quad \text{when} \quad \tau = \tau_0 + \mu \dot{\gamma}$$

where τ_0 is the yield stress, $\dot{\gamma}$ is the shear rate, and μ is the plastic viscosity.

The ideal mixture proportions for a fluid concrete are based on its fluidity and segregation resistance. The simplest approach is to find the minimum fluidity that guarantees adequate filling of formwork and also ensures maximum acceptable stability.

2.8 Segregation and Durability of SCC

Due to its low yield stress and viscosity, SCC is more prone to segregation than conventional vibrated concrete. Segregation can occur in two forms – static and dynamic. Static segregation is described as the settlement of aggregate particles when the concrete is at rest. Dynamic segregation refers to the loss of aggregate particles during the flow of concrete. Both static and dynamic segregation affect the strength and durability of SCC.

Segregation is controlled by viscosity and yield stress of the mixture, binder density, aggregate size, aggregate density as well as content of fines. Large aggregate size and density decreases stability. Stability can be enhanced by increasing viscosity and density of the matrix by decreasing maximum size and density of aggregate. Higher w/cm ratio and/or SP: cement ratio increases segregation. Lower w/cm ratio and SP: cement increases stability. High fines content increases robustness by increasing viscosity. Silica fume is viscosity modifier and slag and limestone are density modifiers. Stability also depends on total amount of fines in the mixture (for mixtures with similar aggregate packing densities).

2.9 Methods for measuring Static Segregation

The Illinois Center for Transportation at the University of Illinois, under the leadership of Profs. Lange and Struble, have recently developed several test procedures for estimating static and dynamic segregation in SCC.

2.9.1 Using Segregation Probe

SCC-7 (2004) introduces a segregation probe to measure static segregation of fresh SCC. The probe is placed on top of the 150*300 mm freshly cast SCC in a cylindrical specimen that has been allowed to rest undisturbed for two minutes. A Measured Stability Index (MSI) is defined as corresponding to various settlement depths of the probe, with mixes yielding MSI of (0, 1) being classified as stable and those with MSI (2, 3) as unstable.

The segregation probe can also be used to characterize the “robustness” of a SCC mix, with robustness being defined as lack of sensitivity of the key attributes of a desired SCC-flow ability (workability) and stability (resistance to segregation) - to small changes in water content and admixture dosage. Saak et al., (2001) proposed the idea of robustness, where the concept of a rheological self-flow zone (SFZ) was introduced, a zone where aggregate segregation is avoided, yet the concrete has high workability. Developing this innovative idea, they pursued the theoretical notion that aggregate segregation is governed by yield stress, viscosity and density of the cement paste matrix. By systematically changing the rheology of the cement paste matrix of fresh concrete, the yield stress and viscosity of three different pastes incorporating silica fume and a cellulose thickening agent were measured as a function of density.

2.9.2 Hardened Visual Stability Index (HVSI)

Another reference source from the University of Illinois group, SCC-6 (2004) describes a parameter referred to as the Hardened Visual Stability Index (HVSI), and is defined as a qualitative measure of the distribution of coarse aggregate as noted from sawing a hardened 6*12 in. (150*300 mm) concrete cylinder length-wise. This method has been developed at the Illinois Center for Transportation and is used to determine the static segregation of SCC. The test produces a parameter known as the Hardened Visual Stability Index (HVSI). HVSI is a qualitative measurement of the distribution of coarse aggregate from a sectioned cylinder. The test is carried out by placing SCC in a standard 6 × 12 in. cylinder and allowing the concrete to harden. The cylinder is then cut length-wise with a concrete saw, exposing a section of the cylinder to view the top to-bottom distribution of coarse aggregate. The ratings are assigned on the basis of visual observation and delineated as being stable or unstable.

2.10 Dynamic Segregation Using Flow Trough Method

Dynamic segregation indicates the separation of coarse aggregates and paste/mortar in the direction of flow (mainly horizontal in most cases) during the movement of concrete (Shen, 2007). A new method has been presented in SCC-9 (2004) to measure the Dynamic Segregation Index (DSI) by allowing SCC to flow over a trough of length of travel of 1.8 m inclined at an angle of 7 degrees. Since typical flow distances of SCC in the field range from 3 to 9 m (sometimes as much as 30m), further validation of the DSI measured was needed. This was carried out through a series of limited field tests where dynamic segregation was measured directly in the formwork

(SCC-8). Good correlation was observed, conforming the effectiveness of the trough for estimating dynamic segregation. The flow trough method has also been used to provide insight into maximum travel distance for SCC projects.

CHAPTER 3

Experimental Program, Materials and Mixes

3.1 Introduction

In this chapter, details of materials used for designing SCC mixes used in the experimental program are described. A reference mix was designed based on low segregation and acceptable flow properties. Nine mixes were then considered by varying the filler content while keeping the aggregate content and water/powder ratio constant. Proportioning was carried out using the absolute volume method. Each mix was then tested for self-compactability, static and dynamic segregation and rheology (i.e. yield stress and plastic viscosity).

3.2 Scope of the Experimental Work

The experimental work involved testing of SCC for self-compactibility, static segregation, dynamic segregation and rheology for developing guidelines for production of robust SCC. It consisted of the following components.

- 1) Slump Flow, V-Funnel, L-Box and J-Ring tests on fresh concretes.
- 2) Static segregation test using segregation probe and dynamic segregation test using Flow Trough.
- 3) Rheological tests to determine yield stress and plastic viscosity.
- 4) Compressive strength tests after 7 and 28 days.
- 5) HVSI rating based on visual inspection of cut cylinders.

3.3 Materials

The specifications of the materials used in the experimental program are as follows.

3.3.1 Ordinary Portland Cement

ASTM C 150 Type I Portland cement which is widely used in Saudi Arabia, was used. The specific gravity of cement used was 3.15.

3.4 Fillers

Silica fume, limestone powder and fly ash were used as filler materials.

3.4.1 Silica Fume

Silica fume is a fine-grain, thin and very high surface area silica. It is a by-product in the reduction of high-purity quartz with coke in electric arc furnaces in the production of silicon and ferrosilicon alloys. Silica fume consists of fine vitreous particles with a surface area on the order of 20,000 m²/kg, when measured by nitrogen adsorption techniques, with particles approximately one hundredth the size of the average cement particle. The silica fume used in this study was obtained from China. Because of its extreme fineness and high silica content, it is a very effective pozzolanic material. It is used in concrete to improve the compressive strength, bond strength and abrasion resistance. The physical properties and typical chemical analysis of silica fume are shown in Table 3-1.

Table 3-1 : Physical Properties and Chemical Analysis of Silica Fume

Physical Properties		Typical Chemical Analysis %	
Surface Area(m ² /kg)	15000-20000	Silica, SiO ₂	98.7
Bulk Density (kg/m ³)	2680	Alumina, Al ₂ O ₃	0.01
Specific Gravity	2.68	Iron, Fe ₂ O ₃	0.01
Particle shape	Spherical	Calcium, CaO	0.28
		Potassium, K ₂ O+Sodium, Na ₂ O	0.09
		Magnesium, MgO	0.01

3.4.2 Limestone Powder

Limestone powder is the fine granules of calcium carbonate. It is white in appearance and is finer than cement with a specific surface of 500-600 m²/kg. The physical properties and typical chemical analysis are shown in Table 3-2.

Table 3-2: Physical Properties and Chemical Analysis of Limestone Powder

Physical Properties		Typical Chemical Analysis %	
Surface Area(m ² /kg)	500-600	Silica, SiO ₂	0.45
Bulk Density (kg/m ³)	2590	Alumina, Al ₂ O ₃	0.33
Specific Gravity	2.59	Iron, Fe ₂ O ₃	0.14
Particle shape	Spherical	Calcium, CaO	52.35
		Potassium, K ₂ O+Sodium, Na ₂ O	0.08
		Magnesium, MgO	1.05
Loss on Ignition			45.6

3.4.3 Fly Ash

Fly ash is one of the residues obtained during the combustion of coal. It is a cement enhancer with all round benefits for high performance concrete, repair mortars and spray concrete. Its pozzolanic activity ensures increased strength and durability, while the particle size distribution and spherical shape increases the workability and reduces the water requirement. Type F fly ash was used in this study, which is pozzolanic in nature and contains less than 20% CaO. It requires a cementing agent, such as Portland cement with the presence of water in order to react and produce cementitious compounds. The physical properties and typical chemical analysis of fly ash are shown in Table 3-3.

Table 3-3: Physical Properties and Chemical Analysis of Fly Ash

Physical Properties		Typical Chemical Analysis %	
Surface Area(m ² /kg)	300	Silica, SiO ₂	62.88
Bulk Density (kg/m ³)	2090	Alumina, Al ₂ O ₃	29.5
Specific Gravity	2.09	Iron, Fe ₂ O ₃	3.27
Particle shape	Spherical	Calcium, CaO	0.86
Color	Light grey	Potassium, K ₂ O+Sodium, Na ₂ O	0.16
		Magnesium, MgO	0.7

3.5 Aggregates

3.5.1 Coarse Aggregates

The coarse aggregates used in this study were crushed limestone from the local quarries of Riyadh Road. The maximum aggregate size was kept at 20 mm. Grading of the coarse aggregates is shown in Table 3-4 and 3-5. The average values of specific gravity and absorption of coarse aggregates, determined in accordance with ASTM C128, were 2.56, and 1.65% for 20mm, 2.54 and 1.75% for 10 mm and 2.54 and 2.55% for 5 mm respectively.

