DEVELOPMENT OF A NEW TEST METHOD TO EVALUATE DYNAMIC STABILITY OF SELF-CONSOLIDATING CONCRETE

A Thesis Submitted to
the Graduate School of Engineering and Sciences of
İzmir Institute of Technology
in Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

in Civil Engineering

by
Mohammad Musa ALAMI

July 2014
İZMİR

We approve the thesis of **Mohammad Musa ALAMI**

Examining Committee Members:

Assist. Prof. Dr. Tahir Kemal ERDEM
Department of Civil Engineering, İzmir Institute of Technology

Assoc. Prof. Dr. Özge Andiç ÇAKIR
Department of Civil Engineering, Ege University

Assoc. Prof. Dr. Halit YAZICI
Department of Civil Engineering, Dokuz Eylül University

07 July 2014

Assist. Prof. Dr. Tahir Kemal ERDEM
Supervisor, Department of Civil Engineering,
İzmir Institute of Technology

Prof. Dr. Gökmen TAYFUR
Head of the Department of Civil Engineering

Prof. Dr. R. Tuğrul SENGER
Dean of the Graduate School of
Engineering and Sciences

ACKNOWLEDGMENTS

I would like to express my endless gratitude to my supervisor Asst. Prof. Dr. Tahir Kemal ERDEM for helping me in so many ways, for his patience and guidance throughout the preparation of this thesis. I am deeply grateful to ministry of higher education of Afghanistan to grand me this opportunity to complete my Master of Science degree.

I would like to express my special thanks to the jury members; Assoc. Prof. Dr. Özge Andiç ÇAKIR and Assoc. Prof. Dr. Halit YAZICI for their attendance at my thesis defense presentation and valuable suggestions to the thesis.

I would like also to express my appreciation to Nisar Ahmad Karimzada, Khwaja Jawid Sediqi, Ahmad Zaher Naie, Tariq Abhar, and Amrudin Haidary for their help during the experimental work of this thesis.

Finally, I would like to express my special thanks to my family for their endless love and patient throughout my life and especially my parents who made me to overcome all the difficulties with her encouragement, support and love. This thesis dedicated to them.

ABSTRACT

DEVELOPMENT OF A NEW TEST METHOD TO EVALUATE DYNAMIC STABILITY OF SELF-CONSOLIDATING CONCRETE

Self-consolidating concrete (SCC) is a new generation of concrete with high performance. It is able to flow under its own weight and fills the formwork without any external vibration. Stability is the most important plastic and crucial property for successful application of SCC and it refers to segregation of constituent in fresh state. Dynamic stability is the segregation resistance of SCC during transportation and placement. Evaluation of dynamic stability is one of the most investigated topics of SCC. Many different test methods have been proposed to evaluate the dynamic stability of SCC. No single and widely accepted method exists for the evaluation of the dynamic stability of SCC.

In this thesis a new apparatus for testing the dynamic stability of SCC was developed. The effect of different mix design parameters such as water-to-cement ratio w/c, slump flow diameter, coarse aggregate-to-total aggregate ratio (CA/TA), and maximum size of aggregate (Dmax) were evaluated on the dynamic stability of SCC. Several fresh concrete tests were carried out on the SCC mixtures: slump flow, T_{500} time, Visual stability index (VSI), V-funnel, L-box, static sieve segregation (GTM), rheometer, and new proposed method (DSST).

Several correlations were established between the test results. It was found that the new proposed test is a suitable method to evaluate the dynamic stability of SCC. Limits were proposed for a dynamically stable SCC.

ÖZET

KENDİLİĞİNDEN YERLEŞEN BETONUN DİNAMİK KARARLILIĞI İÇİN YENİ BİR TEST METODU GELİŞTİRİLMESİ

Kendiliğinden Yerleşen Beton (KYB), yüksek performanslı yeni nesil bir betondur. Bu beton çeşidi, kendi ağırlığı ile akabilmekte ve vibrasyon uygulanmadan kalıpları doldurabilmektedir. KYB'nin başarılı bir şekilde kullanılması için stabilitesinin iyi olması en hayati özellikler arasındadır. Stabilite taze halde iken beton içeriklerinin ayrışmaya karşı direnci olarak tanımlanabilir. Dinamik stabilite, betonun taşınması ve yerleştirilmesi sırasındaki ayrışmaya karşı olan dirençtir.Dinamik stabilite ölçümü, KYB'nin en çok araştırılan konuları arasındadır. KYB'nin dinamik stabilitesini ölçmek için kullanılan genel kabul görmüş tek bir deney metodu bulunmamaktadır.

Bu tezde, KYB'nin dinamik stabilitesini ölçmeye yarayan yeni bir deney aleti geliştirilmiştir. Su/çimento oranı (s/ç), yayılma çapı, iri agrega/toplam agrega oranı (İA/TA) ve agreganın en büyük dane çapı (D_{maks}) gibi çeşitli tasarım parametrelerinin dinamik stabilite ve diğer taze özellikler üzerine etkileri araştırılmıştır. Karışımlar üzerinde, yayılma çapı, T_{500} süresi, görsel stabilite indisi, V-hunisi, L-kutusu, statik segregasyon (GTM), reometre ve yeni önerilen test (DSST) gibi deneyler yapılmıştır.

Test sonuçları arasında çeşitli korelasyonlar kurulmuştur. Sonuçlara göre, yeni önerilen metodun dinamik stabilite ölçümü için uygun bir deney metodu olduğu bulunmuştur. Ayrıca, uygun bir dinamik stabilite için limit değerler önerilmiştir.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

SCC: Self-Consolidating Concrete
DSST: Dynamic Sieve Segregation Test
DSR: Dynamic Segregation Ratio
SF: Slump Flow
GTM: Static Sieve Segregation Test
SR: Segregation Ratio
PA: Passing Ratio
HRWRA: High Rang Water Reducer Admixture
WRA: Water Reducer Admixture
VMA: Viscosity Modifying Admixture
SP: Superplasticizer
GGBFS: Ground Granulated Blast Furnace Slag
EFNARC: The European Guidelines for Self-Compacting Concrete
G: Apparent Yield Stress
H: Torque Plastic Viscosity
SEM: Scanning Electron Microscopy
VSI: Visual Stability Index
w/c: Water to Cement Ratio
w/b: Water to Binder Ratio
w/p: Water to Powder Ratio
Agg: Aggregate
CA/TA: Coarse Aggregate to Total Aggregate Ratio
Dmax: Maximum Size of Coarse Aggregate

CHAPTER 1

INTRODUCTION

Self-consolidating concrete (SCC) is a special type of highly flowable concrete that is able to flow under its own weight. It also completely fills formwork and achieves full consolidation without any external vibration. SCC was first developed in Japan in 1988 by researchers at the University of Tokyo and later in 1990's in European countries.

Stability is also mentioned as segregation resistance which is the ability of an SCC mixture to retain a uniform distribution of all constituent materials during casting process and once all placement and casting operations have been completed. Stability includes two phases: Dynamic stability is the resistance of fresh concrete to segregation during transportation, placement, and consolidation of SCC, and static stability is the resistance of the fresh concrete to segregation and bleeding once the concrete is cast into formworks and until concrete gains rigidity.

1.1. Objective

The evaluation of relevant parameters of the dynamic stability of SCC are the most investigated aspects nowadays. Many researchers work to develop an acceptable test method to assess the dynamic stability parameters. Few test methods are available for stability measurement and some of them may not be useful for certain situations.

The overall aim of this study is to develop a new test method to evaluate the dynamic stability of SCC. This method was named as Dynamic Sieve Segregation Test (DSST).

1.2. Scope

In this research 12 self-consolidating concrete mixtures (SCC) were prepared with different mix designs. For all mixtures the cement and limestone contents were kept constant at 400 kg and 20 kg (5% of cement content) in one cubic meter of concrete, respectively.

The water to cement ratio (w/c), coarse aggregate to total aggregate ratio (CA/TA), slump flow value, and maximum size of aggregate (Dmax) were varied to investigate their effects on the rheology and dynamic stability of SCC. These parameters were among the most important parameters that can affect the SCC stability. The w/c was ranged between 0.42 and 0.50. The CA/TA was varied as 0.45, 0.50, and 0.53, respectively. For the given mixtures, one mixture with w/c = 0.42 and CA/TA = 0.50 and the other mixture with w/c = 0.5 and CA/TA = 0.50, the slump flow values were set to 550 ±20 mm, 650 ± 20 mm and 720 ± 20 mm by changing only the superplasticizer content. Also for a given mixture when the w/c = 0.42, CA/TA = 0.50, and slump flow = 650 mm, the Dmax was changed as 10mm, 15mm, and 20mm.

Slump flow test, T_{500}, Visual Stability Index (VSI), V-funnel test, L-box test, static sieve segregation test (GTM), rheometer, and new test proposed in this research were used to determine flow properties and stability of SCC.

CHAPTER 2

GENERAL INFORMATION

2.1. Self-Consolidating Concrete

Self-consolidating concrete (SCC) is an innovative concrete that does not require vibration or other mechanical consolidation for placing and compaction. It is able to flow under its own weight, totally filling complex formwork and achieving full compaction, even in the presence of congested reinforcement [1]. SCC technology has properties that differ significantly from conventional vibrated concrete in fresh state. However, the hardened state properties are condensed, homogeneous and have similar or superior engineering properties and durability to conventional vibrated concrete.

Concrete that requires little mechanical consolidation has been used in concrete industry before the development self-consolidating concrete. In late 1970’s and early 1980’s pioneering work by German, Italian and Japanese researchers led to development of high-workability concrete mixtures that are commercially known by several names such as self-consolidating concrete, self-compacting concrete, self-leveling concrete, or rheoplastic concrete [2].

After many exploration SCC was first developed in Japan in 1988 by researchers at the University of Tokyo and later in 1990’s in European countries. It was created as a solution for the lack of enough skilled labors for placement of the concrete in construction and to achieve durable concrete structures by improving quality in the construction development. It was also found to offer economic, social and environmental benefits over the conventional consolidated concrete construction [3].

Most important reasons for the increasing demand of SCC in named countries especially in Japan are [2]:

- Restricted shape of concrete structures, e.g. densely arranged bars make it more difficult to use a vibrator.
- Vibration compaction is noisy and harmful to the health of construction worker, as well as an annoyance to the people in the neighborhood.

- In remote areas it is difficult to find skilled workers to fulfill the compaction work at construction sites.

According to mentioned reasons the advantages of SCC are defined as low noise due to no need for compaction, low workmanship, fast placement in the construction site, full compaction, and pumpability to longer distances due to its cohesiveness.

The main characteristics of SCC are the properties in fresh state. When these properties are obtained properly then the hardened state properties such as durability and strength, are also improved.

The key characteristics of SCC in fresh state which are listed by Ouchi et al. [3] and EFNARC guidelines [1] are:

- **Flowing ability**- the ability of fresh concrete to flow into and completely fill all areas within the formwork under its own weight.
- **Viscosity**, (measure of the speed of flow) - The resistance to flow of a material once flow has started.
- **Passing ability**- the ability of fresh concrete to pass through tight openings such as congested reinforcement without any separation of the constituents or blocking.
- **Segregation resistance**- the ability of concrete to retain homogeneous in fresh state.

These properties must all be achieved in order to design a good SCC, together with other requirements including those for hardened state performance.

The highly flowable nature of SCC is due to very careful mix proportioning, usually replacing much of the coarse aggregates with fine aggregates, mineral admixtures, cement, and chemical admixtures. Flowability depends on the sensitive balance between creating more deformability while confirming good stability, as well as maintaining low risk of blockage [7]. High- workability connects to both high consistency and high cohesiveness. With the use of superplasticizers or high range water reducing admixtures (HRWRA) and viscosity modifying admixtures (VMA), it is possible to achieve necessary consistency without an increase in the water to cement ratio (w/c) and sufficiently high cohesiveness.

EFNARC guidelines [1] states the differences between the mix-design principles of SCC and conventional concrete as:

- increased paste content
- lower coarse aggregates content
- low water to powder ratio (w/p)
- increased superplasticizer content
- viscosity modifying admixtures (for some cases)

Figure 2.1 compares the mix proportioning of self-consolidating concrete and conventional concrete [4].

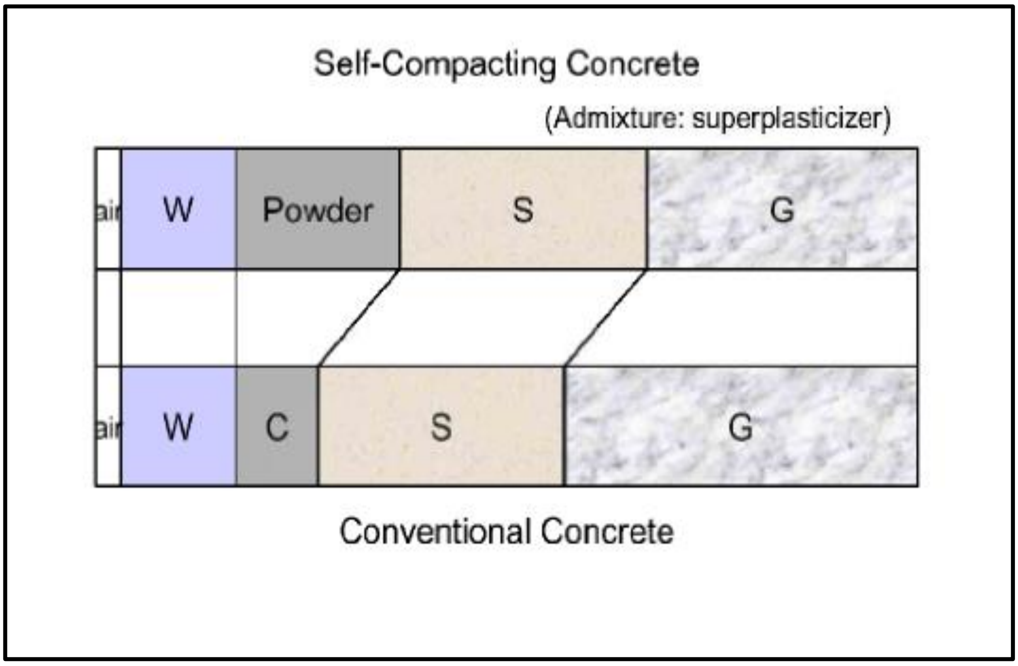


Figure 2.1 Mix proportioning of SCC and conventional concrete [4]

The use of SCC has been amended productivity in structural application such as repair, expedite the filling of restricted sections, and in sections presenting special difficulties to casting and vibration, such as bottom sides of beams, girders, and slabs [6].

Ouchi et al. [3] stated “Several European countries were interested in exploring the significance and potentials of SCC developed in Japan. These European countries formed a large consortium in 1996 to embark on a project aimed at developing SCC for practical applications in Europe. The title of the project is (Rational Production and

Improved Working Environment through using Self-compacting Concrete). In the last six years, a number of SCC bridges, walls and tunnel linings have been constructed in Europe.

In the United States, SCC is beginning to gain interest, especially by the precast concrete industry and admixture manufacturers. The precast concrete industry is beginning to apply the technology to commercial projects when specifications permit. The applications range from architectural concrete to complex private bridges".

According Jeo Nasvik [16] self-consolidating concrete has several advantages and application for producers and contractors in the ready-mixed concrete sector. The advantages for ready-mixed industry are listed below:

- Better perception from customers offering higher value concrete mixture
- Saves customers' or contractors' time and money
- Provides faster turnaround
- Increases profitability of producers
- More efficient use of mixing equipment and delivery
- Expands concrete product offering

Due to the advantages of SCC which was mentioned before, the SCC application has various areas of use such as large scale structures, highway bridges construction, under water concrete and in heavily congested reinforced structures. Below are some examples of structures which are constructed by SCC application technology.

First example is the anchorages of Akashi-Kaikyo (Akashi Straits) Bridge (Figure 2.2). It is a suspension bridge with the longest span in the world (1,991 meters). The two anchorages of the bridge were built by using SCC. They were large scale structures of concrete. The use of SCC has shortened the construction period by 20%, from 2.5 to 2 years [4].

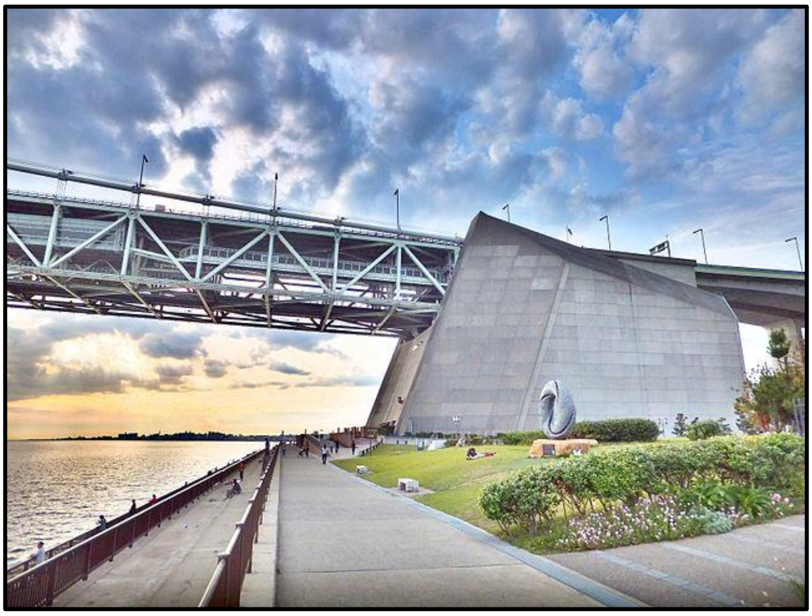


Figure 2.2. Anchorages of Akashi-Kaikyo Bridge [4]

The second example of SCC application is shown in Figure 2.3. Taipei 101 Financial Center building is one of the tallest buildings in the world. This building was constructed in Taipei city, the capital of Taiwan, in 1999-2001 by using SCC. The concrete was pumped up to 88th floor of the building [17].

Figure 2.1. Taipei Financial Center, Taiwan [17]

The third example of SCC application can be seen in Figure 2.4. SCC can effectively be used for bridge piers, and high-rise buildings with dense steel reinforcement in columns, beams, and slabs.

Figure 2.4. Dense steel reinforcement building [5]

The last example of SCC application is the Strelasund Bridge opened in 2007 which is connected the Strelasund city to Regun Island in Germany (Figure 2.5). The tow Y-shaped steel supports and SCC characterized the structure [35]. Good surface view is one of the most attractive performance of SCC, mostly from an architectural point of view. This good surface view is achieved by perfect compaction where vibration is impossible.

Figure 2.5. Strelasund Bridge Germany [35]

Highly flowable concrete mixtures run the risk of bleeding, settlement, high formwork pressure, shrinkage cracking, and segregation. The problems of SCC which are mentioned before have key roles and cause difficulties in production of SCC. These risks become especially great with high placement heights, high shear rates in pumping, and excessive vibration during the consolidation of concrete.

Segregation resistance is fundamental for SCC to have respectable quality. SSC can suffer from segregation during placing and also after placing but before hardening. In SCC application, the concrete can experience two types of segregation [66]:

- **Static segregation**: It will occur due to gravity of constituent materials of SCC in vertical direction.
- **Dynamic segregation**: It will occur due to flow of SCC in horizontal direction.

Many performance aspects of SCC are affected by segregation, producing insufficient filling of formworks, weak interface zone on reinforcement bars, reduced strength, and lower durability [27].

SCC with higher segregation has a higher cracking risk due to settlement of aggregate which leaves a high amount of paste on top layer, therefore SCC may shows more cracking due to shrinkage of past. Cracking due to segregation can reduce the resistance of concrete to freezing-thawing cycles, increase permeability, and reduced mechanical properties impairing the structures' integrity [9].

Segregation resistance is achieved by adding fine powdered materials such as silica fume, fly ash, and limestone powder to increase the paste volume and viscosity. Sometimes a viscosity-modifying admixture (VMA) is used to reduce segregation and obtain homogenous concrete [41].

2.2. Rheology of SCC

Rheology is the science of deformation and flow of materials. It is a complex system which can be used to understand the characteristics of workability of SCC. Ferraris [11] stated in her research in 1999 that the rheological or flow properties of concrete are important because many factors such as ease of placement, consolidation, durability, and strength depend on these properties. Concrete that is not properly consolidated may have defects, such as honeycombs, air voids, and aggregates segregation. Therefore, rheology is an important performance of SCC.

Ferraris [11] also stated that in construction industry, the terms like workability, flowability, cohesion, and interchangeably are also used instead of concrete rheology to describe the behavior of concrete under flow. Kosmatka et al. [12] mentioned the following three terms while referring to rheology of concrete: workability, consistency, and plasticity. The definitions are given as:

- Workability is a measure of how easy or difficult it is to place, consolidate, and finish concrete.
- Consistency is the ability of freshly mixed concrete to flow.
- Plasticity determines concrete’s ease of molding.

Rheology of SCC is best determined by special test devices called rheometers. Rheometers are generally used in the laboratory to search the flow properties of SCC. They are expensive and generally not suitable for site application.

Slump-flow and V- funnel tests are also used to evaluate the flow of SCC, however, they do not completely define the rheology in fundamental terms. Brower and Ferraris [13] gave an example in their research: “two self-consolidating concrete mixtures with the same slump or slump flow values can have different flow capabilities when filling reinforced formwork. Concretes having the same slump can behave differently during placement because flow is not defined by a single parameter”.

Slump-flow, V-funnel, and other similar tests are called field tests or one-point tests. The tests which are made by rheometers are called two-point tests.

SCC behaves as a fluid in the fresh state. The flow properties of SCC could be measured in a rheological point of view. However, it does not follow the Newton’s law. Therefore, the Bingham model should be used to determine the flow properties of SCC [14].

According to Newton's law:

$$\tau = \mu\dot{\gamma}$$

Where:

τ = stress

$\dot{\gamma}$ = shear rate

μ = viscosity

The Bingham model is named after Eugene C. Bingham who proposed the mathematical form for measuring viscous fluid. Brower and Ferraris [14] mentioned that the Bingham model describes a linear relationship between the stress acting to shear concrete and the rate at which it is sheared, as follows:

$$\tau = \tau_o + \mu\dot{\gamma}$$

Where:

τ = shear stress

$\dot{\gamma}$ = shear rate

τ_o = yield stress

μ = plastic viscosity

The viscosity in non-Newtonian materials is not constant at a constant temperature as for the Newtonian materials which illustrate a straight line relation on a shear rate-shear stress diagram. The flow in Bingham model does not start until the yield stress is reached [15]. Figure 2.6 shows the diagrams of Newtonian fluids and Bingham model for non-Newtonian fluids.

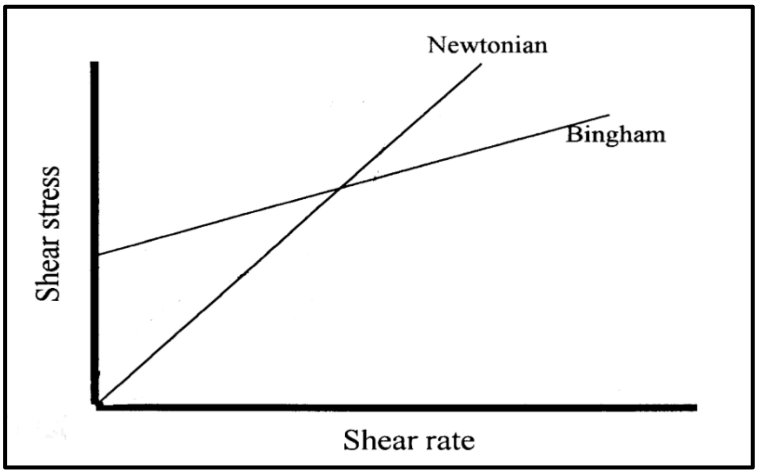


Figure 2.6. Newtonian fluids and Bingham model

The Bingham model has two parameters which are yield stress and plastic viscosity. The definitions of these two parameters are stated in the technical report of GRACE [10] as follows.

- **Yield stress**: the measure of the amount of stress required to make SCC flow.
- **Plastic viscosity**: the measure of the resistance of SCC to flow due to internal friction.

For easily flow of SCC under its own weight, the yield stress of SCC must be very low. SCC must have a high viscosity in order to keep aggregate particles in a homogeneous manner of concrete matrix without any segregation.

For a viscous liquid such as SCC, the yield stress equal to the intersection point on the stress axis and the plastic viscosity is the slope of the shear stress-shear rate plot as shown in Figure 2.7 [11].

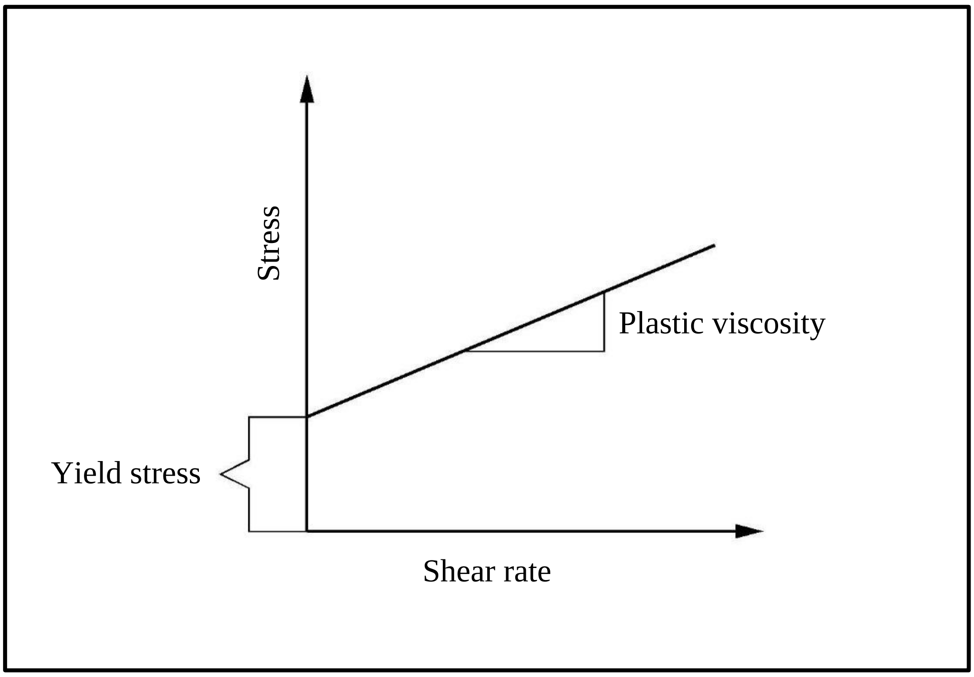


Figure 2.7. Bingham's equation for fluid [11]

2.3. Stability of SCC

Stability is a very important property of SCC in fresh state. Due to the high flowability of SCC, it is much more vulnerable to stability problems than conventionally consolidated concrete. Stability is the ability of self-consolidating concrete to remain homogenous by resisting segregation, bleeding, and air popping during transportation, placing, and after placing until concrete gains rigidity [17,19].

Segregation is the separation of granular particles from mortar, which is often associated to static sedimentation. Segregation of fresh concrete may cause several problems in concrete production, cause instability and non-uniform mixture [20-23]. Adequate stability is also critical in pumped concrete where segregation can lead to heterogeneous flow of the material in the pipeline, which could lead to blockage of the flow [20, 24].

Newman and Choo [18] proposed that SCC must be able to keep its homogeneity under mobile condition when concrete moving. Two situations need to be addressed properly:

- First, the free water content needs to be minimized to avoid bleeding. This can be achieved by the use of superplasticizers to reduce the water demand and obtain a well-graded cohesive and stable concrete.
- Second, the liquid period of SCC needs to be viscous to maintain the coarse particles suspension, when the concrete is moving and reaching the rigidity. This can be achieved by incorporating a high volume of fines in the mix such as mineral admixtures and/or the introduction of viscosity modifying admixtures.

“Reducing the free water content and increasing the concentration of fine particles can enhance the cohesion and viscosity, and hence the stability of SCC. Free (or movable) water is the total mix water minus water that is physically and chemically retained by the aggregate and powder materials as well as any water bound by chemical admixtures, such as water-retaining admixtures” [30].

A proper workability may not be achieved only by increasing the concrete fluidity. Stability of fresh concrete is also an influencing parameter that should be mentioned [26]. There is a strong relationship between fluidity and concrete stability so that an increase in the flowability of concrete would increase the risk of segregation. SCC should be designed to satisfy these requirements [20].

The stability of SCC is affected by numerous variables. These variables can be separated into two main categories; proportioning variables and application variables [27]. In the production of SCC these two variables must be achieved properly.

The dynamic and static stabilities of self-consolidating concrete are the main functional requirements for adequate production and use of such a high performance and highly flowable concrete [28, 29].

2.3.1. Static Stability of SCC

Static stability is the resistance of the fresh concrete to segregation and bleeding once the concrete is cast into formworks and until concrete gains rigidity. It depends on the cohesiveness and viscosity of mixture. Libre et al. [20] define the static stability of SCC as “the resistance to bleeding, segregation, and settlement after casting, while the concrete is still in a plastic state”.

Once concrete is cast into formworks, SCC must develop a high resistance to bleeding, segregation, and surface settlement prior to stiffening. The lack of static stability can lead to surface defects, including the presence of bleed channels [28]. Bleeding, which is alarmed with water migration, can be an internal and a surface bleeding. Surface bleeding takes place when water migrates to the surface and internal bleeding occurs inside the mixture when the steel bars and coarse aggregates are surrounded by water [20].

As described earlier, the settlement of coarse ingredients of SCC will occur due to gravity in vertical direction.

Bleeding and settlement can weaken the quality of the interface between aggregate and cement paste. The bond of cement paste and steel bars get weaker. Mechanical properties of SCC are directly affected by bleeding such as increase in permeability and reduction in durability [25].

However, these problems can be prevented by reducing of free water content by use of superplasticizer, increasing the viscous property by using viscosity modifying admixtures, and the most important one is the proper mix design and good grading of constituent materials of mixture.

2.3.2. Dynamic Stability of SCC

Dynamic stability is the resistance of the fresh concrete to segregation during transportation, placement, and consolidation of SCC application, particularly in the presence of obstructions that promote local segregation and blockage [28]. Libre et al. [20] define the dynamic stability of SCC as “the resistance of concrete to the separation of constituents during transport, placement, and casting process”.

For dynamic segregation, where the fluid is in motion, the viscosity may have an important role. During motion, the fluid structure breaks down which may allow aggregates to settle if the yield stress is reduced sufficiently [31, 32]. Therefore, dynamic instability occurs due to the movement of the fluid. Higher viscosities will support moving of aggregates in the flow and also reduce the rate of settlement until the concrete comes to rest. At this point, the fluid structure can be rebuilt, restoring the yield stress and preventing further static segregation [32].

Several testing methods have been proposed to assess the dynamic stability of SCC. The authors and researchers investigated the suitability of a number of different tests for evaluating deformability and passing ability through a meshwork of reinforcing bars. The results were then correlated to the rheological parameters (yield stress, and plastic viscosity), and constituent materials (size, density, and volume fraction).

The tests that were used to assess dynamic stability included the V-funnel flow time, J-Ring, L box, U-box, flow through, and pressure bleed tests [28]. These investigations will be discussed in Chapter 3.

2.4. Tests for SCC

The properties that differentiate SCC from conventional concrete are mainly those in fresh state of concrete. Therefore, various test methods have been developed to measure and assess the fresh concrete properties. No single test is capable to measuring and assessing all of the key parameters. A combination of tests is required to completely characterize the SCC mixture. Table 2.1 lists the most common tests gathered according the key characteristics of SCC.

Table 2.1 Tests related with the key characteristics of SCC [1]

Characteristic	Test method	Measured value
Flowability/ filling ability	Slump-flow	total spread diameter
	Kajima box	visual filling
Viscosity/ flowability	T_{500}	flow time
	V-funnel	flow time
	O-funnel	flow time
	Orimet	flow time
Passing ability	L-box	passing ratio
	U-box	height difference
	J-ring	step height, total flow
	Kajima box	visual passing ability
Segregation resistance	penetration	depth
	sieve segregation	percent laitance
	settlement column	segregation ratio

Details of the tests which are related and used in the experimental program of this thesis will be mentioned in the coming sections. These tests are slump-flow test, V-funnel test, L-box test, Rheometer test, and static stability test (GTM).

2.4.1. Slump Flow and T_{500} Time Test

The slump-flow is a test method for evaluating and assessing the flowability and flow rate of self-consolidating concrete in the absence of obstruction. EN 12350-2 standard describes the method for this test. The T_{500} time is also a measure of the speed of flow and determines the viscosity of SCC [1].

The apparatus which are used in this test method are: a truncated metal cone (top diameter is 100 mm, base diameter is 200 mm, and height is 300 mm), baseplate made from flat plate area of least 900 mm x 900 mm on which concrete can be placed in Figure 2.8, rule scale graduated from 0 mm to 1000 mm, and a stop watch measuring to 0.1 sec [36].

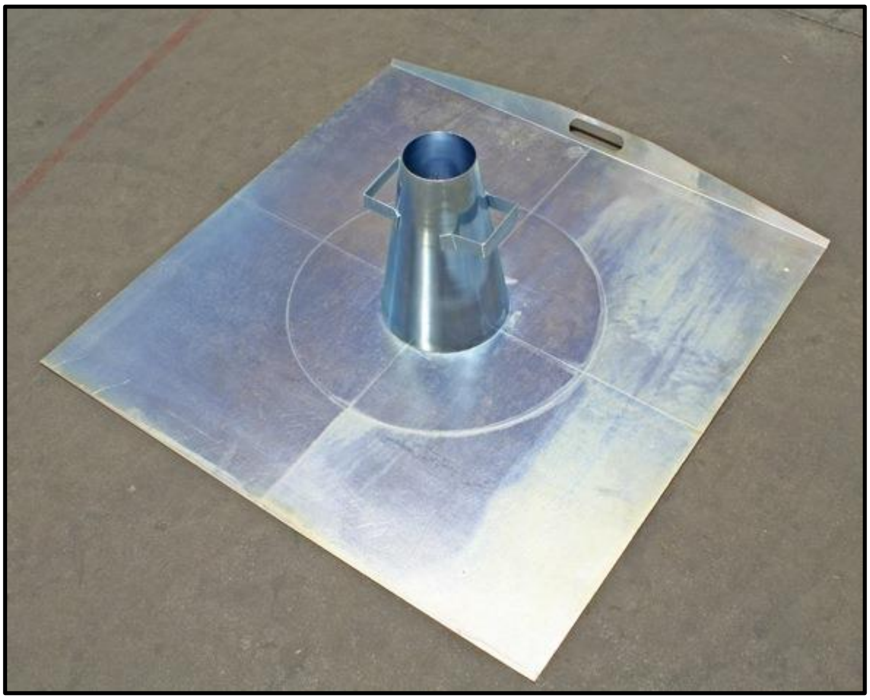


Figure 2.8. Slump cone, and flat plate [37]

The principle of this test method according to the EN 12350-2 is as follows: the fresh concrete is poured into a slump cone which is placed on flat plate. The time is measured for the T_{500} time, when the cone is withdrawn upwards until the concrete has flowed to the diameter of 500 mm (Figure 2.9).

