DYNAMIC SEGREGATION OF SELF-CONSOLIDATING CONCRETE: NEW TEST METHOD AND EFFECTS OF MIX PROPORTIONS

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ABSTRACT

Self-Consolidating Concrete (SCC) is a type of high performance concrete that can fill formworks without external vibration. SCC has three essential workability characteristics which can be described in terms of flowability, passing ability, and segregation resistance. These properties are typically characterized by data that relate to specific testing methods. Of the three unique properties, segregation resistance refers to the ability to retain a homogenous distribution of aggregates. Segregation is categorized as static or dynamic segregations. Cement paste and coarse aggregate tend to separate vertically when the concrete is at rest before setting, this is so-called static segregation. This separation also occurs horizontally in the presence of flow, which refers to dynamic segregation. Normally segregation resistance is achieved by adding finely powdered materials such as fly ash, silica fume, and limestone powder to increase paste viscosity and volume.

Poor segregation resistance can cause an uneven distribution of coarse aggregate, blocking of flow around reinforcement, high drying shrinkage and non-uniform concrete compressive strength (Bui, 2002).Therefore, in this thesis, a new experimental approach named flow trough test was developed to test dynamic segregation. The flow trough test was employed to assess the effect of several parameters on dynamic segregation of fresh SCC.

Twenty-nine SCC mixes made with various mix proportioning parameters, including aggregate size and gradation, super-plasticizer, paste volume, and

slump flow were evaluated. Flow trough tests showed that increasing slump flow or super-plasticizer dosage would increase dynamic segregation and reducing paste volume may increase dynamic segregation. Also a smaller aggregate size and better gradation would reduce dynamic segregation.

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TABLE OF CONTENTS

ABSTRACT……………………...……………………………………………………………...i

AKNOWLEDGEMENTS……………………………………………………………………….iii

1 INTRODUCTION..1

1.1 BACKGROUND 1
1.2 PROBLEM STATEMENT 3
1.3 OBJECTIVE...4

2 LITERATURE REVIEW 5

2.1 DEFINITIONS...5
2.1.1 Self-Consolidating Concrete (SCC)...5
2.1.2 Dynamic Segregation...6
2.2 HISTORY OF SELF CONSOLIDATING CONCRETE...7
2.3 AGGREGATES AND ADMIXTURES..7
2.3.1Aggregate 8
2.3.2 Admixtures 10
2.3.2.1 Super-plasticizer 10
2.3.2.2 VMA..11
2.4 WORKABILITY 11
2.5 MIX PROPORTIONING OF SCC..12
2.6 SCC FRESH PROPERTIES TEST METHODS 14
2.6.1 Slump Flow Test..15
2.6.1.1 Instruments 15
2.6.1.2 Procedure..16
2.6.2 Visual Stability Index (VSI) 17
2.6.3 J-Ring 17
2.6.3.1 Instruments 18
➢ 2.6.3.2 Procedure (ASTM C1621) 18
2.6.4 Penetration Test 19
2.6.4.1 Instruments 19
2.6.4.2 Procedure..20
2.6.5 L-box Test 21
2.6.5.1 Instruments 21
2.6.5.2 Test procedure 22
2.6.6 U-box test 22
2.6.7 Column segregation test 23
2.7 RHEOLOGY OF SELF-CONSOLIDATING CONCRETE 25
2.8 DYNAMIC SEGREGATION STUDIES 27
2.8.1 Dynamic Segregation and Blocking 27
2.8.2 Test Methods of Dynamic Segregation..31

3 NEW APPROACH FOR TESTING DYNAMIC SEGREGATION..............................53

3.1 DYNAMIC SEGREGATION 53
3.2 DESIGN AND TEST PROCEDURE...54
3.2.1 Test Device 55
3.2.2 Test Procedure 57
3.3 SCC MIX 58
3.3.1 Instruments and Materials..58
3.3.2 Mix Proportions 61
3.3.3 SCC Mix Procedure...64
3.3.4 Visual Stability Index (VSI) (ASTM C-1611)..64

3.4 FLOW TROUGH TEST 65
3.5 TEST RESULT 68
3.6 ANALYSIS 70
3.6.1 Comparison of DSI and VSI 70
3.6.2 Relationship between Slump Flow and Dynamic Segregation 71
3.6.3 Effect of Paste Volume on Dynamic Segregation 72
3.6.4 Effect of Super plasticizer on Dynamic Segregation 74
3.6.5 Aggregate size and gradation 76
3.6.6 Further discussion 77

4. CONCLUSION 80

5. FUTURE WORK RECOMMENDATION 82

6. REFERENCE 83

7. APPENDIX A: AGGREGATE PROPERTIES 90

TABLE OF FIGURES

Figure 1-1 Self-Consolidating Concrete 1
Figure 2-1 Basic workability requirements for successful casting of SCC 5
Figure 2-2 Effects of super-plasticizer (Okamura, 1997) 11
Figure 2-3 Flat plate with Mold in the center (Grace Construction product, 2002) 16
Figure 2-4 J-Ring apparatus (Humboldt, 2014) 18
Figure 2-5 Penetration apparatus (De Schutter, 2005) 21
Figure 2-6 Principle of L-Box (De Schutter, 2005) 22
Figure 2-7 U-Box test (Erkmen, 2008) 23
Figure 2-8 Column Segregation Test (Humboldt, 2014) 24
Figure 2-9 Bingham Fluid Equation (Ferraris, 1999) 26
Figure 2-10 Thixotropic Loop of Concrete (Ferraris, 1999) 26
Figure 2-11Blocking on SCC (Roussel, 2014) 28
Figure 2-12 Aggregate Particle trajectories with different mixture of concrete for formwork (Bilgil et al., 2005) 34
Figure 2-13 Viscosity values versus W/C ratios in CM mixtures 35
Figure 2-14 Viscosity values versus W/C ratios in CMS mixtures 35
Figure 2-15 Relationship between viscosity and segregation for fresh concrete (CM mixture) (Bilgil et al., 2005) 36
Figure 2-16 Relationship between viscosity and segregation for fresh concrete (CMS mixture) (Bilgil et al., 2005) 36
Figure 2-17 Relationship between yield stress and segregation for fresh concrete (CM mixture) (Bilgil et al., 2005) 37
Figure 2-18 Relationship between yield stress and segregation for fresh concrete (CMS mixture) (Bilgil et al., 2005) 37
Figure 2-19 PA for segregation tests (Bui et al., 2002) 39
Figure 2-20 L-box apparatus and small cylinder mold N (Bui et al., 2002) 39
Figure 2-21 Pd with different coarse-total aggregate ratios and concrete segregation resistance in the horizontal direction (Bui et al., 2002) 42
Figure 2-22 Pd and mass difference of coarse aggregate in the horizontal direction (Bui et al., 2002) 42
Figure 2-23Pd with different water-binder ratios and concrete segregation resistance in the horizontal direction ((Bui et al., 2002) 42
Figure 2-24 Pd with different paste volumes and concrete segregation resistance in the horizontal direction (Bui et al., 2002) 43
Figure 2-25 (a) Three-compartment hinged cylindrical mold; (b) modified penetration depth apparatus (EI-Chabib and Nehdi, 2006) 45
Figure 2-26 Effect of cementitious materials content on segregation resistance of SCC mixtures, w/cm=0.45 (EI-Chabib and Nehdi, 2006) 47
Figure 2-27 Effect of cementitious materials content on segregation resistance of SCC mixtures, w/cm=0.40 (EI-Chabib and Nehdi, 2006) 47
Figure 2-28 Effect of w/cm on segregation resistance of SCC 48
Figure 2-29Effect of HRWRA on segregation resistance of SCC mixtures (VMA= 0.01%, w/cm = 0.45) (EI-Chabib and Nehdi, 2006) 50
Figure 2-30 Effect of VMA on segregation resistance of SCC mixtures (VMA = 0.56%, w/cm = 0.45) (EI-Chabib and Nehdi, 2006) 51
Figure 3-3-1 Flow Trough 56
Figure 3-2 No.4 Sieve 56
Figure 3-3 Slump flow test apparatus 56
Figure 3-4 4"×8" plastic cylinder 57