Table 3-4: Grading of Coarse Aggregates (20mm)

Sieve opening	Percent passing
25 mm	100
19 mm	99
12.5 mm	17
9.5 mm	2
4.75 mm	1
2.36 mm	1

Table 3-5: Grading of Coarse Aggregates (10mm)

Sieve opening	Percent passing
12.5 mm	98
9.5 mm	60
4.75 mm	3
2.36 mm	1
1.18 mm	1

3.5.2 Fine Aggregates

Table 3-6: Grading of Fine Aggregates

Sieve opening	Percent passing
2.36 mm	100
1.18 mm	100
0.6 mm	95
0.3 mm	40
0.15 mm	12
0.075 mm	1

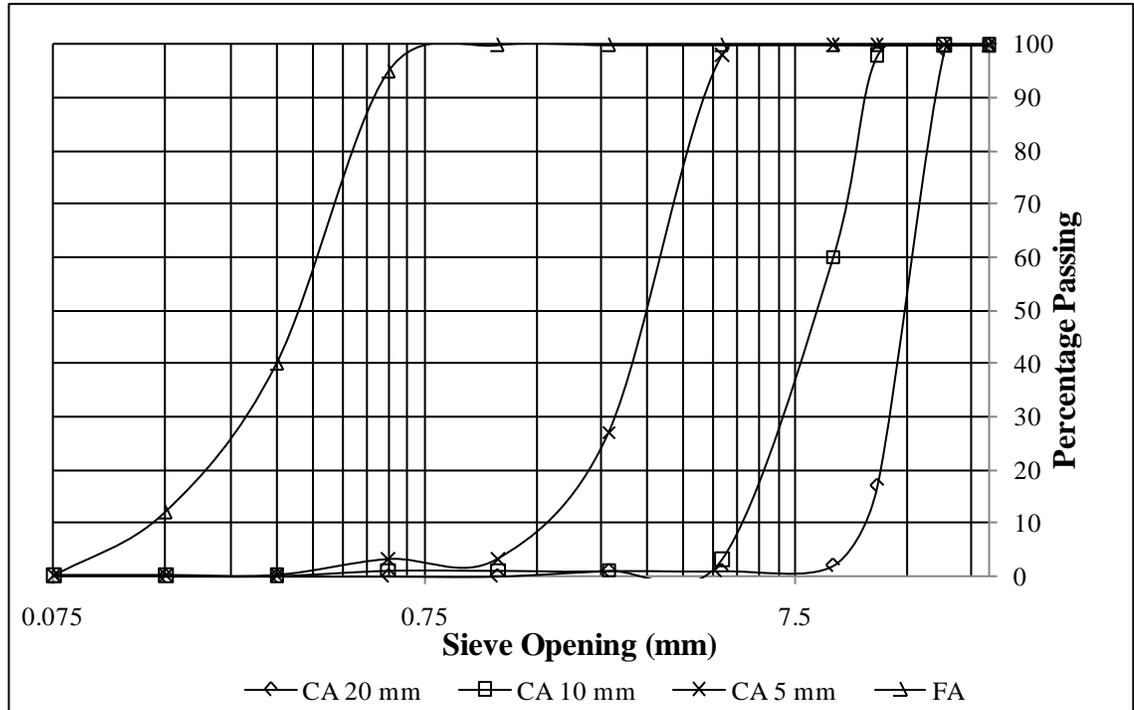


Figure 3-1: Aggregate Gradation

3.6 Super plasticizers

Super plasticizer by the name Viscocrete from Sika Corporation, was used. It is based on polycarboxylic polymer technology, which works by different mechanisms. Through surface adsorption and sterical separation effect on cement particles, in parallel to the hydration process, the following properties are obtained:

- 1) Strong self compacting behavior, therefore suitable for production of self compacting concrete.
- 2) Extremely high water reduction (resulting in high density and strengths).
- 3) Excellent flowability.

- 4) Improved shrinkage and creep behavior.
- 5) Economical in use for production of concrete in Ready Mix Concrete or Precast Industry.

The characteristics of Viscocrete are shown in Table 3-7.

Table 3-7: Characteristics of Viscocrete

Color	Yellowish brown liquid
Specific gravity	1.09 kg/l
pH	7
Chloride content	0

3.7 Mix Proportions

A reference mix was selected after conducting several trials based on low segregation and good flow properties. Water/powder ratio was kept constant at 0.3. Nine mixes were prepared by varying the amount of silica fume, limestone powder and fly ash. Proportions of the mixes, determined using the absolute volume method, are presented in Table 3-8.

Table 3-8: Mix Proportions

	Cement (kg/m ³)	Filler (kg/m ³)	Water (kg/m ³)	Coarse Aggregates (kg/m ³)	Fine Aggregates (kg/m ³)	Viscocrete (kg/m ³)
REF	485	0	144	1067	690	4.47
SF 2.5%	473	12	144	1067	690	3.55
SF 5%	461	24	144	1067	690	5
SF 7.5%	449	36	144	1067	690	5.26
LSP 5%	461	24	144	1067	690	6.31
LSP 10%	437	48	144	1067	690	5
LSP 15%	413	72	144	1067	690	4.2
FA 5%	461	24	144	1067	690	3.42
FA 7.5%	449	36	144	1067	690	3.55
FA 10%	437	48	144	1067	690	3.68

3.8 Preparation of SCC mixes

The method of preparation of mixes was the same for all mixes for uniformity and consistency. A little amount of water was poured in the bottom of the pan to reduce the friction when mixing in dry state. Coarse aggregate was the placed followed by cement, mineral filler and sand at the top. These ingredients were then mixed for 60 sec. One-half of the water was then added during mixing and the other one-half of water and superplasticizer was added slowly. The superplasticizer was very carefully in small increments to prevent bleeding. All the SCC mixes were mixed in a horizontal pan mixer.



Figure 3-2: Mixing of SCC

3.9 Fresh Property Tests

3.9.1 Slump Flow Test and T-50

The basic equipment used is the same as for the conventional Slump test. The test method differs from the conventional one: the concrete sample placed into the mould is not rodded and when the slump cone has been removed and the sample has collapsed. The diameter of the spread of the sample is measured i.e. a horizontal distance is determined as opposed to the vertical distance in the conventional Slump test. As well as measuring the diameter of the spread, the time that it takes the collapsed sample to reach a diameter of 500mm (T-50) is also measured. The Slump Flow test can give an indication as to the filling ability of SCC and an experienced operator can also detect an extreme susceptibility of the mix to segregation. However, this information cannot be obtained from numerical results alone, a substantial previous experience in using the test and carrying out construction in SCC is essential.

The test does not appear to be sensitive enough to distinguish between SCC mixes and super plasticized, fluid but not self-compacting concretes or those prone to segregation, which all can reach values between 550mm to 750mm. The test is the most widely used in practical applications of SCC mixes.



Figure 3-3: Slump flow test

3.9.2 V-Funnel Test



Figure 3-4: Equipment for V-Funnel Test

The V-funnel test is used to assess the viscosity and filling ability of self-compacting concrete. It consists of V-funnel, made as shown in Figure 3-4, fitted with a quick release, watertight gate at its base and supported so that the top of the funnel is horizontal. The V-funnel shall be made from metal with smooth surfaces, and not be readily attacked by cement paste or be liable to rusting. The concrete sample is poured in the funnel, without any agitation or rodding, and a container is placed below for collecting the concrete. The top of the funnel is striked off with a straight edge so that

the concrete is flush with the top of the funnel. After a delay of (10 ± 2) seconds from filling the funnel, the gate is opened and the time is measured starting from opening the gate to seeing the container vertically through the funnel for the first time. The measured time is termed as the V-funnel flow time.

3.9.3 L-Box Test

This method uses a test apparatus comprising of a vertical section and a horizontal trough into which the concrete is allowed to flow on the release of a trap-door from the vertical section passing through reinforcing bars placed at the intersection of the two areas of the apparatus. The time that it takes the concrete to flow a distance of 200mm (T-20) and 400mm (T- 40) into the horizontal section is measured, as is the height of the concrete at both ends of the apparatus (h_1 & h_2). The L-Box test can give an indication as to the filling ability and passing ability. Numerous L-boxes of widely different dimensions have been tried.



Figure 3-5 : L-Box

3.9.4 J-Ring Test

This involves the slump cone being placed inside a 300mm diameter steel ring attached to vertical reinforcing bars at appropriate spacing (the J-Ring itself). Like in the Slump Flow test, the diameter of the spread and the T-50 time are recorded, but the height of the concrete after the test within the J-Ring is also measured. The Slump Flow/JRing combination test is an improvement upon the Slump Flow test on its own as it aims to assess also the passing ability of the fresh mix. The difference in the slump flow spread and J-Ring should be within 0-100 mm.



Figure 3-6 : J-Ring testing equipment

3.10 Rheological Measurements

Rheological properties can be measured in capillary tube viscometers or rotational rheometers. In concrete, rotational rheometers are used predominantly in cases where the rheological parameters are to be determined in fundamental units while variations on capillary tube viscometers are used in limited cases.

According to Hackley and Ferraris(2001), rotational methods are generally better for concentrated suspensions, gels, and pastes despite the fact that capillary tube methods tend to be more precise in measuring viscosity. Rotational methods offer the advantage of being able to shear a sample indefinitely in order to achieve equilibrium and to monitor changes over time. For non-Newtonian fluids, the distribution of shear rate and shear stress is typically better defined in a rotational device than a capillary tube device. The problem of temperature rise due to shearing can be more of a problem in a rotational rheometer, although methods are available to limit temperature change. Capillary tube viscometers are typically cheaper and simpler than rotational rheometers.

3.11 Rotational Rheometers

Rotational rheometers apply shear stress to a single sample of material continuously. By measuring a series of combinations of shear stress and shear rates, a flow curve can be plotted. It is possible to impose a range of shear rates and determine the resulting shear stresses (controlled-rate rheometer) or to impose a range of shear stresses and measure the resulting shear rates (controlled-stress rheometer). Compared to a

controlled-rate rheometer, a controlled-stress rheometer typically has higher sensitivity, particularly at very low shear rates, and can better differentiate between highly non-Newtonian fluids.

Multiple geometrical configurations of rotational rheometers are available; three main rotational rheometer geometries are shown in Figure 3-7. Numerous variations of each geometry exist; the particular test set-up selected depends on the properties of the material to be tested. In a coaxial cylinders rheometer, the fluid is placed between two cylinders. It is possible either to rotate the outer cylinder at a series of fixed speeds while measuring the resulting torque on the fixed inner cylinder or to keep the outer cylinder fixed while torque and rotation speed are measured at the rotating inner cylinder. In a parallel plate rheometer, the bottom plate is fixed while the top plate rotates. Both torque and rotation speeds are measured at the top blade. The cone and plate rheometer is similar to the parallel plate rheometer, with the exception that a cone is used instead of a top plate. Coaxial cylinders and parallel plate rheometers have been used to measure the rheology of concrete and cement paste. The cone and plate rheometer configuration is less applicable to concrete due to the difficulty of fitting aggregates around the cone.

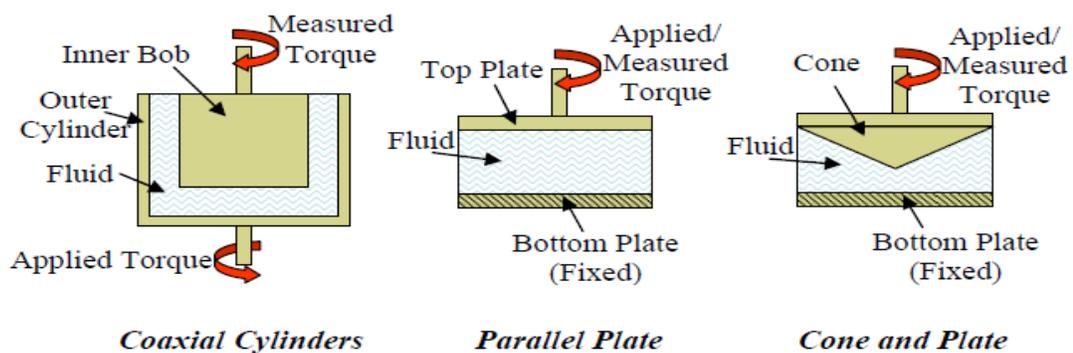


Figure 3-7: Typical Rotational Rheometer Geometries(ICAR, 2008)

In any of the above rheometer geometries, an assumption is made about the distribution of fluid velocity throughout the material. Therefore, using the dimensions of the rheometer, it is possible to develop analytical equations relating the torque and rotation speed measured by the rheometer to the specific parameters of a given constitutive equation.