Slump-flow is measured as the mean of the largest diameter of the flow spread of the concrete and the diameter of the spread at right angles to it (Figure 2.10). Measurement of T_{500} time may not be measured if not requested [1, 36].

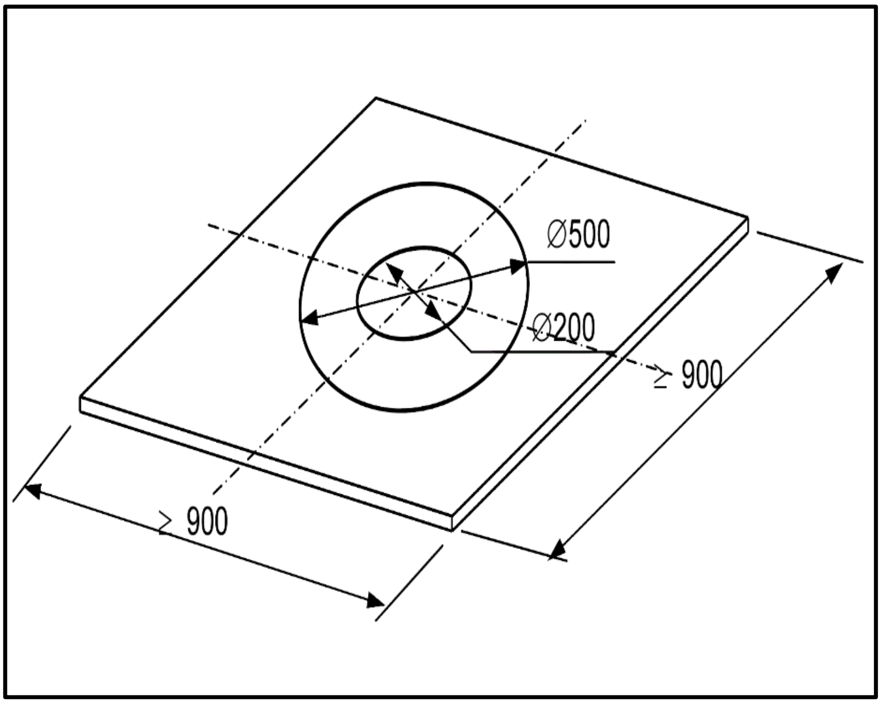


Figure 2.9. The diameters of cone base and T_{500} in baseplate

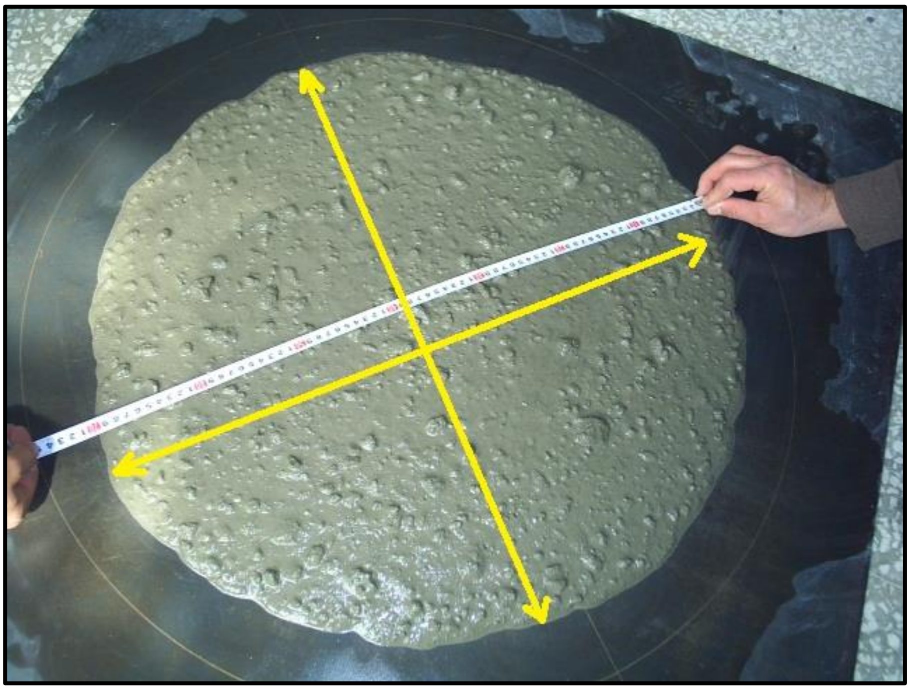


Figure 2.10. Measuring the diameters of the spread concrete at right angles

2.4.2. V-Funnel Test

The V-funnel test consists of a V-shaped metal container with an opening of 65 x 75 mm at the bottom. These dimensions of the set-up are modified from the model proposed by Ozawa et al. [38]. This test is used to measure the viscosity, and filling ability of SCC to spread through the bottom opening of apparatus.

The apparatus which are used in the test method are a V-shaped funnel as shown in Figure 2.11, a container to hold the sample, stop watch which can measure up to 0.1 sec, and straight edge device for cross off concrete level with the top of V-funnel.

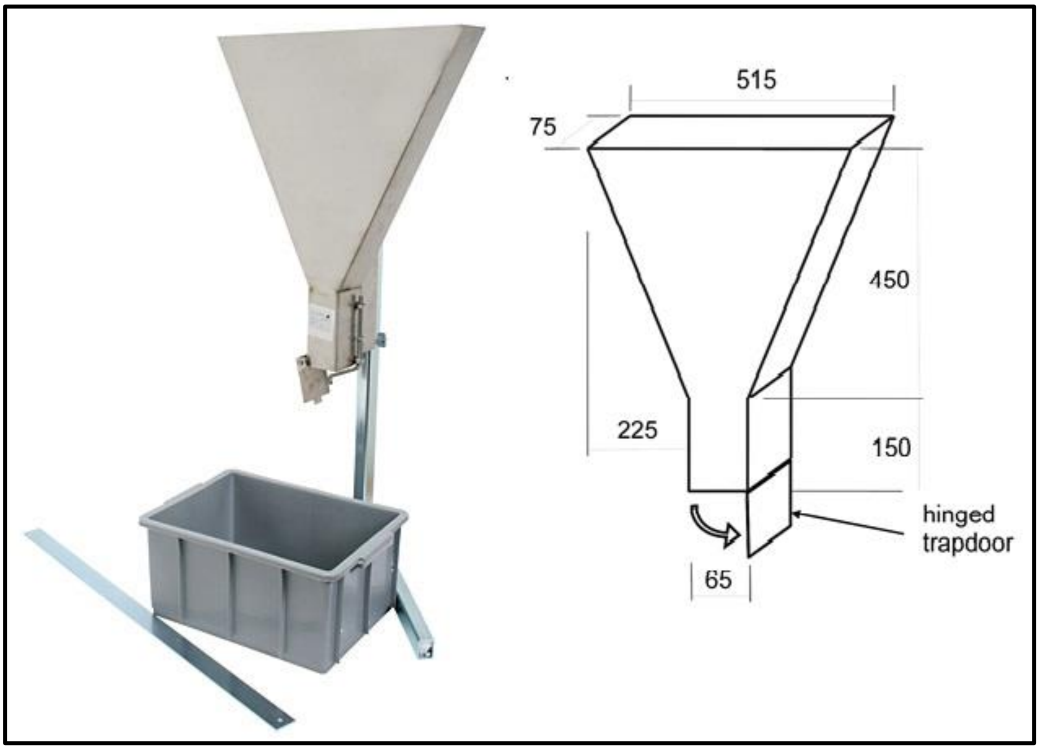


Figure 2.11. V-funnel apparatus and dimensions in millimeters [1]

The principle of this test method is that the funnel is filled with approximately 10 liter of fresh concrete without any agitation or rodding, and cross of the top of funnel. The bottom hinged trapdoor is opened after (10 ± 2) sec, and the time taken for the concrete to flow out of the funnel is measured. This period is recorded as the V-funnel flow time [1, 39].

2.4.3. L-Box Test

The L-box test is a useful method for SCC. It is made from metal with a long rectangular section trough with a vertical column at one end as like as L-shaped equipment (Figure 2.14). This test is used to evaluate the passing ability of SCC to flow through tight opening such as spaces between congested reinforcing bars and other barriers without any segregation or blocking [1, 39].

Figure 2.12. L-box apparatus

The apparatus which are used in this test method are an L-box equipment having the specification as shown in Figure 2.12 and Figure 2.13, and a rule scale which are graduated from (0-300) mm.

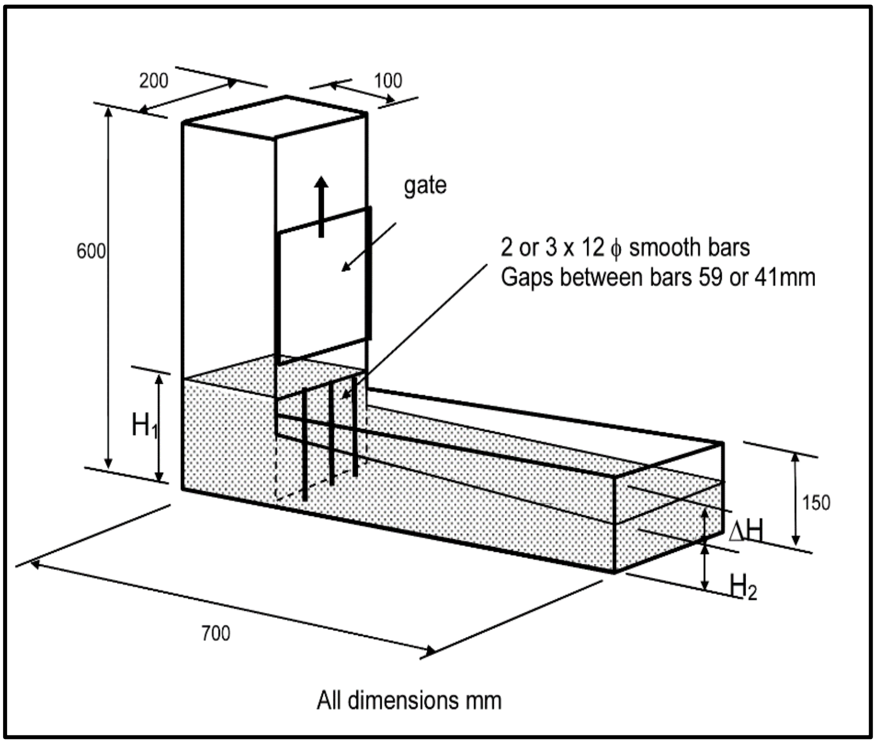


Figure 2.13. L-box apparatus with its dimensions [1]

The principle of this test method is as follows: a measured volume of fresh concrete is allowed to flow horizontally through the gaps between vertical reinforcement bars and the heights of the concrete beyond and front of the reinforcement bars are measured. As seen in Figure 2.14 the two bar test and three bar test are used. The three bar test illustrates congested reinforcement application [1].

The concrete sample around 12.7 liters is poured into the vertical part of the box and left to stand for (60±10) seconds. The gate located between vertical and horizontal sections is then opened to concrete flows into horizontal section of L-box.

Once the concrete reaches the end of the horizontal section, then the height of remaining concrete in the vertical section as (H_1) and the vertical height of concrete in the end of horizontal section of L-box as (H_2) are measured (Figure 2.15). The passing ability (PA) is calculated from the following equation:

$$PA = H_2/H_1$$

The time from opening of the gate until concrete reaches the end of horizontal section is noted for evaluating the viscosity and flowability of SCC.

2.4.4. Rheometer Test

Rheometers are used to measure and assess the rheological properties of SCC. Rheometers are also known as the two point tests. Concrete rheometers determine parameters for Bingham model which are yield stress and plastic viscosity of SCC.

Rheometer technology is based on hydraulic science and originates from models and devices that have been developed for viscous fluids such as oil and polymer. Widely used rheometers measure shear stress while the tested fluid is subjected to a controlled shear rate [13]. Commonly available rheometers are used for more homogeneous liquids, they are not capable for measuring fresh concrete that contain solid particles. A variety of rotational rheometers have been designed in the last two decades to evaluate the flow properties of concrete. These apparatus employ different geometries such as coaxial cylinders, parallel plates, and rotating vanes [11, 13]. Figure 2.14 shows the mechanism of a simple rotational concrete rheometer.

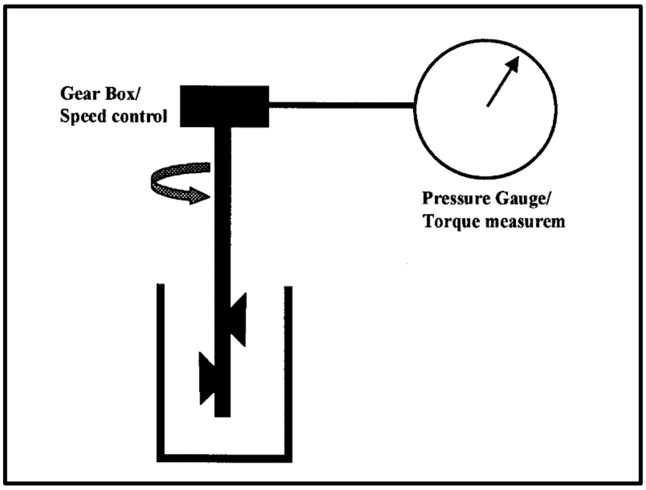


Figure 2.14. Tattersall two-point rheometer [11]

The principle and mechanism of rheometer is to measure the fresh concrete torque at different rotational speeds [40]. The fresh concrete sample is placed into the bucket of rheometer and then the vane of special geometry or other type of impeller is dropped into sample. The impeller starts rotating and the resistance on the impeller due to the materials is measured such as torque or other comparison parameters and then recorded in related computer software for upcoming result and analysis [11].

2.4.5. Static Sieve Segregation Test (GTM)

Static sieve segregation test (GTM) was developed by Cussigh in a group of construction companies of French contactors by the name of GTM in 1999. GTM test measures the degree of separation of the coarse particles and mortar fraction of SCC. This test method is used to assess and evaluate the segregation resistance or static stability of self-consolidating concrete [1, 18].

Equipment and tools which are used in this test method are: perforated plate sieve which having 5 mm square apertures with frame diameter 300 mm and height 40 mm, sieve pan which has same volume as like as perforated plate sieve, metal or plastic container with around 10 liters volume for carrying the concrete sample, and weighing machine with a least capacity of 10 kg [1]. Figure 2.15 shows a simple set up of GTM rest.

Figure 2.15. Static sieve segregation test (GTM) tools [37]

The principle and procedure of this test are: 10 liters of fresh concrete are placed into a test bucket and allowed to settle over 15 minute without any disturbance. In this period, if the concrete shows any separation or bleeding water should be noted. The coarse aggregates settle at bottom and the upper part of the sample in the bucket about 5 kg is then poured into the sieve with 5 mm opening. After two minute waiting the weight of materials which are passed the sieve is recorded. The segregation ratio (SR) is calculated as the ratio of the weight of materials that passing through the sieve (Wps) to the total initial weight of concrete sample on the sieve (Wc) [1, 18]. The segregation ratio is calculated from the following equation.

$$SR = (Wps / Wc) \times 100$$

CHAPTER 3

LITERATURE REVIEW

3.1. Rheology of SCC

As described in Chapter 1, the rheological performance of self-consolidating concrete in fresh state is characterized through the yield stress and plastic viscosity defined according to the Bingham model and other rheological formulas. The yield stress can be divided into two types which are static yield stress and dynamic yield stress.

Koehler and Fowler [59] specified that rheology of SCC is typically measured in terms of static yield stress, dynamic yield stress, plastic viscosity, and thixotropy. "Static yield stress is defined as the minimum stress to initiate flow from rest. Dynamic yield stress is the minimum stress to maintain flow. Plastic viscosity expresses the increase in shear stress with increasing shear rate once the yield stress has been exceed. The difference between static and dynamic yield stress is due to thixotropy, which is defined as the reversible, time-dependent decrease in viscosity at a given shear rate" [60].

Rheology of SCC is evaluated by special test devices called rheometers and slump-flow, V- funnel, and other one-point tests. Yen et al. [45] defined that the rheometers could provide more stable results than any other test method to evaluating the rheological parameters and flowability of SCC.

Different researchers developed a variety of rheological rheometer tests for concrete. The best known ones are coaxial cylinders rheometers, parallel plate rheometers, and rheometers with impellers, which can be separated by geometry [13].

To extract fundamental results out of actual measurements of torque and rotational velocity, we need to take out the results from these test equipment into mathematical equation to make some assumptions [42]. The relationship between the measured torque and angular velocity of the rotating cylinder is plotted on the graph. Different authors, researchers, and different equipment manufactures use slightly different computations, but they all use a few assumptions [42, 43]. The description of flow of a fluid uses concept of Bingham model which is defined by two parameters yield stress and plastic viscosity was discussed in details in Chapter 1.

The rheology of fresh concrete affects its compacting and casting ability, and it helps us to understand concrete in more detail, namely with concern to interactions in the fresh concrete state. The size and shape of aggregate particles influence concrete viscosity, just as other ingredients have an effect on other rheological properties [44].

The moisture content, water absorption, specific gravity, grading and variations in fines content of all aggregates should be closely and always monitored and must be noted into explanation in order to produce SCC of constant quality. Using washed aggregates will normally give a more consistent product. Changing the source of supply is likely to make a significant change to the concrete properties and should be carefully evaluated [1].

Production of SCC involves many factors playing with that affect stability, deformability, and segregation. These factors include water to cement ratio, properties of aggregates such as size, shape, density, distribution and spacing, void content, ratio between fine and coarse aggregates. The most important factor is using of chemical admixtures play key role in production of SCC [7].

In this section a short literature review of recent researches and studies that have been done about effect of mix-design parameters on rheology is discussed.

Ferraris et al. [54] categorized the factors affecting the rheology of concrete. The elementary factors are the composition of the concrete, including the chemical and mineral admixtures dosage and type; the gradation, shape, and type of aggregates; the water content; and the cement characteristics. The same mixture design may appear different rheological properties if secondary factors are not taken properly. The secondary factors are processing and environmental factors as below:

- Mixer type: pan, truck, and so on. These may cause various levels of deflocculation and air entrainment.
- Mixing sequence of introduction of the materials into the mixer.
- Mixing duration.
- Temperature.

Water to cement ratio (w/c) is the most significant parameter influencing the rheological properties of cementitious mixtures, especially their stability. Furthermore, the maximum allowable w/c for preventing inhomogeneity could not be a fixed value for all the mixtures and should be adjusted for the target fluidity.

Libre et al. [20] studied the effect of water to cement ratio on rheological parameters and dynamic stability of SCC. The summary of the results obtained from this research is as below:

- The most significant parameters affecting mixtures fluidity are the w/c and superplasticizer content.
- The w/c affects viscosity exponentially such that increasing w/c up to 0.45 strongly decreases the viscosity. Furthermore, using fly ash increases viscosity, but other parameters did not significantly influence the viscosity.
- To minimize the unpleasant effects of high fluidity on the stability, addition of superplasticizer instead of increasing w/c is suggested.
- The w/c is the most significant parameter influencing rheological parameters of cementitious mixtures. Higher w/c tends to inhomogeneous mixtures, while reducing the viscosity.

Physical appearance of aggregate, such as size, gradation, shape, surface texture and volume fraction, all have significant effects on concrete rheology [2, 46, 49]. Geiker et al. have stated that the yield stress and viscosity of concrete significantly increase with increased coarse aggregate volume fraction [50]. The yield stress and plastic viscosity of SCC is higher than mortar or cement paste which have no coarse aggregate inside. From cement paste to concrete, the yield stress and plastic viscosity increase as the particle size increases.

Due to higher surface area the water requirement increases for SCC with decreasing aggregate particle size. Very fine aggregate requires more water for a given consistency. A good aggregate gradation provides a higher degree of packing and requires less paste to reach a given consistency as less cement paste is required to fill the space between the aggregate particles [46-48]. The amount of mortar necessary for a workable concrete depends on the voids content between the coarse aggregate particles and the total surface area of the coarse aggregate to be coated.

The high volume of paste in SCC mixes helps to reduce the internal friction between the sand particles but a good grain size distribution is still very important. Many SCC mix -design methods use blended sands to match an optimized aggregate grading curve and this can also help to reduce the paste content [1].

Hu and Wang [46] investigated several effects of coarse aggregate on concrete rheology in their study. Different concrete proportions, coarse aggregate gradations, and coarse aggregate volume fractions with different mortar proportions were considered in the concrete mix-design. The summary of the results obtained from this research is as below:

- Results showed that both coarse aggregate content and mortar composition had significant effects on concrete yield stress and viscosity. These two factors are important in concrete mix-design for a workable concrete. The yield stress and viscosity of concrete typically increase with the sand content in the mortar and high coarse aggregate content.
- Compared with single-sized aggregate, graded aggregate can considerably reduce yield stress and viscosity of concrete. However, the effect of aggregate on concrete yield stress and viscosity are sometimes less clear due to the combined effect from size and gradation of aggregate.
- Aggregate properties can be quantitatively characterized by easily implemented parameters such as fineness modulus, uncompacted void content and friction angle. Concrete rheological behavior is affected by these parameters. Rheology of concrete may also be influenced by the coarse content and mortar properties of concrete.
- Particles with a nearly spherical shape and a smooth surface texture provide more workable concrete.

The other most important difference between SCC and conventional concrete is the combination of mineral admixtures and higher content of powder. Since the Portland cement is the most expensive material of concrete, reducing the cement content and using of cheaper materials such as limestone powder, fly ash and ground granulated blast furnace slag (GGBFS) in SCC is an economical solution [51-53, 70]. Use of the recycled materials as in concrete also protects the environment from waste materials.

Proper selection of powdered materials additionally enhances the packing density of solid particles, which assists reduction of water or the HRWRA dosage required to achieve inter-particle sliding, which is related to flowability [55, 56]. Better packing and gradation not only leads to enhanced flowability but also promotes the hardened properties of SCC such as higher compressive strength and durability due to the denser paste matrix [56-58]

Several studies concerning the effects of mineral admixtures on the properties of SCC have been established. Ghoddousi et al. [51] searched in their study the rheological parameters of SCC with the use of various mineral admixtures. It was found that the addition of metakaolin and silica fume the mixture increases the yield stress. It is also noted that adding GGBFS to SCC mixture causes a strong reduction of yield stress. Results also show that metakaolin and GGBFS increased the plastic viscosity of the mixtures. Using the coarse sand in the SCC mixture lead to increases in the yield stress and plastic viscosity, but with using higher percent of fine sand in the SCC mixture, plastic viscosity is decreased and yield stress is increased significantly.

Kim et al. [56] pointed out that replacing Portland cement with limestone filler increases the slump flow and decreases the dynamic yield stress as the replacement ratio increases. Using fly ash provides the optimum value of 40% replacement in terms of flowability. It was also found that high powder content enhances workability but has a negative effect on formwork pressure. The increase of the formwork lateral pressure may cause safety and economic problems.

Chemical admixtures are used to help rheological properties of SCC. Chemical admixtures such as superplasticizers or high range water reducing admixtures (HRWRA) are the essential constituents of SCC. Viscosity modifying admixtures (VMA) may also be used to support rheological behavior and reduce segregation. Other admixtures including air entrainers, accelerators and retarders may be used in the same way as in traditional vibrated concrete but advice should be pursued from the admixture manufacturer on use and the optimum time for addition [1].

The high flowability of SCC mixtures is obtained by using superplasticizers which influence many fresh and hardened properties of SCC mixtures [61- 63]. The superplasticizer should use about the required water reduction and fluidity but should also maintain its dispersing effect during the time required for transport and application [1].

There are four different families of superplasticizers: Lignosulphonates, melamines, naphtalenes and polycarboxylates. The first three families show electrostatic repulsion whereas polycarboxylates show both electrostatic repulsion and steric hindrance [64].

Electrostatic repulsion: molecules of the admixture neutralize the cement particles and cause all surfaces to carry uniform charges of the same sign. The particles having the same charge repel each other. Electrostatic repulsion is seen in all WR and HRWR admixtures.

Steric hindrance: long polymer chains adsorbed on the surface of the cement particles prevent them to come closer to each other. Steric hindrance is seen in the admixtures containing polycarboxylates. Admixtures containing polycarboxylates, show both electrostatic repulsion and steric hindrance, therefore this type of superplasticizers has a higher ability to reduce the water content. Figure 3.1 shows the electrostatic repulsion and steric hindrance effect of superplasticizers.

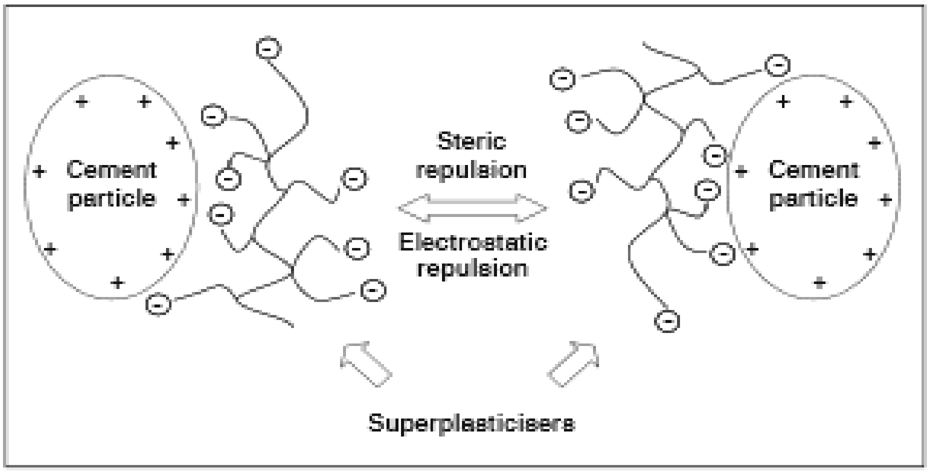


Figure 3.1. Electrostatic repulsion and steric hindrance effect of superplasticizer

The effect of different types of new generation chemical admixtures such as superplasticizer, air-entraining, viscosity modifying and anti-foaming admixtures on the air content and workability of high performance SCC have been studied by many researchers.

Lazniewska [65] discussed the use of different types of chemical admixtures in SCC. The result suggested that admixtures from different sources cannot be used interchangeably, even if they appear to have a similar chemical composition. Chemical admixtures can have adverse effects, therefore they have to be tested before use.

Admixtures will normally be very constant from batch to batch but moving to another source or to another type from the same manufacturer is likely to have a significant effect on SCC performance and should be fully checked before any change is made [1].

Aghabaglou et al. [61] investigated the effects of four types of polycarboxylate ether-based superplasticizer admixtures having same main chain and same polymer structure but different molecular weight and different side chain density of carboxylic acid groups on the fresh and rheological properties as well as compressive strength of SCC. The following conclusions were drawn:

- V-funnel flow time as well as plastic viscosity of SCC mixtures decreased with increasing side chain density of the superplasticizer admixture.
- The apparent yield stress was affected by the superplasticizer dosage; however, the other properties of the admixture had no significant effect on the apparent yield stress of the SCC mixtures.
- As the amount of side chains of the polymer increased, the slump retention of the cementitious system decreased. This may be due to the interlocking of the side chains.
- When the admixture and the cement were compatible, the early strength was dependent on the type of admixture whereas at the ages beyond 7 days the strength became independent of the admixture type. The admixture causing the highest slump loss caused the highest concrete strength at early ages.

3.2. Dynamic Stability of SCC

SCC is designed to cast and fill formwork under its own weight without external compaction with minimum segregation. Fresh properties of SCC can influence the mechanical properties, structural performance, and durability of the concrete [29]. Successful mix-design of SCC should meet three initial criteria which are high filling ability, high passing ability, and good stability [67]. Stability is a very important plastic property for successful application of SCC. SCC is much more susceptible to stability problems than conventional concrete due to high flowability, particularly if it is not proportioned to be cohesive [18].

Stability is also mentioned as segregation resistance which is the ability of an SCC mixture to retain a uniform distribution of all constituent materials during casting process and once all placement and casting operations have been completed. The former is referred as dynamic stability and the later as static stability [19].

Dynamic instability can be caused by the input of any form of vibration energy into the system during concrete transport or placement on the other hand, static stability is the ability of concrete to resist bleeding, segregation, and settlement which are influenced by the gravity of materials and the period of plastic state of concrete until setting [71].

Segregation in SCC is the tendency of coarse aggregate to separate from the cement paste. Segregation included two phases: dynamic segregation which refers to separation when the concrete is flowing in horizontal direction while being cast in formwork and static segregation which is defined as the separation of coarse aggregate and paste when the concrete is at rest [66].

Static instability can result in differential accumulation of light constituents and settling of aggregate and leaving a mortar layer on top of the concrete [9]. Dynamic instability can gradually grow over the flow distance when the SCC spreads over a relatively large distance or immediately after an impact during casting. Such stability is governed by flow patterns, e.g. flow direction and flow rate time during placement, as well as the rheological properties of materials [68].

Dynamic stability is completely related to the rheological properties of SCC. Rheological properties of SCC have been discussed in the previous section in detail. Effect of various parameters on stability of SCC is shown in Table 3.1 that summarizes previous experience on how the concrete raw materials, application variables, and fluidity level affect both static and dynamic segregation. This table gives practical experience on segregation and can be very helpful in practical applications.

Beyond the inhomogeneity of the aggregate and other components distribution in fresh state the instability can also weaken the interface between the aggregate and the cement paste and can adversely affect the bond behavior between steel and concrete which reduces the hardened properties of SCC [69].

Shen et al. [66] analyzed that all coarse aggregates moved together, even if their size were different, but it is not true for a few very large aggregates which experienced static segregation and settled down to the bottom at the beginning of the flow process. Another observation is that paste moved faster than coarse aggregate and dragged the coarse aggregate forward. Paste flowing faster than aggregate always appeared to be the cause of dynamic segregation.

Table 3.1. Effects of proportioning and application on segregation of SCC [27]

Factors	**Effect of Static Segregation**	**Effect of Dynamic Segregation**
Cementitious Materials	Provides viscosity and yield stress to reduce static segregation	Provides viscosity and yield stress to reduce dynamic segregation
Coarse Aggregate	Volume, specific gravity, and gradation affect static segregation	Higher volume reduce passing ability through restricted sections
Fine Aggregate	Gradation and specific gravity affect static segregation	No effect outside of balancing coarse aggregate volume
Water	Volume controls the viscosity of paste and thereby static segregation	Volume controls the viscosity of paste and thereby dynamic segregation
Superplasticizer	High dose can create excessive flow resulting in static segregation	High dose can create excessive flow resulting in dynamic segregation
Viscosity Modifying Admixture	Provides viscosity to the paste resulting in lower static segregation	Provides viscosity to the paste resulting in lower dynamic segregation
Air-Entrainer	Helps to suspend aggregate and reduce static segregation	Minimal to none
Fluidity	Greater fluidity results in higher static segregation	Greater fluidity results in higher dynamic segregation
Flow distance	Minimal to none	Promotes separation of paste from aggregate
Free Fall	Minimal to none	Promotes separation of paste from aggregate
Form dimensions	Minimal to none	Narrow form increases wall effects and increases dynamic segregation
Transport without agitation	Minimal to none	Vibration can cause dynamic segregation
Pumping	Minimal to none	Pressure can cause segregation in the pump lines

In this section the recent researches and studies that have been done about test methods to evaluate the dynamic stability of SCC and results achieved by these methods are discussed.

Many different test methods have been proposed to evaluate the dynamic stability and the relationship between segregation and rheology of SCC. So far no single method or combination of methods has achieved the universal approval and most of them have only their believers and followers. Also no single test method has been found that illustrates all the relevant workability aspects such as dynamic stability, therefore each mixture design need to be tested by more than one test method to find different workability parameters [1, 72].

The only current standard test method for evaluating dynamic stability of SCC is visual stability index *(*VSI) in (ASTM C1611/C1611M-5, Standard Test Method for Slump Flow of Self-Consolidating Concrete, 2005). This test generally measures dynamic segregation, which is affected by static segregation in some extent. When there is no layer of paste and water due to settlement of constituents, the concrete is observed to have good dynamic stability [66].

To differentiate the textural properties of SCC, the slump flow was qualitatively ranked. The VSI procedure is a numerical rating of 0 to 3 with 0.5 increments according to set criteria given in Table 3.2. Homogeneity of the mixture is based on observation made for SCC after steering the slump flow [39, 73]. It is important to note that this observation is considered as part of the dynamic stability given the fact that the concrete can show some nonuniform texture following some mixing and transport.

Table 3.2. The criteria for VSI rating of SCC [76]

Rating	**Criteria**
0 = Highly Stable	No evidence of segregation or bleeding.
1 = Stable	No evidence of segregation or slight bleeding observed as a sheen on the concrete mass.
2 = Unstable	A slight mortar halo < 0.5 in.(< 10 mm) and/or aggregate pile in the center of the concrete mass
3 = Highly Unstable	Clearly segregating by evidence of large mortar halo > 0.5 in. (> 10mm) and/or a large aggregate pile in the center of the concrete mass

However, as mentioned before that no single test can evaluate the dynamic stability of SCC. Esmaeilkhanian [74] cited in his research that Shen et al [66] found that “SCC with good VSI may have severe dynamic segregation problems especially over long travel distances. While the VSI does not quantify a property of the concrete mixture, it is useful for quality control/consistency testing”.