Figure 3-5 Mixer 59
Figure 3-6 VMA and Super-plasticizer 59
Figure 3-7 Gradation curves of coarse and fine aggregates 61
Figure 3-8 VSI =0(left) and VSI =1 (right) 65
Figure 3-9 VSI =2 (left) and VSI =3 (right) 65
Figure 3-10 Slump flow test 66
Figure 3-11 Prime the flow trough 67
Figure 3-12 SCC flowing on the flow trough 67
Figure 3-13 4"×8" Sample from flow trough 67
Figure 3-14 Wash Aggregate in No.4 sieve 68
Figure 3-15 Aggregate in No.4 Sieve 68
Figure 3-16 VSI versus DSI 71
Figure 3-17 Effects of slump flow on dynamic segregation 72
Figure 3-18 Paste volume versus DSI 74
Figure 3-19 Super plasticizer versus DSI (Graded Aggregate type) 75
Figure 3-20 Super plasticizer versus DSI (Mineral Filler type) 76
Figure 3-21 Super plasticizer versus DSI (VMA type) 76
Figure 3-22 Effects of aggregate size and gradation on dynamic segregation 77
Figure 3-23 Estimation of maximum travel distance 79
Figure 7-1 Basalt sand 90
Figure 7-2 Basalt sand gradation Curve 90
Figure 7-3 Halawa 3F 91
Figure 7-4 Halawa 3F Gradation Curve 91
Figure 7-5 Maui Dune Sand 92
Figure 7-6 Maui Dune Sand Gradation Curve 92
Figure 7-7 Kapa'a Chips 93
Figure 7-8 Kapa'a Chips Gradation Curve 93
Figure 7-9 Halawa 3F 2 94
Figure 7-10 Halawa 3F 2 Gradation Curve 94

1 Introduction

1.1 Background

Self-Consolidating Concrete (SCC), Self-Compacting Concrete, vibration-free concrete, and self-leveling concrete are terms used to identify the type of concrete that was first developed in Japan in the early 1980s. SCC is a type of high performance concrete that flows and consolidates under its own weight and fills the formwork without any external vibration, see Figure 1-1 (Okamura, 1997).

SCC offers great potential for improved ease of placement, work environment and safety, because it eliminates the use of vibrators for concrete placement, thus minimizing vibration and noise exposures. It also eliminates trip hazards caused by cords, which reduces fall hazards as workers do not have to stand on the forms to consolidate concrete. In addition, SCC improves aesthetics since it provides unique formed surfaces. Furthermore, it increases the rate of construction and reduces reducing time and labor cost (Okamura, 1997).

Figure 1-1 Self-Consolidating Concrete

SCC is different from conventional concrete since it is highly workable and flows through the rebar under its own weight, filling the formwork without any vibration. Flowable concrete can be produced by increasing the water to cementitious materials ratio, but both concrete strength and durability require limitations on the w/cm ratio. It is known that as the water to cementitious materials ratio increases, concrete viscosity decreases and the likelihood of concrete segregation increases. In this case, it has been difficult to produce a type of flow-able and stable concrete.

SCC is designed to meet specific applications requiring high flowability, high passing ability, and good segregation resistance. These properties are achieved by properly proportioning the constituent materials and admixtures. Because SCC consolidates without any help of external vibration, the properties of fresh SCC control the quality of the placement and final product. Also, when the fresh state of SCC shows signs of segregation, the concrete will not perform as expected (e.g., it will have poor mechanical properties). Therefore, it is important to properly evaluate the properties of fresh SCC (Erkmen, et,al. 2008)

Note that a successful SCC mixture must not undergo any form of segregation, whether “dynamic” or “static”. Dynamic segregation refers to the horizontal segregation while flowing, and static segregation is the vertical segregation that occurs when the fresh SCC is static.

Segregation resistance refers the ability to retain a homogenous distribution of aggregates. A good resistance to segregation allows a regular distribution of coarse aggregates throughout the mixture. Dynamic segregation must be studied during the mix design and can be avoided by adoption of an adequate composition.

1.2 Problem Statement

Due to the advantages of SCC over conventional concrete, there is an increasing interest in local concrete plants to use SCC for construction. Despite the higher initial materials costs, the use of SCC may result in economic benefits for local concrete plants. Some benefits can be quantified such as faster construction, reduced noise level, and improved surface finish, which eliminates patching. Other benefits include worker safety improvements and extended life of forms. SCC also has made the construction of highly congested structural elements possible.

Although SCC has been developed and successfully used for some applications and both fresh and hardened properties of SCC have been investigated, there remain concerns regarding acceptance criteria in its fresh condition such as segregation resistance. While at rest, static segregation occurs primarily in the form of constituent sedimentation or excessive bleeding. While in motion, dynamic segregation occurs primarily in the form of forced separation of aggregate from mortar as the concrete passes through restricted spacings or other obstacles.

Poor segregation resistance can cause uneven distribution of coarse aggregate, blocking of flow around reinforcement, and high drying shrinkage as well as non-uniform concrete compressive strength (Bui, 2002). Therefore, segregation resistance is an important property of SCC that must be monitored and controlled throughout its production, transportation, and placement.

Several test methods were designed to measure the dynamic segregation of SCC. Currently, the only standard test for dynamic segregation of SCC is

Visual Stability Index (VSI), which is determined by observation of the periphery of SCC during the slump flow test. The range of VSI value is from 0 to 3(ASTM C-1611). While VSI is just an approximation to estimate dynamic segregation of SCC, it is also limited to a very small flow length. Therefore, a more reliable and precise testing method is urgently needed to assess dynamic segregation.

1.3 Objective

Because SCC compacts without any external vibration, the properties of fresh SCC control the quality of concrete placement and the final product. And if fresh SCC shows signs of segregation or insufficient ability to flow, SCC will not perform as intended. Therefore, it is essential to develop and utilize testing methods to evaluate fresh properties of SCC properly.

The purpose of this thesis is to develop a new dynamic segregation test method and use this method to assess the effects of various parameters on dynamic segregation of fresh SCC.

2 Literature Review

2.1 Definitions

2.1.1 Self-Consolidating Concrete (SCC)

According to ASTM C-125-06, SCC is defined as:

"Concrete that can flow around reinforcement and consolidate under its own weight without additional effort and without exceeding specified limits of segregation."

The highly flowable nature of SCC is due to very careful mix proportioning, generally replacing much of the coarse aggregate with fines and cement, and adding chemical admixtures. It depends on the sensitive balance between creating more deformability while ensuring good stability, along with maintaining low risk of blockage (Flannery, 1999). See Figure 2-1.