3.12 Determination of Rheological Parameters of Yield Stress and Viscosity

An ICAR rheometer (ICAR, 2008) shown in Figure 3-8 was used to measure the rheology of SCC. It is composed of a container to hold the fresh concrete, a driver head that includes an electric motor and torque meter; a four-blade vane that is held by the chuck on the driver; a frame to attach the driver/vane assembly to the top of the container; and a laptop computer to operate the driver, record the torque during the test, and calculate the flow parameters. The container contains a series of vertical rods around the perimeter to prevent slipping of the concrete during the test. The size of the container and length of the vane shaft are selected based on the nominal maximum size of the aggregate. The vane has a diameter and height of 127 mm.



Figure 3-8: ICAR Rheometer

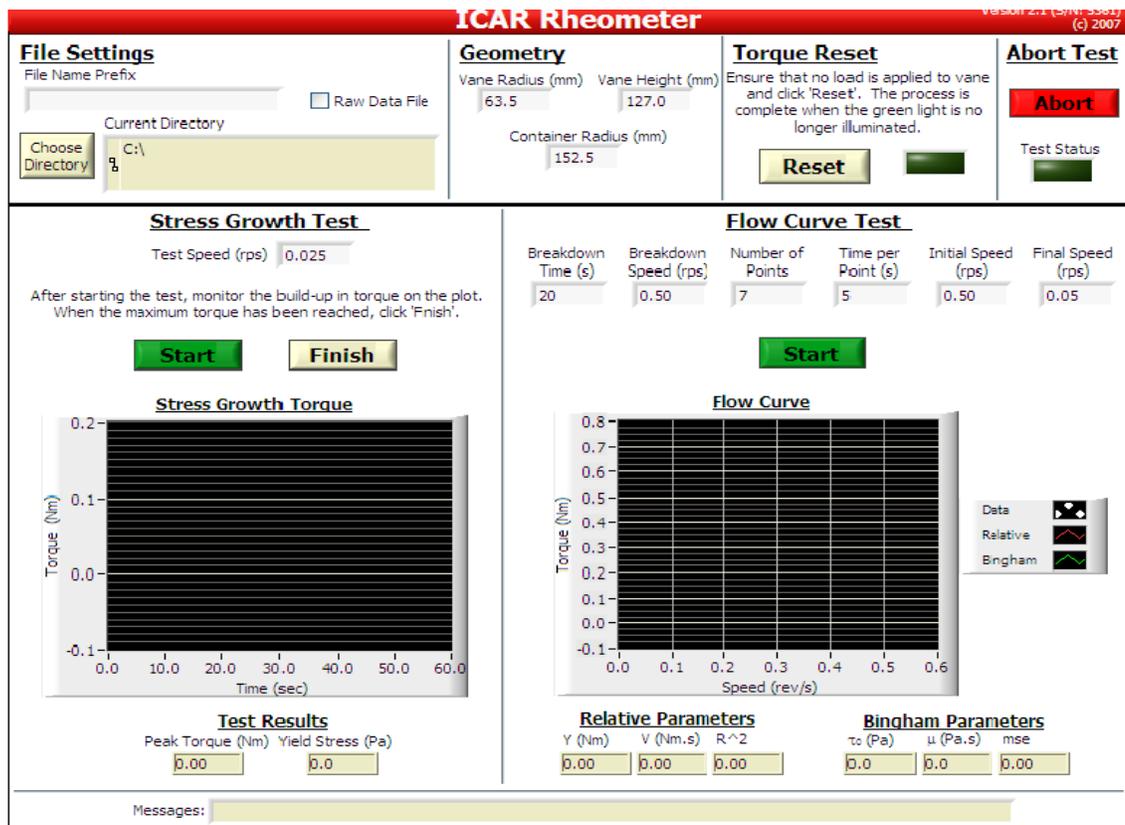


Figure 3-9: ICAR Rheometer Software Window

Two types of tests can be performed using the ICAR rheometer to study the rheology of SCC. They are the stress growth test and the flow curve test.

3.12.1 Stress Growth Test

In the stress growth test, the vane is rotated at a constant speed of 3.76 rad/sec. The build of torque is measured as a function of time. The maximum torque measured during the test is used to calculate the static yield stress.

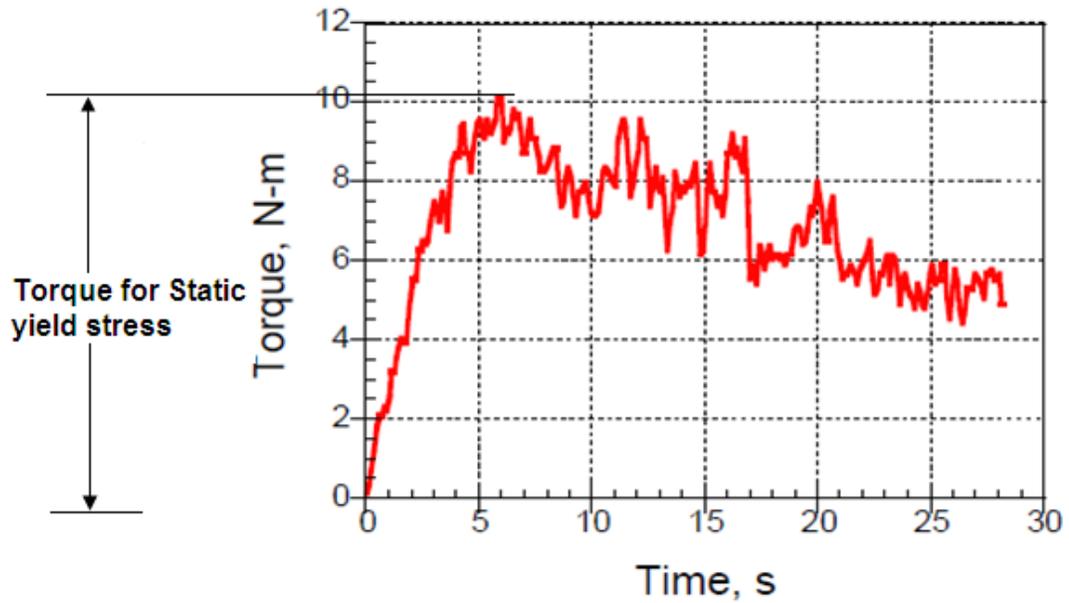


Figure 3-10: Stress growth test

The Figure 3-10 shows the results of a typical stress growth test. The peak torque and test geometry are used to calculate the static yield stress, which is displayed at the bottom of the computer display.

3.12.2 Derivation of Static Yield Stress

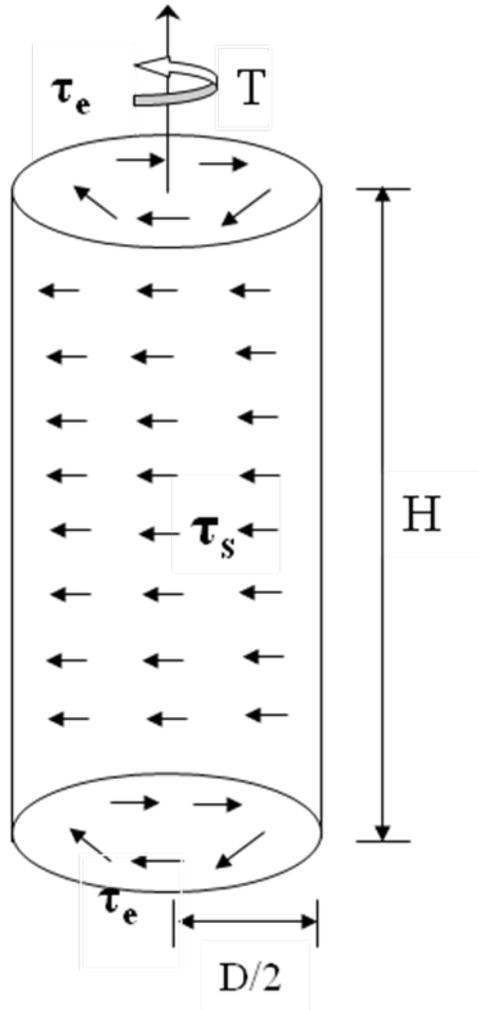


Figure 3-11: Shear Stress Distribution

In order to calculate the static yield stress from the torque readings, it is necessary to consider analytically the distribution and magnitude of the shear stress acting on the ends of the vane. From equilibrium, the total torque acting on the vane, T , is the sum of torques attributable to the side, T_s , and the two ends T_e , of the vane.

$$T = T_s + 2T_e \quad (3-1)$$

$$T_s = \tau_s(2\pi R)H(R) = \frac{\pi D^2 H}{2} \tau_s \quad (3-2)$$

$$T_e = 2\pi \int_0^{D/2} \tau_e(r) r^2 dr \quad (3-3)$$

Assuming the shear stresses acting on the side and ends of the vane are evenly distributed i.e. $\tau_s = \tau_e = \tau_{ys}$, we obtain

$$T = \frac{\pi D^2 H}{2} \tau_{ys} + 2(2\pi \int_0^{D/2} \tau_{ys} r^2 dr) \quad (3-4)$$

$$\Rightarrow \tau_{ys} = \frac{2T}{\pi D^3 \left(\frac{H}{D} + \frac{1}{3} \right)} \quad (3-5)$$

The calculation of the stress at the other points in the stress growth test is done by using the Reiner-Riwlin equations depending on whether all the material in the container is flowing or not.