Slump flow test is also used with different ways to evaluate the dynamic stability of SCC. Tregger et al. [32] considered the radial aggregate distribution method from the slump flow test for determining the dynamic stability of SCC. As shown in Figure 3.2 the aggregate distribution was determined from the slump-flow results by measuring the aggregate content in three concentric areas; directly under the initial location of the slump cone, between a diameter of 50 cm and the edge of the slump cone and between the final spread and a diameter of 50 cm. The aggregate content was measured by first separating the concrete region by region and then wet-sieving to wash out the cement and sand. To find the radial aggregate distribution the remaining aggregates were then oven-dried and weighed.

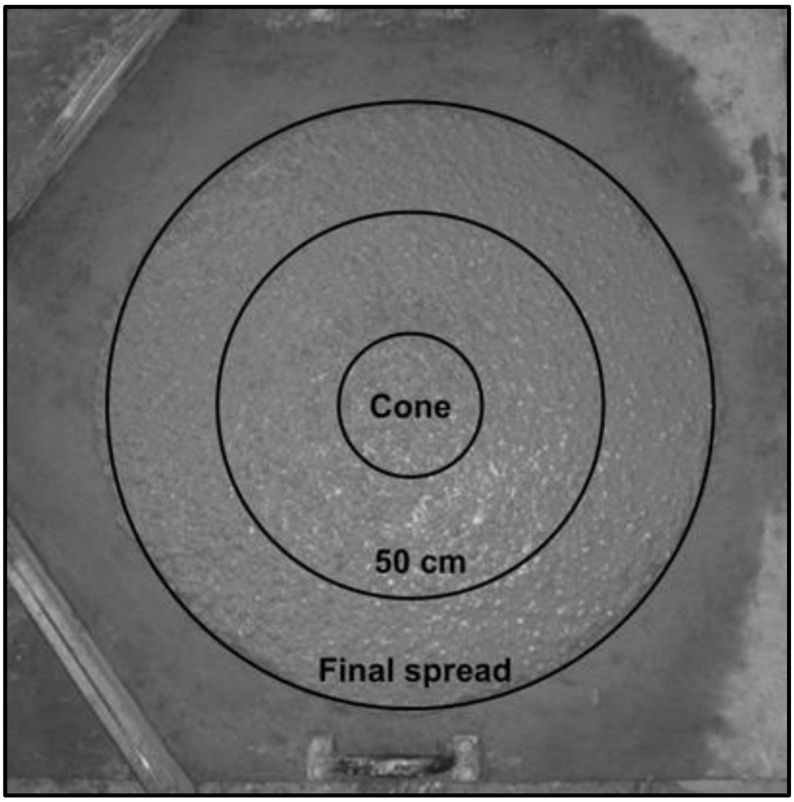


Figure 3.2. Concentric areas for radial aggregate distribution [32]

They found from their study that the slump-flow test has been shown to be capable of indicating dynamic segregation resistances in addition to flowability. It was also mentioned that final diameter from slump flow test is commonly used to give an indication of the yield stress and the T_{500} is commonly measured in the field to give an indication of the viscosity of the SCC [32, 39].

Shen et al. [66] developed a new test method to calculate the dynamic stability of SCC. The geometry of the test device called flow trough. The test measures the change in course aggregate content in an SCC mixture flowing through on the trough. The set-up is made of assembling 25-mm thick wood board which has dimension of 150 x 150 x 1800-mm with 230 mm height difference between two ends as shown in Figure 3.3.

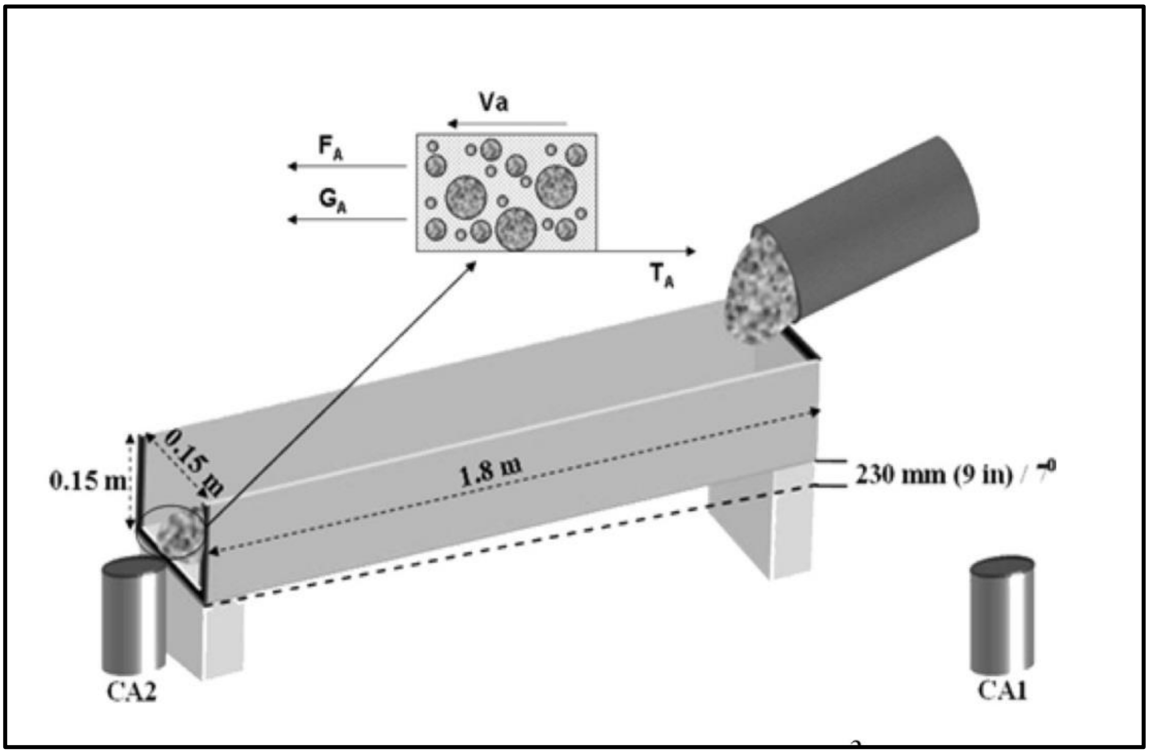


Figure 3.3. Flow trough apparatus [66]

The procedure of this test method is as follows: the surface of trough is wetted with water before the test. Fresh concrete is cast into one 100 x 200-mm cylinder and two 150 x 300-mm cylinders. The concrete in one of the 150 x 300-mm cylinders is poured on the higher end of the trough. After the concrete stops flowing, the trough is straightened up vertically for 30 seconds to let the priming concrete flow off and leave a mortar layer on the trough surface. The trough is then put back into the initial inclined position and the concrete in the other 150 x 300-mm cylinder is poured on the trough from the higher end. A 100 x 200-mm cylinder is filled by the leading portion of concrete flowing through the trough. Concrete samples in both 100 x 200-mm cylinders are washed over a #4 sieve and the coarse aggregates are weighed [74]. From this measurement the dynamic segregation index (DSI) is calculated as follows:

$$DSI = (CA_1 - CA_2)/CA_1$$

Where CA_1 is the mass of coarse aggregate in the SCC, measured in a standard volume of concrete and CA_2 is the mass of in SCC that has flowed through the trough which measured in the same volume as like as CA_1.

Limitations of the flow trough are: it measures dynamic segregation only over a fixed, and somewhat limited, flow distance. The thickness of the flow inside this device is so thin that friction forces between concrete and the bottom of the setup play a significant role in the segregation of SCC. Also it is difficult to carry the apparatus in the site and washing of samples over the sieve is time and energy consuming method [66, 74].

Esmaeilkhanian [74] proposed a new test method named as Tilting Box Test. The Tilting box apparatus (T-box) is contained of rectangular channel box with 100 cm length, 20 cm width, and 40 cm height that hinged in the middle to a support. The tilting motion of the channel is controlled to only one side by means of another support placed under one end of the apparatus as shown in Figure 3.4.

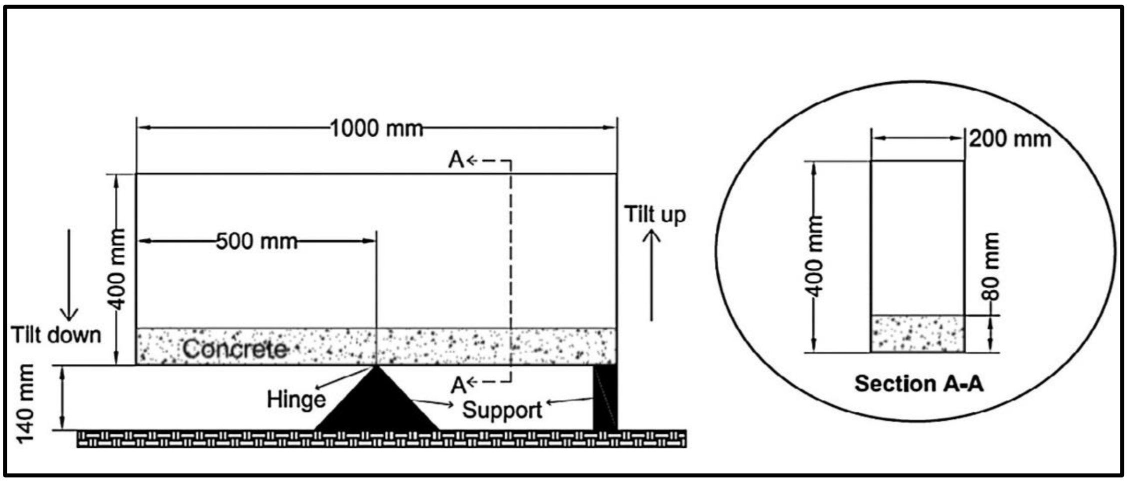


Figure 3.4. Configuration of the T-box test [74]

The T-box test is performed as [68, 75]: (1) the device is placed on a level surface. A sample of concrete about 16 L is introduced into the box from the middle; (2) the box is tilted for 120 cycles at a frequency of 2 sec per cycle; (3) at the end of tilting cycles the box is held horizontally. Samples are taken from the two opposite ends of the box within an approximate area of 200 by 200 mm, i.e. tilt up and tilt down sections, and are washed out over a 4.75 mm (No. 4) sieve. The mass of the coarse aggregate retained on the sieve is then determined. The volumetric dynamic segregation index (VI) is derived as:

$$VI = [(V_{td} - V_{tu}) / \text{average}\ (V_{td}, V_{tu})]\ 100$$

Where V_{td} is the relative coarse aggregate volume (ratio of volume of aggregates >4.75 mm to the total volume of the SCC sample) in the tilt down section, and V_{tu} is the relative coarse aggregate volume in the tilt up section. A $VI \leq 25\%$ can be considered as a limit for acceptable dynamic segregation resistance.

Limitations of T-box test are: its result is not precise enough for SCC with extremely low slump flows and high V-funnel times. The test also does not show good results for highly unstable SCC, either statically or dynamically. The device must be horizontally balanced before the test and a slope of more than a few degrees would adversely affect the results [74].

Bui et al. [22] developed a simple penetration test which can be used with the L-box test to roughly evaluate dynamic segregation of SCC. The structure of penetration apparatus (PA) is indicated in Figure 3.5. PA consists of a Frame F, Slot E, Reading scale M, Screw D, and a penetration head. The penetration head, which has a mass of 54 g, is assembled from a Cylinder C and Rod K. The inner diameter, height and wall thickness of the cylinder is 75, 50, and 1 mm, respectively. A set of small cylinder molds with height of 70 mm and a diameter of 80 mm was used to assess the segregation resistance of concrete in horizontal direction of L-box as shown in Figure 3.6.

The L-box apparatus and penetration apparatus was used together to determine the dynamic segregation resistance, deformability and blocking behavior of SCC. The test from both of these apparatus together named as (Rapid Testing Method for Segregation Resistance of Self- Consolidating Concrete).

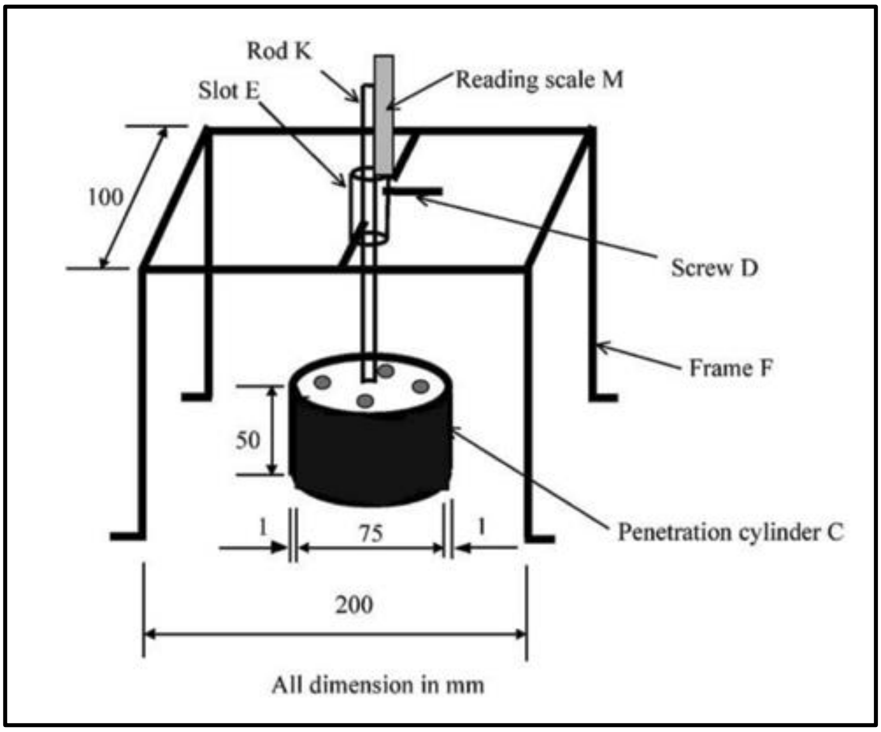


Figure 3.5. Penetration apparatus (PA) for segregation tests

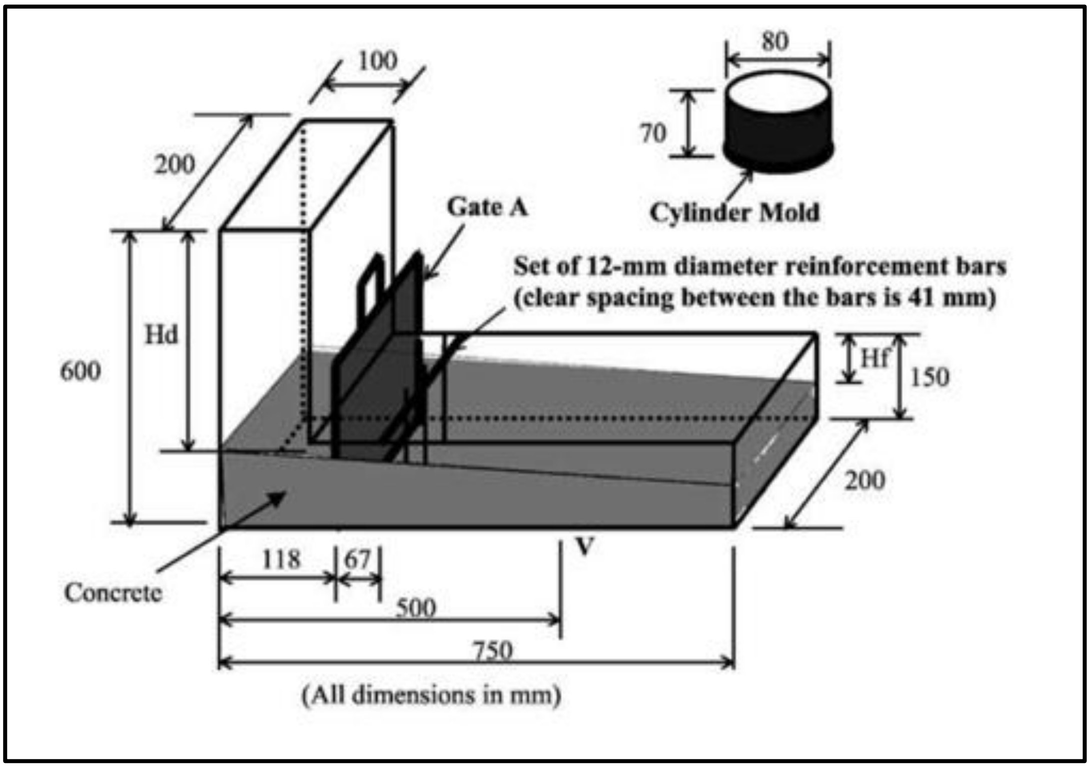


Figure 3.6. L-box apparatus with small cylinder mold

The test procedure is that with gate A of the L-box closed, concrete is placed into the vertical leg of the L-box without any consolidation such as rodding or vibration, and the top is levelled. After 2 minutes, the PA is located on the top of the vertical leg of the L-box, the penetration cylinder adjusted to just touch the upper surface of concrete, and then the cylinder allowed to penetrate freely into the concrete. After 45 seconds, the penetration depth (Pd) of the cylinder head is recorded from the scale. The average Pd of three measurements at two sides and the center is calculated and considered as the final Pd.

The L-box apparatus gate is lifted in a vertical direction to allow the concrete to flow through the clear spacing between the reinforcement bars. When the concrete stops, fresh concrete is taken from the region in front of the reinforcement set and filled into a pair of small molds. Similarly, fresh concrete is taken at the end of the horizontal leg of the L-box and again filled into the other pair of small molds. Afterwards, the concrete from the small molds is washed out, and coarse aggregate particles larger than 9.5 mm are separated, dried and weighed. The average mass of the coarse aggregate, for each pair of the small molds, is calculated and compared in order to assess segregation resistance of concrete in horizontal direction.

Concrete is of satisfactory segregation resistance if the difference (specified as Rh) of average masses of coarse aggregate from the front of the reinforcement set and at the end of the L-box is smaller than 10%. The difference Rh and the Pd are compared to determine the optimum range of Pd, which can be used to rapidly evaluate the segregation resistance of SCC in the horizontal direction.

The limitations of this test method are, such segregation measurements are associated with the effects of blocking (due to L-box geometry) and then cannot be considered as pure segregation assessment. Besides, the total length of L-box device is not long enough to be indicative of dynamic segregation occurring in full-scale elements [74].

Some of tests which are mentioned in Table 2.1 of previous chapter from (The European Guidelines for Self-Compacting Concrete) are also used as indirect indicators of dynamic segregation.

Khayat et al. [39] compared the suitability of a number of field-oriented test methods in assessing the stability of SCC. The testing methods considered for the dynamic stability include the V-funnel, JRing, L-box, U-box, and pressure bleed tests.

The rheological parameters from concrete rheometer test, slump flow consistency, and visual stability index of the slump were also considered.

Khayat et al. [39] compared the results of these different tests to each other to examine the probable correlations between their results and their outcomes and the rheological parameters of SCC. In addition, they aimed to seek the adequacy of the mentioned tests for assessment of dynamic stability of SCC. Based on their observations they finally conclude that:

- The J-Ring, L-box, and U-box tests are suitable for evaluating the passing ability of SCC through closely spaced reinforcing hitches. These tests can be well correlated and can be easily conducted at the job site, and their results could give general information about the stability level of the concrete from the relationship between passing ability and dynamic segregation.
- Similar to the slump flow/L-box tests, the slump flow/J-Ring tests can evaluate both the deformability and passing ability characteristics. The L-box is preferable, since it can reflect the viscosity of the mixture by means of the flow time value.
- The T_{500} and the flow times evaluated from the V-funnel, L-box, and U-box tests can be used to assess viscosity. For a given deformation capacity, the longer the flow time, the higher the viscosity of the mixture. Hence, if the relationship between viscosity and dynamic segregation is known, such results could be used to evaluate dynamic stability.

CHAPTER 4

EXPERIMENTAL STUDY

4.1. Materials

Materials which were used in this experimental program are explained below.

4.1.1. Cement

A commercially available blended cement, CEM IV/B (P-W) 32.5 R, conforming to TS EN 197-1: 2012 was used during all this investigation. The chemical composition, presented in Table 4.2, was obtained by XRF method in the Materials Research Center of İzmir Institute of Technology. Specific gravity and Blaine fineness values are presented in Table 4.1. Specific gravity was determined according to (ASTM C 188) in the Materials of Construction Laboratory in the Civil Engineering Department of İzmir Institute of Technology. Blaine fineness was measured according to (ASTM C 204) in Çimentaş cement factory. Figure 4.1 shows micrograph of the blended cement particles. The photo was taken by Scanning Electron Microscopy (SEM) in the Materials Research Center of İzmir Institute of Technology. The micrographs were taken under a voltage of 5 kV, a working distance of 9.2 mm, a magnification of 5000, and a spot size of 3 with ETD detector.

Table 4.1. Physical properties of the blended cement and limestone powder

Properties	**Cement**	**Limestone Powder**
Specific gravity	2.2963	2.75
Blaine specific surface, cm^2/g	3620	3945

Table 4.2. Chemical composition of the blended cement and limestone powder

Oxides	**Cement (%)**	**Limestone Powder (%)**
SiO_2	23.11	0.0011
Al_2O_3	12.3	0.2067
Fe_2O_3	2.785	0.0047
CaO	48.95	95.16
MgO	2.564	0.958
SO_3	1.644	0.00047
K_2O	1.154	0.0012
Na_2O	6.62	2.68

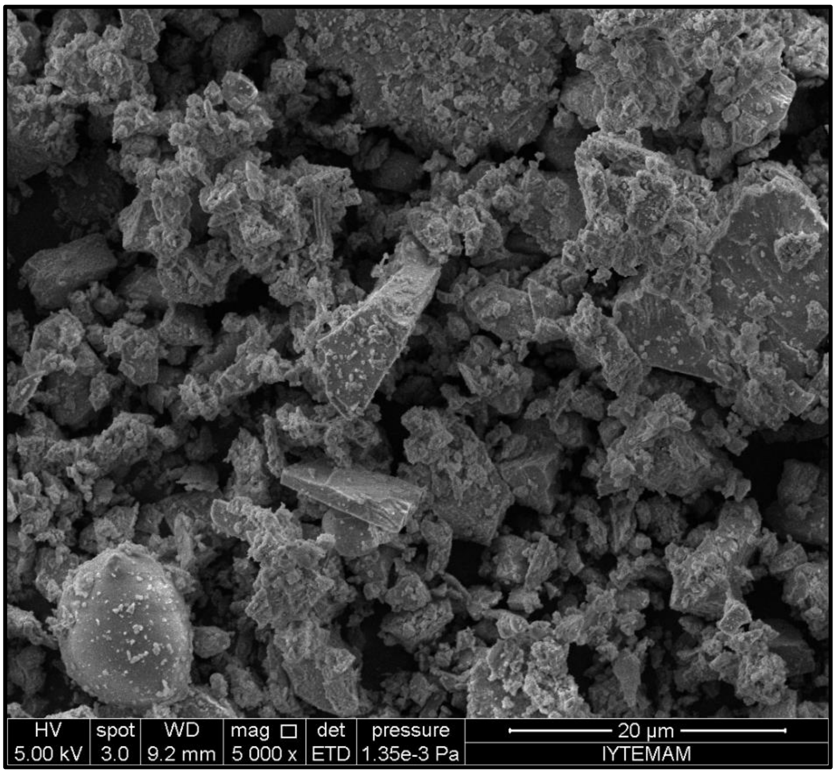


Figure 4.1. Micrograph of the blended cement particles

4.1.2. Limestone Powder

Limestone powder was added to the mixtures as a filler material. Due to its fine particle size, it was used to adjust the water to powder ratio (w/p) of SCC mixtures. Increasing the fines content of the concrete makes the mixture more stable against segregation. The chemical composition and basic physical properties of the limestone powder are presented in Table 4.2 and Table 4.1, respectively. Figure 4.2 shows micrograph of the limestone particles. The properties of the limestone powder were determined by the same methods in the same places as the cement (See Section 4.1.1).

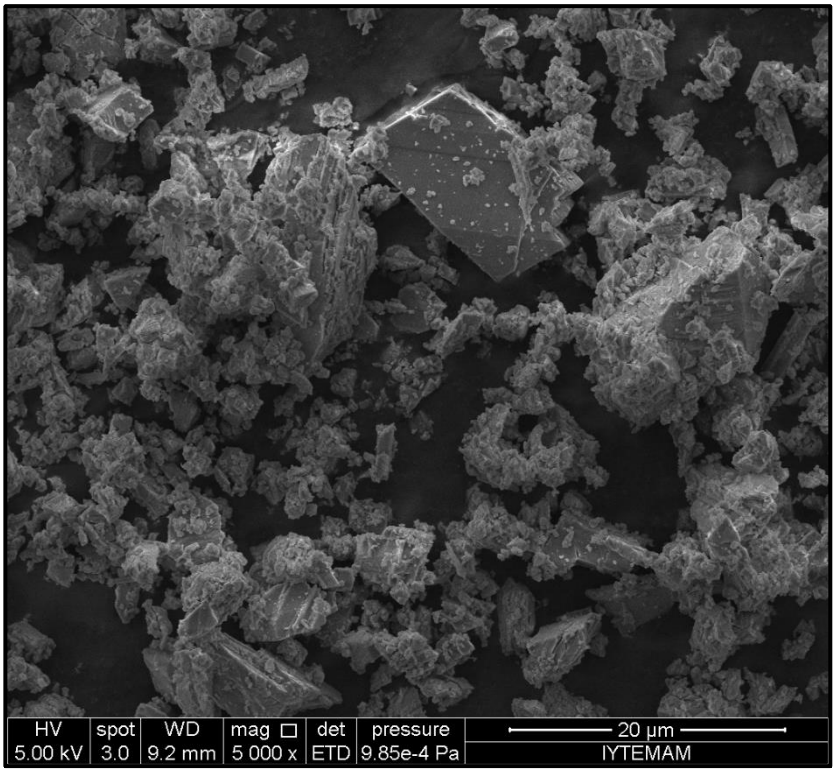


Figure 4.2. Micrograph of the limestone particles

4.1.3. Aggregates

Two aggregate groups were used in this research. The first group (Aggregate 1.) contained mostly coarse aggregate with 13 % of fine aggregate. The second group (Aggregate 2.) was fine aggregate. Aggregate 1 was crushed limestone while Aggregate 2 was river sand. Physical properties for both aggregate groups are demonstrated in

Table 4.3. SSD bulk specific gravity and water absorption capacity of the aggregates were determined according ASTM C 127 and 128 respectively. These tests were performed in the Materials of Construction Laboratory in the Civil Engineering Department of İzmir Institute of Technology.

Table 4.3. Physical properties of aggregates

Physical Properties	**Aggregate 1.**	**Aggregate 2.**
SSD Bulk specific gravity	2.564	2.585
Water absorption (%)	1.37	2.67

Table 4.4. Sieve analysis data for aggregates

Sieves	**Sieve size, mm**	**Passing %**			
		Agg 1. Dmax 10 mm	Agg 1. Dmax 15 mm	Agg 1. Dmax 20 mm	Agg 2.
7/8 in	22.2	100	100	100.00	100
3/4 in	19	100	100	91.83	100
3/8 in	9.5	100	77	64.17	100
4 #	4.75	54.81	42	35.17	100
8#	2.36	3.17	2.44	2.03	83.18
16#	1.18	1.35	1.04	0.87	55.38
30#	0.6	0.52	0.4	0.33	32.5
50 #	0.3	0	0	0	21.08
100 #	0.15	0	0	0	7.54
Pan	Pan	0	0	0	0

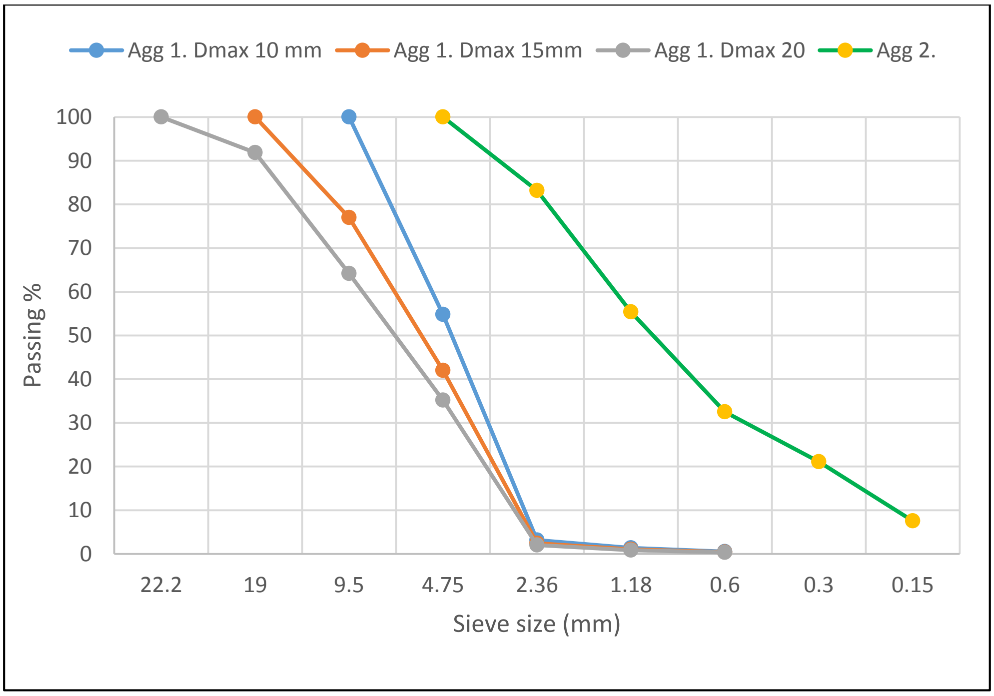


Figure 4.3. Gradation curve for Aggregates

As will be explained later in this chapter, 3 different Dmax values were employed in this study. In most of the mixtures, Dmax was 15 mm. To have Dmax = 10 mm, aggregate 1 was sieved through the 3/8 inch sieve. To have Dmax = 20 mm, particles with the same source having a diameter of 15 – 20 mm was added. The ratio of the new particles to Aggregate 1 was 1/5. This ratio was selected to satisfy the grading limits given in TS EN 706 Aggregates for Concrete. The sieve analysis (made according to ASTM C 136) data and gradation curve for aggregates are shown in Table 4.4 and Figure 4.3, respectively.

4.1.4. Superplasticizer

Commercially available superplasticizer (MGlenium SKY 608) used in this research is a polycarboxylate based superplasticizer. The admixture is classified as type F according to ASTM C 494/ C 494M 38. The admixture is particularly recommended for SCC mixtures where high flowability and less segregation are needed. Desired high slump value for SCC can easily be achieved by usage of superplasticizers, however attention has to be paid during mix proportioning since small changes in their dosage can affect the fresh properties significantly. The properties of the abovementioned superplasticizer obtained from the manufacturer are given in Table 4.5.

Table 4.5. Properties of the superplasticizer

Type	Polycarboxylic-based
Color	Opaque
Density	1.063-1.103 kg / liter
Chlorine content	< 0.1 %
Alkali content	< 3 %
Recommended dosage	About 1% of cement content

4.2. Testing Methods

Slump flow test, T_{500}, VSI, V-funnel, L-box, static sieve segregation (GTM), rheometer, and new test proposed in this research were used in order on fresh concrete to determine the flow properties and stability of fresh SCC. All the tests were performed as soon as the mixing was finished. The tests used in this experimental program are explained below:

4.2.1. Slump Flow Test, T_{500}, and VSI

The slump flow test was made according to ASTM C 1611/C 1611M-05, Standard Test Method for Slump Flow of Self-Consolidating Concrete, 2005 for this research. The purpose of the test is to monitor the consistency of fresh SCC. The apparatus and principle of this test are discussed in detail in Chapter 2.

The slump flow average diameter was measured after raising the slump cone at the center of the base plate and after the flow stopped completely. At the time of performing the slump flow test, the T_{500} time was measured from flow of SCC from outer edge of the slump cone on the base plate until reaching the diameter of 500 mm. Afterwards, photos were taken from each sample to evaluate the Visual Stability Index

(VSI). Table 4.6 and 4.7 show the recommended conformity criteria for slump flow diameter and T_{500} time according to EFNARC guidelines [1]. The standard criteria for VSI is shown in Table 3.2 in Chapter 3.

Table 4.6. Conformity criteria for slump flow [1]

Classes	Slump-flow in mm
Slump-flow class 1 (SF1)	550 to 650
Slump-flow class 2 (SF2)	660 t0 750
Slump-flow class 3 (SF3)	760 – 850

Table 4.7. Conformity criteria for T_{500} time [1]

Classes	T_{500}, s
Viscosity class 1 (VS1)	≤ 2
Viscosity class 2 (VS2)	> 2

4.2.2. V-Funnel Test

The V-funnel test was made by following EFNARC guidelines [1]. The V-funnel test is used to assess the viscosity and filling ability of SCC. Viscosity and filling ability parameters are related to dynamic stability of SCC as discussed in detail in previous chapters. The test is not suitable when the maximum size of the aggregate exceeds 20 mm. The geometry of the apparatus and principle of this test method are discussed in detail in Chapter 2. Table 4.8 shows the recommended conformity criteria for V-funnel flow time according EFNARC guidelines [1].

Table 4.8. Conformity criteria for V-funnel flow time [1]

Classes	**V-funnel time in s**
V-funnel time class 1 (VF1)	≤ 8
V-funnel time class 2 (VF2)	9 to 25

4.2.3. L-Box Test

A wooden L-box with three rebars was used in this research. The test was done by following EFNARC guidelines [1]. This test is used to assess the passing ability of SCC to flow through small openings like highly congested reinforcements and other obstructions without blocking or segregation. At the time of performing the L-box passing ratio, the flow time was also measured from opening the gate until the concrete reached the end of horizontal section. The geometry of the apparatus and principle of this test method are discussed in detail in Chapter 2. Table 4.9 demonstrates the recommended conformity criteria for L-box passing ratio according EFNARC guidelines [1].