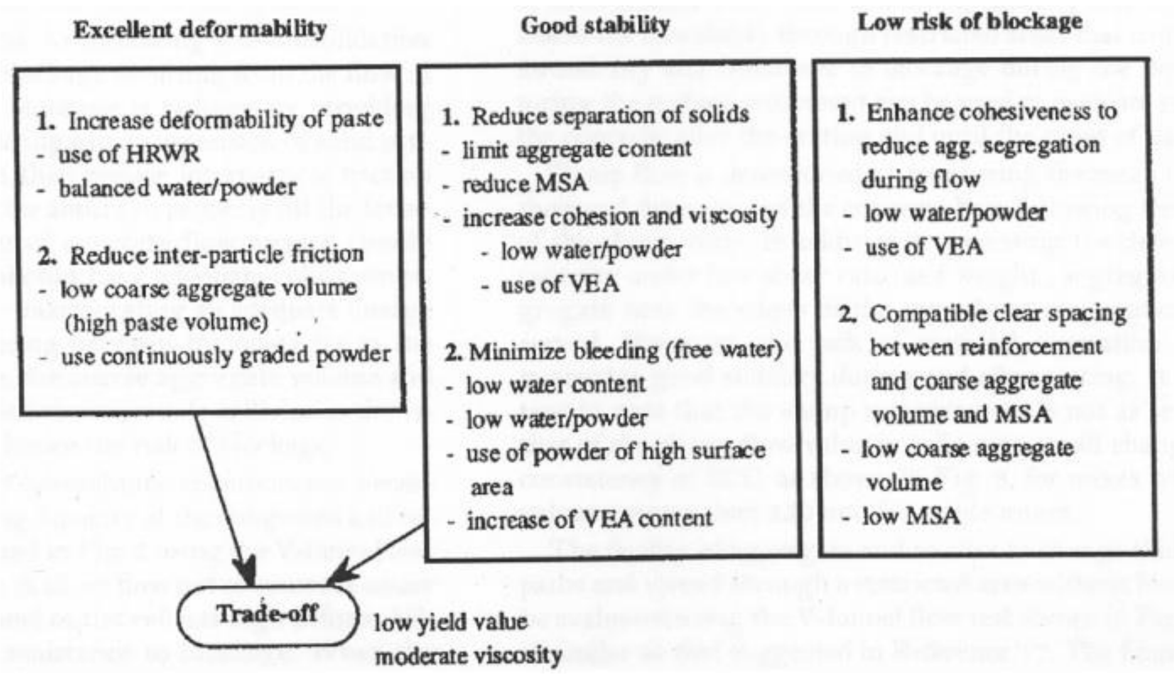

Figure 2-1 Basic workability requirements for successful casting of SCC (Flannery, 1999)

In general, the benefits of the application of SCC are (Thrane, 2007):

- Provision of more flexibility for architectural design of concrete structures.
- Reduction of the risk of having non-filled zones, poor compaction, and honeycomb issues in structures.
- Improvement of the working environment by the elimination of vibration.
- Faster construction through reduced manpower, worker safety improvements, and extended life of forms.

2.1.2 Dynamic Segregation

Concrete is a composition of the filler and the binder. The binder (cement paste) "glues" the filler together and forms a synthetic conglomerate. The binder is cement paste and the filler can be fine or coarse aggregate. Due to the differences in their physical properties along with gravitational force and buoyance, cement paste and coarse aggregate tend to separate vertically when the concrete is at rest before setting. This is the so-called static segregation. This separation also occurs horizontally in the presence of flow, which refers to dynamic segregation.

Rich cement paste could cause dynamic segregation, and eventually lead to blocking of flow around reinforcement, higher shrinkage, and lower and non-uniform compressive strength. The separation of coarse aggregate and cement paste in SCC drew much attention from concrete industry researchers. Most of the attention has been paid to static segregation of SCC. Only limited research on dynamic segregation of SCC has been carried out.

2.2 History of Self Consolidating Concrete

The arrival of Self-Consolidating Concrete (SCC) was a revolution in the field of concrete technology in 1986. To address durability concerns of the Japanese government, Hajime Okamura, a professor of Kochi University of Technology in Japan, proposed the concept of SCC. During his research, Okamura found that inadequate consolidation of the concrete in the casting operations was the main cause of the poor durability performance of concrete. By 1988, the concept was developed and ready for the first real-scale test. In the following year (1989), the first paper on SCC was presented at the second East-Asia and Pacific Conference on Structural Engineering and Construction (EASEC-2). Another presentation occurred in 1992 at a meeting of the Energy Diversification Research Laboratories (CANMET)/American Concrete Institute (ACI). Since then, SCC has been studied worldwide with papers presented in almost each concrete-related conference (Vachon, 2002).

2.3 Aggregates and Admixtures

Similarly to conventional concrete, SCC is comprised of fine and coarse aggregates, cement, water, and mineral and chemical admixtures. But SCC has properties that differ from conventional concrete. The three essential properties of SCC are flowability, passing ability, and segregation resistance.

Domone (2006) stated that the composition of SCC is based on the following:

1. The gravel volume is between 28% and 38% of the total volume of SCC.
2. The cementitious paste is between 30% and 42% of the total volume of SCC.
3. Water to cementitious ratio is less than 0.48.
4. The binder proportion is between 385 kg/m^3 and 635 kg/m^3.

5. The Super-plasticizer dosage is near the saturation value (Domone, 2006).

2.3.1Aggregate

Aggregates are generally classified into two categories: fine aggregates and coarse aggregates. The diameter of fine aggregates is less than 4.75 mm and that of coarse aggregates is greater than 4.75 mm. Aggregates are commonly thought of as inert fillers that account for 30 to 42% of the SCC volume and reduce the cost, but that is not particularly the case. Aggregates play an important role in creating a workable concrete mix, even though admixtures have the ability to change the fresh properties of the concrete mixture. In addition, if the less amount of cement is used, concrete will have less durability problems caused by the paste such as porosity and drying shrinkage.

The aggregates play a main role in affecting both fresh and hardened properties of SCC. SCC is sensitive to changes in aggregate characteristics such as shape, texture, maximum size, and grading. Therefore, the aggregate should be selected carefully before mixing SCC.

Because the study of aggregate characteristics is essential in designing SCC, many researchers have investigated coarse aggregate properties and their effects on both fresh and hardened properties of SCC.

The shape and size of coarse aggregate influence the necessary mortar and cement paste volume to cover all aggregate grains. Naturally uncrushed gravel consumes less mortar or cement paste than does limestone. Crushed aggregate tends to reduce flow because of interlocking of the angular particles, while rounded aggregate improve the flowability because of lower internal friction (Alexander and Prosk 2003). Tviksta states that it is possible to utilize natural, rounded, semi-crushed or crushed aggregates to produce SCC. A well-graded aggregate source to produce successful SCC should be used. SCC mixes could use a poorly graded aggregate, but higher viscosity needs to be provided to avoid segregation (Neuwald 2004).

In addition, decreasing coarse aggregate content should be required because high coarse aggregate content could decrease passing ability. Also, the choice of the maximum size of coarse aggregate depends on the gaps between reinforcement bars. The optimum coarse aggregate depends on two parameters: maximum size and shape.

1. A lower value of the maximum size of coarse aggregate could increase the passing ability (Domone, 2006).

2. A higher content of rounded shape could increase passing ability of using high content of coarse aggregate (EFNARC, 2002).

Petersson stated that the maximum size of aggregate that is suitable to produce SCC is in the range of 10 to 20mm (Petersson, 1997).

The following list provides a summary of findings of :

1. A threshold of coarse to total aggregate ratio of 0.45 where concrete shows minimal segregation (Chabib, 2005);
2. The higher the packing density of aggregate, the less amount of paste content is consumed to achieve the same workability(Jeenu, 2005);
3. Crushed aggregates need more paste volume to cover their surface area than rounded aggregates due to the higher packing density of rounded aggregates(Khaleel, 2011);

4. When the smaller the aggregates used, the less amount of Super-plasticizer is consumed and the less segregation occurrs(Bui, 2002);
5. Increasing the maximum size of coarse aggregate reduces flowability and passing ability (Chabib, 2005);
6. When uncrushed gravel is used in the concrete mixture, flowability, passing ability and segregation resistance increase as compared to concrete with crushed gravel (Chabib, 2005).