The effective radius separates the flowing region from the non-flowing region. It is calculated using the equation

$$R_{2,eff} = \sqrt{\frac{T}{2\pi h \tau}} \quad (3-6)$$

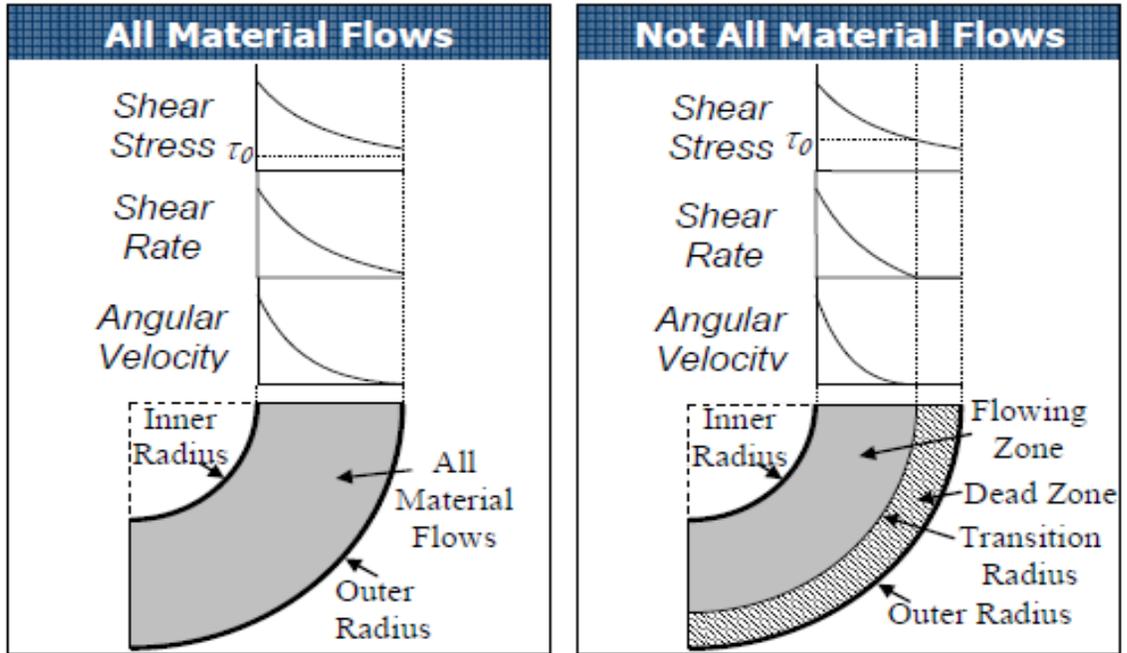


Figure 3-12: Illustration of cases where all material flows and not all material flows (ICAR, 2008)

In the region where the shear stress in a portion of the material in the annulus is below the yield stress, the material does not flow and the effective radius is less than the container radius. In the case of the material flowing completely, the effective radius is more than the container radius. At the start of the stress growth test, the material will be partly flowing in the container and after passage of time; it flows completely in the container.

For the case for where all material flows, the Reiner-Riwlin equation (ICAR, 2008) is

$$\dot{\gamma} = \frac{T}{4\pi h\mu} \left(\frac{1}{R_1^2} - \frac{1}{R_2^2} \right) - \frac{\tau}{\mu} \ln \left(\frac{R_2}{R_1} \right) \quad (3-7)$$

For the case where not all material flows:

$$\dot{\gamma} = \frac{T}{4\pi h \mu} \left(\frac{1}{R_1^2} - \frac{2\pi h \tau}{T} \right) - \frac{\tau}{2\mu} \ln \left(\frac{T}{2\pi h \tau R_1^2} \right) \quad (3-8)$$

h - Vane height (mm)

R_1 - Vane Radius (mm)

R_2 - Container Radius (mm)

T - Torque (N-mm)

3.12.3 Flow Curve Test

The flow curve test was used to determine the dynamic yield stress and the plastic viscosity. It begins with a “breakdown” period in which the vane is rotated at maximum speed of 3.76 rad/sec. This is done to breakdown any thixotropic structure that may exist and to provide a consistent shearing history before measuring the Bingham parameters. The vane speed is then reduced in seven steps. During each step the speed is held constant and the average speed and torque is recorded. The plot of torque versus speed of vane rotation is the flow curve as shown in Figure 3-13. The ICAR Rheometer software performs all the necessary functions: operates the drivers, records the torque, computes test results, and stores data. The entire program is operated from a single screen as shown below. The user defines the test geometry and provides the test parameters to run the flow curve test. A single test takes less than two minutes to complete.

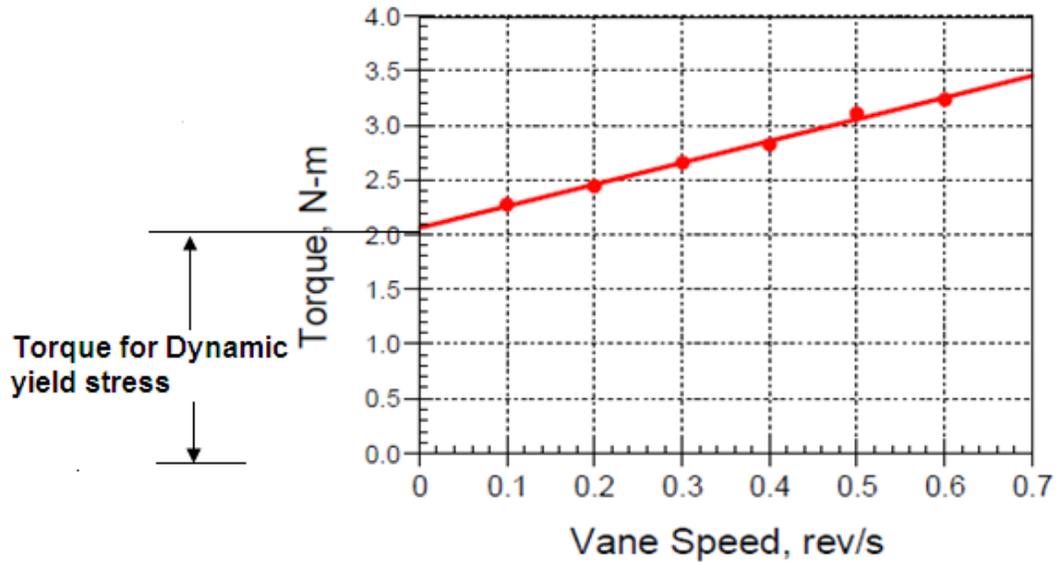


Figure 3-13: Flow Curve Test

Figure 3-13 shows the plot of the average torque and average vane rotation measured during the seven steps of decreasing vane speed. The software computes a best-fit line to the data and reports the intercept and slope as relative parameters. The software also computes the Bingham parameters of dynamic yield stress and plastic viscosity.

3.13 Testing SCC for Static Segregation

The following tests were carried out:

1) Static segregation tests including:

a) Hardened VSI:

This method SCC-6(2004) assesses static segregation of SCC by using a hardened cast cylinder of the material. The test produces a parameter known as the Hardened Visual Stability Index (HVSI). HVSI is a qualitative measurement of the distribution of coarse aggregate from a sectioned cylinder. A minimum of two cylinders obtained from a single sample of SCC are required. The method is conducted by placing SCC in a standard 6 × 12 in. cylinder and allowing the concrete to harden. The cylinder is then cut length-wise with a concrete saw, exposing a section of the cylinder to view the top to bottom distribution of coarse aggregate. The ratings shown in Table 3-9 are assigned on the basis of visual observation from Figure 3-14.

Table 3-9: Hardened Visual Stability Index (HVSI)

HVSI	Criteria
0 stable	No paste/mortar layer on top of the cylinder, and no difference in size and area percentage of coarse aggregates lengthwise.
1 stable	No paste mortar layer on top of the cylinder, but slight difference in size and area percentage of coarse aggregates lengthwise.
2 unstable	Slight paste/mortar layer-less than 1 in. (25 mm) – on top of the cylinder.
3 unstable	Significant paste/mortar layer- greater than 1 in. (25 mm) – on top of the cylinder, and/or clear evidence of difference in size and area percentage of coarse aggregates lengthwise.

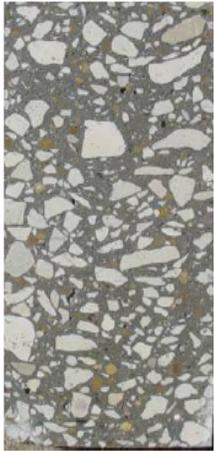
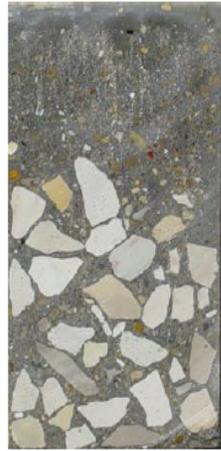
Rating	0 (Stable)	1 (Stable)	2 (Unstable)	3 (Unstable)
Image				
Description	No mortar layer at the top of the cut plane and no variance in size and percent area of coarse aggregate distribution from top to bottom.	No mortar layer at the top of the cut plane but slight variance in size and percent area of coarse aggregate distribution from top to bottom.	Slight mortar layer, less than 25 mm (1 in.) tall, at the top of the cut plane and distinct variance in size and percent area of coarse aggregate distribution from top to bottom.	Clearly segregated as evidenced by a mortar layer greater than 25 mm (1 in.) tall and/or considerable variance in size and percent area of coarse aggregate distribution from top to bottom.

Figure 3-14: HVSI ratings

b) Segregation Probe:

A segregation probe (SCC-7, 2004) was used to measure static segregation of fresh SCC. The segregation probe is placed on the top of a sample of SCC in a 6 × 12 in. (150 × 300 mm) cylinder that has been allowed to rest undisturbed for two minutes. Any static segregation will be revealed by the probe as it comes to rest on top of the coarse aggregate that may have settled. The segregation probe used in the study was made from a 3/32-in. (2.38-mm) diameter steel wire, and shaped to have a circular base with a diameter of 4-in. (100-mm). The penetration depth is an indicator of the thickness of the paste layer that exists at the top of a segregated sample of SCC. An

illustration of the probe is shown in Figure 3-15. The interpretation of results is shown in Table 3-10.

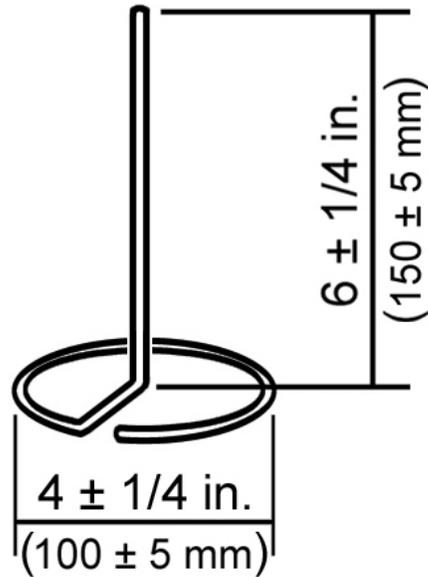


Figure 3-15 : Segregation Probe

Table 3-10 : Measured Stability Index (MSI)

Settlement depth, in. (mm)	MSI	Corresponding HVSI from a cut cylinder
< 1/8 (4)	0 stable	0 stable
1/8-1/4 (4-7)	1 stable	1 stable
1/4-1 (7-25)	2 unstable	2 unstable
>1 (25)	3 unstable	3 unstable

3.14 Testing SCC for Dynamic Segregation

The Flow Trough Method (SCC-9, 2004) was used to estimate the dynamic segregation index. It is made by assembling 1-in. (25-mm) thick wood boards to form a 6 × 6 × 72 in. (150 × 150 × 1800 mm) trough as shown in Figure 3-16. The inclined angle is 7° (9-in. (230-mm) height difference between the two ends). The surface of the trough is painted to make it water-resistant and easy to clean.