Table 4.9. Conformity criteria for L-box passing ratio [1]

Classes	Passing ability ratio
Passing ability class 1 (PA1)	≥ 0.80 with 2 rebars
Passing ability class 2 (PA2)	≥ 0.80 with 3 rebars

4.2.4. Static Sieve Segregation Test (GTM)

The test method for static sieve segregation (GTM) with # 4 sieve was used in this research. However, the general principle and concept of the original test method was followed. Almost two kg of concrete from each mixture was poured on the # 4 sieve which was placed on its pan. Afterwards, the concrete was left at rest for 10 minutes and then the passing amount of concrete was weighed. The general principles and procedure of this test method are discussed in detail in Chapter 2. Table 4.10 shows the recommended conformity criteria for GTM test segregation ratio according EFNARC guidelines [1].

Table 4.10. Conformity criteria for GTM test segregation ratio [1]

Classes	**Segregation resistance in %**
Segregation ratio class 1 (SR1)	≤ 20
Segregation ratio class 2 (SR2)	≤ 15

4.2.5. Rheometer Test

A Tattersall type pallet rheometer (Contec 4SCC) shown in Figure 4.4 was used to determine the rheological parameters of SCC in this research. The impeller of rheometer was rotated at six different speeds (0.8, 0.70, 0.55, 0.40, 0.25, and 0.10 rps). Rheometer 4SCC is controlled with a software that runs on windows. A screenshot of the program can be seen in Figure 4.5. Start and abort buttons, a menu to adjust and set the rotation speed and time, a graph that displays the measured resistance at each rotation speed are the elements of the program window.

Fresh concrete shearing procedure was started at the highest speed and finished with the slowest speed (down-curve). Four torque values per second were recorded at each speed. Torque measurements were taken for eight seconds for each speed value. However, for each speed level, the torque was found to be stabilized after the first two seconds; thus, the average readings of the last six seconds were used in the calculations. The torque value corresponding to each speed value (averaged by 6x4 = 24 data) was recorded and the Bingham model was constructed by adding a linear trendline to the torque-speed plot. The intersection of the trendline with the torque axis (specified as the apparent yield stress) and the slope of this line (specified as the torque plastic viscosity) were determined on the graph as shown in Figure 4.6. The geometry of apparatus, and principle of this test method were discussed in detail in Chapter 2.

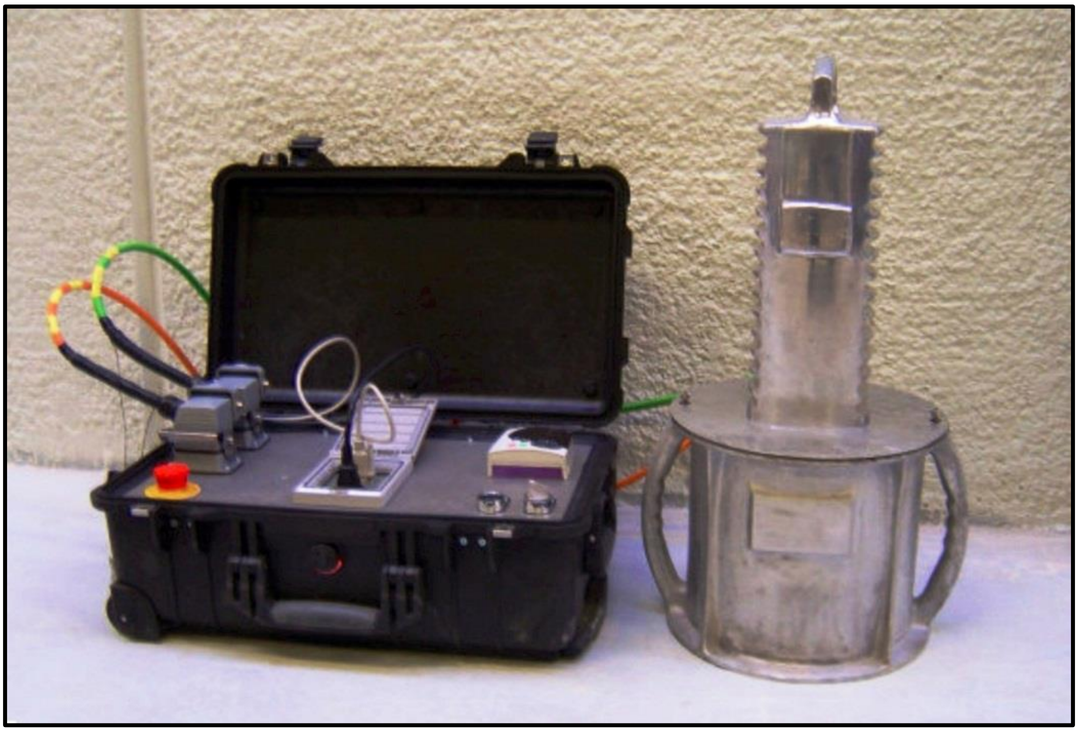
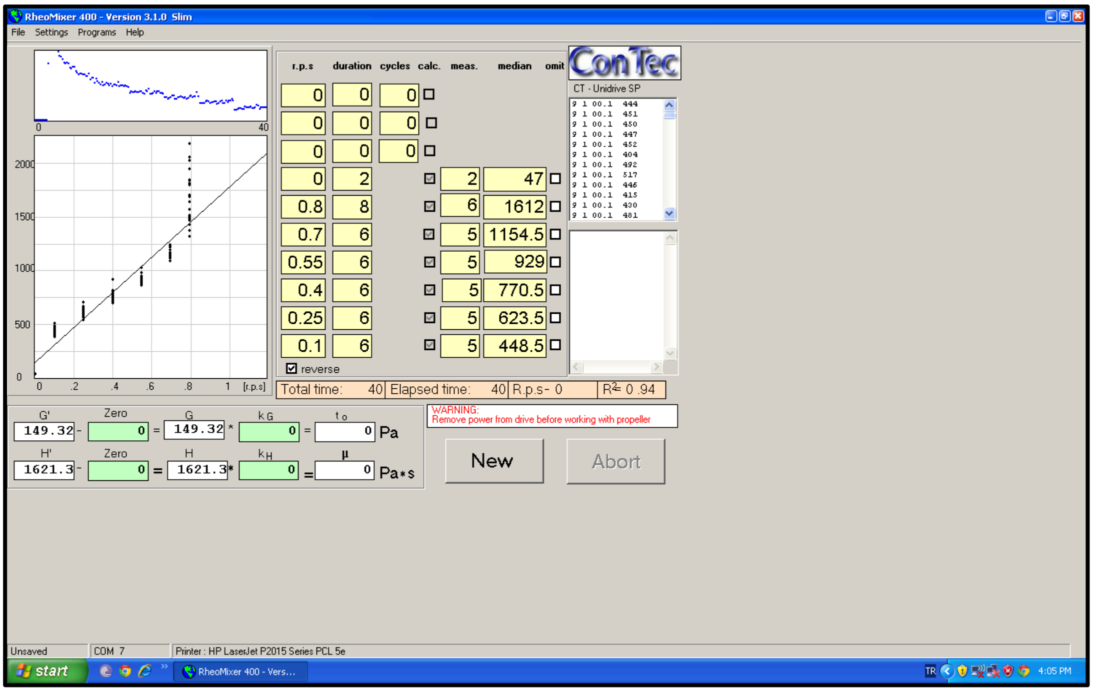


Figure 4.4. Contec 4SCC rheometer



r.p.s	duration	cycles	calc.	meas.	median	omit
0	0	0	☐			
0	0	0	☐			
0	0	0	☐			
0	2		☑	2	47	☐
0.8	8		☑	6	1612	☐
0.7	6		☑	5	1154.5	☐
0.55	6		☑	5	929	☐
0.4	6		☑	5	770.5	☐
0.25	6		☑	5	623.5	☐
0.1	6		☑	5	448.5	☐

☑ reverse

```
9 1 00.1  444
9 1 00.1  451
9 1 00.1  450
9 1 00.1  447
9 1 00.1  452
9 1 00.1  404
9 1 00.1  492
9 1 00.1  517
9 1 00.1  446
9 1 00.1  415
9 1 00.1  430
9 1 00.1  481
```

Total time: 40 | Elapsed time: 40 | R.p.s- 0 | R² = 0.94

G' 149.32 - Zero 0 = G 149.32 * kG 0 = to 0 Pa

H' 1621.3 - Zero 0 = H 1621.3 * kH 0 = μ 0 Pa∗s

WARNING:
Remove power from drive before working with propeller

Unsaved | COM 7 | Printer : HP LaserJet P2015 Series PCL 5e

Figure 4.5. Contec 4SCC rheometer software

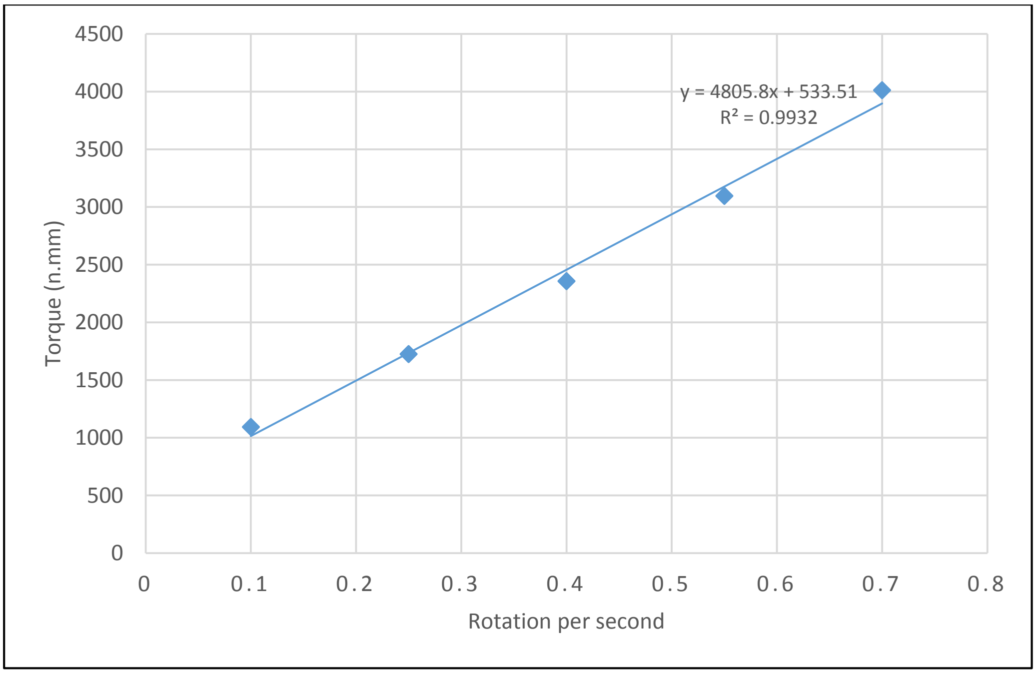


Figure 4.6. Bingham model graph

4.2.6. New Proposed Test Method (DSST)

New proposed method is a Dynamic Sieve Segregation Test (DSST) which contained a rectangular channel box with 6 mm sieve opening at the bottom. This apparatus is made of steel. The inner dimensions of the apparatus are 150 cm long, 20 cm wide, and 20 height that hinged in the middle to a 50 cm high support as shown in Figure 4.7 and Figure 4.8.

The aim of this test method is to evaluate the dynamic stability of SCC in fresh state to flow over long distance. The idea for this method is to check whether the mortar has the ability to hold the coarse aggregates while the concrete is moving. The device is freely moveable on the support point so that the ends can move up and down, which allows it to produce possible flow cycles.

Figure 4.7. New proposed test method (DSST) apparatus

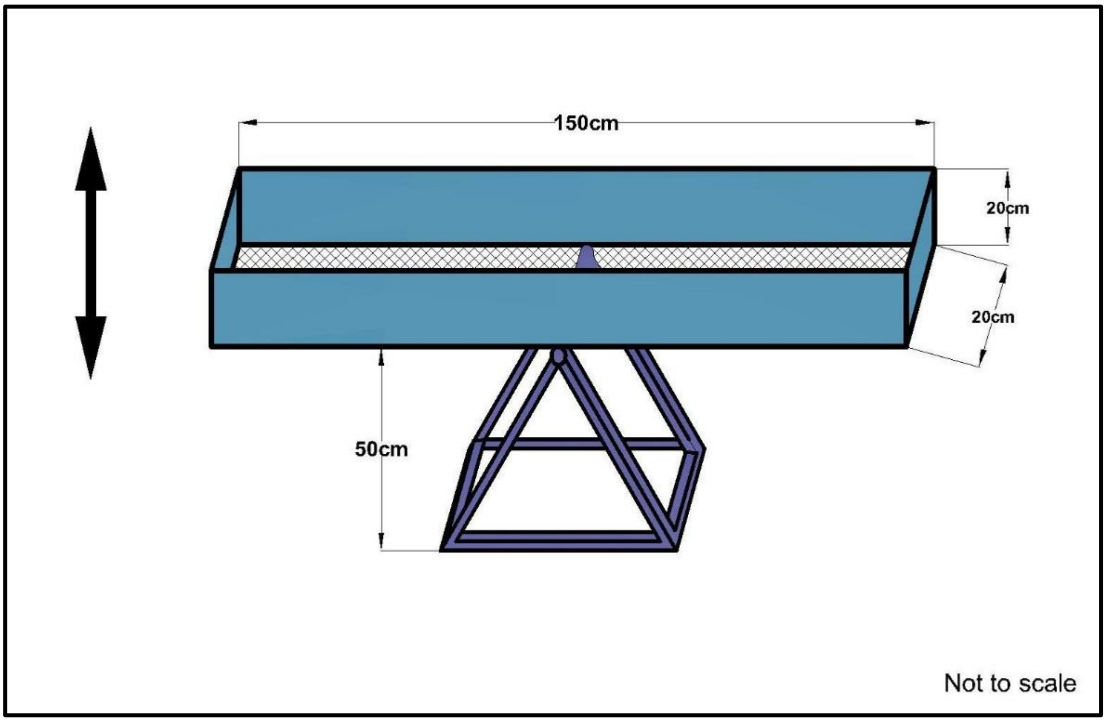


Figure 4.8. New proposed test method (DSST) apparatus

The procedure and principle of this test method is as follows: (1) the empty channel box is weighed to know the weight of device (Wd); (2) the channel box is placed on the support stand in the middle; (3) a sample of concrete weighing 18 kg (Wc) is poured into the box from the middle using a bucket while the box was horizontal; (4) the channel box is cycled four times by the up and down movement of the ends. After each cycle the device is hold for 15 seconds to allow the concrete to flow in the channel box, i.e. the channel is slanted for 4 cycles at a frequency 15 seconds per cycle; (5) then the channel box is hold horizontally on support stand for 10 seconds; (6) finally, the channel box with remained concrete is weighed (Wf) on the balance.

The dynamic segregation ratio (DSR) is calculated as the ratio of the weight of materials that passed through the sieve (Wps) to the total initial weight of concrete sample poured into the channel box (Wc). The dynamic segregation ratio is calculated from the following equation.

$$DSR = (Wps / Wc) \times 100 = [(Wd + Wc - Wf)/ Wc] \times 100$$

The 4 cycles of channel box are fixed by trial and error, and passing rate of concrete through the sieve was checked. When the number of cycles was less than 4, the passing rate was very high, and when it was higher than 4, the amount of concrete passing the sieve was very low. Therefore, it is found that the channel box will be cycled four times by the up and down movement of the ends. The frequency of the cycles was determined as 15 seconds per cycle again by trial and error. In most of the mixtures, the concrete was able to reach the ends of the channel box after 15 seconds. In the 5th step of the test procedure, the channel box is hold horizontally on support stand for 10 seconds to minimize the passing by resting the concrete from dynamic state.

4.3. Mixture Proportions and Testing Program

In this section the mixture proportions, mixing procedure, and the sequence of the tests are discussed.

4.3.1. Mixture Proportions

As summarized in Table 4.12, 12 SCC mixtures were prepared for this research. In this study the cement and limestone powder contents were kept constant at 400 kg and 20 kg (5% of cement content) in 1 m^3 of concrete, respectively. The water to cement ratio (w/c), coarse aggregate to total aggregate ratio (CA/TA), slump flow value, and Dmax were varied in the study to investigate their effects on the rheology and dynamic stability of SCC. The water to cement ratio (w/c) was 0.42 or 0.50. The coarse aggregate to total aggregate ratio (CA/TA) was 0.45, 0.50 or 0.53. For a given w/c and CA/TA = 0.50, the slump flow values were set to 550 ±20 mm, 650 ± 20 mm and 720 ± 20 mm by changing only the superplasticizer content. When the w/c = 0.42, CA/TA = 0.50, and slump flow = 650 mm the Dmax was changed as 10mm, 15mm, and 20mm. The mix-design variables are given in Table 4.11.

Table 4.11. SCC mix design variables

w/c	**CA/TA**	**Slump flow diameter (mm)**	**Dmax (mm)**
0.42	0.45	650	15
	0.50	550, 650, 720	Slump flow = 650, Dmax = 10, 15, & 20
	0.53	650	15
0.50	0.45	650	15
	0.50	550, 650, 720	15
	0.53	650	15

Table 4.12. Mixture proportioning of tested SCC

Mixtures	Slump-flow, mm	Dmax, mm	W/C	CA/TA	Cement, kg/m^3	Water, kg/m^3	Limestone powder, kg/m^3	Coarse aggregate, kg/m^3	Fine aggregate, kg/m^3	Superplasticizer, kg/m^3	W/powder (by volume)
1	650 ± 20	15	0.42	0.45	400	168	20	775.72	948.10	6.375	0.98
2	550 ± 20	15		0.50	400	168	20	861.55	861.55	4.875	1.00
3	650 ± 20	15			400	168	20	861.55	861.55	5.55	1.00
4	720 ± 20	15			400	168	20	861.55	861.55	6.625	1.00
5	650 ± 20	10			400	168	20	861.55	861.55	6.625	1.00
6	650 ± 20	20			400	168	20	861.55	861.55	5	1.00
7	650 ± 20	15		0.53	400	168	20	913.02	809.66	5.25	1.01
8	650 ± 20	15	0.50	0.45	400	200	20	738.63	902.77	4.125	1.18
9	550 ± 20	15		0.50	400	200	20	820.36	820.36	3.25	1.20
10	650 ± 20	15			400	200	20	820.36	820.36	3.425	1.20
11	720 ± 20	15			400	200	20	820.36	820.36	3.75	1.20
12	650 ± 20	15		0.53	400	200	20	869.37	770.95	3.25	1.21

4.3.2. Mixing Procedure

Rotating drum mixer with 100 Liter capacity was used as shown in Figure 4.9. The mixing sequence is presented in Table 4.13.

Figure 4.9. Rotating drum mixer with 100 Liter capacity

Table 4.13. Mixing sequence for SCC tested mixtures

Step	Description
1	Introducing the sand into the mixer and mixing for 1 minute
2	Moisture correction for aggregates
3	Adding coarse aggregates to the mixer and mixing for 2 minutes
4	Introducing the 2/3 of water and mixing for 30 seconds
5	Introducing the cement and limestone powder and mixing for 1 minute
6	Adding the 2/3 amount of designed superplasticizer diluted in 1/3 remaining amount of water and mixing 2 minutes
7	Stopping the mixer for 2 minutes
8	Mixing again for 2 minutes
9	Examining the slump flow of SCC by using slump flow test to check the aimed slump flow value
10	If necessary , making modifications to the mixture by using remaining 1/3 amount or extra amount of superplasticizer

4.3.3. Testing Sequence

Since testing sequence can affect the rheology of SCC, the testing sequence were kept as same for all of the mixtures. The testing sequence for all aimed tests are as follows: (1) slump flow test with slump flow spread values, T_{500} time, and photos were taken for Visual Stability Index (VSI); (2) V-funnel test; (3) L-box test; (4) rheometer test; (5) dynamic sieve segregation test (DSST); (6) static sieve segregation (GTM). In order to increase the speed of the test program, no concrete was returned to the mixture. Before each test, the remaining concrete in the mixer was mixed for 30 seconds to forget the shear history and to regain the homogeneity. All the tests were completed in 12 minutes after mixing has finished.

CHAPTER 5

RESULTS AND DISCUSSIONS

5 .1. Slump Flow Test, Superplasticizer demand, T_{500} and VSI

The results of slump flow test for all 12 tested mixtures are summarized in Table 5.1. Mixtures proportioned to have greater deformability with same water to cement ratio (w/c), required higher amount of superplasticizer, i.e. the superplasticizer demand increased with increasing the slump flow values from 550 ± 20 mm to 720 ± 20 mm. The effect of slump flow value and w/c on superplasticizer demand is shown in Figure 5.1. On the other hand, increasing the w/c decreased the demand of superplasticizer because water molecules were able to separate the solid particles with less amount of superplasticizer.

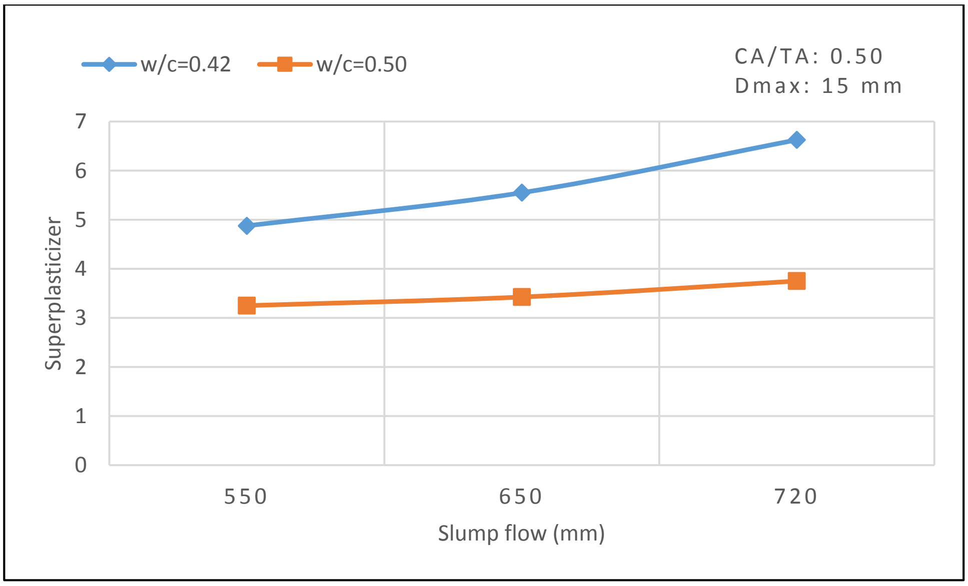


Figure 5.1. Effect of slump flow value and w/c on superplasticizer demand

As shown in Figure 5.2 increasing the coarse aggregate to total aggregate ratio (CA/TA) decreased the demand of superplasticizer. Similarly, increasing the coarse aggregate size (Dmax) decreased the demand of superplasticizer as illustrated in Figure

5.3. Increasing CA/TA and Dmax reduces the surface area of the aggregates to be wetted, supplying more free water to achieve the desired slump flow [46, 48].

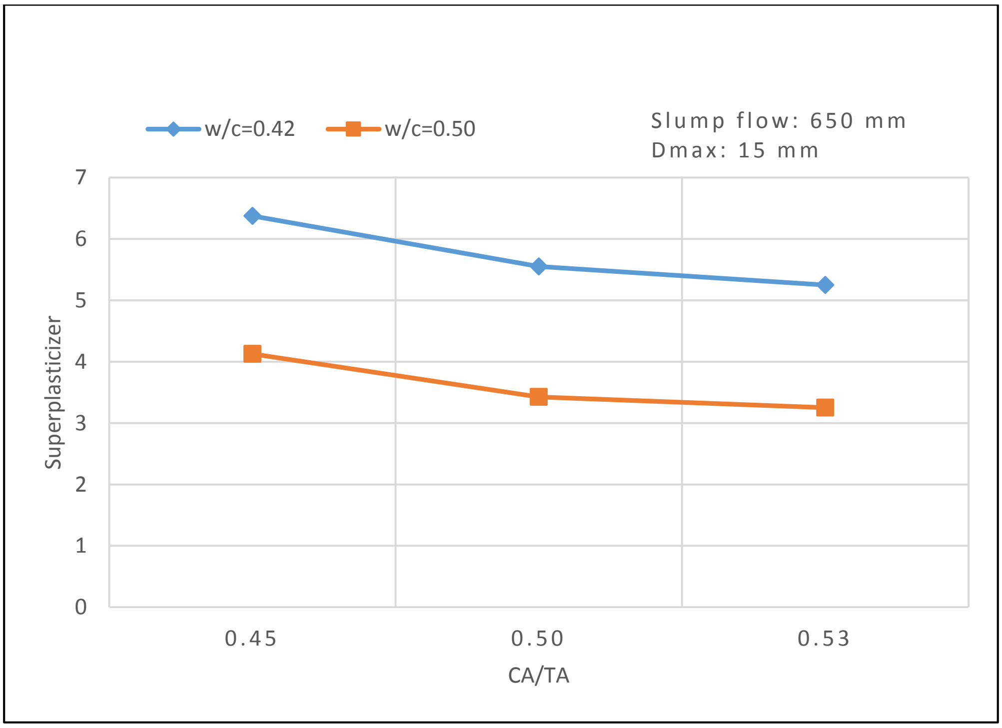


Figure 5.2 Effect of CA/TA and w/c on superplasticizer demand

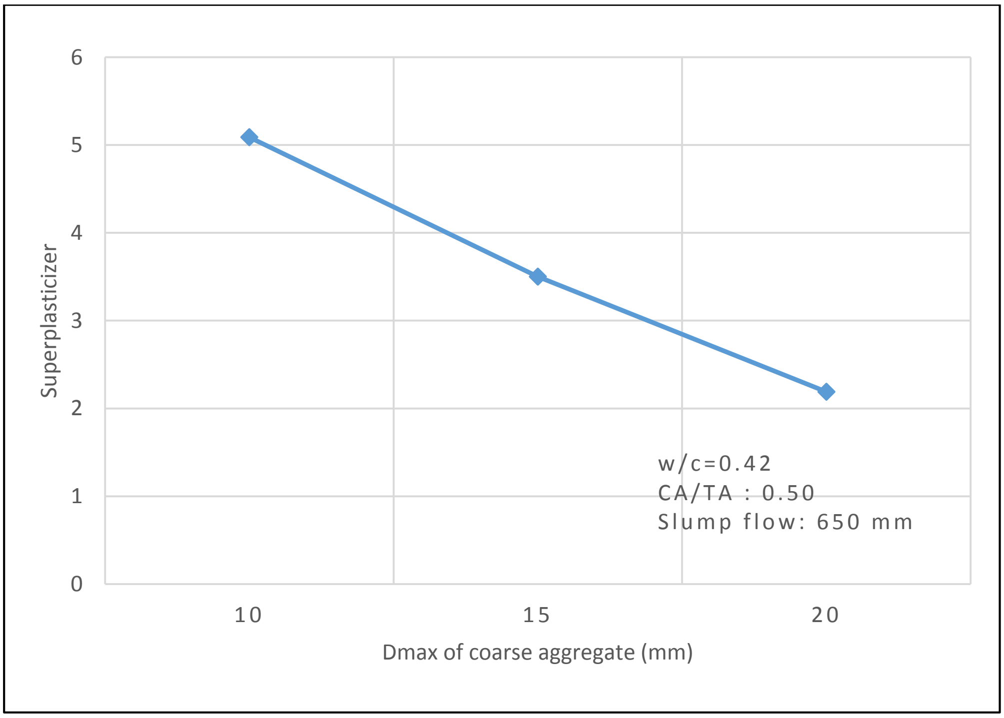


Figure 5.3 Effect of Dmax on superplasticizer demand

The velocity of deformation was determined through the measurement of slump flow T_{500} time required to reach 500 mm spread. The T_{500} cannot reflect the viscosity of SCC at all, however it can be a useful index for the relative evaluation of viscosity for SCC. The results show that the SCC with higher w/c has shorter T_{500} time. In the same way with increasing slump flow values the T_{500} time decreased. The reason is that SCC mixtures with lower w/c or lower slump flow have higher viscosity as will be explained later in section 5.2 and 5.5. The effect of slump flow and w/c on T_{500} time is shown in Figure 5.4. Similarly, the T_{500} time decreased with both increasing the Dmax of coarse aggregate and CA/TA as demonstrated in Figure 5.5 and Figure 5.6. The reason is that larger size aggregate generally results in concrete with lower viscosity. However, the effect of aggregate on concrete yield stress and viscosity are sometimes less clear due to the combined effect from size and gradation of aggregate [46].

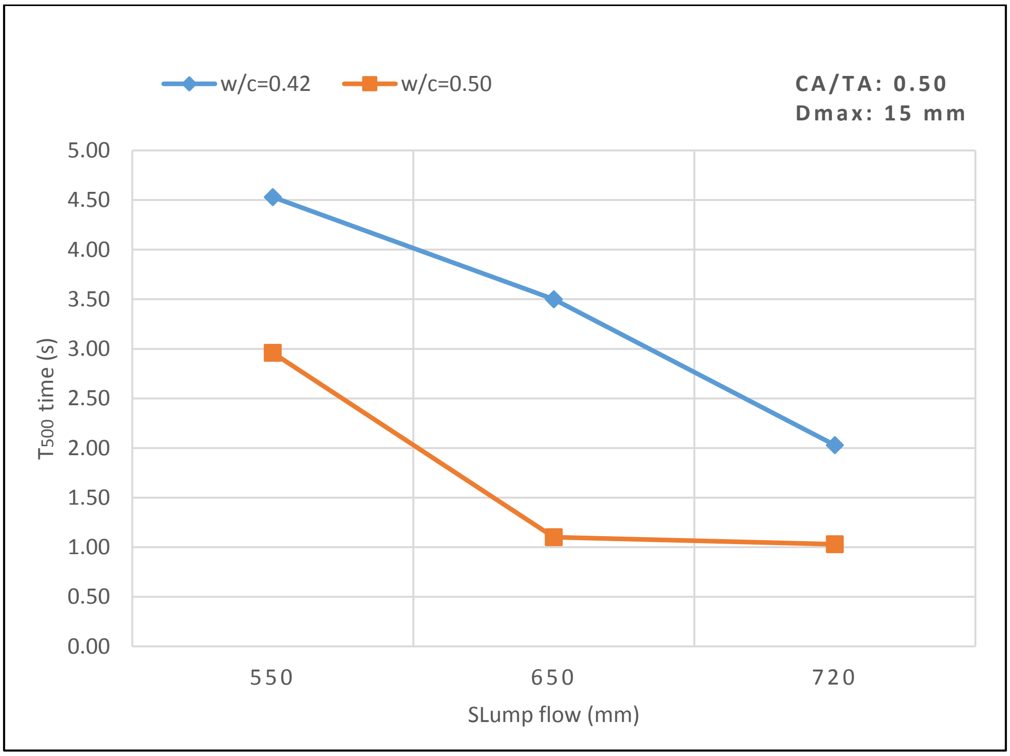


Figure 5.4. Effect of slump flow value and w/c on T_{500} time

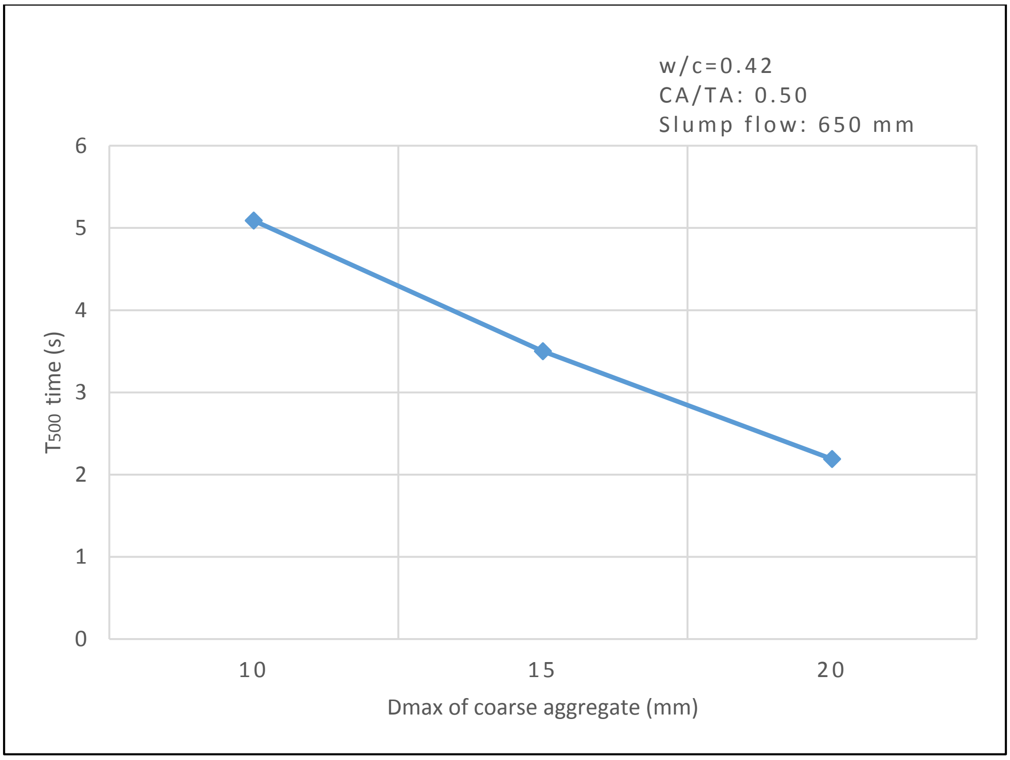


Figure 5.5. Effect of Dmax on T_{500} time

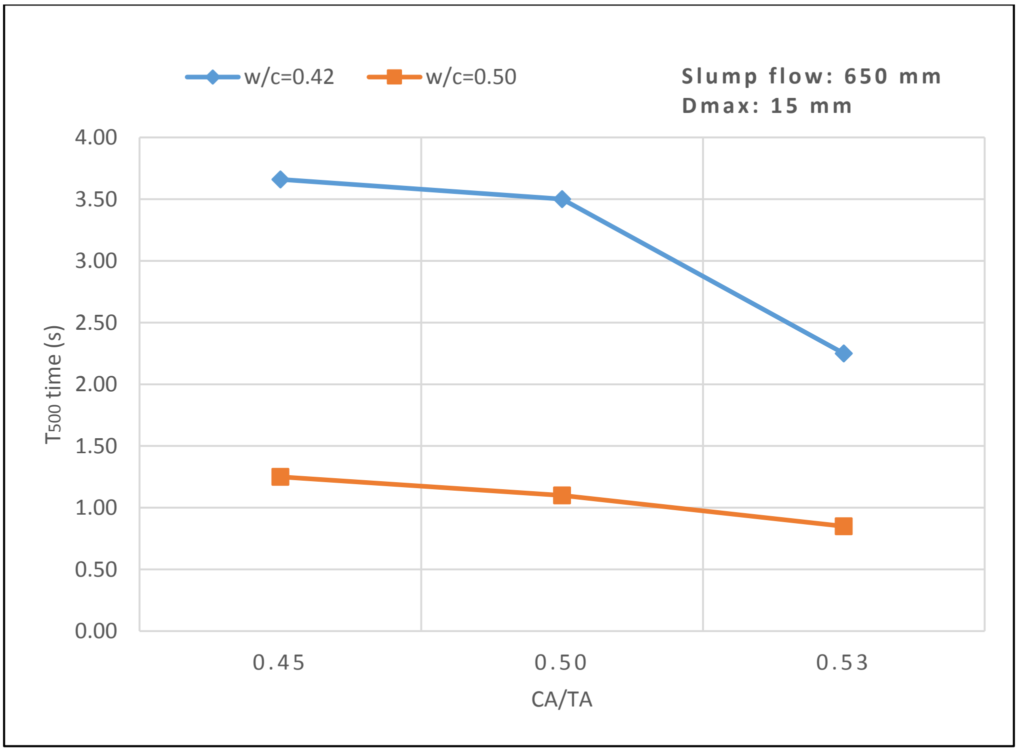


Figure 5.6. Effect of CA/TA and w/c on T_{500} time

Table 5.1 Test results for evaluated mixtures

Mixtu-res	Slump-flow, mm		Dmax, mm	W/C	CA/TA	Slump flow			V-funnel flow time, s		L-box			(SR) GTM, Wps/Wc %		Rheometer		(DSR) New method, Wps/Wc %	SP requirement, kg/m^3
	Designed SF, mm	EFNARC, Classes				T_{500}, s	EFNARC, Classes	VSI	Tested	EFNARC, Classes	H_2/H_1	EFNARC, Classes	Flow time, s	Tested	EFNARC, Classes	Apparent Y.S (g), N.m	Torque P.V (h), N.m.s		
1	650	SF1[a]	15	0.42	0.45	3.66	VS2[c]	1	22	VF2[e]	0.819	PA2[g]	6.5	3.90	SR2[h]	0.568	3.237	25.0	6.375
2	550	SF1	15		0.50	4.53	VS2	1.5	35	–	0.645	–	14	1.40	SR2	0.534	4.806	17.3	4.875
3	650	SF1	15			3.5	VS2	1.5	21	VF2	0.750	–	8	4.75	SR2	0.497	2.980	26.2	5.55
4	720	SF2[b]	15			2.03	VS2	2	14.54	VF2	0.813	PA2	4	5.55	SR2	0.386	2.200	27.9	6.625
5	650	SF1	10			5.09	VS2	1.5	19.8	VF2	0.788	–	4.96	3.40	SR2	0.244	3.214	24.2	6.625
6	650	SF1	20			2.19	VS2	2	38	–	0.600	–	9.44	6.65	SR2	0.657	4.338	33.1	5
7	650	SF1	15		0.53	2.25	VS2	2	19	VF2	0.702	–	12	5.25	SR2	0.295	1.879	28.4	5.25
8	650	SF1	15	0.50	0.45	1.25	VS1[d]	0	13	VF2	0.847	PA2	3	0.40	SR2	0.680	1.261	21.2	4.125
9	550	SF1	15		0.50	2.96	VS2	0.5	32	–	0.659	–	9	0.25	SR2	0.885	1.665	14.0	3.25
10	650	SF1	15			1.1	VS1	1	11	VF2	0.811	PA2	4.3	1.75	SR2	0.600	1.120	24.0	3.425
11	720	SF2	15			1.03	VS1	1	7	VF1[f]	0.880	PA2	2.8	2.60	SR2	0.420	0.610	26.7	3.75
12	650	SF1	15		0.53	0.85	VS1	1.5	8	VF1	0.790	–	6	2.05	SR2	0.420	0.898	24.9	3.25

a. SF1: 550 to 650 mm c. VS2 > 2 sec e. VF2: 9 to 25 sec g. PA2 ≥ 0.80 with 3 rebars
b. SF2: 650 to 750 mm d. VS1 ≤ 2 sec f. VF1 ≤ 8 sec h. SR2 ≤ 15 %