2.3.2 Admixtures

The two principal admixtures in SCC are synthetic high-range water reducer (HRWR) (Super-plasticizer) and viscosity modifying admixtures (VMA). They may be used by themselves but are more commonly used together.

2.3.2.1 Super-plasticizer

A Super-plasticizer is one of the main elements used to produce an SCC mix. Super-plasticizers (Glenium 3030NS or Glenium 7500 in this research) create flow ability by creating a negative charge around the cement particles, making them to repel each other. When this occurs, the cement particles no longer lump together and are free to flow.

To produce SCC with high flow-ability and good segregation resistance, an optimum combination of Super-plasticizer (both in type and dosage) and water to cementitious material ratio needs to be set up. It is known that concrete with high flow ability can be achieved by increasing water to cementitious material ratio, but increasing water to cementitious material ratio leads to lower viscosity, more segregation, and poor hardened concrete properties such as lower strength and durability. However, with Super-plasticizers, adequate flow ability can be achieved with little decrease in viscosity and segregation resistance (Okamura, 1997). See figure 2-3.

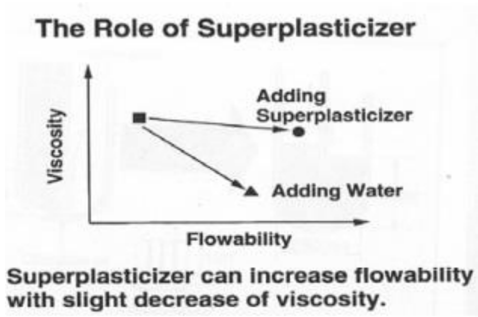

Figure 2-2 Effects of super-plasticizer (Okamura, 1997)

2.3.2.2 VMA

VMA is used to stabilize the rheology of SCC. It essentially thickens the mix to prevent segregation. The viscosity buildup comes from the association and entanglement of polymer chains of the VMA at a low shear rate, which further inhibits flow and increases viscosity. Meanwhile, added VMA causes a shear-thinning behavior, decreasing viscosity when there is an increase in shear rate.

2.4 Workability

Workability is defined either quantitatively by rheological parameters or qualitatively as the ease of placement. It is correlated with the filling ability, passing ability, and stability as determined by various test methods.

The filling ability is the ability of a concrete mix to fill formwork and distribute itself evenly under its own weight without honeycombing. The passing ability is the capacity for concrete to flow around obstacles such as rebar and other confined spaces without clumping or forming obstructions and air voids. Concrete stability is the capability that concrete possesses to resist segregation and bleeding (water segregating out of the paste) the ability to maintain a uniform and homogenous distribution of constituents. The two types of stability are dynamic stability and static stability. Dynamic stability is the ability of concrete to resist segregation and bleeding when in motion, whether the motion is prompted by the flow of the concrete through formwork or by the transportation of concrete to the site. The static stability of concrete is the ability of concrete to maintain homogeneity while sitting still and setting ("ACI 237R-07," 2007).

The most common test to determine workability is the slump flow test. Either the vertical slump distance or the horizontal spread of the concrete can be measured. The most common rheological parameters used to quantify workability and defined by the Bingham equation. The Bingham equation is a linear relationship between the shear rate ($\dot{\gamma}$) and the shear stress (τ). The viscosity (η) is the slope and the yield stress (τ_0) is the intercept. The Bingham equation is shown in equation (2-1) below:

$$\tau = \tau_0 + \eta\dot{\gamma} \qquad \text{(Eqn. 2-1)}$$

In some cases, the Herschel-Bulkley equation was better suited to describe the workability. A linear approximation of the Herschel-Bulkley curve was introduced by F. de Larrard et al to define the plastic viscosity.

2.5 Mix Proportioning of SCC

Since SCC mixes usually have low water to cement ratio, SCC tends to be much stronger, less permeable and eventually more durable compared with conventional concrete. Such characteristics make it possible to produce durable structures when using SCC independent of on-site conditions relating to the quality of labor, casting and compacting systems available (Okamura, 1997).

The amount of coarse aggregate in SCC mixes must be controlled to prevent blockage and segregation (Okamura, 1997). Okamura has proposed that the limiting value of coarse aggregate content should be around 50% of total aggregate. The limit varies from 36% to 60% in the literature with the average about 50%. If the coarse aggregate content of SCC mixes increases, the frequency of collision and contact between aggregate particles will increase when SCC pass through the rebar.

To produce SCC, high range water reducers, which are chemical admixtures also known as Super-plasticizers are necessary. An optimum combination of Super-plasticizer dosage and water to cementitious material ratio needs to be set up in terms of type and quantity to obtain SCC with high flow-ability and segregation resistance. Concrete with high flow ability can be achieved by increasing water to cementitious material ratio, but increased water to cementitious material ratio leads to decreased viscosity, increased segregation, and poor hardened concrete properties such as lower strength and durability. However, with Super-plasticizers, adequate flow ability can be achieved with little decrease in viscosity and segregation resistance (Okamura, 1997).

Viscosity-modifying admixtures can be used to control bleeding, segregation, and surface settlement of SCC mixes (Khayat et al., 1997). Therefore, to increase segregation resistance of SCC, VMA can be used to improve concrete viscosity. In addition, VMA lessens the sensitivity of the properties of fresh SCC to small variations in aggregate moisture content (Gurjar, 2004).

High viscosity can reduce the ability of concrete to flow under its own weight and pass through the rebar. Therefore, a suitable balance must be reached between flow ability and segregation resistance (Yahia et al., 1999). VMA may not be necessary when using well-graded aggregates and high powder content.

Fillers such as silica fume, fly ash, and slag are commonly used mineral additives to produce SCC in order to increase workability, flow ability, strength, durability and to reduce the costs. Fillers work in this way to increase concrete viscosity and reduce inter-particle friction. The functions of these mineral additives include the following (Chen, 1999):

(1) "Improving the workability;

(2) Improving the resistance to chemical attack and the durability;

(3) Reducing the porosity of SCC and increasing hydration products;

(4) Adjusting grading of the components to reach optimum compaction;

(5) Achieving both economic and environmental benefits by partial cement replacement."

The difference between an SCC mix and a typical conventional concrete mix is that SCC incorporates a lower content of coarse aggregate to prevent segregation (i.e., a portion of coarse aggregate is replaced by fillers such as cement, silica fume, and fly ash,), and a high dosage of Super-plasticizer 8 to 14 oz./cwt to improve flow ability.

2.6 SCC Fresh Properties Test Methods

In order to assess the three properties of SCC, various tests were conducted in the following sequence: slump flow and visual stability index (VSI), J-Ring, penetration test, L-box, U-box, and column segregation. The time required to carry out the tests was limited to 20 minutes. The first five testing methods are described in the following sections.

2.6.1 Slump Flow Test

The slump flow test is the only standardized test by the American Society for Testing and Materials (ASTM) for SCC. The test reveals information on passing ability and flow ability of fresh SCC mix.