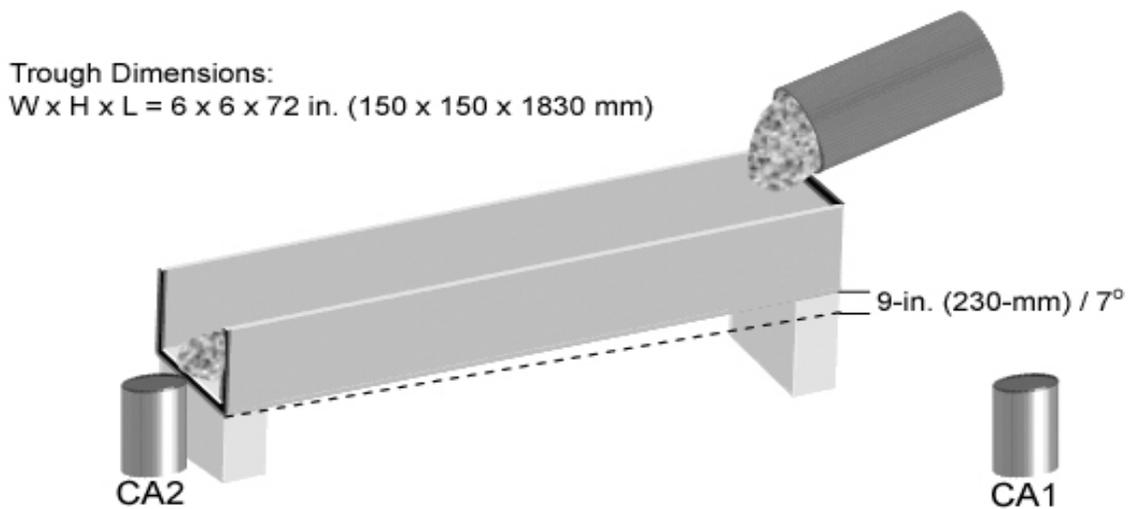


Figure 3-16 : Flow Trough

The test is conducted by pouring a sample of SCC at the top end of the trough, and collecting a sample at the bottom end. The coarse aggregate contents of the two samples collected in 4 × 8 in. (100 × 200 mm) cylinders is obtained by washing the material over a #4 sieve and weighing the aggregate remaining on the sieve. The dynamic segregation index (DSI) is then calculated as

$$DSI = \frac{CA_1 - CA_2}{CA_1} \quad (3-9)$$

where CA1 is weight of coarse aggregate from the sample of original SCC and CA2 is weight of coarse aggregate from the sample collected at the bottom of the trough.

CHAPTER 4

RESULTS

4.1 Introduction

In this chapter, test results of all the SCC mixes will be described. These cover tests on fresh concrete i.e. slump flow, T-50 (flow time), V-funnel time, L-box, J-Ring, static segregation test using the segregation probe, dynamic segregation test using the Flow Trough, determination of rheological parameters of yield stress and viscosity using the ICAR Rheometer and tests on hardened SCC cylinders which consist of determining static segregation on cut hardened cylinders and compressive strength.

4.2 Tests on Fresh SCC

The results of workability tests such as slump flow (spread), slump flow time (T-50), V-funnel time, L-box ratio, J-Ring test are summarized in Table 4-1. Results were evaluated according to “The European Guidelines for Self Compacting Concrete.” (EFCA, 2005)

Table 4-1: Fresh Properties of SCC

Mix	Slump flow (mm)	T-50 (s)	V-funnel(s)	L-Box Ratio	J-Ring (mm)
REF	720	4.5	12	0.97	630
SF 2.5%	690	6	11.4	1	630
SF 5%	680	4.5	11	1	650
SF 7.5%	700	5.4	12	0.96	660
LSP 5%	720	4	14	1.13	610
LSP 10%	755	3.5	17	1.15	580
LSP 15%	720	5	10	0.93	620
FA 5%	725	4.25	13	1.15	630
FA 7.5%	720	5.4	12	0.86	650
FA 10%	730	5.5	11.2	1.15	620

4.2.1 Slump Flow

All the mixes exhibited slump flow values within the acceptable range of 650-800 mm. SCC mix with 10% LSP gave a slump flow of 755 mm. Based on the slump flow diameter, SCC is categorized as: SF1 (550-650 mm), SF2 (660-750 mm), SF3 (760-800 mm)(EFCA, 2005). None of the mixes fall into the SF1 category since the minimum targeted slump flow was above 650 mm. All the mixes except LSP 10% fall into the SF2 category which is suitable for many normal applications (e.g. walls, columns). LSP 10% which has a slump flow of 755 mm falls into the SF3 category and can be used for vertical applications in very congested structures, structures with complex shapes, or for filling under formwork. SF3 generally gives better surface finish than SF2 for normal vertical applications but segregation resistance is more difficult to control.

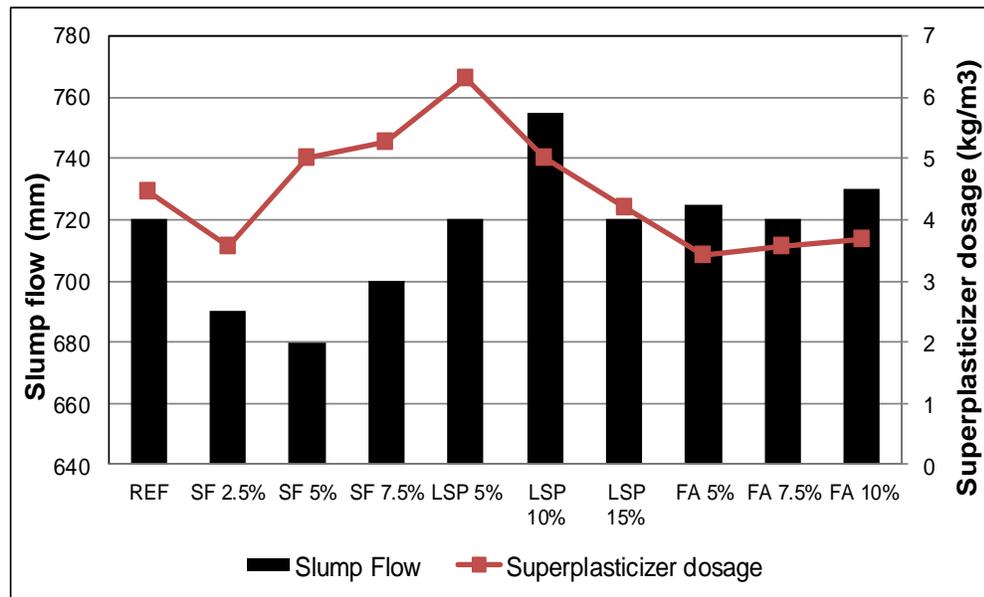


Figure 4-1: Superplasticizer Dosage Requirement

Figure 4-1 shows the superplasticizer dosage requirement for all the mixes to achieve satisfactory slump flow. The SP requirement for the reference mix was 4.47 kg/m³. For SCC mix with 2.5% SF the SP dosage was 3.55 kg/m³ which increased to 5.26 kg/m³ for mix with 7.5% SF. The SP dosage for 5% LSP was 6.31 kg/m³ which decreased to 4.2 kg/m³ for 15% LSP. SP requirement for FA did not vary much when the dosage of FA was increased from 5-10%.

4.2.2 Flow time (T-50)

T-50 for all the mixes is found to be within the range of 2-5 sec except for SF 2.5%. SCC can be classified as VS1 for $T-50 \leq 2$ seconds or as VS2 for $T-50 > 2$ seconds. Class VS1 has good filling ability while class VS2 is more likely to become fluid when shaken or stirred, and is helpful in limiting the formwork pressure and improving segregation resistance. All the mixes fall into the VS2 category meaning they are less prone to segregation.

4.2.3 V-Funnel Time

Concrete mixtures are classified as VF1 if the V-funnel flow time is ≤ 8 seconds and VF2 if it is between 9 and 25 seconds. VF1 mixtures have good filling ability even with congested reinforcements and capable of self-leveling producing a good surface finish. VF2 mixtures tend to exhibit thixotropic effects, which may be helpful in limiting formwork pressure or improving segregation resistance.

All the mixes fall into the VF2 category with the range being 10-17 seconds. SCC mixes with silica fume had a V-funnel time of around 12 seconds while mixes with

limestone powder had a big variation from 10-17 seconds and mixes made with flyash also had a V-funnel time around 12 seconds.

4.2.4 L-Box Passing Ability

Aggregate blocking has to be avoided when SCC flows through the reinforcement and the L-box test gives an indication of the passing ability. An L-box ratio between 0.8-1 represents an SCC with good passing ability with three rebars.

All the mixes have a good passing ability with an L-box ratio above 0.8. They are classed as PA2. These mixes can be used for structures with a rebar spacing of 60-80 mm.

4.2.5 J-Ring

The J-Ring test is also used to determine the passing ability of an SCC mixture. The difference between the flow diameter in the slump flow test and the J-Ring test should be between 0-100 mm. All mixes satisfy this criteria showing that they have adequate passing ability.

4.3 Rheological Parameters of Yield Stress, Viscosity and Thixotropy

The rheological parameters of dynamic yield stress and plastic viscosity, τ_0 and μ measured for the ten SCC mixes are shown in Table 4-2. The flow curves of all the mixes are plotted in Figure 4-2. If the yield stress of a SCC mix is high, then the concrete will not flow freely but will resist bleeding and segregation. The plastic viscosity on the other hand gives a measure of the workability and stickiness of the SCC mix. A SCC with high plastic viscosity will present difficulty in pumping of concrete. The yield of the SCC mixes investigated in the experimental program stress ranges from 32 Pa for 10% FA mix to about 65 Pa for 2.5% and 5% SF mix. The plastic viscosity of the mixes varies from 48 Pa-s for the reference and 5%FA mixes to about 71 Pa-s for the 7.5% SF mix. For SF mixes, it can be observed that the plastic viscosity increases with the increase in the dosage of SF, although the variation is not much. It can be seen that SCC with 7.5% SF may present difficulty in pumping due to stickiness although the conventional test shows that the slump flow is 700mm. For limestone powder and fly ash, the plastic viscosity first decreases and then increases as the dosage of LSP and FA is increased. The yield stress is plotted against plastic viscosity in Figure 4-3. All the mixes lie out of the self compacting zone suggested by Nielsson and Wallevik (2003), but still have satisfactory flowing and passing ability as confirmed by the conventional tests. The slump flow is plotted against the yield stress in Figure 4-4 and it can be seen that the slump flow decreases as the yield stress increases.