The resistance to segregation and extent of bleeding were examined visually and ranked in Table 5.1 according the VSI ranking system presented in Table 3.2.The photos for evaluating VSI of all 12 SCC mixtures are given in Appendix. Generally, all mixtures exhibited good spread with no more evidence of segregation. A significant amount of bleeding was noted for the mixtures with w/c=0.42 which required more amount of superplasticizer. VSI was ranked from 1 to 2 for mixtures with w/c=0.42 and 0 to 1.5 for mixtures with w/c=0.50. VSI ranking increased as CA/TA and Dmax increased. Effect of slump flow value, w/c, CA/TA, and Dmax on VSI is shown in Figure 5.7, 5.8, and 5.9, respectively.

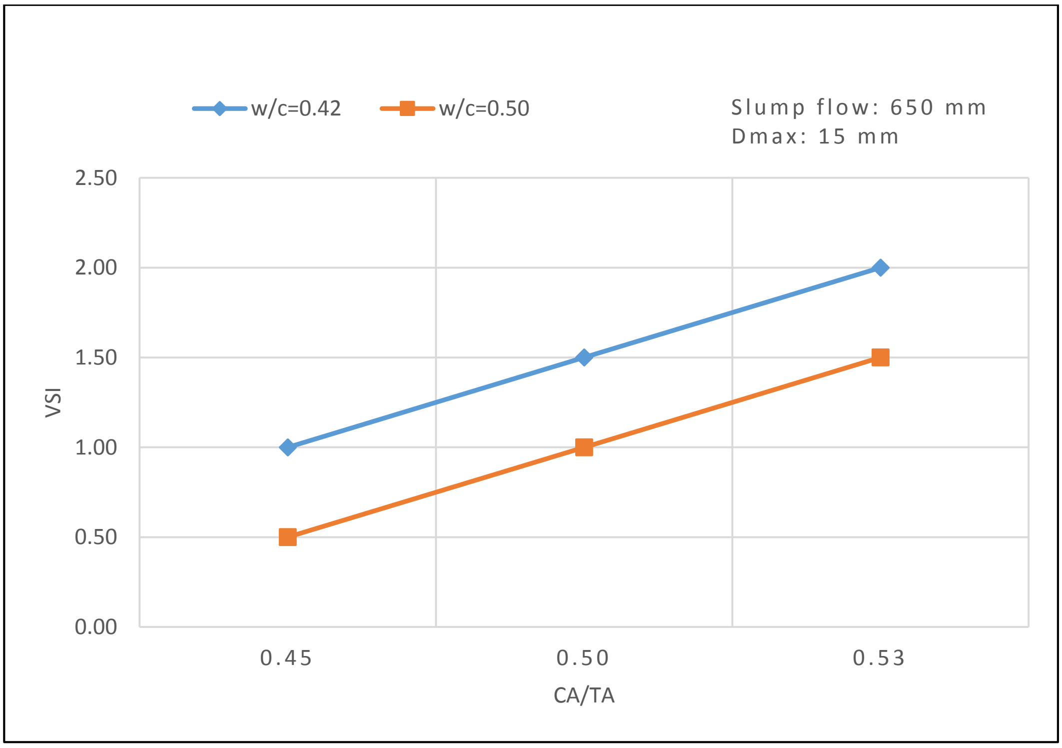


Figure 5.7. Effect of CA/TA and w/c on VSI

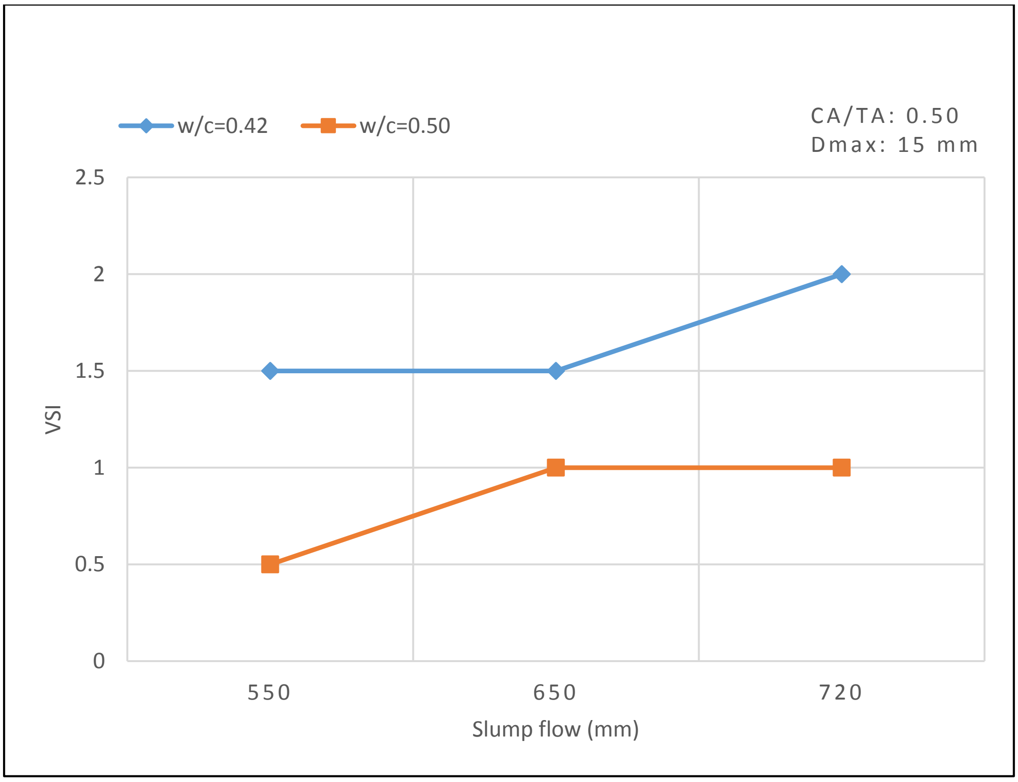


Figure 5.8. Effect of slump flow value and w/c on VSI

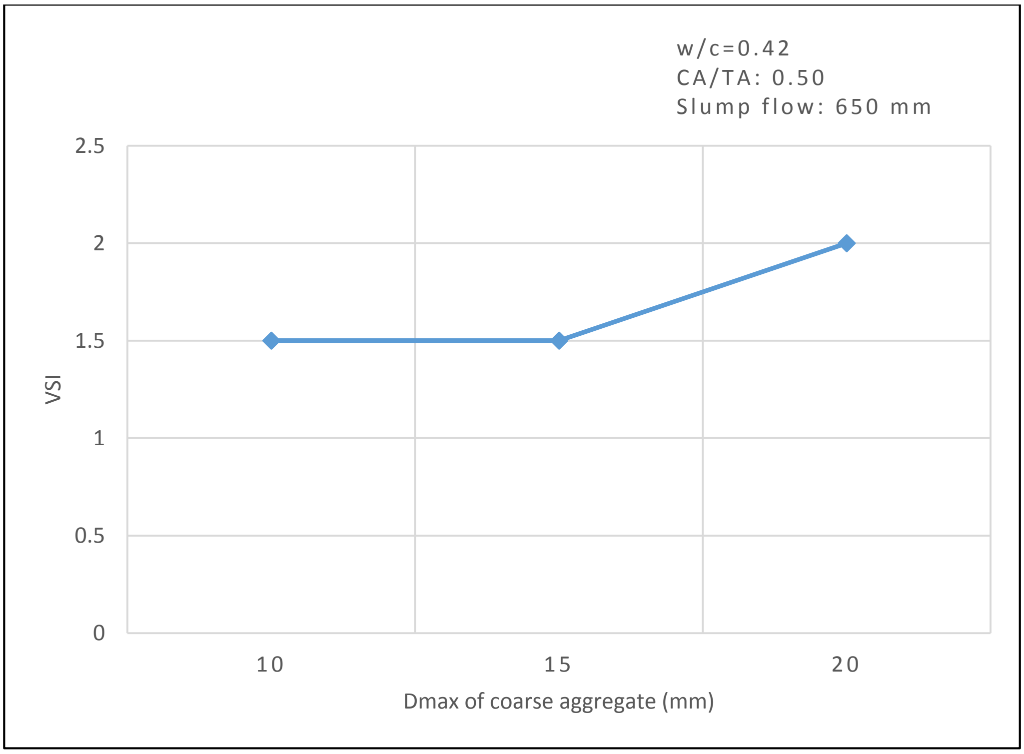


Figure 5.9. Effect of Dmax on VSI

5.2. V-Funnel Test

The V-funnel flow time values ranged between approximately 7 and 38 seconds for all 12 prepared mixtures as demonstrated in Table 5.1. According to the EFNARC guidelines [1] the V-funnel flow time of the mixtures should be less than 25 sec. As can be seen from Table 5.1, there are three mixtures which have flow times beyond this limit. These mixtures are Mix No 3, 6, and 9 which have slump flow of 550 mm or Dmax = 20 mm.

The effect of w/c ratio and slump flow on the V-funnel flow time of the mixtures is shown in Figure 5.10. The V-funnel flow times have shown a considerable decrease by increasing the target slump flow diameter. The increase in slump flow from 550 mm to 650 mm and from 650 mm to 720 mm resulted in a significant decrease in V-funnel flow time. As expected, the V-funnel flow times of the mixtures increased with a decrease in w/c due to their higher viscosity. As known, V-funnel flow time is an indirect indicator of viscosity of the fresh concrete. Similar results were also reported by other researchers [72, 77].

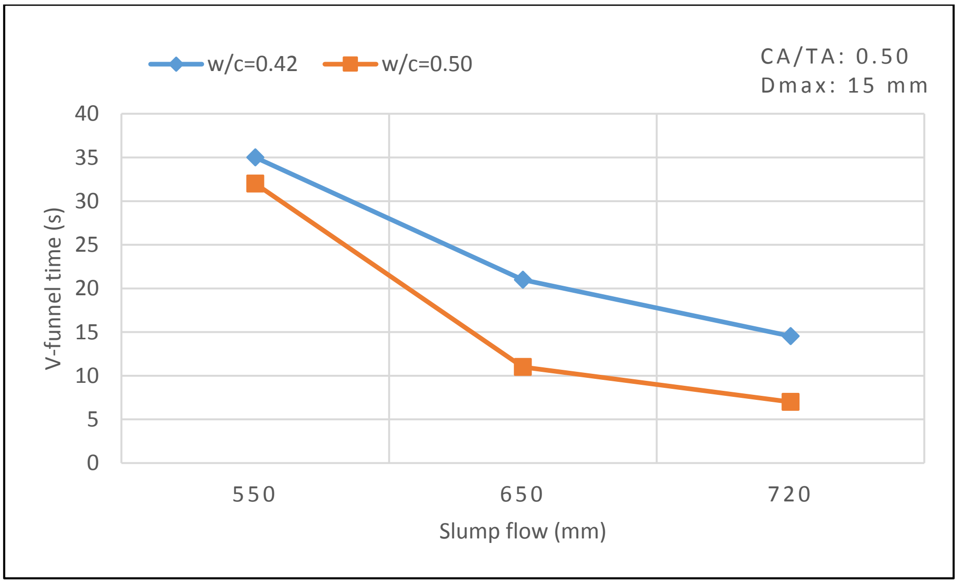


Figure 5.10. Effect of slump flow value and w/c on V-funnel flow time

The effect of CA/TA and w/c ratio on the V-funnel flow time of the mixtures is shown in Figure 5.11. The V-funnel time is affected by CA/TA as well. It should be also noted that the flow time is affected by changing the Dmax of coarse aggregate. An increase in Dmax of coarse aggregate increased the V-funnel flow time as well. The effect of Dmax on V-funnel flow time is given in Figure 5.12. These factors lead to greater risk of collision among coarse aggregate particles at the tapered outlet of the V-funnel apparatus and it delayed the passing of concrete from the trapdoor. As shown in Table 5.1, the mixture with 20 mm Dmax has the highest V-funnel time when compared to other mixtures.

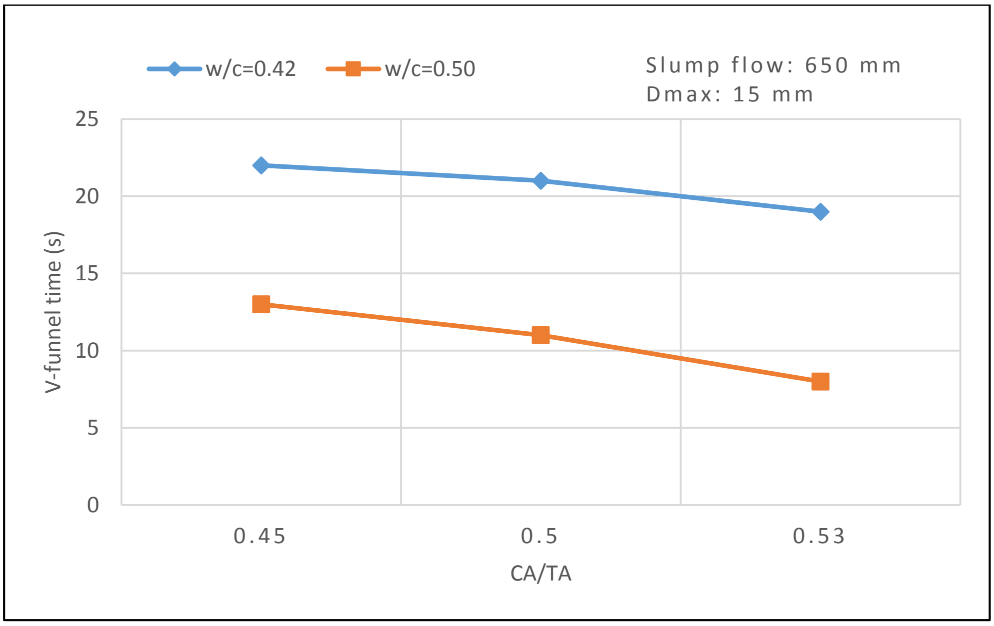


Figure 5.11. Effect of CA/TA and w/c on V-funnel flow time

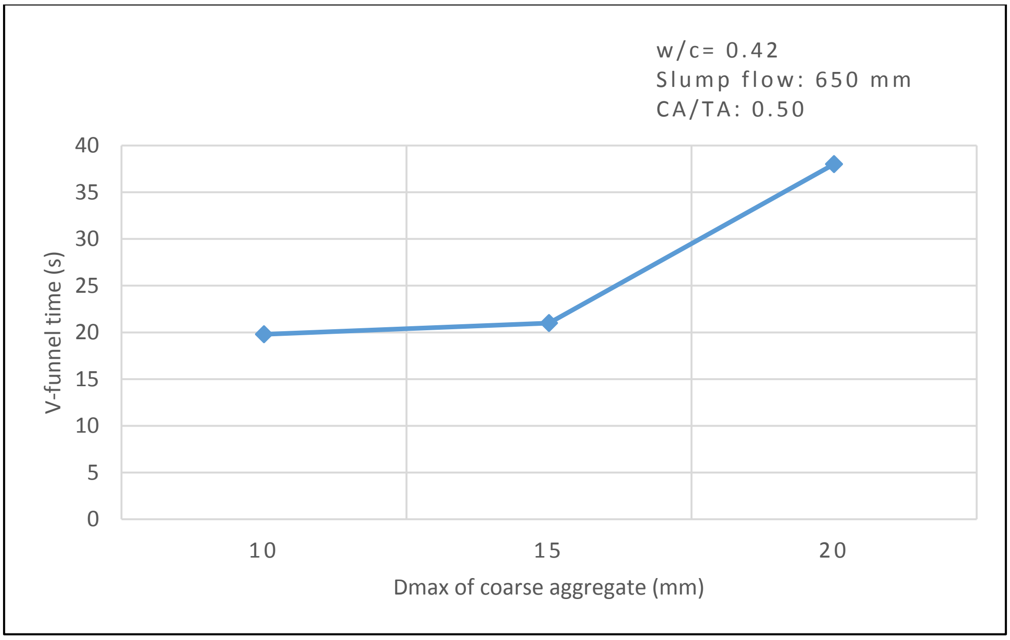


Figure 5.12. Effect of Dmax on V-funnel flow time

5.3. L-Box Test

The results of L-box test achieved in the laboratory for all 12 SCC tested mixtures is presented in Table 5.1. H2/H1 parameter denotes the L-box passing ability. Flow time value indicates the time from opening the gate until the concrete reached the end of horizontal section. The L-box test offers an additional advantage compared with the other tests, as it allows simultaneous evaluation of the deformability and the narrow-opening passing ability of the SCC.

Passing ability results show that the SCC mixtures with higher w/c ratio have greater passing ability ratio. Moreover, SCC mixtures with high values of slump flow show greater passing ability ratio as shown in Figure 5.13. The SCC mixtures which contained higher Dmax or CA/TA indicates the less passing ability as shown in Figure 5.14 and Figure 5.15.

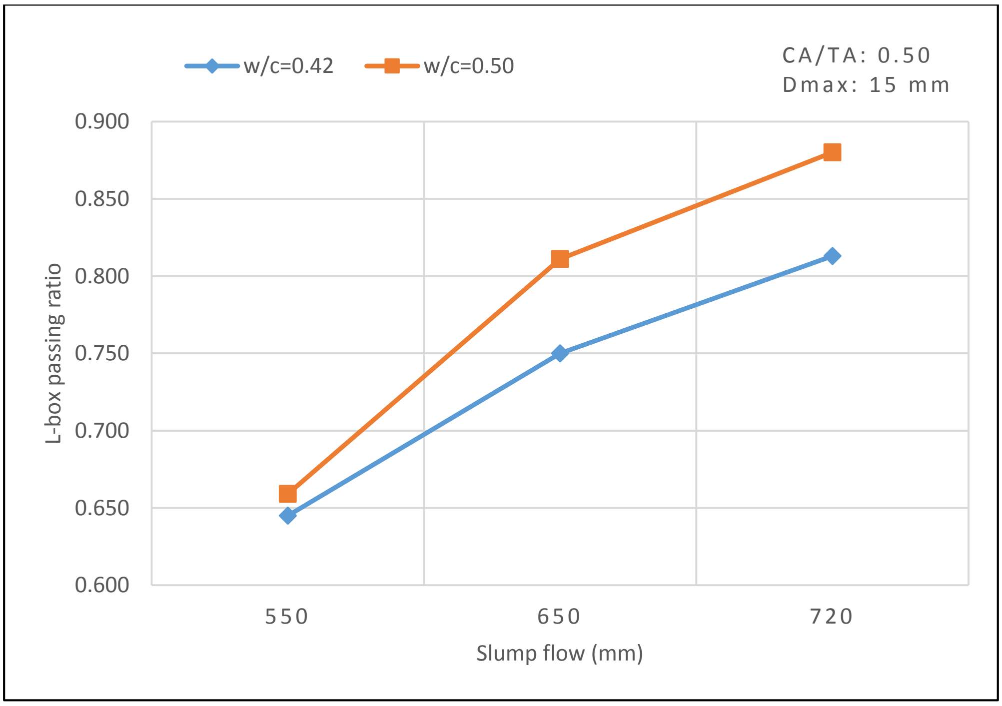


Figure 5.13. Effect of slump flow value and w/c on L-box passing ratio

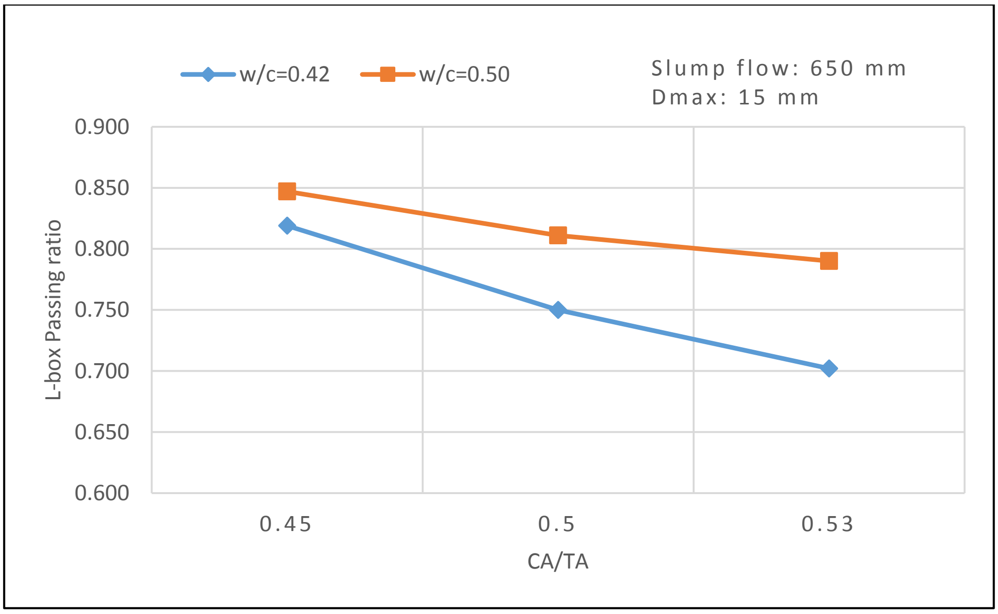


Figure 5.14. Effect of CA/TA and w/c on L-box passing ratio

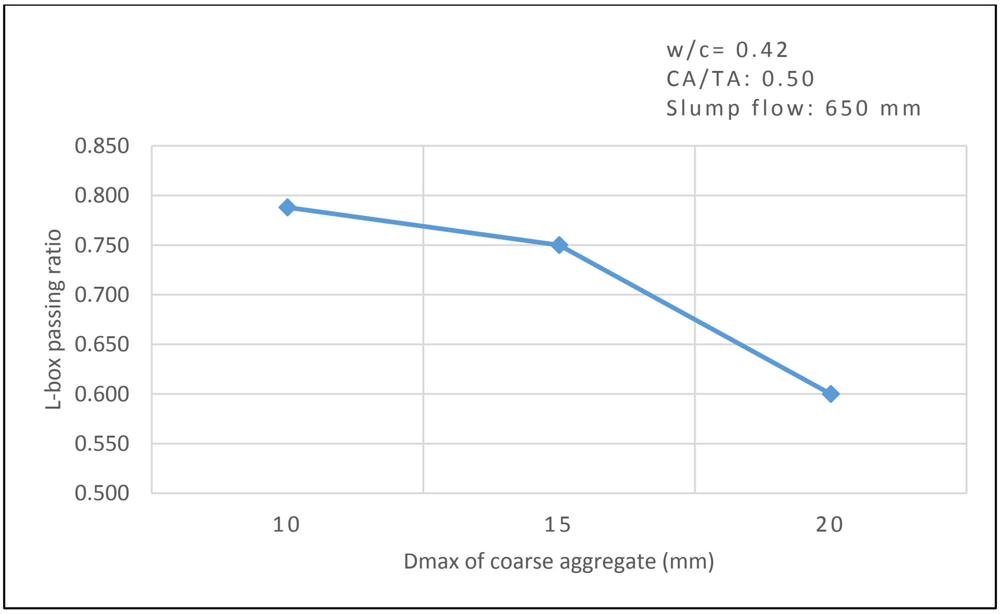


Figure 5.15. Effect of Dmax on L-box passing ratio

L-box flow times ranged between 2 to 14 seconds. The highest time relates to Mixture 2 with less w/c and lowest slump value (550 ± 20), and the lowest time relates to Mixture 11 with high w/c and highest slump flow value (720 ± 20). It means that as the w/c or slump flow value increases, the L-box flow time decreases as illustrated in Figure 5.16 due to the lower viscosity of the mixtures having high w/c or high slump flow.

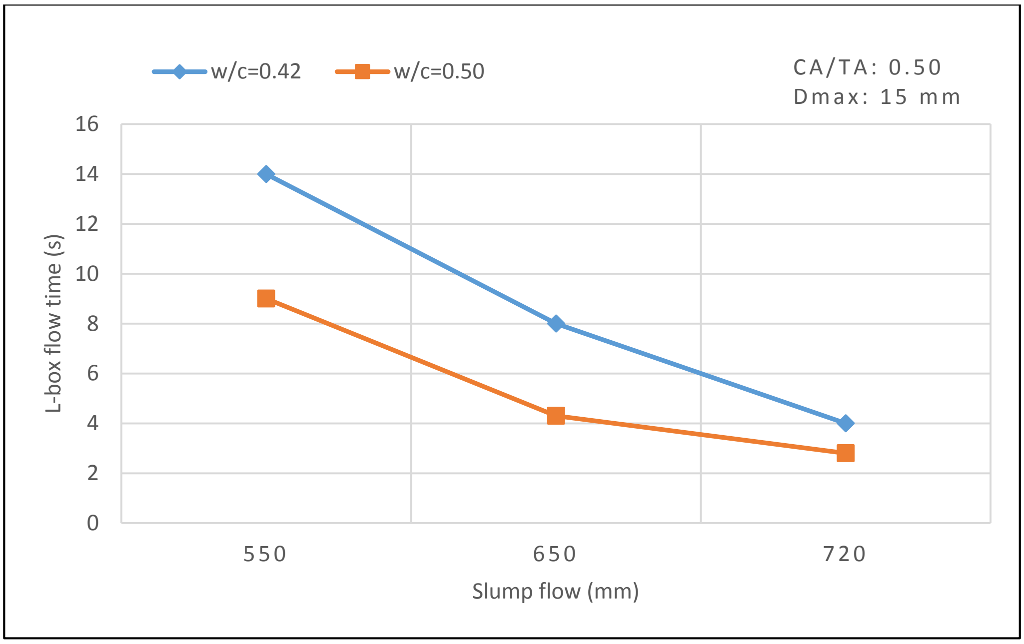


Figure 5.16. Effect of slump flow value and w/c on L-box flow time

Figure 5.17 shows that the SCC mixtures with high CA/TA have more L-box flow time. Similarly, with an increase in the Dmax of coarse aggregate, the L-box flow time increases as presented in Figure 5.18. The higher CA/TA and Dmax lead the collision among coarse aggregate particles at gaps between vertical reinforcement bars of L-box apparatus and it delayed the passing of concrete between reinforcement bars.

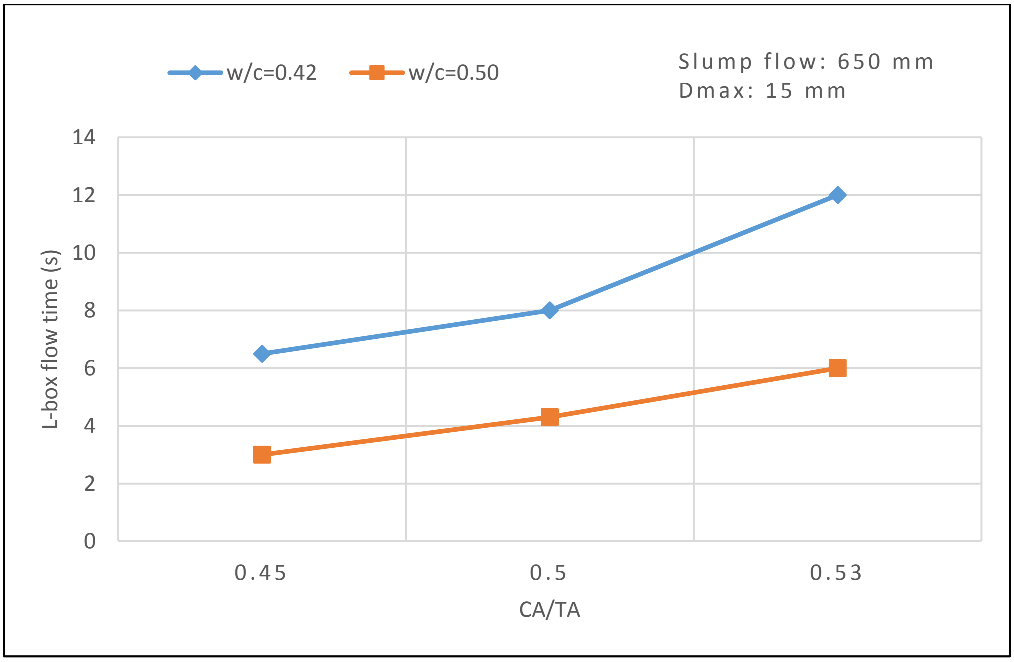


Figure 5.17. Effect of CA/TA and w/c on L-box flow time

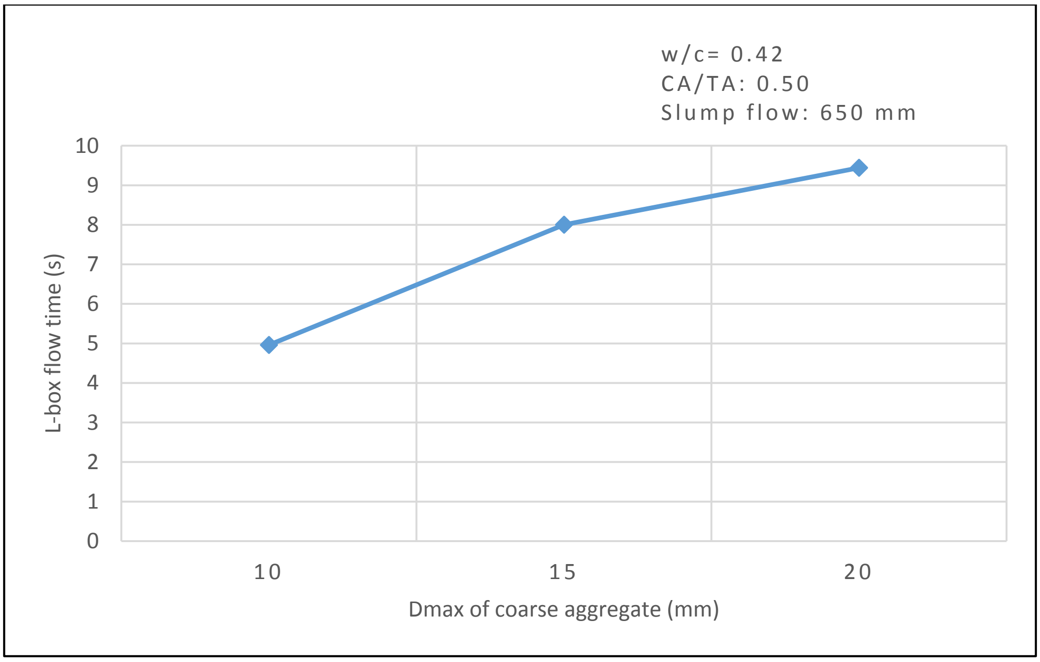


Figure 5.18. Effect of Dmax on L-box flow time

5.5. Rheometer Test

The results of rheometer test are summarized in Table 5.1. The rheological behavior of fresh SCC is characterized through the apparent yield stress (g) and torque plastic viscosity (h) defined according to the Bingham model. The linear correlations used to determine g and h parameters had correlation coefficient values (R^2) greater than 0.93.