2.6.1.1 Instruments

a. A flat nonabsorbent base plate- the base plate is about one square meter in dimension with an 8 centimeters (20 inches) diameter circle drawn on its center (See Figure 2-3).
b. Mold – The mold used in this test method shall conform to the described in FOP for AASHTO T119.
c. A suitable container
d. Strike-off bar
e. Scoop
f. Ruler

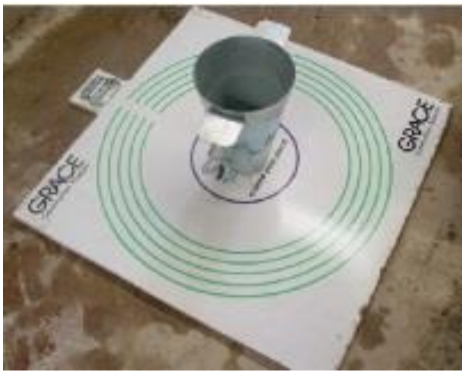

Figure 2-3 Flat plate with Mold in the center (Grace Construction product, 2002)

2.6.1.2 Procedure

a. Position the base plate so it is fully supported, flat, and level;

b. Dampen place the mold, with the smaller opening of the mold at the center of the base plate.

c. Using a suitable container fill the mold with fresh SCC. At the same time, the mold should be held firmly in place during filling. Overfill the mold a little bit.

d. Strike off the surface of the SCC level at the top of the mold with a strike-off bar. The mold is then steadily upward lifted to a height of 230±75mm (9 ± 3 inches) within 3 ± 1 seconds without lateral or torsional motion allowing the concrete to flow out and across the base plate. The time required for the sample to reach the 20 inches diameter ring (T_{20}) is recorded along with the average final diameter of the spread sample. Normal values for the T_{20} are 2-5 seconds and values for the final diameter usually range from 22 to 30 inches. Less viscous SCC tends to have smaller T20 and a bigger final radius. (Grace Construction Products, 2005)

2.6.2 Visual Stability Index (VSI)

The visual stability index test is a rating of the visual appearance of slump flow patty to evaluate several parameters including segregation, bleeding, and aggregate size distribution as an indication of the stability of the SCC. VSI rates the segregation of SCC visually on a scale of 0 through 3 in increment of 0.5, with 0 rating represents no segregation and 3 indicating severe segregation. (New Jersey Department of Transportation, 2007)

Table 2-1: Visual Stability Index Criteria (ASTM C1611)

Rating	Criteria
0	No evidence of segregation in slump flow patty or in the wheelbarrow.
1	No mortar halo or aggregate pile in the slump flow patty but some slight bleed or air popping on the surface of the concrete in the wheelbarrow.
2	A slight mortar halo (<3/8 inch) and/or aggregate pile in the slump flow patty and highly noticeable bleeding in the wheelbarrow.
3	Clearly segregating by evidence of a large mortar halo (>3/8 inch) and/or large aggregate pile in the center of the concrete patty and a thick layer or paste on the surface of the resting concrete in the wheelbarrow.

2.6.3 J-Ring

The J-ring test gives the information on both the filling ability and the passing ability of fresh SCC. It can also be used to investigate the segregation resistance of SCC by comparing test results from two different portions of sample. The J-ring test measures three parameters: flow spread, flow time T50J (optional) and blocking step. The J-ring flow spread indicates the restricted deformability of SCC due to the blocking effect of reinforcement bars and the flow time T50J indicates the rate of deformation within a defined flow distance. The blocking step quantifies the effect of blocking.

2.6.3.1 Instruments

a. A flat nonabsorbent steel base plate- the base plate is about one square meter in dimension with an 8 centimeters (20 inches) diameter circle drawn on its center

b. A slump cone- The mold used in this test method shall conform to the described in FOP for AASHTO T119

c. J-Ring with smooth rods

d. Bucket with a capacity of 10 liters.

e. Strike-off bar

Figure 2-4 J-Ring apparatus (Humboldt, 2014)

2.6.3.2 Procedure (ASTM C1621)

a. Place the steel base plate on a stable and level position.

b. Fill the bucket with 6~7 liters of fresh SCC and let sample stand still for 1 minute (±10 seconds).

c. Under the 1 minute waiting period, dampen the inner surface of the cone and the base plate, and place the slump cone in the center of the base plate.

d. Place the J-ring on the base plate around the cone.

e. Fill the slump cone with the sample from the bucket without any external compacting action. The surplus concrete above the top of the cone should be struck off, and any concrete remaining on the base plate should be removed.

f. Make sure that the test surface is neither too wet nor too dry. No dry area on the base plate is allowed and any surplus of water should be removed.

g. After less than 30 seconds, the slump cone is lifted perpendicularly to the base plate to allow SCC flow out freely without obstruction from the cone. The stopwatch is started the moment the cone looses the contact with the base plate.

h. The stopwatch is stopped when the front of SCC touches the circle of diameter 500mm.

i. The stopwatch reading is recorded as the T50J value. The test is completed when SCC flow has ceased (Schutter, 2005)

2.6.4 Penetration Test

The penetration test is used to investigate the segregation resistance of SCC by penetrating a cylinder with a given weight into the fresh SCC sample. If the SCC has poor resistance to segregation, the cylinder will penetrate deeper due to the less amount of aggregate in the upper layer of the sample. Therefore the penetration depth indicates whether the SCC is stable or not.

2.6.4.1 Instruments

Penetration apparatus- illustrated in Figure 2-5 consisting of a frame, slot, screw, reading scale and penetration head. The penetration head is assembled with an aluminum cylinder and rod. The rod should be able to move inside the slot, reading scale and penetration head. The inner diameter, height and thickness of the cylinder are 75 mm, 50 mm and 1 mm, respectively. The total weight of the penetration head is 54 g.

Bucket - bucket has capacity of 10~12 liters.

2.6.4.2 Procedure

a. Place the bucket in a stable and level position.

b. Fill the bucket with 10 ± 0.5 liters of fresh SCC sample and let sample stand still for 2minutes ± 10 seconds.

c. Put the penetration on the top of the bucket, adjust the penetration cylinder until it just reaches the upper surface of the concrete, and then let the cylinder penetrate freely into the concrete.

d. After 15 to 20 seconds of the stabilization of the cylinder, the penetration depth of the cylinder head is recorded from the scale. Measure the penetration depths at the center P_1 and two sides P_2 and P_3 of the width of the bucket. Also make sure the duration of the three measurements should be less than 3 minutes.

Figure 2-5 Penetration apparatus (De Schutter, 2005)

2.6.5 L-box Test

The purpose of the L-box test is to investigate the passing ability and segregation resistance of SCC. The reached height of fresh SCC after passing through the designated gaps of steel bars and flowing within a defined flow distance is measured. With this reached height, the passing or blocking behavior of SCC can be estimated.

2.6.5.1 Instruments

1. L- Box, as shown in Figures 2-6. Two types of gates can be used, one with 3 smooth bars and one with 2 smooth bars. The gaps are 41mm and 59 mm, respectively.
2. Suitable tool for ensuring that the box is level i.e. a spirit level.
3. Suitable buckets for taking concrete sample.

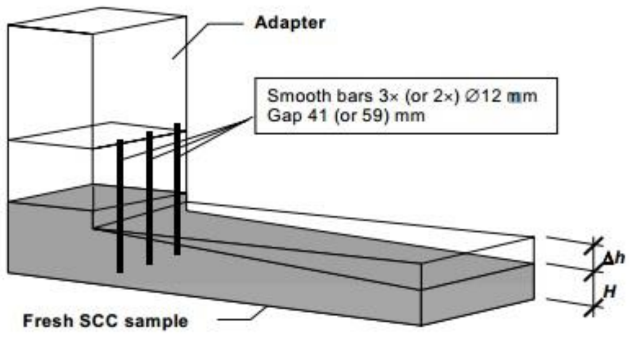

Figure 2-6 Principle of L-Box (De Schutter, 2005)

2.6.5.2 Test procedure

1. Place the L-box in a stable and level position.
2. Fill the vertical part of the L-box, with the extra adapter mounted, with 12.7 liters of representative fresh SCC.
3. Let the concrete rest in the vertical part for one minute (± 10 seconds). During this time the concrete will display whether it is stable or not.
4. Lift the sliding gate and let the concrete flow out of the vertical part into the horizontal part of the L-box.
5. When the concrete has stopped moving, measure the average distance, noted as Δh (see Figure 2-6), between the top edge of the box and the concrete (Koehler, 2007).