Table 4-2 : Bingham Parameters

Mix	τ_0 (Pa)	μ (Pa-s)
REF	56.3	48.4
SF 2.5%	65.1	52.5
SF 5%	65.5	54.9
SF 7.5%	58.4	71.2
LSP 5%	39.3	59.2
LSP 10%	45.5	53.1
LSP 15%	36	63
FA 5%	34	48.9
FA 7.5%	47.4	62.9
FA 10%	32.2	58.6

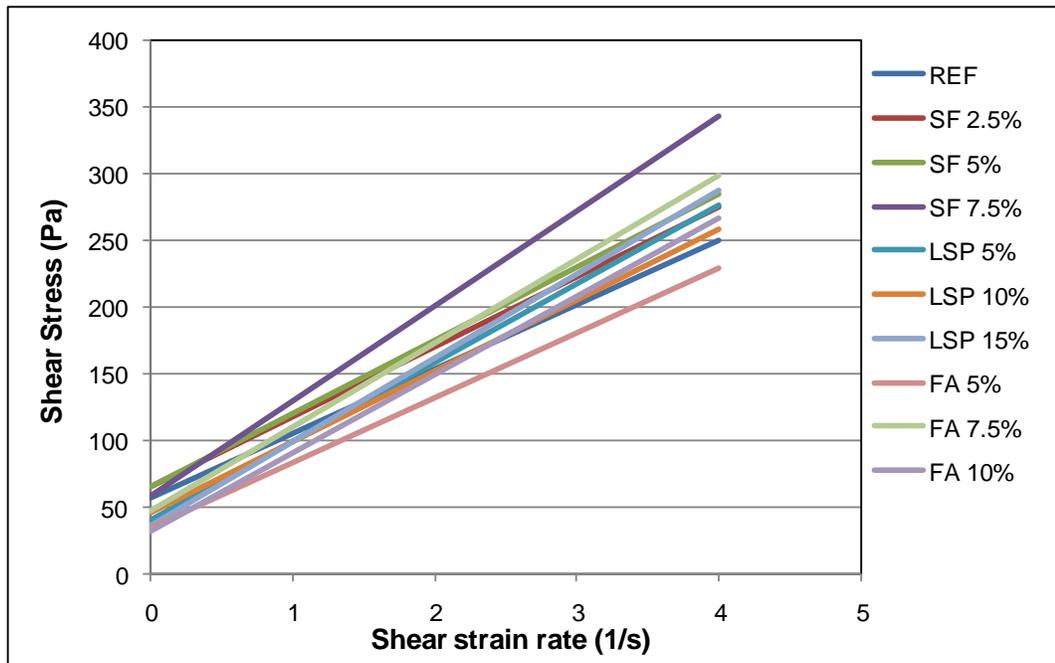


Figure 4-2: Shear stress vs Shear strain rate

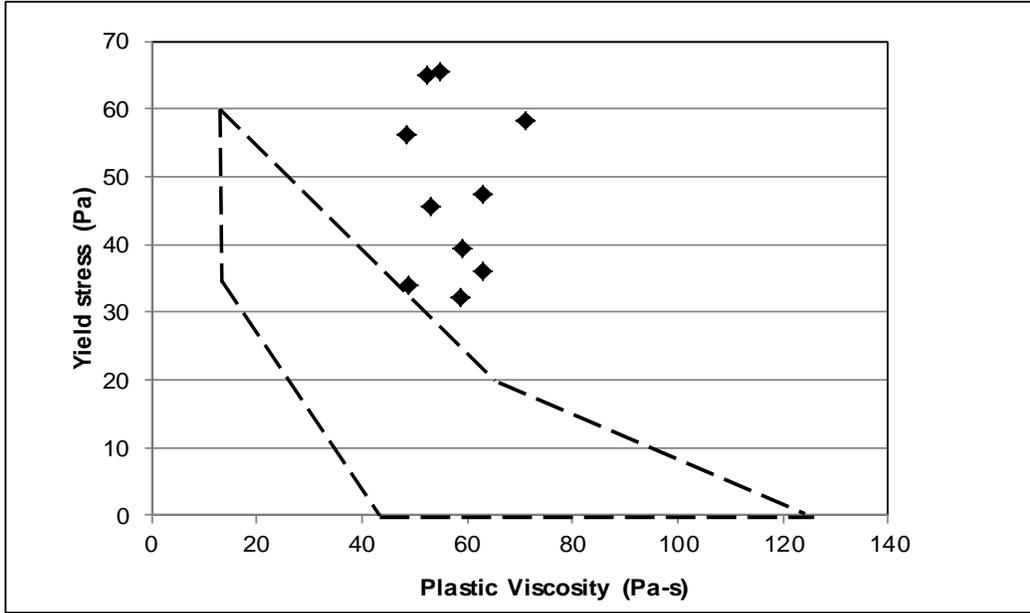


Figure 4-3 : Yield stress vs Plastic Viscosity

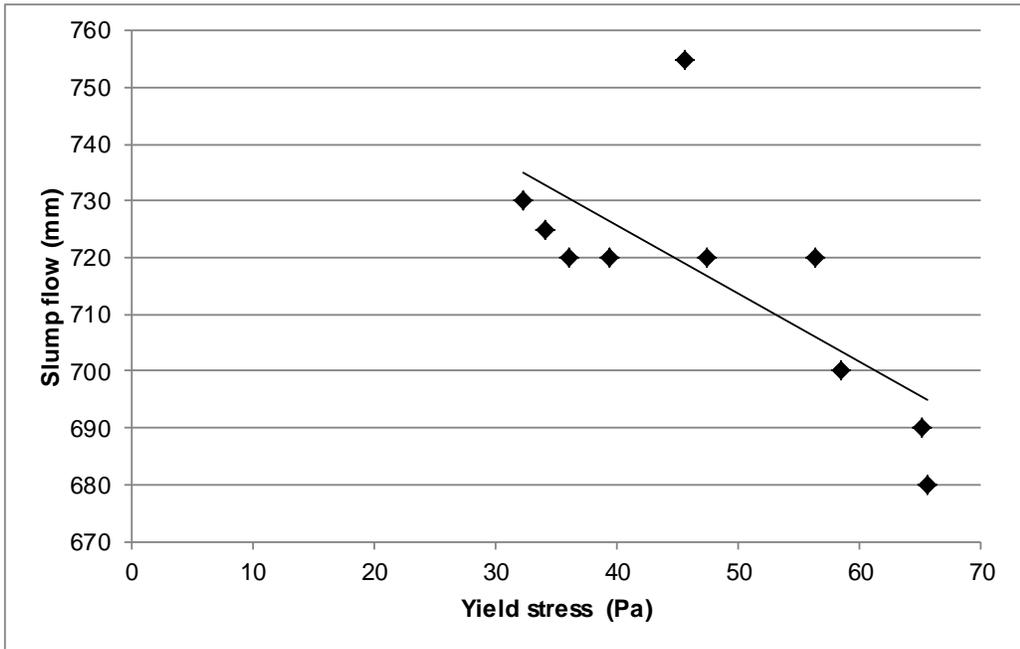


Figure 4-4: Slump Flow vs Yield stress

4.4 Thixotropy Parameters

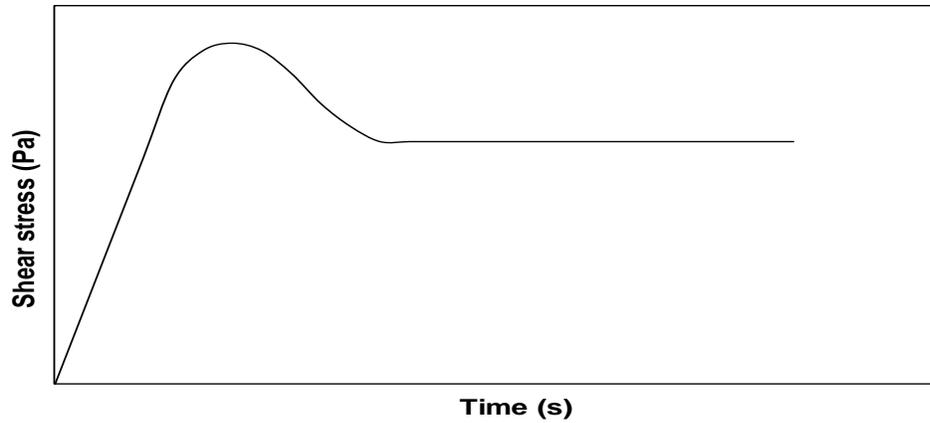


Figure 4-5: Shear stress vs time at constant shear rate

The thixotropy parameters were determined by performing the stress growth test at a constant shear rate of 3.76 s^{-1} after various resting times (1 minute, 5 minutes and 15 minutes). The static yield stress and the time needed to reach steady state increases with increase in resting time. A typical plot from the stress growth test can be seen in Figure 4-5.

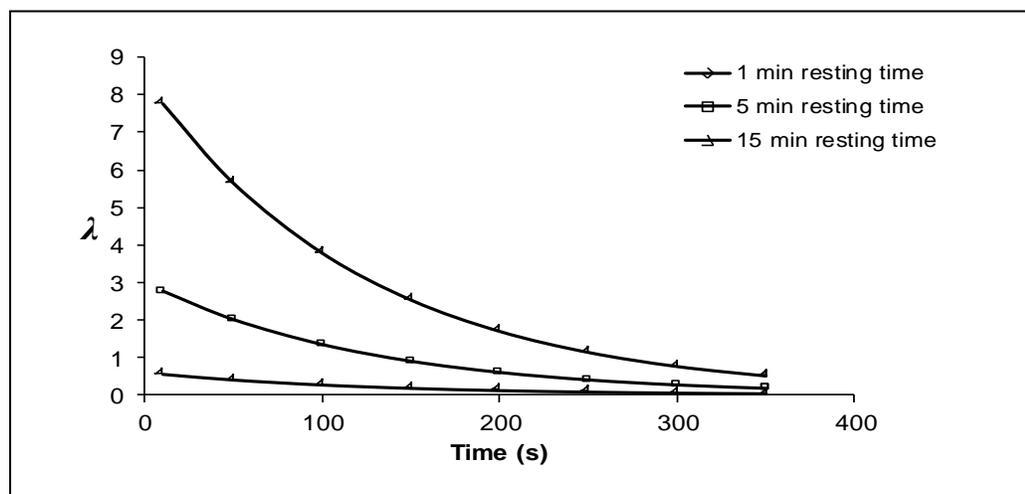


Figure 4-6: λ vs time at constant shear rate

The value of the λ parameter is calculated from Equation (2-7), wherein $\dot{\gamma} = 0$ and τ is calculated using Equation (3-5) for the the peak torque and Equations (3-7) and (3-8) for the other points. The initial value of lambda (λ_0) is high due to flocculation and when shearing is started, λ decreases exponentially towards zero with time (Equation (2-10)) as shown in Figure 4-6.