The effect of slump flow value and w/c ratio on g for a constant CA/TA ratio of 0.50 is given in Figure 5.19. For SCC mixtures with having w/c=0.42 and w/c=0.50, the g values decreased by an increase in target slump flow diameter. The dosage of superplasticizer was increased for increasing target slump flow diameter. The increased superplasticizer content led to further dispersion of cement particles and contributed to higher flow. Considering the mixtures having same slump flow diameter, the g values increased with an increase in w/c ratio. For low w/c ratio mixtures, the superplasticizer demand of the SCC mixtures were higher than high w/c ratio mixture (Figure 5.19), therefore, it was easier to give a start to concrete flow and g values were decreased.

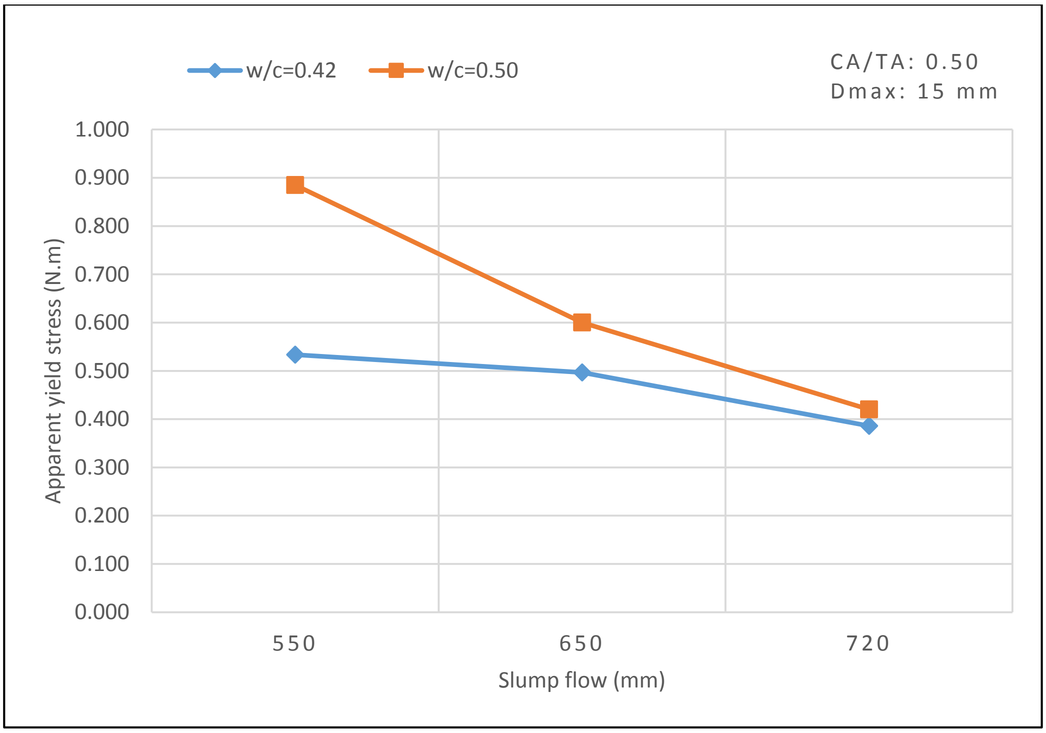


Figure 5.19. Effect of slump flow value and w/c on apparent yield stress

The effect of CA/TA ratio and w/c ratio on the g values for a constant slump flow diameter of 650 mm is given in Figure 5.20. The g value decreased with an increase in CA/TA ratio. This fact can be explained by a change in fine particles as follows: The increase in CA/TA ratio results in an increase in coarse aggregate proportion and a corresponding decrease in fine aggregate content in the mixture. A decrease in fine particles content also results in the increase of free water in the mixture while decreasing the amount of stress to start the flow of the mixture (g).

The effect of Dmax of coarse aggregate on the g values for a constant slump flow diameter of 650 mm, w/c=0.42, and CA/TA=0.50 is given in Figure 5.21. The g value increased with an increase in Dmax of coarse aggregate. When the Dmax is increased the drag force exerted by the mortar is decreased on the coarse aggregate. A reduction in the overall drag force exerted on aggregate results in an increased rate of settlement of particles to the bottom [66, 68]. Due to increased frictional force between coarse particles and with the bottom of apparatus' bucket, therefore, it was difficult to give a start to concrete flow and g values were increased.

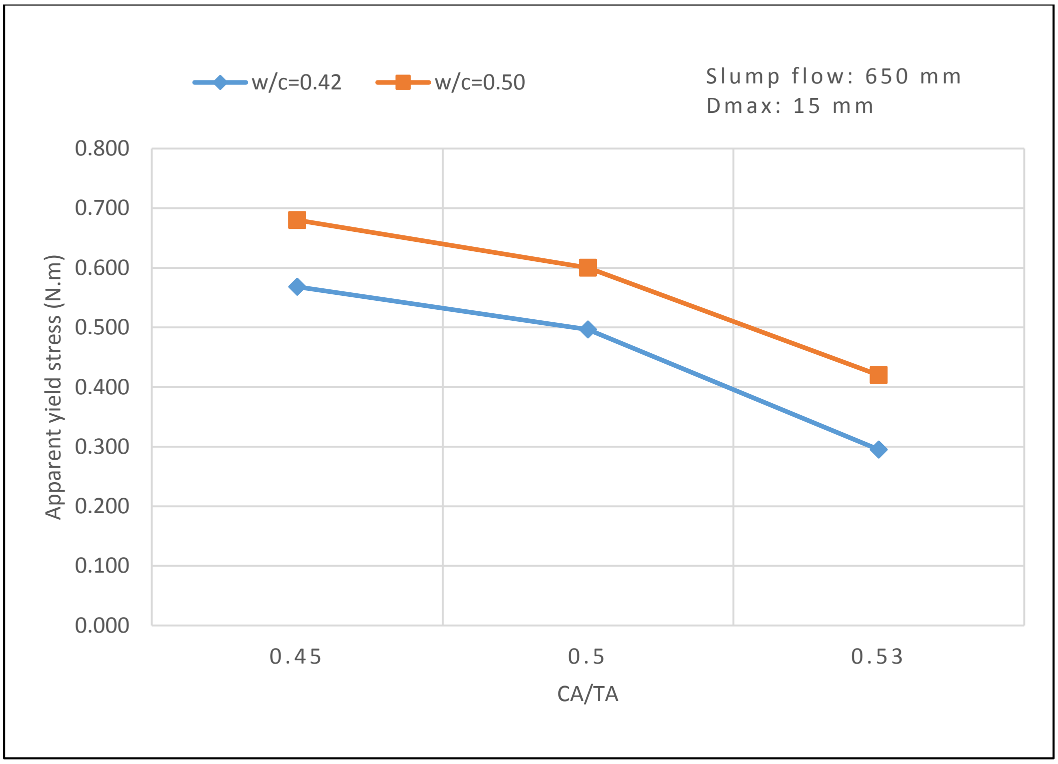


Figure 5.20. Effect of CA/TA and w/c on apparent yield stress

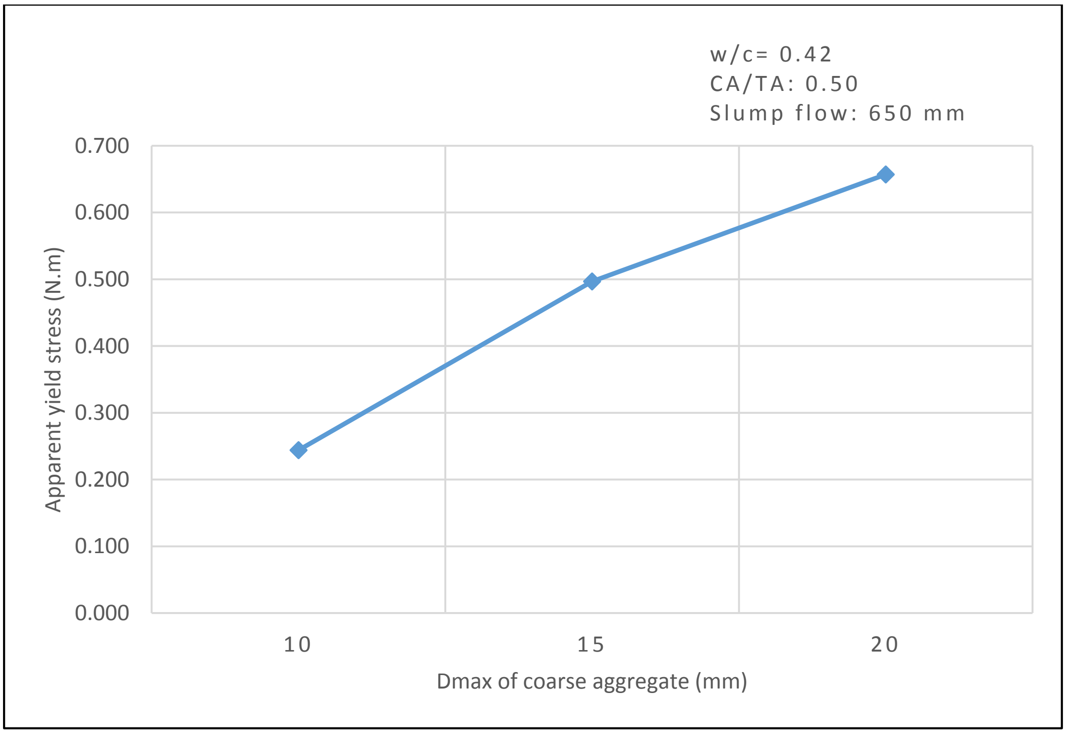


Figure 5.21. Effect of Dmax on apparent yield stress

The effect of slump flow value and w/c on h for a constant CA/TA ratio of 0.50 is given in Figure 5.22. The h values were decreased by an increase in slump flow diameter. The superplasticizer demand was higher for the mixtures with higher slump flow diameter. Thus, as the flow of the mixture became easier with an increase in superplasticizer dosage, the h values were also decreased. Regarding the mixtures having same slump flow diameter value, the h values were decreased by an increase in w/c. The mixtures having high w/c required less superplasticizer compared to the mixture having low w/c. Therefore, a decrease in viscosity was noticed for high w/c mixtures compared to that of low w/c mixture.

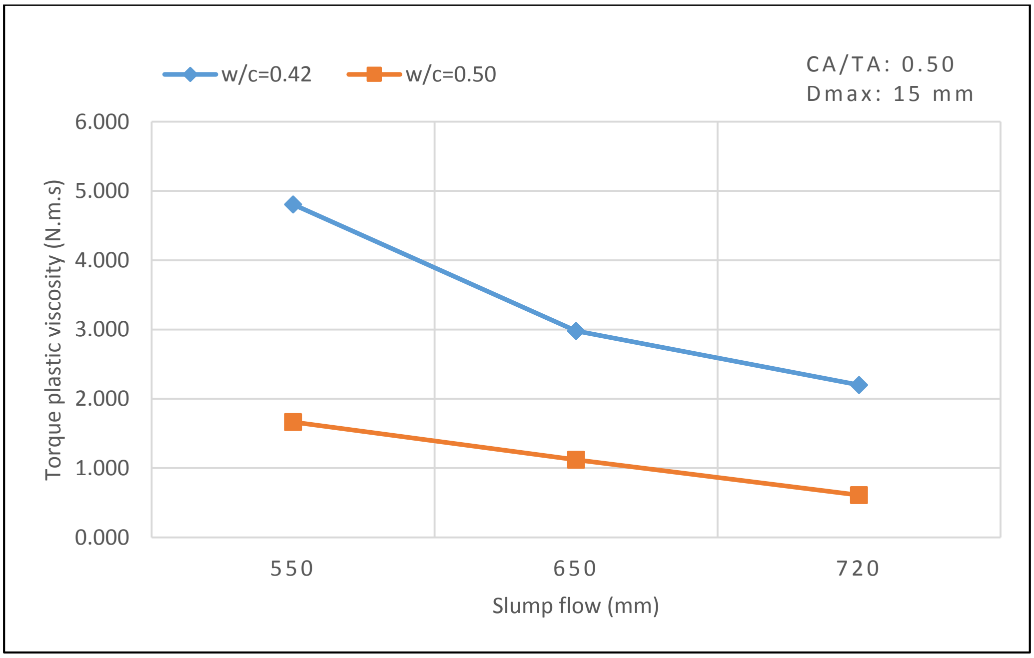


Figure 5.22. Effect of slump flow value and w/c on torque plastic viscosity

The effect of CA/TA ratio and w/c on the h value for a constant slump flow diameter of 650 mm was given in Figure 5.23. The h values decreased with an increase in CA/TA. Increasing the w/c with constant slump flow the h values decreased.

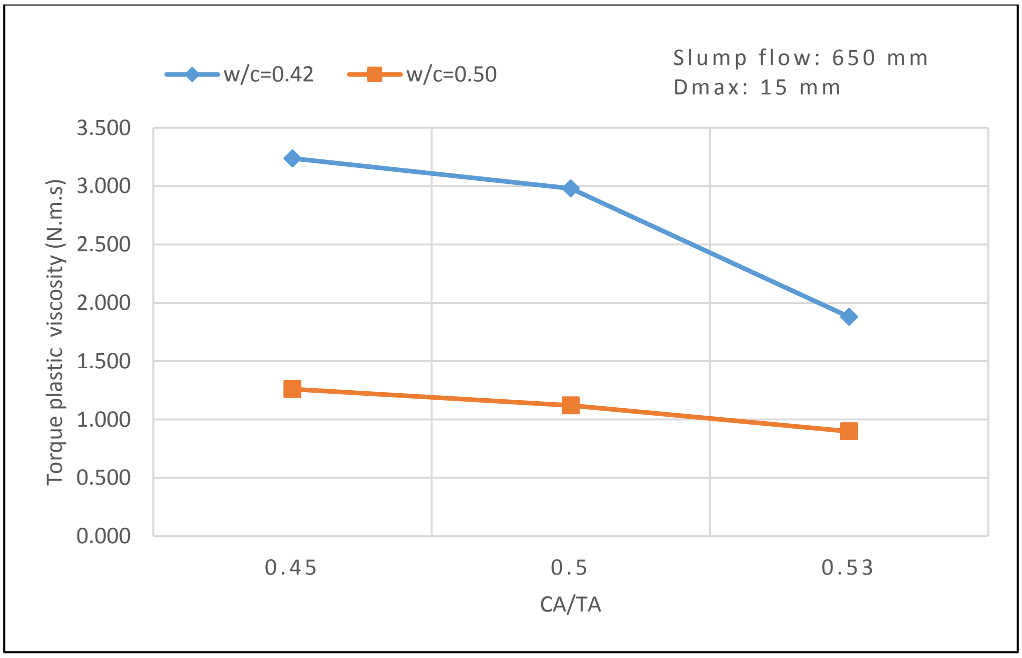


Figure 5.23. Effect of CA/TA and w/c on torque plastic viscosity

The effect of Dmax of coarse aggregate on the h values for a constant slump flow diameter of 650 mm, w/c=0.42, and CA/TA=0.50 is given in Figure 5.24. The h value increased with an increase in Dmax of coarse aggregate, due to increased frictional force between coarse particles and with the bottom of apparatus' bucket.

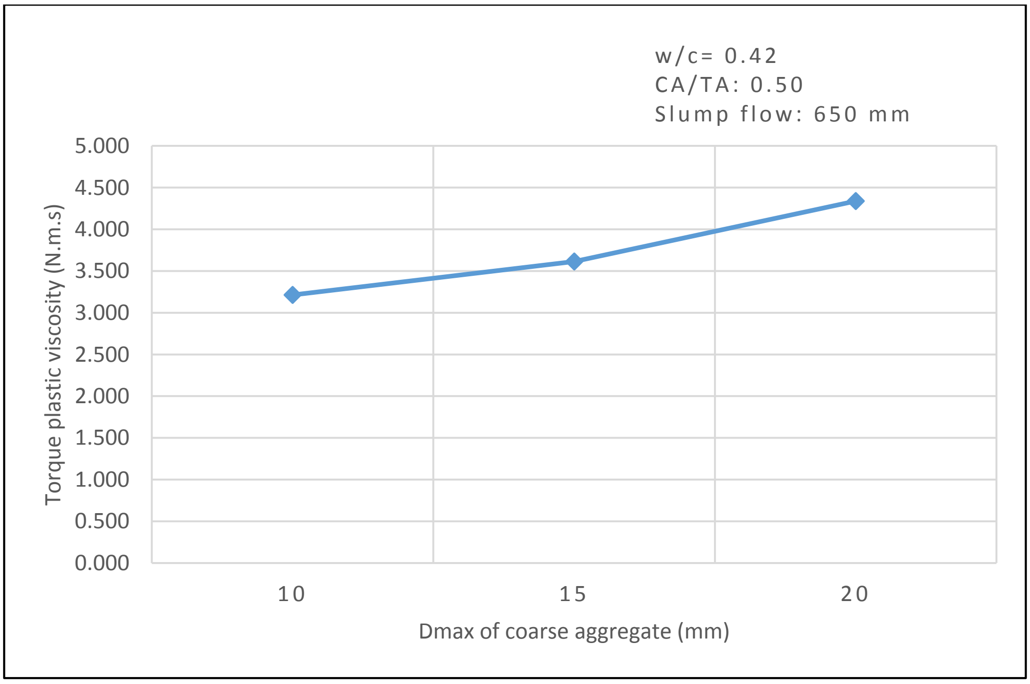


Figure 5.24. Effect of Dmax on torque plastic viscosity

5.4. Static Sieve Segregation Test (GTM)

The static sieve segregation test is used to assess the static stability of SCC. The aim of this test used in the research is to compare its results with the new proposed test method (DSST) results since both of these test are related with stability. The GTM test evaluates the segregation resistance of SCC with sieve in static state and the new test method evaluates segregation resistance of SCC with sieve while the concrete in moving. The results of GTM test are illustrated in Table 5.1.

The results show that the SCC mixtures with high slump flow values have higher segregation ratio (SR). Conversely, increasing the w/c decreased the segregation ratio due to less demand of superplasticizer as shown in Figure 5.25. The reason for this is, when the high slump flow value is aimed with less w/c, the need of superplasticizer increased. Therefore, in this case the high dose of superplasticizer creates excessive flow and increase bleeding which cause instability [27]. Figure 5.26 shows that the results for SCC mixtures with high CA/TA indicates higher segregation ratio. In the same way with increasing the Dmax of coarse aggregate the segregation ratio increased as given in Figure 5.27.

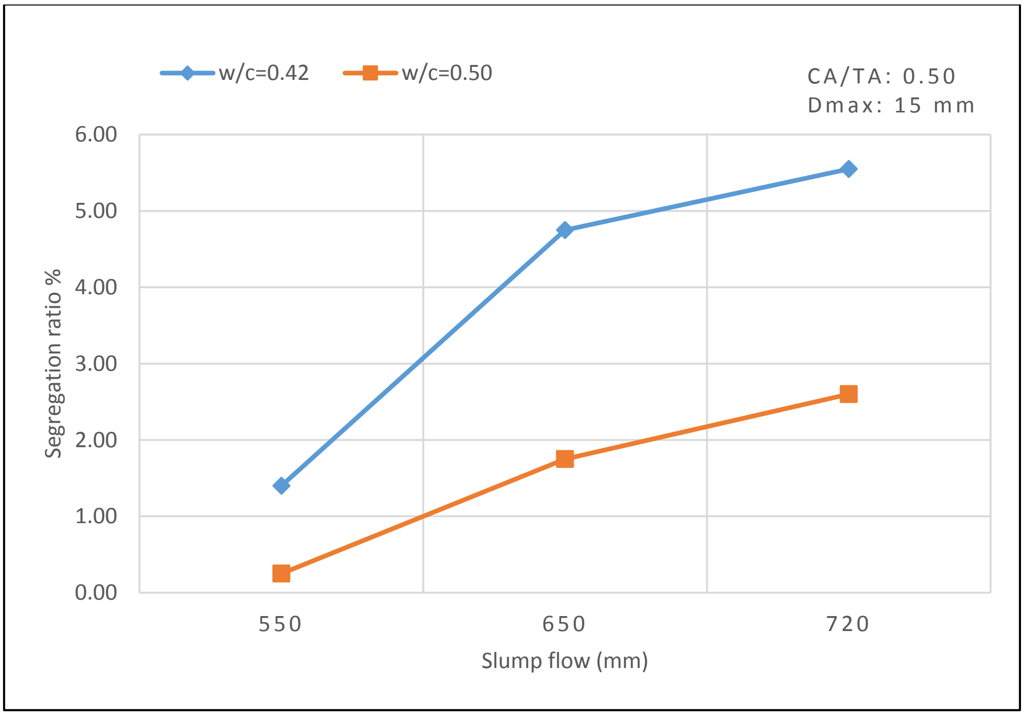


Figure 5.25. Effect of slump flow value and w/c on SR

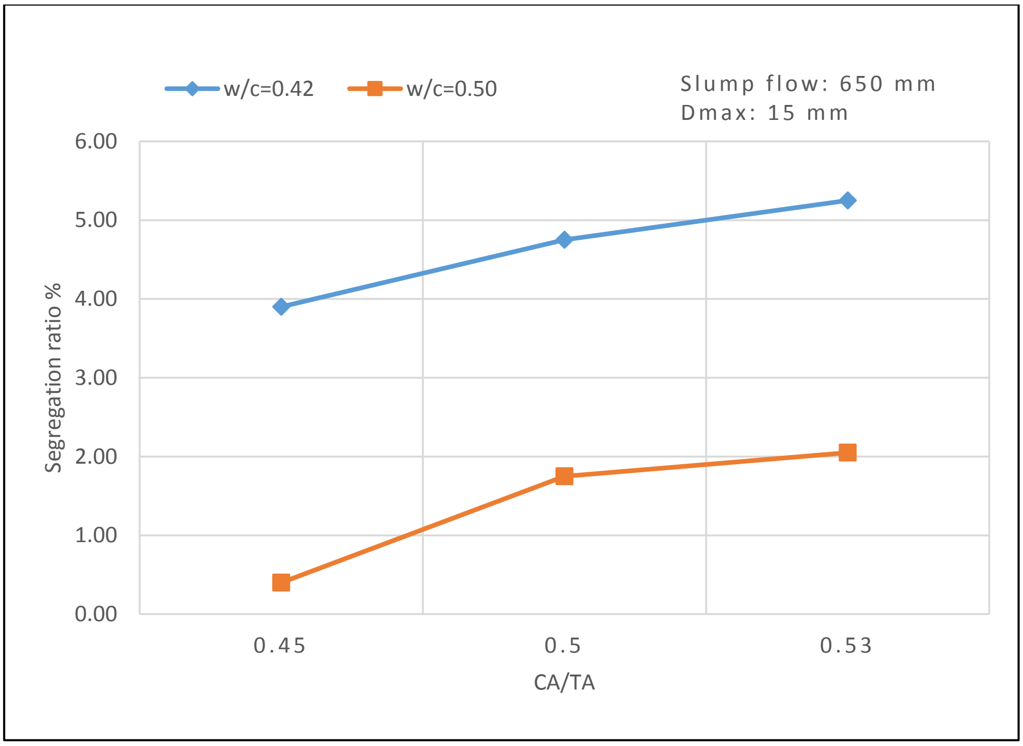


Figure 5.26. Effect of CA/TA and w/c on SR

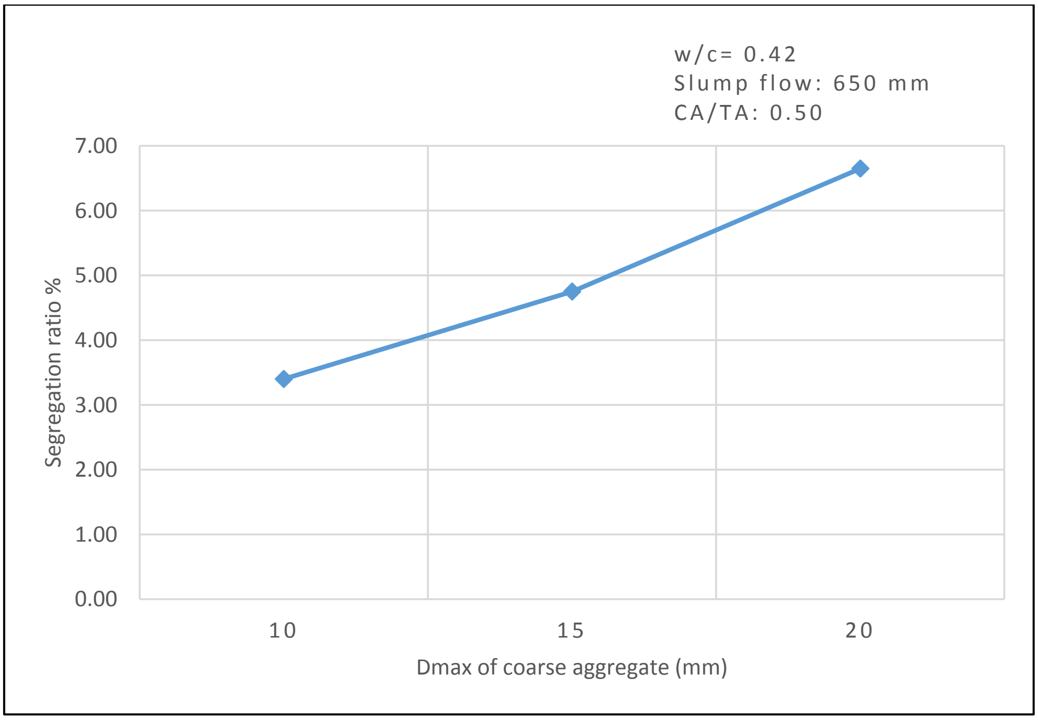


Figure 5.27. Effect of Dmax on SR

5.6. New Proposed Test Method (DSST)

Table 5.1 illustrates the results of new proposed method dynamic sieve segregation test (DSST). The results of this test were calculated as dynamic segregation ratio (DSR). The effect of slump flow value and w/c on DSR for a constant CA/TA ratio of 0.50 is given in Figure 5.28. The SCC mixtures with high slump flow values show higher DSR. On the other hand, increasing the w/c decreased the DSR due to less demand of superplasticizer. As explained in static sieve segregation test (GTM), when the high slump flow value is aimed with less w/c, the need of superplasticizer increased. Therefore, in this case the high dose of superplasticizer creates excessive flow and increase bleeding which cause instability [27]. Also the increased superplasticizer content led to further dispersion of cement particles and contributed to higher flow which caused separation of mortar.

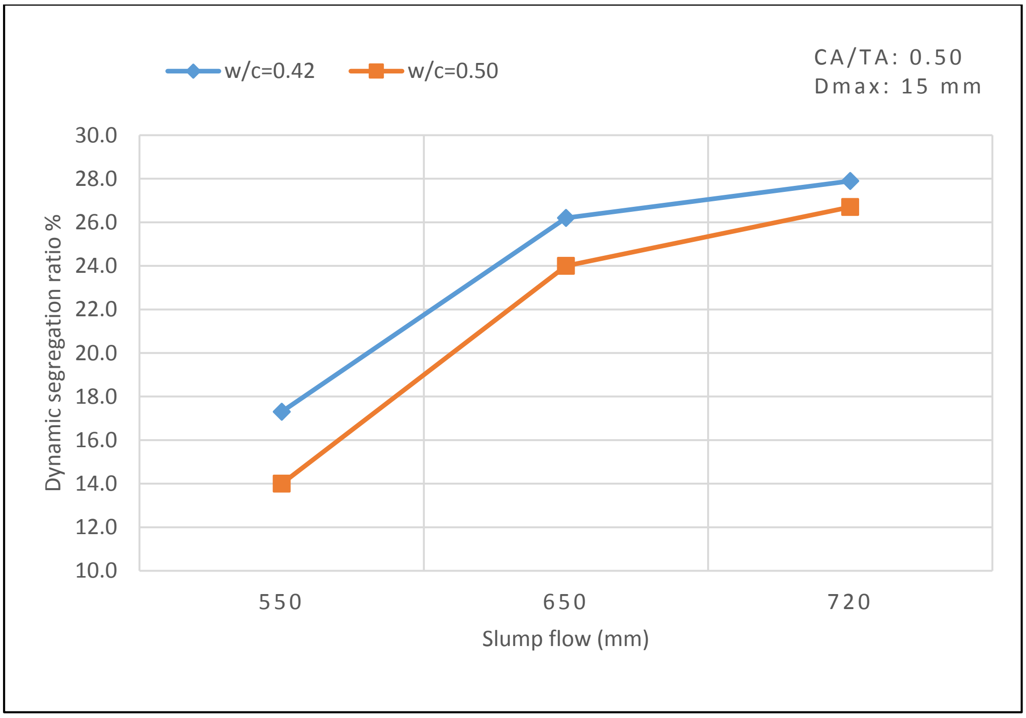


Figure 5.28. Effect of slump flow value and w/c on DSR

The effect of CA/TA ratio and w/c on the DSR for a constant slump flow diameter of 650 mm was given in Figure 5.29. The results show that increasing the CA/TA of SCC increased DSR as well. Similarly, increasing Dmax of coarse aggregate increased DSR as illustrated in Figure 2.30. The principal factor contributing to less stable concrete can be explained as follows: When the Dmax is increased the drag force exerted by the mortar is decreased on the coarse aggregate. Increasing Dmax decreases the aggregate surface area-to-mass ratio which is directly proportional to the magnitude of the drag force [66, 68]. Therefore, increasing the CA/TA increased the DSR as well.

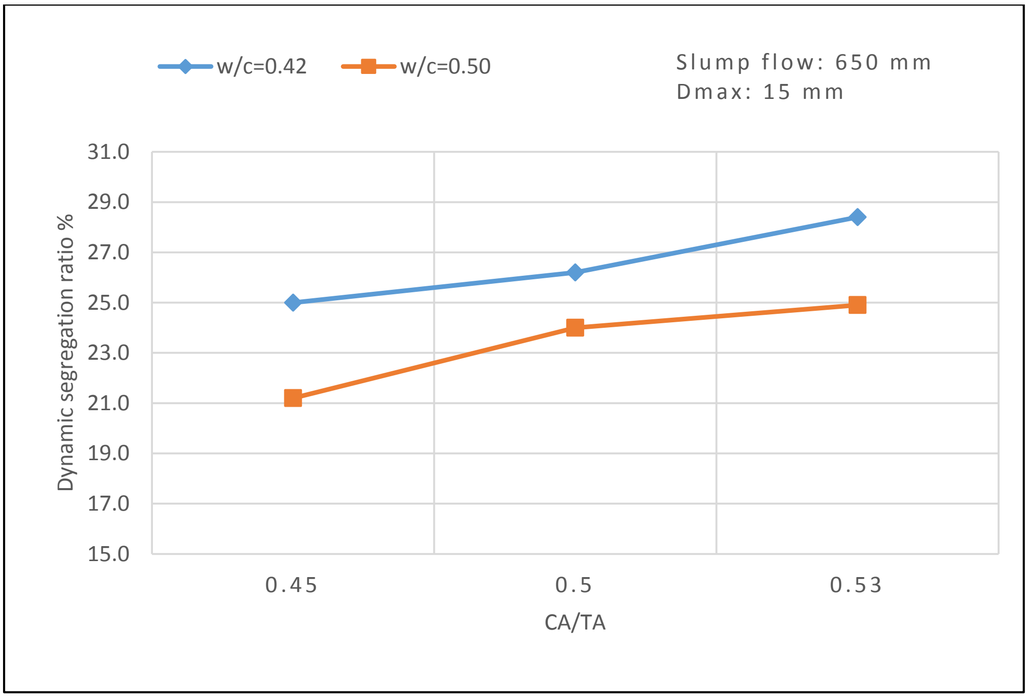


Figure 5.29. Effect of CA/TA and w/c on DSR

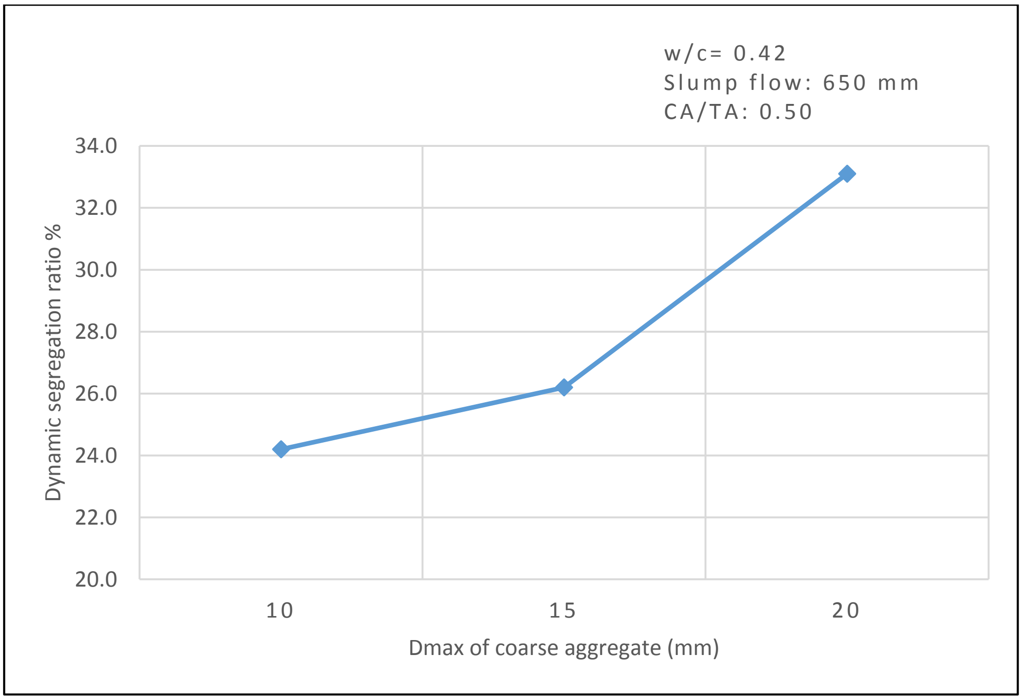


Figure 5.30. Effect of Dmax on DSR

The DSR values follow the expectations established according to the literature. In the other words, the effects of the tested parameters (w/c, CA/TA, Dmax, and slump flow) were in good agreement with the related literature. These effects could be identified by the new proposed method. Therefore, the DSST method can be regarded as successful to evaluate the dynamic segregation. The w/c ratio is less effective on dynamic segregation test compared to static segregation test.