2.6.6 U-box test

The U-box test was developed by the Technology Research Centre of the Taisei Corporation in Japan. It is used to evaluate filling ability of SCC in heavily reinforced areas (PCI, 2003). The apparatus consists of a vessel that is divided into two components by a middle wall, see Figure 2-7. A sliding gate is fitted between the two sections, and three No.4 reinforcing bars are installed at the gate with 2-inch center-to-center space. The left-hand section of the apparatus is filled in one lift of concrete, and after a 1 minute rest, the sliding gate is opened allowing concrete to flow into the other compartment. When the concrete flow stops, the height of concrete in each compartment is measured. The results are presented as the ratio of the concrete heights on the two sides of the obstacle (h2/h1), which is called the U-box blocking ratio (see Figure 2-2). Acceptable values of h2/h1 are between 0.80 and 1.00 in (JSCE, 1998).

The test is simple to conduct, but the equipment might be difficult to construct. This test provides a good direct assessment of filling ability.

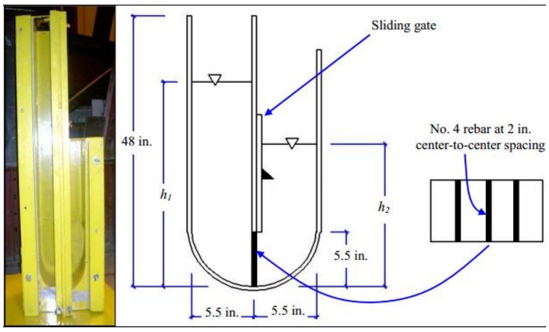

Figure 2-7 U-Box test (Erkmen, 2008)

2.6.7 Column segregation test

This test method was developed to determine static segregation of SCC by measuring the coarse aggregate content in the top and bottom portions of a cylindrical specimen (or column), see Figure 2-8.

Figure 2-8 Column Segregation Test (Humboldt, 2014)

This test is performed by filling concrete into a 26-inch tall, 8-inch diameter column, which is split into 3 sections. The top and bottom sections are 6.5-inch in height and the middle section is 13-inch.

The surface of the concrete is then leveled to the top of the mold by means of both lateral and horizontal motion of a thin steel plate (less than 1/16 in. in thickness). The same steel plate and technique is used to separate the column sections after a rest of 15 minutes, after which individually transfer the contents of the top and bottom sections to separate No. 4 sieves, and discard the contents of the middle section. Wash each concrete sample over the No. 4 sieve to remove all paste and fine aggregate, leaving behind only clean coarse aggregates on each sieve. Collect the coarse aggregates retained on each sieve, dry each sample in an oven until it reaches a constant mass, and measure the mass of each sample of coarse aggregates as M_{top} and M_{bottom}, separately, and percent of static segregation is obtained by Eqn. 2-2 (ASTM C1610).

Percent of static segregation $= 2(\frac{M_{bottom}-M_{top}}{M_{bottom}+M_{top}}) \times 100\%$ (Eqn. 2-2)

Where

M_{bottom}= the weight of coarse aggregate from the bottom section

M_{top}= the weight of coarse aggregate from the top section

2.7 Rheology of Self-Consolidating Concrete

The rheological properties of fresh SCC significantly affect the construction operations such as transportation, placement, consolidation and formwork pressure, which eventually influence the hardened properties and long term behavior of concrete. The rheological properties of fresh concrete are mostly described by means of the Bingham model which is defined by two factors: plastic viscosity and yield stress. After flow is initiated in a Bingham Fluid by applying the yielding stress, the rate of flow will increase proportionally to any stress increases. The proportion of increase is defined by the plastic viscosity of the concrete (see Figure 2-9). The yielding stress and plastic viscosity of a concrete mix is determined by inter-particle forces which can be broken or altered by shear stress. The yield stress and plastic viscosity is therefore dependent on time, shear history and shear rates applied. For instance, at any given shear rate, more stress is induced in a concrete mix when the shear rate is increasing, and less stress is induced when the shear rate is decreasing (see Figure 2-10) (Ferraris, 1999). Concrete in general tends to display a thixotropic behavior, where the particles de-flocculate while the concrete is in motion (e.g. concrete in a mixer), and then re-flocculate when the concrete is kept still. This property of concrete makes it quite necessary to hold studies and carry out experiments with the shear rate of the concrete held constant in a mixer (Banfill, 2003).

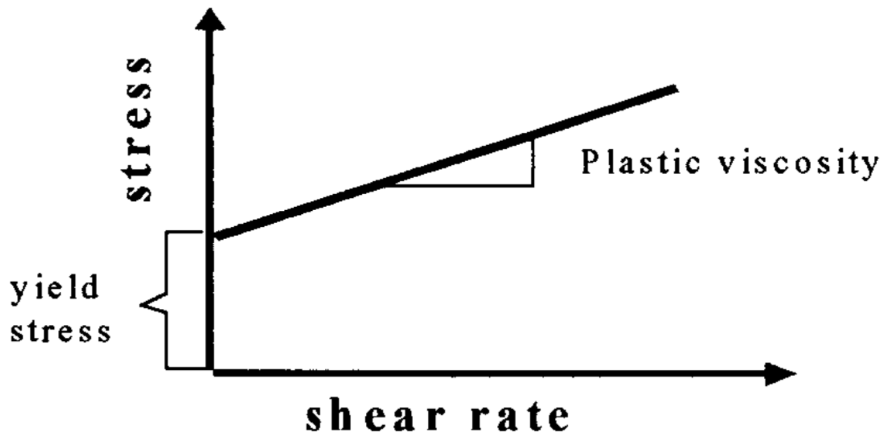

Figure 2-9 Bingham Fluid Equation (Ferraris, 1999)

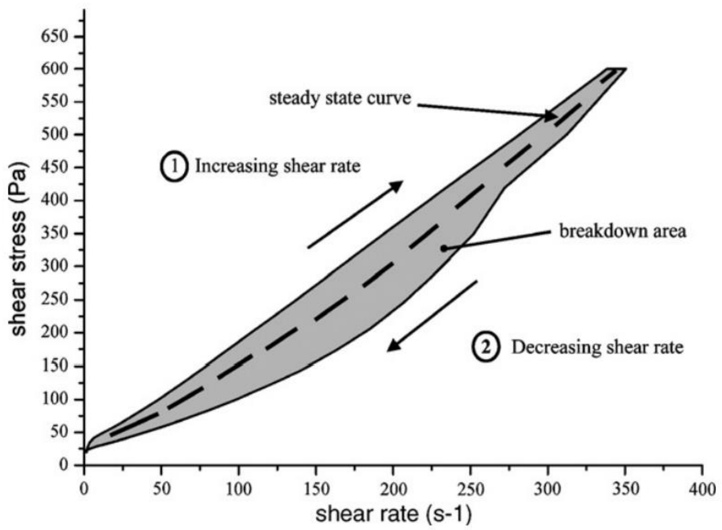

Figure 2-10 Thixotropic Loop of Concrete (Ferraris, 1999)

For self-compacting concrete, the Bingham model is applicable in many cases but some authors report that the rheological behavior is non-linear. The apparent viscosity increases with increasing shear rate, which shows that shear thickening behavior. Shear thickening becomes important in operations occurring at high shear rates, like mixing and pumping. In these circumstances, shear thickening should not be forgotten in order to avoid breaking of the mixer, pump or pipes (Feys, 2009).