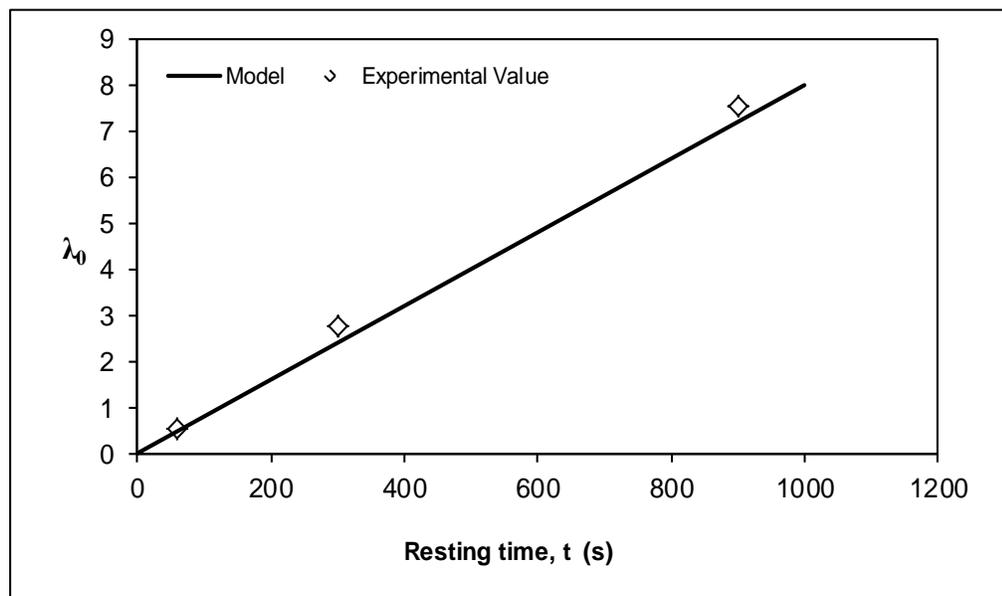


Figure 4-7: λ_0 vs Resting time

The initial lambda values λ_0 (computed from increased values of τ due to resting times) are plotted in Figure 4-7. The characteristic flocculation time T is calculated from the plot of λ_0 vs resting time, since $\lambda_0 = t/T$. The deflocculation parameter α is obtained by fitting an exponential function in the plot of lambda vs time for different resting times (Figure 4-6).

The relative viscosity as defined by Roussel (2006) is the ratio of measured apparent viscosity to the steady state apparent viscosity. For every resting time, the apparent

viscosity tends towards the steady state apparent viscosity. The apparent viscosity and the steady state apparent viscosity can be calculated using Equation (4-1), by substituting for τ_0 , μ , $\dot{\gamma}$ and λ as a function of time (Figure 4-8).

$$\mu_{\text{app}} = \frac{\tau_0(1 + \lambda)}{\dot{\gamma}} + \mu \quad (4-1)$$

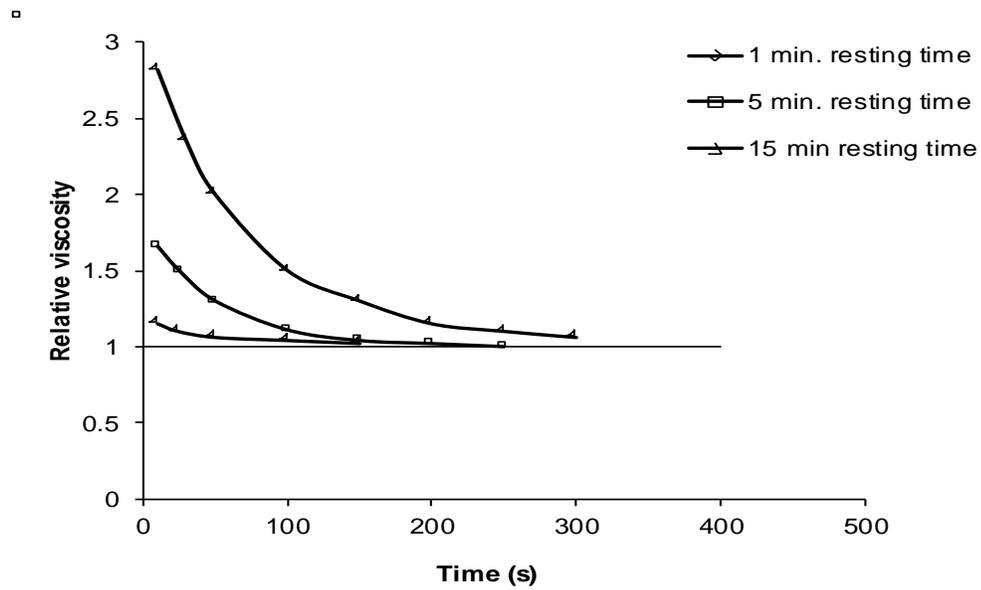


Figure 4-8: Relative viscosity vs Time for SF 5%

The results of all the thixotropic parameters (T , α , A_{thix}) for all the mixes is summarized in Table 4-3.

Table 4-3: Thixotropy Parameters for all Mixes

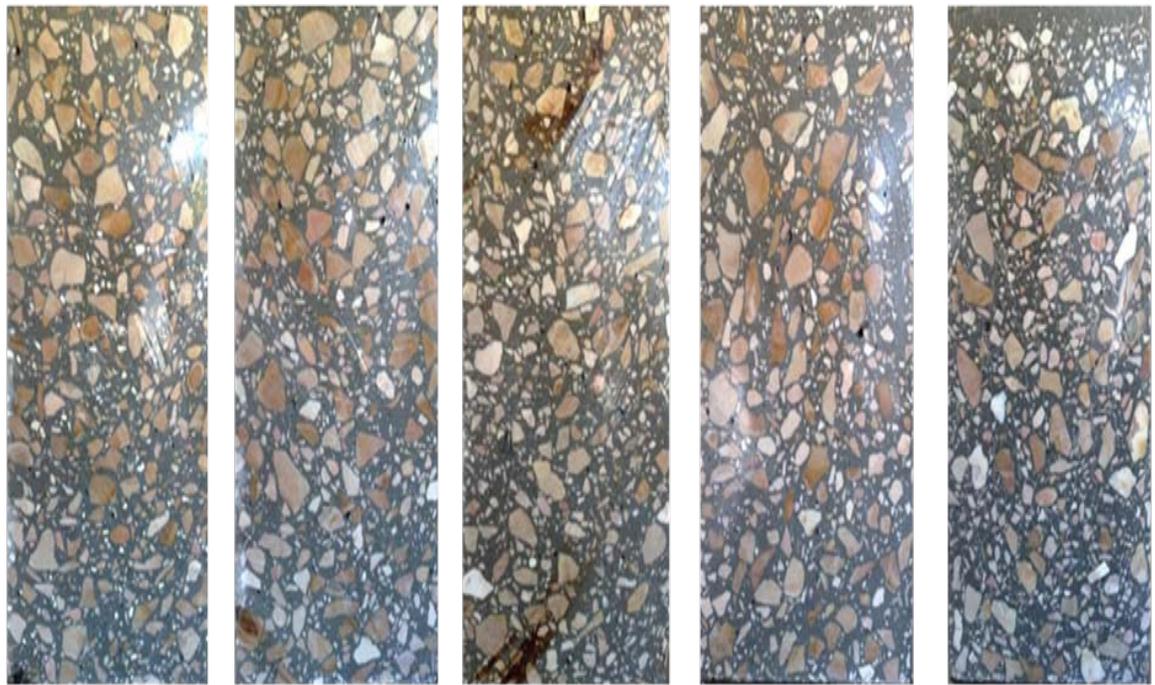
Mix	T(s)	λ_0			α	A_{thix}
		1m	5m	15m		
REF	125	2.1	3	6.8	0.0038	0.46
SF 2.5%	90.9	3.5	5.6	9.6	0.0025	0.715
SF 5%	111	0.5	2.7	7.5	0.0019	0.53
SF 7.5%	111	3	4.4	11.5	0.0037	0.52
LSP 5%	76.9	4	6.5	11.2	0.0027	0.51
LSP 10%	71.4	4.8	7.5	11.2	0.0037	0.63
LSP 15%	52.6	5	7.8	16.5	0.0039	0.68
FA 5%	111	2	5	8	0.0039	0.3
FA 7.5%	67	3.5	7.4	13	0.0027	0.7
FA 10%	20	8	20	42	0.0027	1.6

4.5 Static Segregation

The results of static segregation test conducted on the SCC mixes using the segregation probe are shown in Table 4-4. It can be seen from this table that two mixes with 5% and 10% LSP are slightly unstable. These mixes also have high flow in the slump test. SCC with 2.5% SF, 5% FA and 7.5% FA have a stability rating of 0, which indicates a good mix in which the penetration depth of the segregation probe is less than 4 mm. SCC with 5% SF, 7.5% SF, 15% LSP and 10% FA have a stability rating of 1, indicating a penetration of 4 to 7 mm. Figure 4-9 shows the cut section through the cylinder. It can be seen from this figure that SCC mix with 5% and 10% LSP has a mortar layer less than 25 mm at the top, which indicates segregation. The SCC mixes with 2.5% SF, 5% FA and 7.5% FA and the reference mix shows no variance in size and percent area of coarse aggregate distribution from top to bottom. Other mixes have slight variation in size and percent area of coarse aggregate distribution across the section and are also stable without significant segregation.

Table 4-4 : Segregation Probe and HVSI rating

Mix	Segregation probe penetration depth (mm)	Corresponding rating in HVSI of cut cylinder
REF	0	0 Stable
SF 2.5%	0	0 Stable
SF 5%	0	1 Stable
SF 7.5%	0	1 Stable
LSP 5%	5	2 Unstable
LSP 10%	12	2 Unstable
LSP 15%	0	1 Stable
FA 5%	0	0 Stable
FA 7.5%	0	1 Stable
FA 10%	0	1 Stable



Base mix: 0 stable

SF 2.5%: 0 stable

SF 5%: 1 stable

SF 7.5%: 1 stable

LSP 5%: 2 unstable



LSP 10%: 2 unstable

LSP 15%: 1 stable

FA 5%: 0 stable

FA 7.5%: 1 stable

FA 10%: 1 stable

Figure 4-9 : HVSI rating of cut cylinders

4.6 Dynamic Segregation

The dynamic segregation test was performed for all the concrete mixes using the Flow Trough method. The dynamic segregation Index of all the mixes was found to be less than 15% except for 10% LSP which showed high dynamic segregation of 37.52%, indicating that the aggregates will not segregate for all mixes except 10% LSP. 7.5% SF could not reach the bottom of the flow trough, because of its high viscosity.