5.7. Correlation Between the Test Results

A relationship between V-funnel flow time and L-box passing ratio is presented in Figure 5.31 for all 12 investigated mixtures. The relationship between these values is a negative linear relation with correlation coefficient (R^2) of 0.8011. As seen in the figure there is a gradual decrease in the V-funnel flow time by increasing L-box passing ratio. It means that the mixtures with lower V-funnel flow time show good passing ability. As the V-funnel flow time represents the viscosity of SCC, high viscosity does not guarantee high passing ability or high dynamic stability.

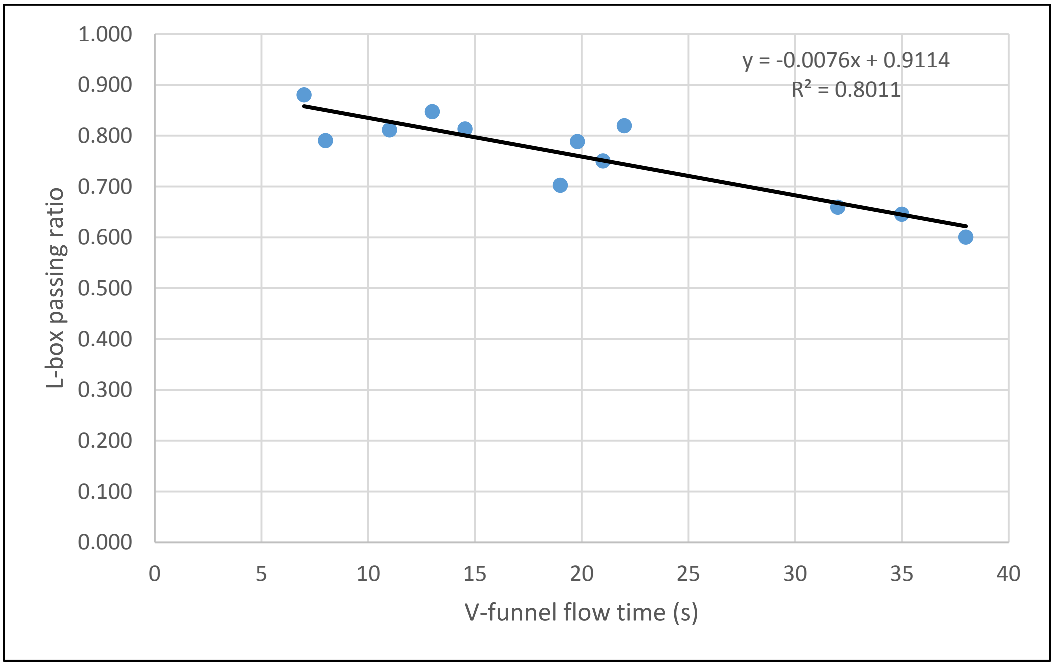


Figure 5.31. Correlation between V-funnel flow time and L-box PR

Figure 5.32 shows the relationship between V-funnel flow time and L-box flow time. These values have a good direct relation because both of them are related with the speed of flow. In the L-box test, the concrete flows through the reinforcement and in the V-funnel test the concrete flows through a narrow section. The relationship shows that the L-box flow time increases as the V-funnel flow time increases.

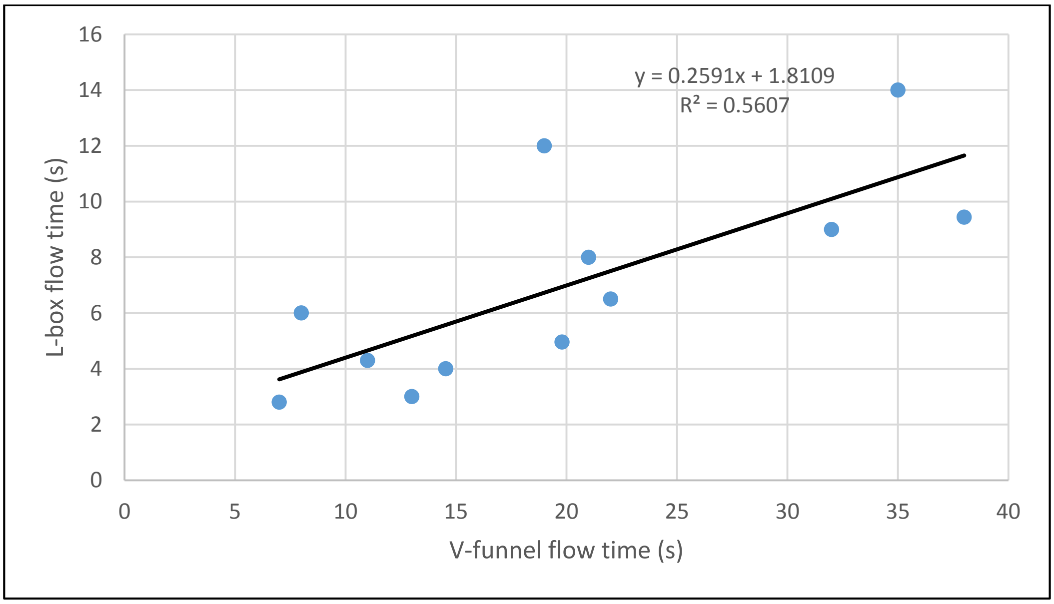


Figure 5.32. Correlation between V-funnel and L-box flow times

The relationship between T_{500} time and V-funnel flow time is plotted in Figure 5.33. It was observed that there is a strong positive relationship between the results of these tests especially for lower values (V-funnel time < 20 s). When the V-funnel time > 20 s, the data showed much deviation from the trendlines.

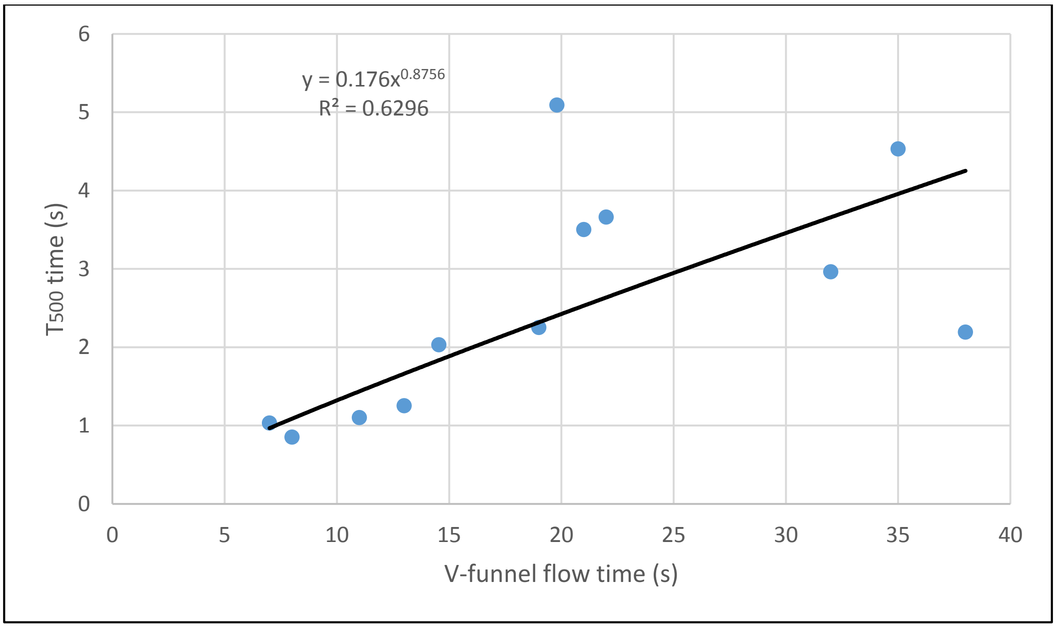


Figure 5.33. Correlation between V-funnel flow time and T_{500} time

V-funnel and T_{500} time values were tried to correlate with rheological parameters obtained from rheometer test. Although no significant relationship was observed between apparent yield stress and other tests, good relationships were obtained between torque plastic viscosity and T_{500} time or V-funnel time.

The correlation between V-funnel flow time and torque plastic viscosity is given in Figure 5.34. There is a positive power relation with correlation coefficient (R^2) of 0.7636. As mentioned before the V-funnel flow time indicates the viscosity of SCC, therefore, torque plastic viscosity increased with increasing V-funnel flow time.

Figure 5.35 illustrates the correlation between T_{500} time and torque plastic viscosity. The relationship between T_{500} time and torque plastic viscosity is a positive power relation. The results indicate that the T_{500} values increases with an increase in torque plastic viscosity.

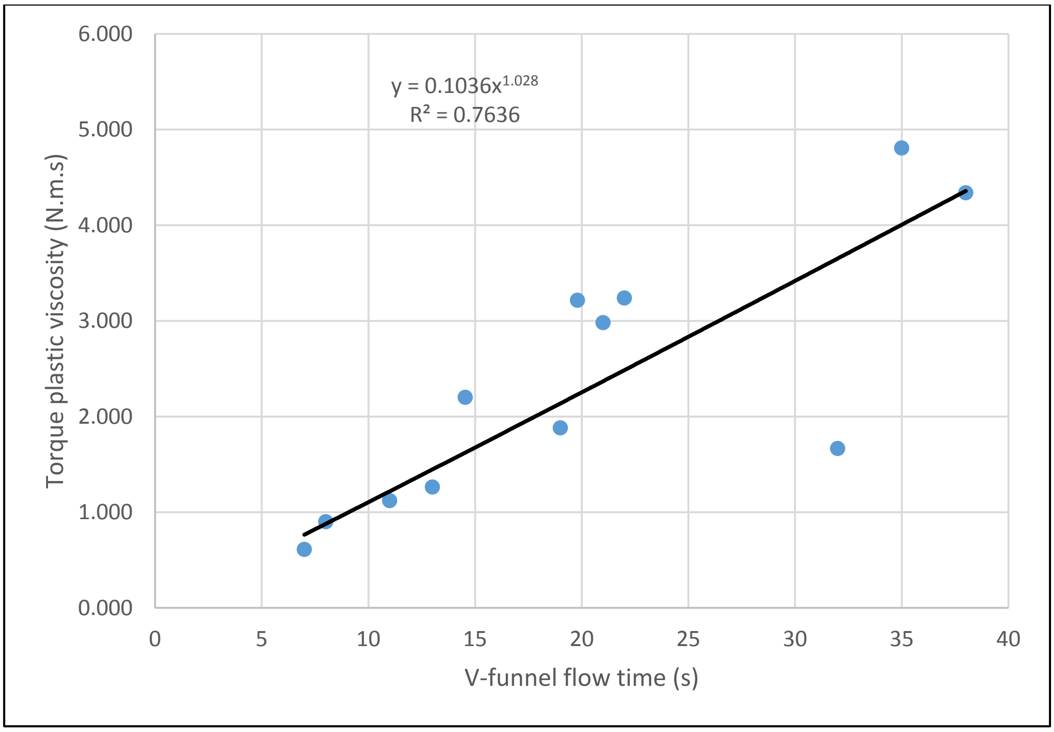


Figure 5.34. Correlation between V-funnel flow time and torque plastic viscosity

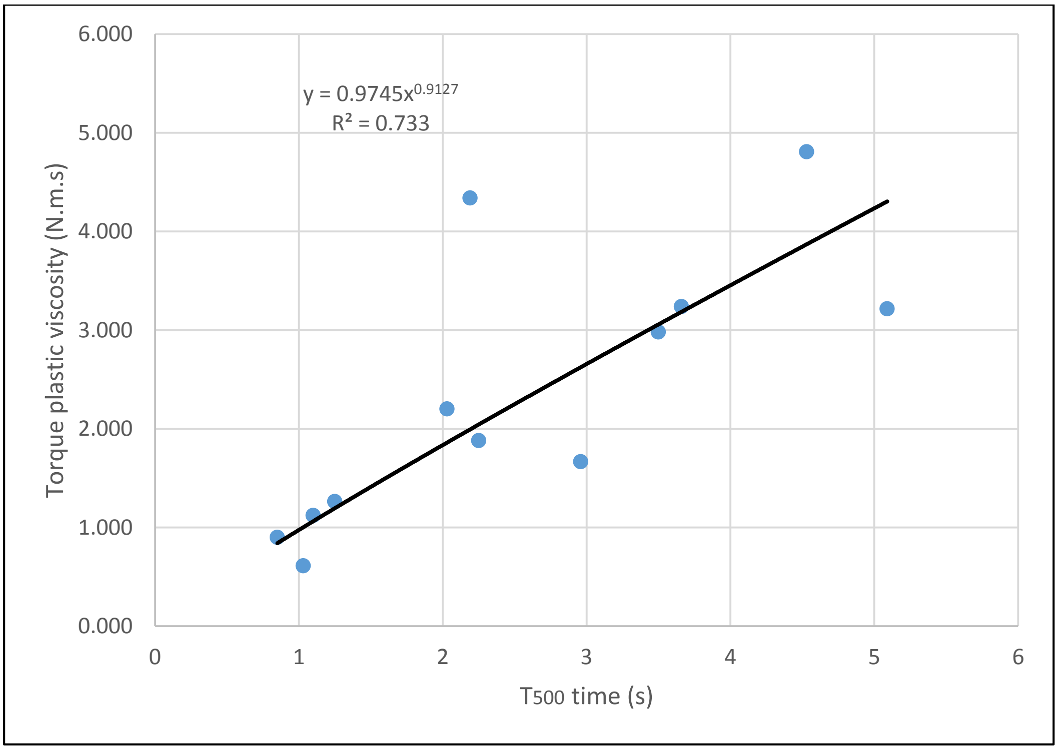


Figure 5.35. Correlation between T_{500} time and torque plastic viscosity

5.8. Correlation of New Test Method (DSST) With Other Tests

Figures 5.36- 5.42 show the correlation of DSST with other tests. In these figures, the DSR values in dashed boxes are in good agreement with the other test results. In other words, the points outside these boxes show great deviations from the trendlines. Generally, the mixtures 2, 6, and 9 are outside of these boxes. Mixtures 2 and 9 have a low slump flow value (550) and very high V-funnel time. These two mixtures (2 and 9) are very stable as can be understood from static segregation tests. Mixture 6 has also very high V-funnel flow time but this value is not high due to the high stability of the mixture as can be seen from the relatively high static segregation test results and low L-box passing ratio. The high duration for Mixture 6 is due to the severe segregation. The paste left the V-funnel quickly and the remaining aggregates took more time to leave the funnel.

Considering the above discussion, good SCC which is dynamically stable should have a DSR value between 20 – 30 %. In other words, for the new proposed test method, the recommended limits for a dynamically stable and still having satisfactory flow properties are 20 % and 30 %. Lower values can result in concretes with low self-consolidating properties. Upper values can show severe segregation when the concrete is in motion.

Figure 5.36 and 5.37 illustrate the correlation between slump flow test parameters (T_{500} time and VSI) and new method (DSST). These relationships show that the values in dashed box are in good agreement with each other.

The correlation between V-funnel flow time and new method (DSST) is plotted in Figure 5.38. The values in dashed box for both tests are in good agreement with each other. As known, V-funnel time should be less than 25 seconds for SCC according to EFNARC guidelines [1]. The dashed box contains the data conforming to this limit. The correlation failed beyond this limit. This consideration shows the suitability of the recommended limits (20 – 30 %) for the new test method.

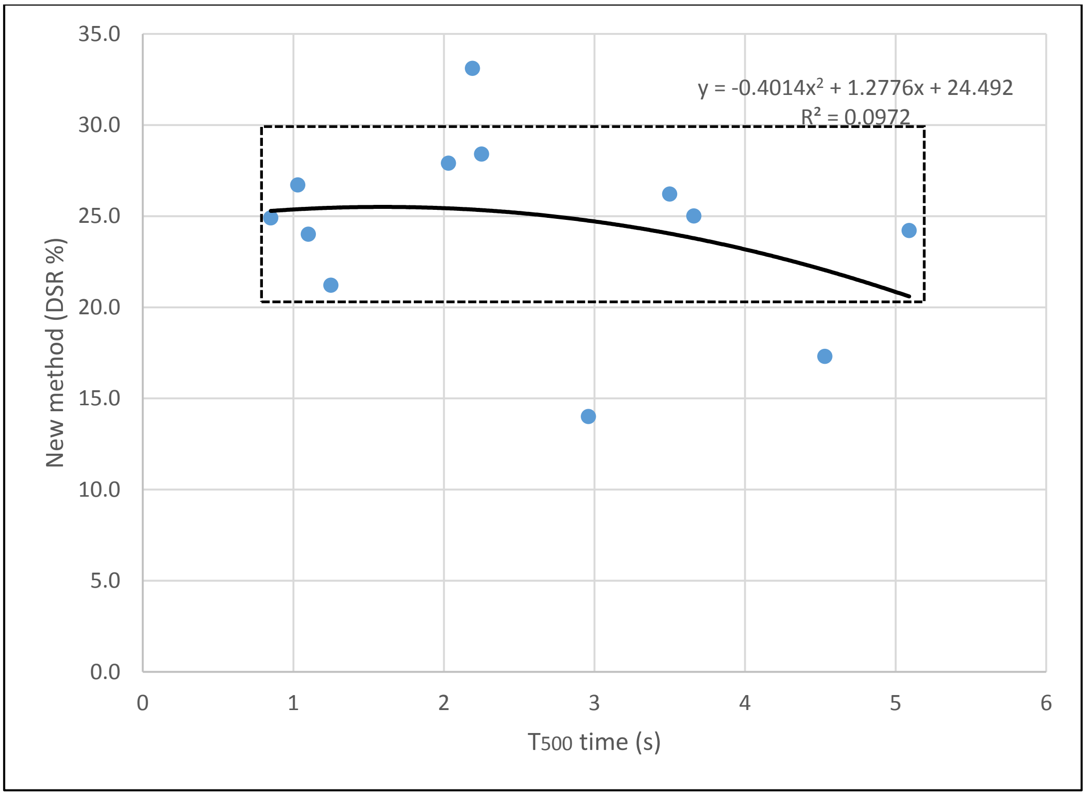


Figure 5.36. Correlation between new method and T_{500} time

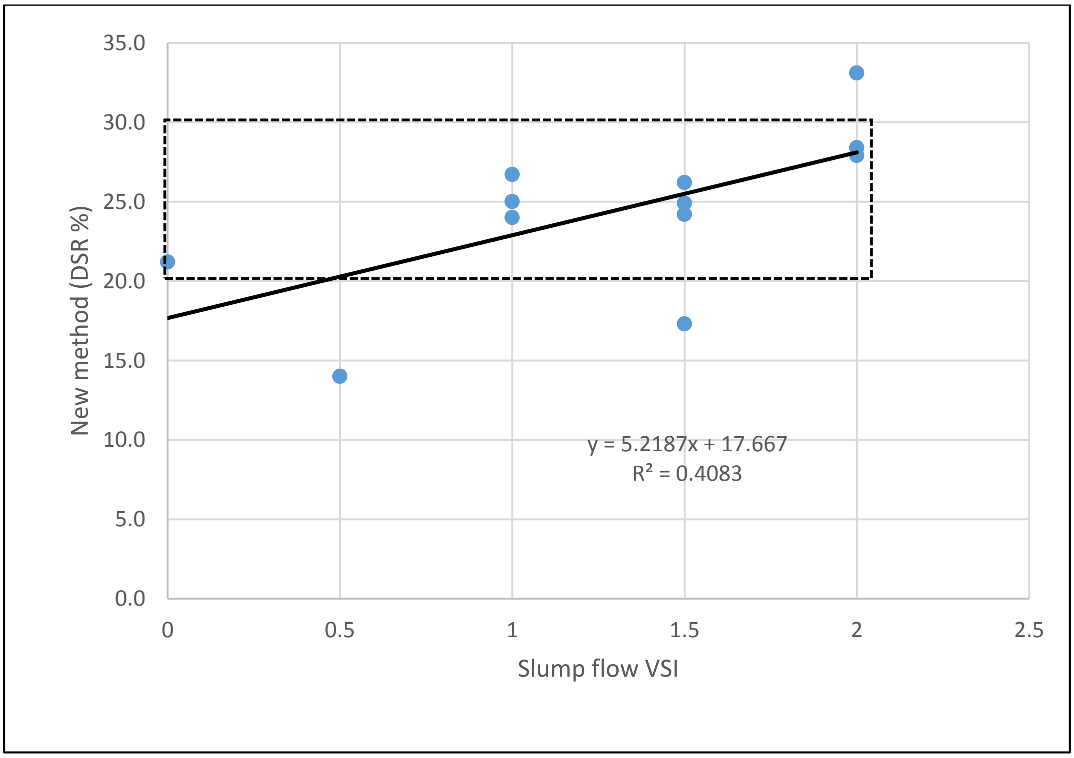


Figure 5.37. Correlation between new method and VSI

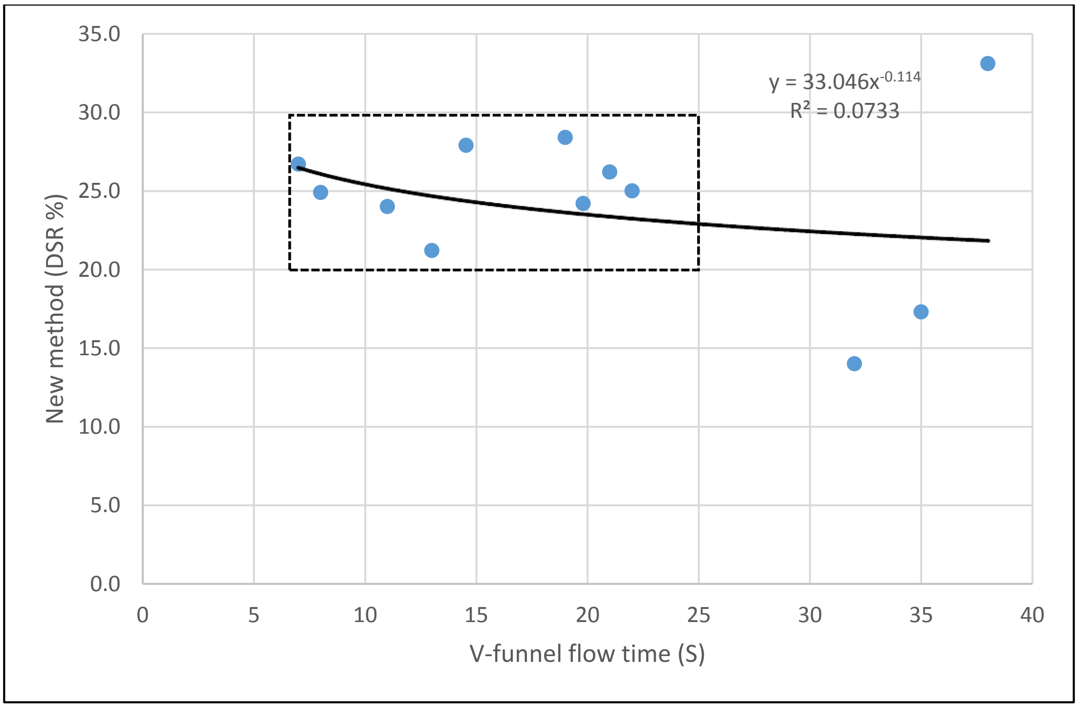


Figure 5.38. Correlation between new method and V-funnel flow time

The correlations between L-box parameters (passing ratio and flow time) and new method (DSST) are given in Figure 5.39 and 5.40. These relationships also show that the values in the dashed box have good agreement with each other. As known, L-box passing ratio should be equal or higher than 0.80 for SCC according to EFNARC guidelines [1]. The data points in the dashed box are located close to this limit. Similarly, L-box flow times which take place in the box are within the recommendations of Khayat et al [39] (1.9 – 14.4 sec).

Figure 5.41 shows the correlation between static sieve segregation test (GTM) and new method (DSST). The graph shows a strong linear positive relationship. The dynamic segregation ratio increased with an increase in GTM test segregation ratio for all 12 tested mixtures. As given in the dashed box, the relationship also shows good agreement with each other.

Figure 5.42 and 5.43 presents the correlation of new method test (DSST) with rheological parameters of all 12 mixtures. All values from new method and rheometer test show good agreement in dashed box.

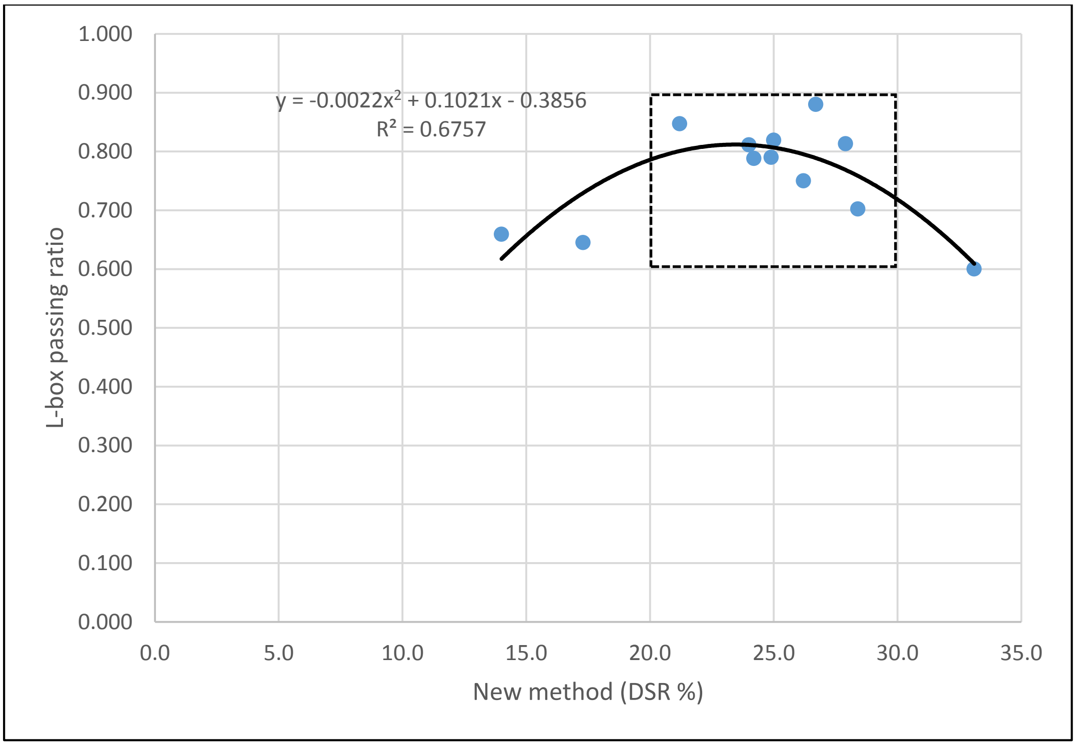


Figure 5.39. Correlation between new method and L-box passing ratio

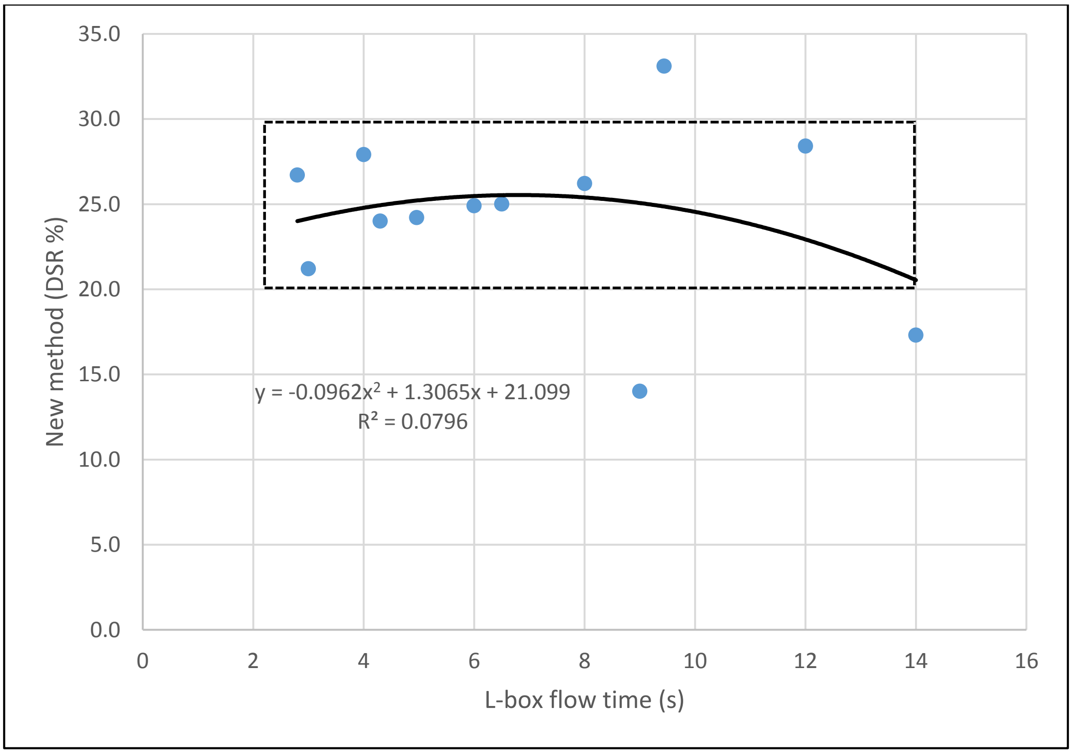


Figure 5.40. Correlation between new method and L-box flow time

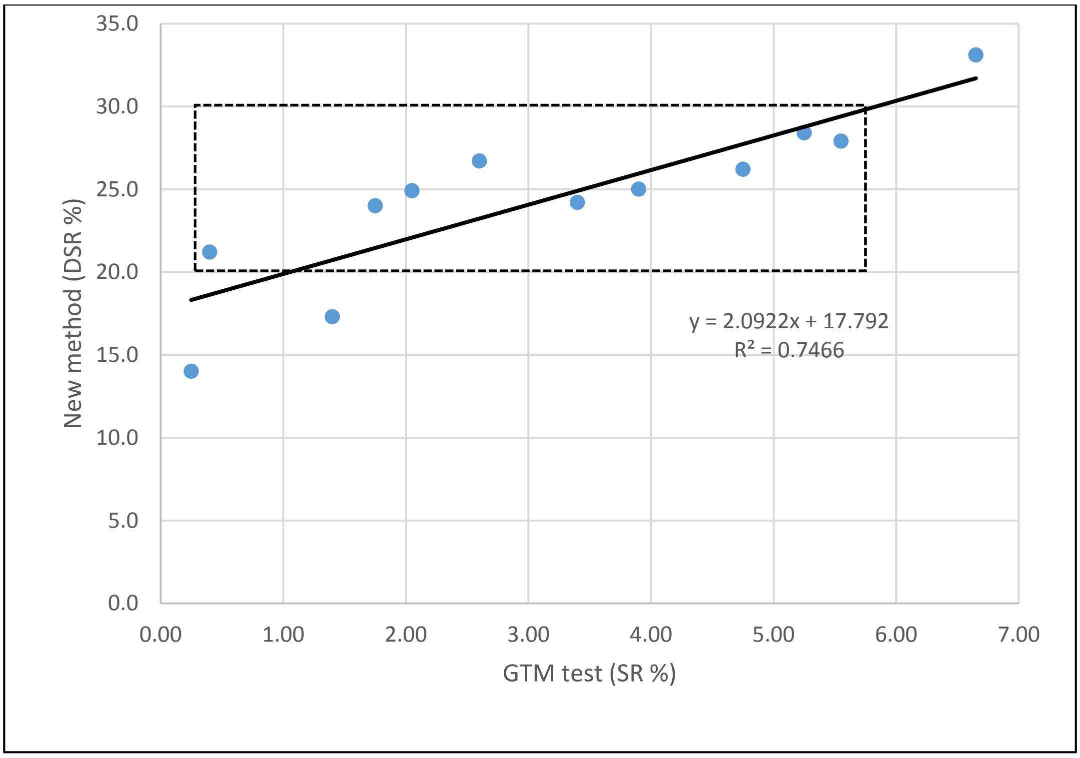


Figure 5.41. Correlation between new method and GTM test

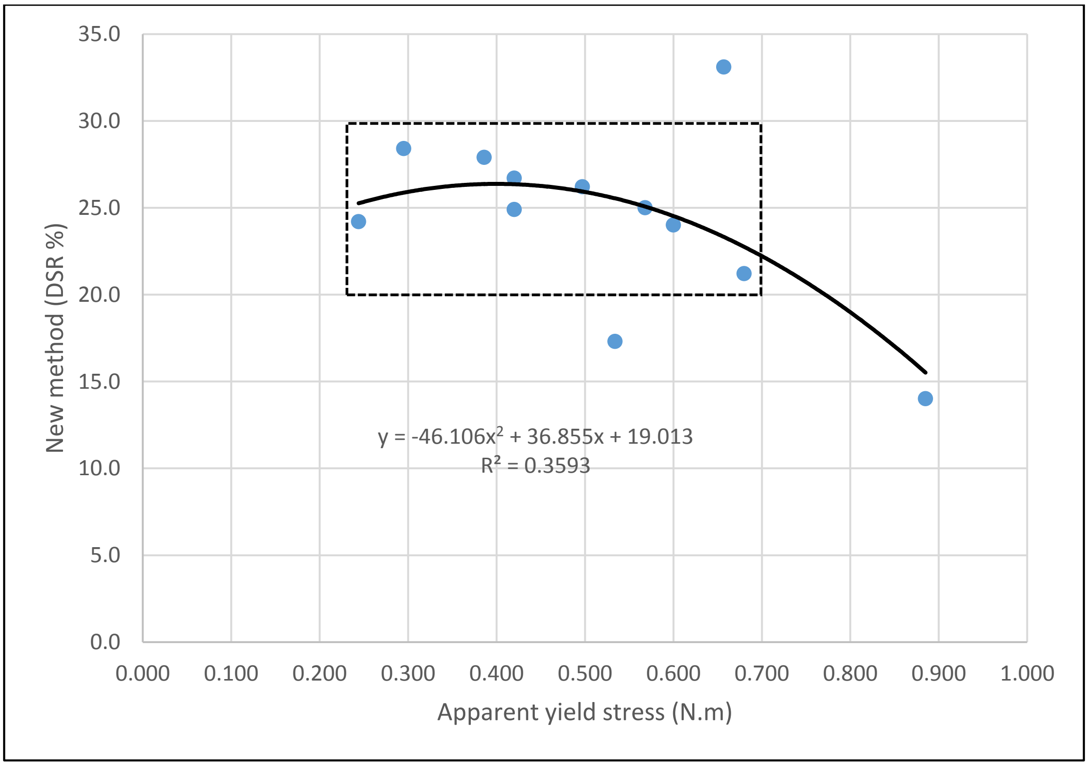


Figure 5.42. Correlation between new method and g from rheometer

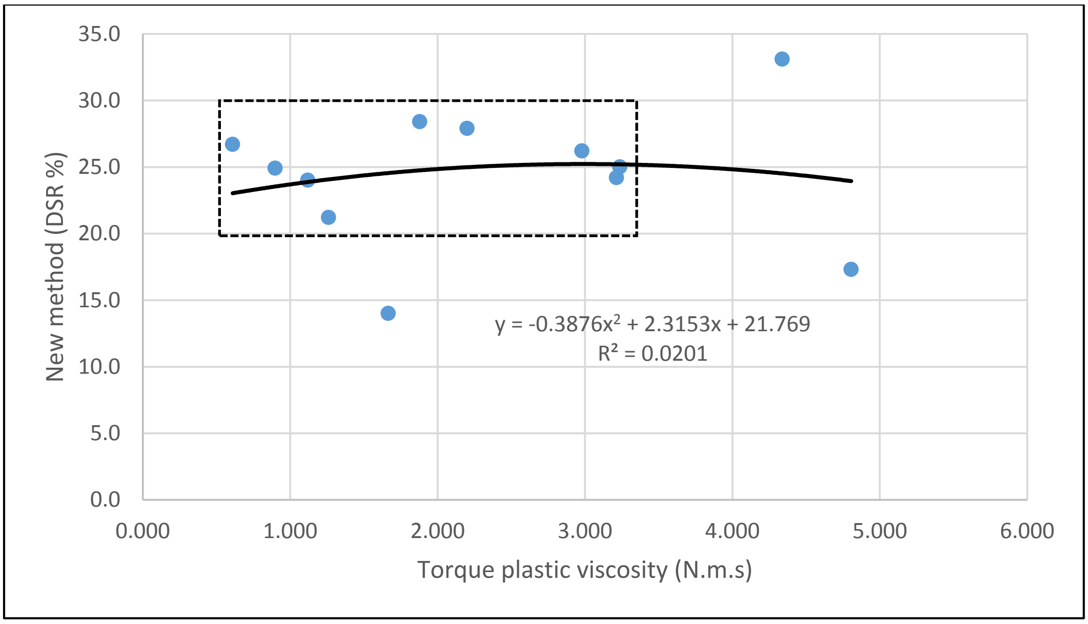


Figure 5.43. Correlation between new method and h from rheometer

Table 5.2 Correlation coefficient (R^2) for all mixtures and except 2, 6, and 9

Test results	**Correlation Coefficient (R^2)**	
	All mixtures	All mixtures; except mixtures 2, 6, and 9
DSR vs. T_{500} time	0.0972	0.2576
DSR vs. VSI	0.4083	0.7218
DSR vs. g	0.3593	0.7212
DSST vs. h	0.0201	0.0722
DSR vs. GTM SR	0.7466	0.7420
DSR vs. L-box time	0.0796	0.2958
DSR vs. L-box PR	0.6757	0.1950
DSST vs. V-funnel time	0.0733	0.0097