Interparticle forces primarily depend on the proximity of particles which give rise to strong interactions. The strength of the bonds depends on the shape and size of particles along with their concentration in the liquid. Net interactions cause flocculation's of particles, which is the property where random particles come together and stick (Banfill, 2003). Thus, the interparticle forces can be affected by some variables such as cement properties, water-to-cementitious materials ratios, as well as the addition of chemical and mineral admixtures. Generally speaking, the most common way of changing the interparticle forces is the addition of Super-plasticizer (Glenium 3030NS or Glenium 7500 in this study).

2.8 Dynamic Segregation Studies

2.8.1 Dynamic Segregation and Blocking

Although concrete could allow for the filling of formworks with complex shapes, concrete contains coarse aggregates which could get jammed in the most reinforced zones during the casting process (see Figure 2-11). When concrete flows through an obstacle such as rebar, both dynamic segregation and blocking could occur (Roussel, 2014)

Figure 2-11Blocking on SCC (Roussel, 2014)

In order to better understand the physical phenomenon of dynamic segregation, it would be helpful to review another phenomenon also taking place during concrete flow which is blocking.

Blocking is the accumulation of aggregates behind reinforcement bars and/or between bars and formwork, which is mainly caused by physical interactions between aggregates and solid obstacles in the flow path (Roussel, 2014).

For a yield stress type of concrete, the concrete weight can generate a shear stress which is a complex function of the obstacle geometry. If the shear stress becomes lower than the yield stress of the concrete, flow stops before the concrete can self-level (Roussel *et al.,* 2009). This effect has been quantified in the case of the L-Box test with and without steel bars, and it is demonstrated that the thickness variation (h_1-h_2) between the case with bars and without bars is of the order of $\frac{3\tau_0}{\rho g}$, where τ_0 and *pg* are the yield stress and the density of the tested SCC, respectively (Nguyen *et al.,* 2006).

"For traditional SCC (or semi-SCC), with a yield stress of the order of 100 Pa, this variation is on the order of 1cm. This value was validated by means of testing stable limestone filler suspensions that did display a yield stress of the same order as SCC, but the constitutive particles of which were too small to create a granular blocking in the vicinity of the obstacle"(Nguyen *et al.,* 2006; Roussel *et al.,* 2009). This also explains why there exists, even for stable concretes which do not display any granular blocking, a systematic difference between slump flow and J-Ring test (Tam *et al.,* 2005; Nguyen *et al,* 2006). It is interesting to note here that, in (Tam *et al.,* 2005), all the measurements and conclusions may be explained by the yield stress variation between the various tested concrete and that there is no granular blocking at all.

If the characteristic size of the obstacles (e.g. the gap between the bars) is not far from the size of the coarsest particles, proper granular blocking may occur and granular arches may appear stable enough to resist the flow. At the origin of the formation of these granular arches is granular clogging, jamming or blocking, consequence of the suspended particles at some time jam somewhere in the obstacles formed by the steel reinforcements. Granular blocking may occur for particles with a diameter smaller than the gap between obstacles, and it is thus essentially a collective effect. Segregation induced by flow or weight may lead to an increase in the local volume fraction of coarse aggregates which could itself locally increase the risk of granular blocking (Roussel, et al., 2009).

The coarsest particles in concrete are subjected to weight and are immersed in a fluid with a lower density, and of viscosity possibly too low to prevent them from settling or segregating within the flow duration. When concrete is at rest, the yield stress of cement paste may prevent those coarse particles from settling. If concrete is flowing, the drag force exerted by the suspending fluid (mortar or cement paste) on each particle has to be high enough to "carry" the particles (Roussel, 2014). If the studied concrete is not stable, the presence of the obstacle could increase segregation effects. It is a known feature of suspensions that particles migrate from high shear rates zones to lower shear rates zones (Ovarlez, et al., 2006).

The flow perturbations induced by steel bars locally increase these shear rate gradients and can thus increase shear induced segregation. Although the above phenomenon, namely dynamic segregation, does not lead directly and systematically to granular blocking, it can strongly affect the distribution and volume fraction of coarsest particles at the vicinity of the obstacles (Roussel, et al., 2009).

The rheology of the cement paste should not affect the granular blocking phenomenon. It is natural to imagine that a low viscosity cement paste and thus a very fluid SCC would be more prone to have its coarsest particles blocked in highly reinforced zones (Roussel, 2014). However, the material is too fluid to carry its own particles during flow and is not directly at the origin of the granular blocking. The coarse particles volume fraction may increase above the volume fraction deduced from mix proportions. This increased volume fraction due to segregation may be sufficient to create granular blocking although the volume fraction deduced from mix proportions was not (Roussel, 2014).

Concrete in a plastic state can segregate in horizontal direction, vertical direction, or both directions at the same time. Segregation is often associated with static segregation. When the material is not flowing, the aggregate particles near the bottom of a given sample or of a formwork as their density is higher than the density of suspending fluid.

2.8.2 Test Methods of Dynamic Segregation

Many negative effects brought up by segregation include deficient covering on the rebar, insufficient filling of the forms, lower durability, and decreased strength. The causes of segregation could be external to the mixture, such as drop height, pumping pressure (inside the pipes), placement technique, or inside the mixture, such as the raw material properties or mixture proportions (Daczko, 2002).

Daczko (2002) summarized previous experience on how the concrete raw materials, application variables, and various factors affect both static and dynamic segregation in Table 2-2. This table is very helpful in practical applications.

Table 2-2 Effects of Proportioning and application variable on segregation of SCC (Daczko, 2002)

Factor	Effect on Dynamic Segregation	Effect on Static Segregation
Cementitious Materials	Provides viscosity and yield stress to reduce dynamic segregation	Provides viscosity and yield stress to reduce static segregation
Coarse Aggregate	Higher volume reduce passing ability through restricted sections	Volume, specific weight, and gradation affect static segregation
Fine Aggregation	No effect outside of balancing coarse aggregate volume	Gradation and specific weight affect static segregation
Water	Volume controls the viscosity of paste and thereby dynamic segregation	Volume controls the viscosity of paste and thereby static segregation
Super-plasticizer	High dose can create excess flow resulting in dynamic segregation	High dose can create excess flow resulting in static segregation
Viscosity Modifying Admixture	Provides viscosity to the paste resulting in lower dynamic segregation	Provides viscosity to the paste resulting in lower static segregation
Air-Entrainer	Minimal to none	Helps to suspend aggregate and reduce static segregation
Fluidity	Greater fluidity results in higher dynamic segregation	Greater fluidity results in higher static segregation
Flow Distance	Promote separation of paste from aggregate	Minimal to none
Free Fall	Higher distance increases dynamic segregation	Minimal to none
Form dimensions	narrow form increases wall effects and increases dynamic segregation	Minimal to none
Transport Agitation	vibration can cause dynamic segregation	Minimal to none
Pumping	pressure can cause segregation in the pump lines	Minimal to none

Results of some research work on dynamic segregation by other researchers are presented below.

1) Ahmet Bilgil et al.)