Figure 4-10: Dynamic Segregation Test

The results from the dynamic segregation test are presented in Table 4-5.

Table 4-5: Dynamic Segregation Index (%)

Mix	Dynamic Segregation (%)
REF	13.66
SF 2.5%	10.14
SF 5%	14.4
SF 7.5%	-
LSP 5%	11.8
LSP 10%	6.29
LSP 15%	37.52
FA 5%	15.04
FA 7.5%	12.50
FA 10%	7.40

4.7 Compressive Strength

Compressive strength tests were performed at 7 days and 28 days for all the mixes. It is observed that all the mixes are high strength concretes with the maximum 28 d strength reaching 89 MPa for silica fume 2.5% and limestone powder 15%. The strength of decreases with increase in silica fume content from 2.5% to 7.5%, whereas it increases with increase in limestone powder content from 5% to 15% and the compressive strength for fly ash is maximum for fly ash content of 7.5%.

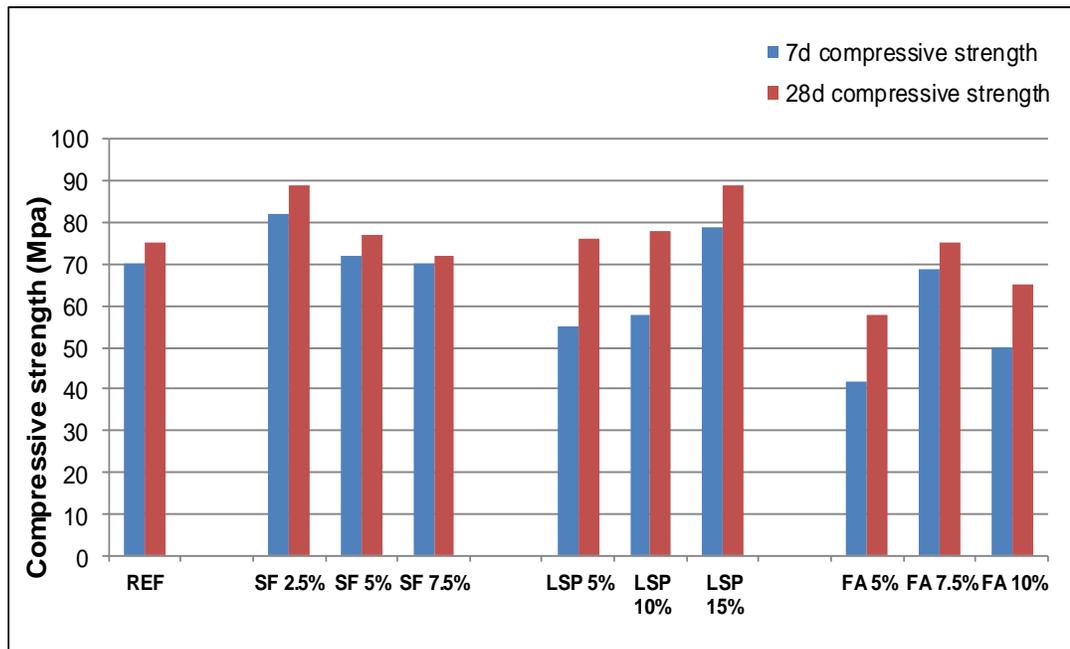


Figure 4-11: 7days and 28days compressive strength

4.8 Cost calculation for all mixes

The cost of all mixes is calculated for 1 m³ to obtain a general idea of the cost comparison of mineral admixed self compacting concrete using local materials. The cost of an ordinary concrete with a slump of 175 mm is about 237 SR/m³. The cost for the mineral admixed SCC's varies from 268-309 SR/m³. It was seen that SCC made with FA turns out to be the most economical among the mineral admixed SCC's.

Table 4-6 : Unit material cost for all mixes

Material Cost(SR/m ³)	Ordinary Concrete	REF	SF 2.5%	SF 5%	SF 7.5%	LSP 5%	LSP 10%	LSP 15%	FA 5%	FA 7.5%	FA 10%
Cement	120.0	145	142	138	134	138	131	124	138	134	131
Mineral Admixture	-	-	5.5	11.0	16.5	18.0	36.0	54.0	5.5	8.3	11.0
Water	1.5	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Coarse Aggregate	58.0	62.7	62.7	62.7	62.7	62.7	62.7	62.7	62.7	62.7	62.7
Fine Aggregate	29.0	27.6	27.6	27.6	27.6	27.6	27.6	27.6	27.6	27.6	27.6
Super plasticizer	28.5	42.5	34.0	47.5	50.0	60.0	47.5	40.0	32.5	33.8	35.0
Total Price (SR/m ³)	237	279	273	288	292	308	306	309	268	268	268

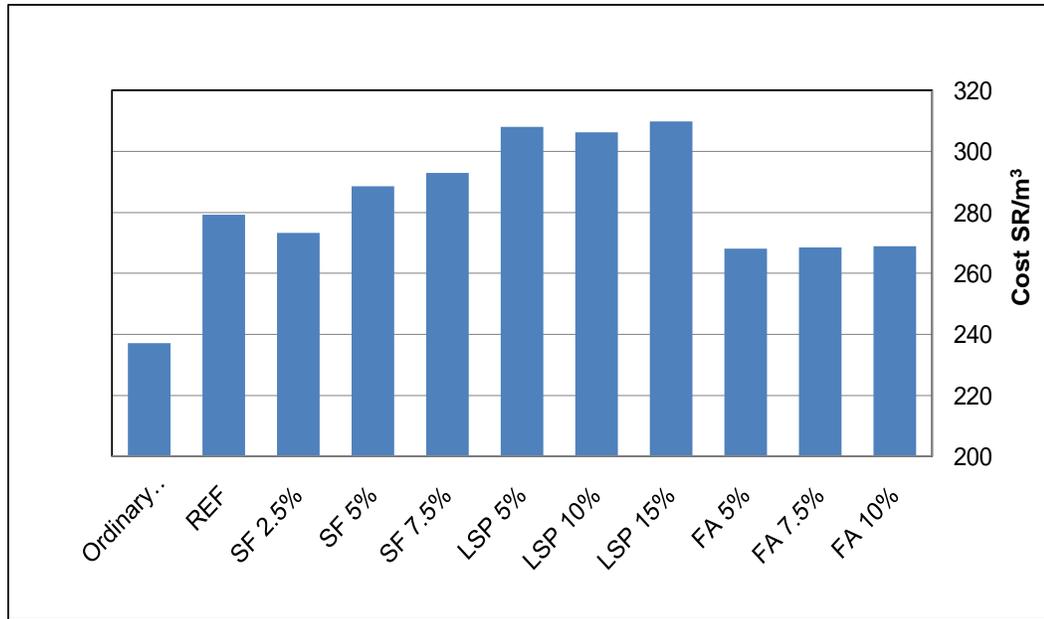


Figure 4-12 : Material cost for all mixes per m³

Figure 4-12 shows the cost comparison of all mixes used in this research.

CHAPTER 5

Conclusions and Future Work

5.1 Conclusions

The objective of this research was to determine the effect of different type of mineral admixture, aggregate gradation and volume fraction on rheology and segregation attributes of SCC to identify parameters for preparation of robust mixes.

1. It has been shown that SCC can be made using Silica Fume (SF), Limestone Powder (LSP) and Fly Ash (FA) as filler having acceptable flowability with high compressive strength ranging from 58-89 MPa.
2. For all the mixes satisfying the target slump of 700 ± 50 mm, the range of Bingham parameters τ_0 and μ using the ICAR rheometer was found to be 32-65 Pa and 48-71 Pa-s.

3. It was found that SCC mixes with 5% and 10% limestone powder suffered from slight static segregation with all the other concretes exhibiting no static segregation.
4. All the mixes have a dynamic segregation index (DSI) less than 15% except 10% LSP which has a DSI of 37.5%.
5. SCC mixes prepared using SF showed higher yield stresses when compared to mixes with LSP and FA.
6. The plastic viscosity varied over a small range since water and powder content was kept constant.
7. Based on the test results, the order of robustness is Silica Fume Admixed SCC > Fly Ash Admixed > Limestone Powder Admixed.
8. Mineral admixed SCC can be modeled in the same manner as the Roussel Model for SCC without admixtures, i.e. as a Bingham paste with thixotropy.
9. Rheological characterization helps to understand the broad behavior of SCC and provides great add on benefit to results obtained from conventional tests.
10. For the nine mineral admixed robust SCC mixes, the thixotropy index was found to be higher than the reference SCC in most of the cases.
11. It is noted that A_{thix} is equipment dependent and not an universal invariant.
12. A_{thix} characterization can help to specify appropriate mix design depending on application of SCC in walls, slabs etc.
13. Using thixotropy indexing, 10% FA admixed SCC would be most suitable for use in vertical wall constructions, whereas for horizontal slabs and raft

foundations, (5% FA , Ref mix, 5% LSP, 7.5% SF) admixed SCC's would be more suitable.

5.2 Future Work

Following are some suggestions for future research.

1. Studies can be conducted to determine the effects of thixotropy, viscosity and yield stress on parameters like formwork pressure and pumping of SCC.
2. Different mixes can be tried by varying the coarse aggregate content, cement content, different superplasticizers to develop a more clear understanding of the segregation attributes of SCC.
3. This rheological characterization of SCC should be the catalyst for opening new area of computational flow modeling of SCC as a thixotropic fluid using local materials and mixes. This would yield data of value to the construction industry.
4. Development of more sophisticated models based on rheology to study static and dynamic segregation
5. Effect of retarders on rheological attributes needs to be studied.

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NOMENCLATURE

τ	-	Shear Stress (Pa)
τ_0	-	Dynamic Yield Stress (Pa)
τ_{ys}	-	Static Yield stress (Pa)
μ	-	Plastic viscosity (Pa-s)
γ	-	Shear strain rate (1/s)
λ	-	Lambda
α	-	Deflocculation parameter
T	-	Characteristic time (s)
h	-	Vane height (mm)
R_1	-	Vane Radius (mm)
R_2	-	Container Radius (mm)
T	-	Torque (N-mm)

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