Correlation coefficients (R^2) obtained so far were determined by considering all of the mixtures. The correlation coefficients were calculated again by excluding the data points out of the dashed boxes. In other words, Mixture 2, 6, 9 were disregarded and new correlation coefficients were calculated. The old and new R^2 values are given in Table 5.2. Generally, the new R^2 values are higher except the following relations: (DSR vs. L-box PR) and (DSST vs. V-funnel time). Therefore, the higher R^2 values proof that the recommended limitation (20 – 30 %) for DSR of new method (DSST) is found correctly.

5.9. Repeatability of Tests

In order to see whether the new test method gives similar results for the same mixture or not, one of the mixtures (Mixture 8) were prepared three times. All of the results are given Table 5.3. The standard deviation, mean and coefficient of variation values for each test method are presented in Table 5.4.

Table 5.3 Repeatability results of tested Mixture 8

Mixtu-res	Slump-flow, mm	Dmax, mm	W/C	CA/TA	Slump flow		V-funnel flow time, s	L-box		GTM, Wps/Wc	Rheometer		New method, Wps/Wc	SP, kg/m3
					T500, s	VSI		H2/H1	Flow time, s		Yield stress (g), N.m	Plastic viscosity (h), N.m.s		
8.1	650	15	0.50	0.45	1.25	0	13	0.647	3	0.0040	0.680	1.261	19.80	4.125
8.2	650	15		0.45	1.2	0	11.5	0.563	2.22	0.0045	0.453	1.218	20.20	4
8.3	650	15		0.45	1.18	0	10	0.588	2.76	0.0045	0.325	1.151	22.00	4.25

The coefficient of variation is useful because the standard deviation of data must always be understood in the context of the mean of the data. In contrast, the actual value of the coefficient of variation is independent of the unit in which the measurement has been taken, so it is a dimensionless number. For comparison between data sets with different units or widely different means, one should use the coefficient of variation instead of the standard deviation. Table 5.4 indicates that the new method has high repeatability since it has very low coefficient of variation. Apparent yield stress was found to have low repeatability.

Table 5.4. Repeatability of the tests

	Slump flow		V-funnel flow time	L-box		GTM, Wps/Wc	Rheometer		New method, Wps/Wc	SP
	T500	VSI		H2/H1	Flow time		Apparent Y.S	Torque P.V		
Standard Deviation	0.036	0	1.5	0.043	0.3995	0.03	0.180	0.056	1.11	0.125
Mean	1.21	0	11.5	0.799	2.66	0.43	0.486	1.210	21.00	4.125
Coefficient of Variation, %	2.98	-	13.04	5.396	15.019	6.66	37.011	4.590	5.30	3.030

CHAPTER 6

CONCLUSIONS

6.1. Summary of Findings

Following outcomes can be drawn from this study.

- Mixtures proportioned to have greater deformability with same water to cement ratio (w/c) required higher amount of superplasticizer.
- Increasing the CA/TA and Dmax decreased the demand of superplasticizer. Increasing CA/TA and Dmax reduces the surface area of the aggregates to be wetted, supplying more free water to achieve the desired slump flow.
- The SCC mixtures with higher w/c has shorter T_{500} time. In the same way, as the slump flow increased, the T_{500} values decreased. The T_{500} time also decreased with an increase in the Dmax of coarse aggregate.
- A significant amount of bleeding was noted for the mixtures with w/c=0.42 which required more amount of superplasticizer. VSI was ranked from 1 to 2 for mixtures with w/c=0.42 and 0 to 1.5 for mixtures with w/c=0.50. VSI ranking increased as CA/TA and Dmax increased.
- The increase in slump resulted in a significant decrease in V-funnel flow time. As expected, the V-funnel flow times of the mixtures increased with a decrease in w/c due to their higher viscosity.
- The V-funnel time is affected by CA/TA as well. It should also be noted that the flow time is affected by changing the Dmax of coarse aggregate. An increase in Dmax of coarse aggregate increased the V-funnel flow time as well.
- SCC mixtures with high values of slump flow show greater L-box passing ability ratio.
- The SCC mixtures which contained higher CA/TA and have larger Dmax had less L-box passing ability.

- SCC mixtures with high slump flow values have higher segregation ratio (SR) of GTM test. Conversely, increasing the w/c decreased the segregation ratio due to less demand of superplasticizer.
- Results for SCC mixtures with high CA/TA indicate higher segregation ratio of GTM test. In the same way with an increase in the Dmax of coarse aggregate segregation ratio increased.
- SCC mixtures having w/c=0.42 and w/c=0.50, the g values decreased by an increase in target slump flow diameter.
- Considering the mixtures having same slump flow diameter, the g values increased with an increase in w/c ratio. The g values decreased with an increase in CA/TA ratio.
- The g value increased with an increase in Dmax of coarse aggregate.
- The h values were decreased by an increase in slump flow diameter and also the h values were decreased by an increase in w/c.
- The h values decreased with an increase in CA/TA and Dmax.
- For new proposed test method the SCC mixtures with high slump flow values show higher DSR. On the other hand, increasing the w/c decreased the DSR due to less demand of superplasticizer.
- Increasing the CA/TA of SCC increased the DSR values as well. Similarly, with an increase in Dmax of coarse aggregate, DSR values increased.
- The relationship between V-funnel and L-box tests shows that the L-box flow time increases as the V-funnel flow time increases and V-funnel flow time decreases by increasing L-box passing ratio.
- Correlation between V-funnel flow time ant T_{500} time shows that there is a strong positive relationship between the results of these tests. T_{500} time increases as the V-funnel flow time increases.
- Good relationships were obtained between torque plastic viscosity and T_{500} time or V-funnel time.
- It was found that the new proposed test is a suitable method to evaluate the dynamic stability of SCC.
- It is also found that the high demand of superplasticizer causes bleeding and shows significantly effect on the results of new proposed method.

- For the new proposed test method, the recommended limits for a dynamically stable and still having satisfactory flow properties are 20 % and 30 %. Lower values can result in concretes with low self-consolidating properties. Upper values can show severe segregation when the concrete is in motion.
- The repeatability of the new test method was found to be high.

6.2. Recommendations

1) The effect of dynamic segregation, evaluated by the new test method, can be investigated on hardened concrete specimens by mechanical tests such as compressive strength and tensile strength. This effect can also be searched by splitting the hardened specimens and inspecting the fracture surface.

2) The validity of the test method can be verified by:

- Using more mix-design parameters which were not studied in this thesis such as use of several mineral admixtures, use of viscosity modifying admixtures etc.
- Varying the range of the studied parameters: lowering the w/c, varying the cement or binder content, increasing Dmax, etc.
- Comparing the results with the more dynamic stability tests proposed in the literature.

3) The application of the new test method can be standardized further by placing the concrete on the new device by using a proper chute placed at the middle of the device.

REFERENCES

1. EFNARC, *The European Guidelines for Self-Compacting Concrete.* www.efnargc.org, [2005].

2. Mehta PK, Monteiro PJM. *Concrete – structure, properties and materials*. 3rd edition. Published by McGraw-Hill Book, New York, USA [2006].

3. Ouchi M, Nakamura SA, Osterberg T, Hallberg SE, Lwin M. *Application of self-compacting Concrete in Japan, Europe, and the United States*. ISHPC [2003]. Webpage: http://www.fhwa.dot.gov/bridge/scc.cfm

4. Okamura H, Ouchi M. *Self-Compacting Concrete.* Advance Concrete Technology Journal [2003]; Vol. 1, No. 1, pp., 5-15.

5. Goodier CI. *Development of self-compacting concrete.* Structures and Building Journal [2003]; vol. 156, no. 4, pp. 405-414.

6. Hwang SD, Khayat KH, Bonneau O. *Performance-Based Specifications of Self-Consolidating Concrete Used in Structural Applications.* ACI Materials Journal [2006]; vol. 103, no. 2, pp. 121-129.

7. ACI report no. 237 IR-07. *Self-consolidating concrete.* American Concrete Institute [2007].

8. Turcry P, Loukili P, Haidar K, Pijaudier-Cabot G, Belarbi A. *Cracking tendency of self-compacting concrete subjected to restrained shrinkage: experimental study and modeling*, Materials in Civil Engineering Journal [2006]; vol. 8, no. 1, pp. 46-54.

9. Panesar DK, Shindman B. *The effect of segregation on transport and durability properties of self-consolidating concrete.* Cement and Concrete Research Journal [2012]; vol. 42, pp. 252-264.

10. GRACE Construction Products. *An introduction to Self-Consolidating Concrete.* Technical Bulletin TB 1500 [2005], Printed in Washington, USA FA/GPS/1M.

11. Ferraris CF, *Measurement of the Rheological Properties of High Performance Concrete.* National Institute of Standards and Technology Journal [1999]; vol. 104, pp. 461-478.

12. Kosmatka SH, Panarese WC. *Design and Control of Concrete Mixtures*. 15th Edition,Published by Portland Cement Association, Washington, USA [2011]; ISBN-13: 978-0-89312-272-0, ISBN: 0-89312-272-6.

13. Ferraris CF, Brower LE. *Comparison of concrete rheometers*. International tests at LCPC (Nantes, France) in October, 2000, Research report, NIST, [2001].

14. Karunarathna HMGU, Abeyruwan H, Gunasoma HHM, Situge JMT. *Characterization of self-compacting concrete in terms of Bingham constants. Research project No: C/2006/01.*

15. Erdogan TY, Tokyay M, Yaman O, Erdogan ST. *Introduction to Material Science for Civil Engineering.* Published by METU Press, Ankara, Turkey [2010].

16. Nasvik J. *The ABCs of self-consolidating concrete in concrete constructions.* Publication no. C03C040 by Hanley-Wood LLC, Washington, USA [2003].

17. Shi C, Mo Y. *High-performance construction materials: Science and Application.* Published by World Scientific, New York, USA [2002].

18. Newman J, Choo BS. *Advanced Concrete Technology processes book.* Published by Butterworth-Heinemann Elsevier Ltd, Burlington, UK [2003]. ISBN 0 7506 51059.

19. ACI report no. 238 IR-08. *Report on measurement of workability and rheology of fresh concrete.* American Concrete Institute, Farmington Hills MI [2008].

20. Libre NA, Khoshnazar R, Shekarchi M. *Relationship between fluidity and stability of self-consolidating mortar incorporating chemical and mineral admixtures.* Construction and Building Materials Journal [2010]; vol. 24, pp. 1262-1271.

21. Li Z. *State of workability design technology for fresh concrete in Japan*. Cement andConcrete Research Journal [2007]; vol. 37, no.9, pp. 1308–20.

22. Bui VK, Montgomery D, Hinczak I, Turner. *Rapid testing method for segregation resistance of self-consolidating concrete.* Cement and Concrete Journal [2002]; vol. 32, pp. 1489-1496.

23. Valcuende MO, Parra C, Jarque JC. *Self-consolidating concrete homogeneity*. Construction and Building Materials Journal [2007]; vol. 57, no. 287, pp. 37–52.

24. Khayat KH, Vanhove Y, Pavate TV, Jolicoeur C. *Multi-electrode conductivity method to evaluate static stability of flowable and self-consolidating concrete*. ACI Materials Journal [2007]; vol. 104, no. 4, pp.424–33.

25. Khayat KH, Manai K, Trudel A. *In situ mechanical properties of wall elements cast using self-consolidating concrete*.ACI Materials Journal [1997]; vol. 94, no. 6, pp. 491-500.

26. Daczko JA. *Static stability of self-consolidating concrete*. In: Malhotra VM, editor. Proceedings of seventh CANMET/ACI international conference on recent advances in concrete technology. [2004]

27. Daczko J. A. *Stability of self-consolidating concrete, assumed or ensured*? In: Shah SP, Daczko JA, Lingscheit JN, editors. Proceedings of first North American conference on the design and use of self-consolidating concrete [2002], p.227-235.

28. Assaad J, Khayat KH, Daczko J. *Evaluation of static stability of self-consolidating concrete* [2004]; vol. 101, No. 3, pp. 207-215.

29. Khayat KH. *Workability, Testing, and Performance of Self-Consolidating Concrete*. ACI Materials Journal [1990]; v. 96, no. 3, pp. 346-353.

30. Khayat KH, Hu C, Monty H. *Stability of self-consolidating concrete, advantages , and potential applications.* Publisher, RILEM Publications SAR [1999]; ISBN: 2-912143-09-8, pp. 143 – 152.

31. Song T, Chiew YM. *Settling characteristics of sediments in moving Bingham fluid*. Hydraulic Engineering Journal [1997]; vol. 123, no, 9.

32. Tregger N, Gregori A, Ferrara L, Shah S, *Correlating dynamic segregation of self-consolidating concrete to the slump-flow test.* Construction and Building Materials Journal [2012]; vol. 28, pp. 499-505.

33. Atzeni C, Massidda L, Sanna U. *Comparison between rheological models for Portland cement pastes*. Cement and Concrete Research Journal [1985]; vol. 15, no. 3, pp. 511-519.

34. Yahia A, Khayat KH. *Analytical models for estimating yield stress of high performance pseudo-plastic grout*. Cement and Concrete Research Journal [2001]; vol. 31, pp. 731-738.

35. RIB Running Together, Global web site. Industries: *Architecture, engineering, and construction.* Website: [www.rib-software.com]

36. EN 12350-1, Testing fresh concrete*: Sampling* and EN 12350-2, Testing fresh concrete: *Slump-flow*. [European Engineering Standards]

37. SCC test methods, Control Masters of Technology website, [www.controls-group.com]

38. Ozawa K, Sakata N, Okamura H. *Evaluation of Self-Compatibility of Fresh Concrete Using the Funnel Test*. Library of Japan Society of Civil Engineering [1995]; no. 25.

39. Khayat KH, Assaad J, Daczko J. *Comparison of Field-Oriented Test Methods to Assess Dynamic Stability of Self-Consolidating Concrete.* ACI Materials Journal [2004]; vol. 101, no. 2, pp. 168-176.

40. Jau WC, Yang CT. *Development of modified concrete rheometer to measure the rheological behavior of conventional and self-consolidating concrete.* Cement and Concrete Composites Journal [2010]; vol. 32, pp. 450-460.

41. Shen L. *Role of aggregate packing in segregation resistance and flow behavior of self-consolidating concrete.* PhD thesis in the Graduate College of the University of Illinois at Urbana-Champaign [2007].

42. Koehler EP, Fowler DW. *Development of a Portable Rheometer for Fresh Portland Cement Concrete,* Research report, ICAR, [2004].

43. Wallevik JE. The Bingham-Model, *Retrieving the Bingham parameters when using the coaxial cylinders viscometer*, Lecture notes for the ICI rheocenter rheology course, Innovation center Iceland, Reykjavik, [2009].

44. Andraz H, Franci K, Violeta B. *Rheological parameters of fresh concrete comparison of rheometers,* Gradevinar Journal [2013]; vol. 65, no. 3, pp. 99-109.

45. Yen T, Chang C, Chen K. *Flow behavior of high strength high-performance concrete*. Cement and Concrete Composite [1999]; vol. 21, no. 5-6, pp. 413-424.

46. Hu J, Wang K. *Effect of coarse aggregate characteristics on concrete rheology*. Construction and Building Materials Journal [2011]; vol. 25, pp.1196-1204.

47. Jamkar SS, Rao CBK. *Index of aggregate particle shape and texture of coarse aggregate as a parameter for concrete mix proportioning*. Cement and Concrete Research Journal [2004]; vol. 34, no. 11, pp. 2021–2027.

48. Struble LJ, Szecsy R, Lei W, Sun G. *Rheology of cement paste and concrete*. Cement Concrete and Aggregate Journal [1998]; vol. 20, no. 2, pp.269–277.

49. Kosmatka SH, Kerkhoff B, Panarese WC. *Design and control of concrete mixture*. 14th edition. Skokie: Portland cement Association; [2002]

50. Geiker MR, Brandl M, Thrane LN, Nielsen LF. *On the effect of coarse aggregate fraction and shape on the rheological properties of self-compacting concrete*. Cement Concrete and Aggregate Journal [2002]; vol. 24, no. 1, pp. 3–6.

51. Ghoddousi P, Javid AAS, Sobhani J. *Effects of particle packing density on the stability and rheology of self-consolidating concrete containing mineral admixtures.* Construction and Building Materials Journal [2014]; vol. 53, pp. 102-109.

52. Uysal M, Yilmaz K. *Effect of mineral admixtures on properties on self-consolidating concrete*. Cement and Concrete Composite Journal [2011]; vol. 33, pp. 771-776.

53. Naik TR, Kumar R, Ramme BW, Canpolat F. *Development of high-strength, economical self-consolidating concrete*. Construction and Building Materials Journal [2012]; vol.30, pp. 463-469.

54. Ferraris CF, Larrard FD, Martys N. *Fresh concrete rheology: Recent development.* Materials Science of Concrete Journal [2001]; vol. 5, pp. 215-241.

55. Ferraris CF, Obla KH, Hill R. *The influence of mineral admixtures on the rheology of cement paste and concrete*. Cement and Concrete Research Journal [2001]; vol. 31, pp. 245–255.

56. Kim JH, Noemi N, Shah SP. *Effect of powder materials on the rheology and formwork pressure of self-consolidating concrete.* Cement and Concrete Composites Journal [2012]; vol. 34, pp. 746-753.

57. Sahmaran M, Yaman ÖI, Tokyay M. *Transport and mechanical properties of self-consolidating concrete with high-volume fly ash*. Cement and Concrete Composites Journal [2009]; vol. 31, pp. 99–106.

58. Nehdi M, Pardhan M, Koshowski S. *Durability of self-consolidating concrete incorporating high-volume replacement composite cements*. Cement and Concrete Research Journal [2004]; vol. 34, pp. 2103–2112.

59. Koehler EP, Fowler DW. *Static and dynamic yield stress measurement of self-consolidating concrete* [2008]; Proceeding of SCC 2008, Chicago, IL.

60. Koehler E, Jeknavorian, Klaus S. *Selecting admixtures to achieve application-required rheology* [2010]; RILEM Book series 1; Proceeding of design, production, and placement of self-consolidating concrete, Montreal, Canada, September 26-29, 2010.

61. Aghabaglou AM, Tuyan M, Yilmaz G, Arioz O, Ramyar K. *Effect of different types of superplasticizer on fresh, rheological and strength properties of self-consolidating concrete*. Construction and Building Materials Journal [2013]; vol. 47, pp. 1020-1025.

62. Sahmaran M, Christianto HA, Yaman IO. *The effect of chemical admixtures and mineral additives on the properties of self-compacting mortars*. Cement and Concrete Composites Journal [2006]; vol. 28, no. 5, pp. 432-440.

63. Felekoglu B, Sarikahya H. *Effect of chemical structure of polycarboxylate-based superplasticizer on workability retention of self-consolidating concrete*. Construction and Building Materials Journal [2008]; vol. 22, no. 9, pp. 1972-1980.

64. Cement Admixtures Association. *Admixture Technical Sheet – ATS 2 Superplasticising/High range water reducing* [2006].

65. Lazniewska P. *The influence of admixtures type on the air-voids parameters of non-air-entrained and air-entrained high performance SCC*. Construction and Building Materials Journal [2013]; vol. 41, pp. 109-124.

66. Shen L, Struble L, Lange D. *Modeling Dynamic Segregation of Self-Consolidating Concrete.* ACI Materials Journal [2009]; vol. 106, no. 4, pp. 375-380.

67. Skarendahl A, Petersson O. *State-of-the-Art Report of RILEM Technical Committee 174-SCC.* Self-consolidating concrete [2001]; vol. 23, pp. 141.

68. Esmaeilkhanian B, Khayat KH, Yaha A, Feys D. *Effects of Mix Design Parameters and Rheological Properties on Dynamic Stability of Self-Consolidating Concrete.* Cement and Concrete Composites Journal accepted [18 March 2014]; DOI. H http://dx.doi.org/10.1016/j.cemconcomp.2014.03.001

69. Zhu W, Gibbs JC, Bartos PJM. *Uniformity of in situ properties of self-consolidating concrete in full scale structural elements.* Cement and Concrete Composites Journal [2001]; vol. 23, no. 1, pp. 57-64.

70. Mehdipour I, Razzaghi MS, Amini K, Shekarchi M. *Effect of mineral admixtures on fluidity and stability of self-consolidating mortar subjected to prolonged mixing time.* Construction and Building Materials Journal [2013]; vol. 40, pp. 1029-1037.

71. El-Chabib H, Nehdi M. *Effect of mixture design parameters on segregation of self-consolidating concrete*. ACI Materials Journal [2006]; vol. 103, no. 5, pp. 374-383.

72. Felekoğlu B, Türkel S, Baradan B. *Effect of water/cement ratio on the fresh and hardened properties of self-consolidating concrete*. Building and Environment Journal [2007]; vol. 42, pp. 1795-1802.

73. Daczko J, Kurtz M. *Development of High Volume Coarse Aggregate Self-Compacting Concrete*. Proceedings of the Second International Symposium on Self Compacting Concrete, Tokyo, Japan, [2001], pp. 403-412.

74. Esmaeilkhanian B. *Dynamic Stability of Self-Consolidating Concrete: Development of Test Methods and Influencing Parameters.* PhD Thesis [2011], Sherbrooke University, Civil Engineering Department CANADA.

75. Esmaeilkhanian B, Feys D, Khayat KH, Yahia A. *New test method to Evaluate Dynamic Stability of Self-Consolidating Concrete*. ACI Materials Journal [2014]; vol. 111, no. 3, pp. 299-307.

76. ASTM C1611/C1611M-05, *Standard Test Method for Slump Flow of Self Consolidating Concrete*. ASTM International, West Conshohocken, PA [2005].

77. Yahia A, Tanimura M, Shimoyama Y. *Rheological properties of highly flowable mortar containing limestone filler-effect of powder content and w/c ratio.* Cement and Concrete Research Journal [2005]; vol. 35, no, 3. pp. 532–539.

APPENDIX A

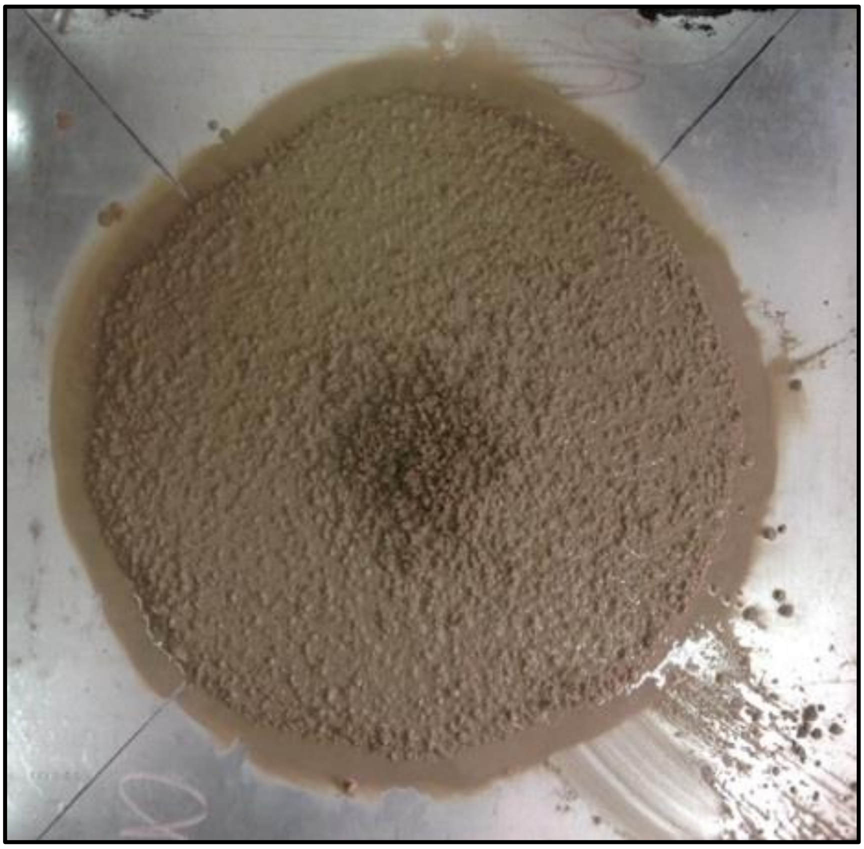
Visual Stability Index (VSI) Photos

Mixture 1

Mixture 2

Mixture 3

Mixture 4

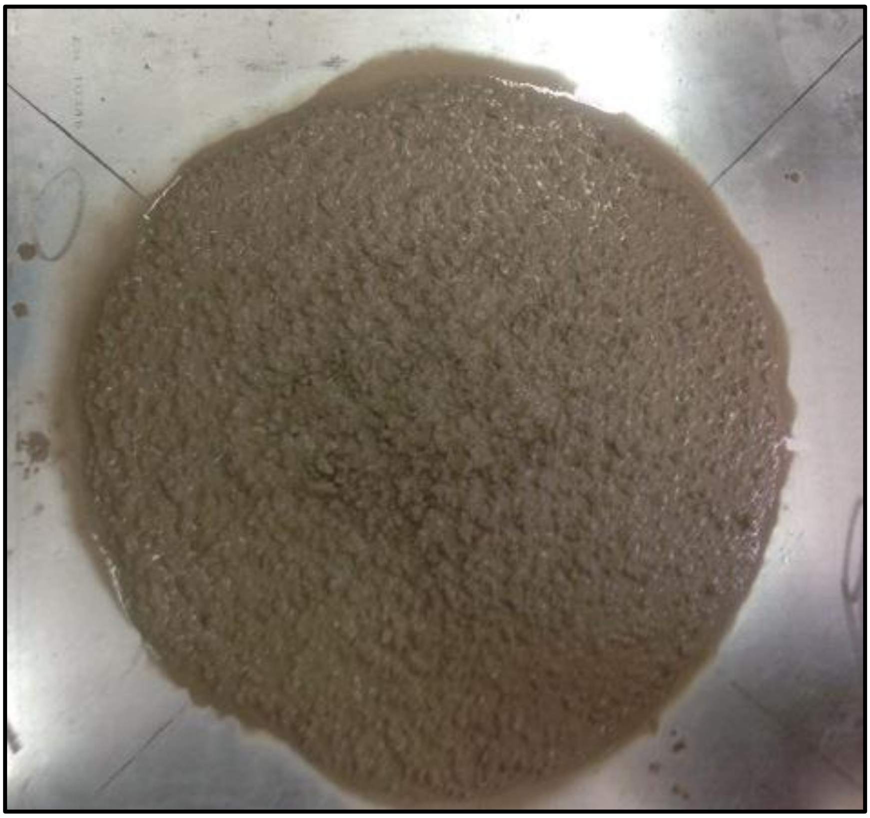


Mixture 5

Mixture 6

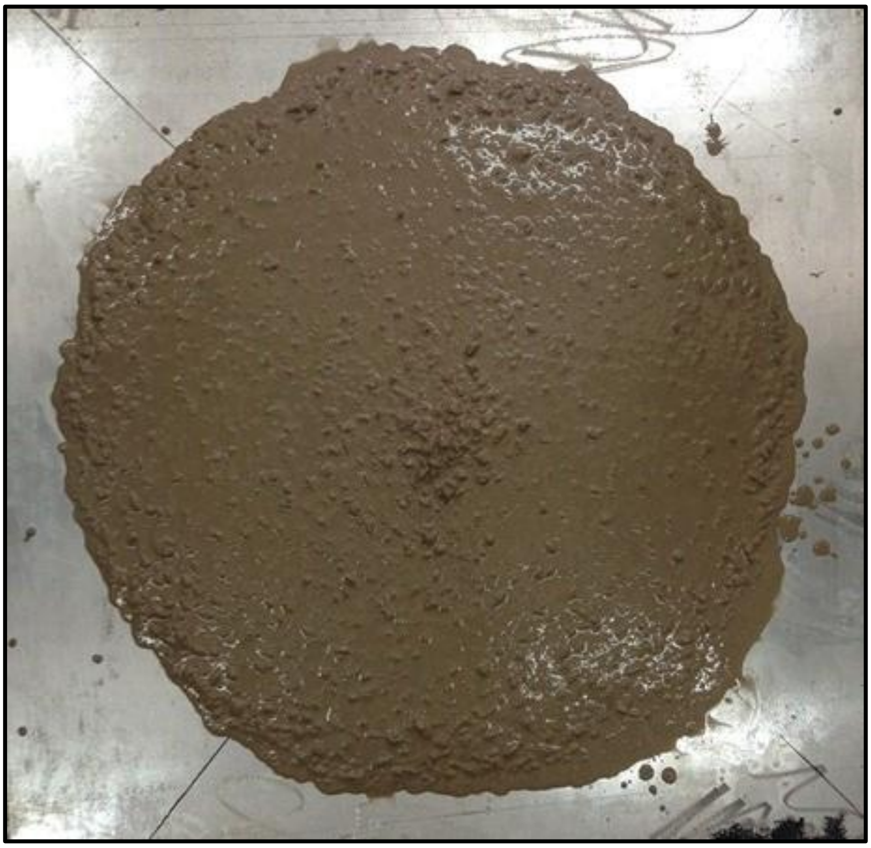
Mixture 7

Mixture 8



Mixture 9

Mixture 10



Mixture 11

Mixture 12