A. Bilgil et al. (2005) numerically investigated the mechanism of segregation during the filling of fresh concrete into formwork. This study was carried out on normal concrete in which aggregate interactions (friction) are very important. The aggregates are considered as Lagrangian particles whose trajectories determine segregation. Aggregate segregation is partially affected due to concrete viscosity. The relationship between aggregate segregation and viscosity during the fill of fresh concrete for both CM (concrete mixture) and CMS (concrete mixture includes super-plasticizer) is investigated. CMS is concrete mixture including super-plasticizers for the same composition of CM. Cylindrical formwork (30 cm by 150 cm) is employed. It is found that CM concrete mixture has an aggregate segregation level of 50%, while it reduces to a level of 20% for CMS concrete mixture (Bilgil et al., 2005)

A mathematical model is developed in Figure 2-12, which shows the trajectories of the representative velocity of aggregate in concrete during flow, and different colors show the velocity distribution of aggregate particles. According to the presence of boundary shear stress, velocity distribution of aggregate particles changes during the filling of fresh concrete. The particle velocity at the central axis of formwork is shown with dark blue (on the left) while at the boundary where particle velocity reduces trajectories are shown with a dark green color (on the right). The fraction of segregation is defined by the following equation

$$\eta = 1 - \frac{\sum N}{N_0} \qquad \text{(Eqn. 2-3)}$$

where N_0 is the total number of particles introduced at the inlet and $\sum N$ is the predicted sum of the all particles that reached to the top of the mould. On the top end of the formwork, the aggregate segregation is at its maximum value. This is the result of cylindrical mould walls that prevent motion of the particles, and the development of boundary shear stress.

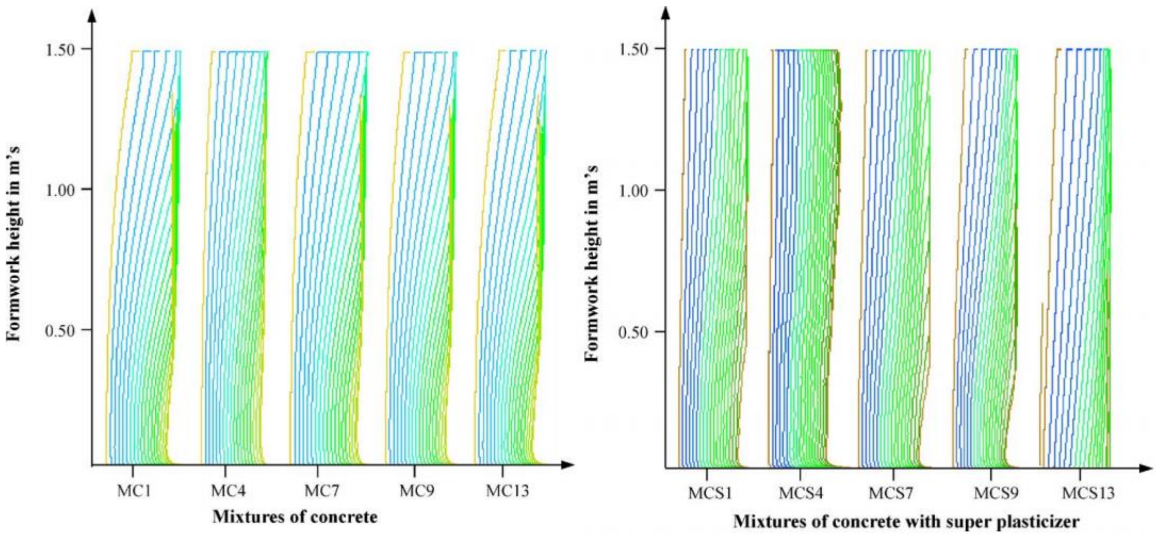

Figure 2-12 Aggregate Particle trajectories with different mixture of concrete for formwork (Bilgil et al., 2005)

In Figure 2-13 (CM concrete mixture) and Figure 2-14 (CMS concrete mixture) the relationship between different W/C ratios and viscosity values calculated with the Herschel–Bulkley equation are given by Bilgil et al. (2005). By comparing the two factors, it is noticed that there is a remarkable increase in viscosity as super-plasticizers are introduced in CMS mixture.

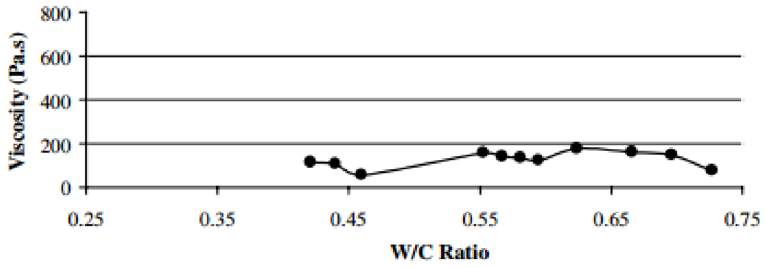

Figure 2-13 Viscosity values versus W/C ratios in CM mixtures
(Bilgil et al., 2005)

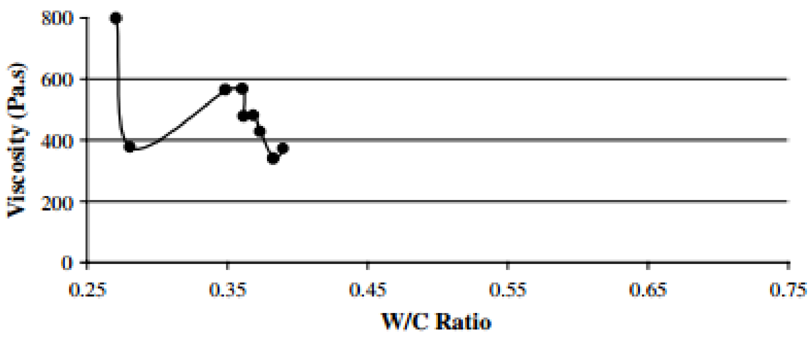

Figure 2-14 Viscosity values versus W/C ratios in CMS mixtures
(Bilgil et al., 2005)

Figures 2-15 and 2-16 show the relationship between viscosity and segregation. It is observed that it is very hard to correlate viscosity values of fresh concrete with segregation, while there is less segregation with lower viscosity values. In CMS mixture less segregation is observed at higher viscosity values.

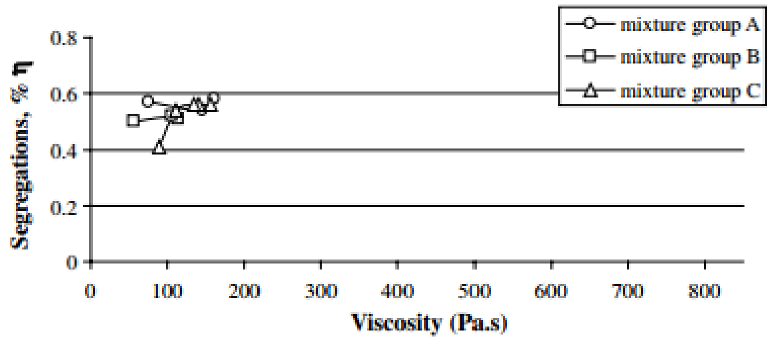

Figure 2-15 Relationship between viscosity and segregation for fresh concrete (CM mixture) (Bilgil et al., 2005)

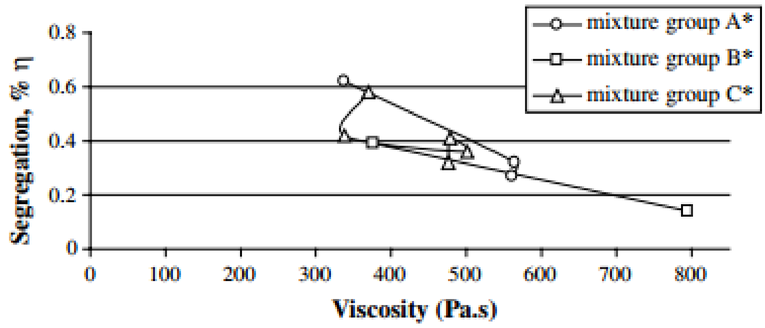

Figure 2-16 Relationship between viscosity and segregation for fresh concrete (CMS mixture) (Bilgil et al., 2005)

Figures 2-17 and 2-18 illustrate the relationship between yield stress and segregation. Similar observations could be made as those for the effects of viscosity.

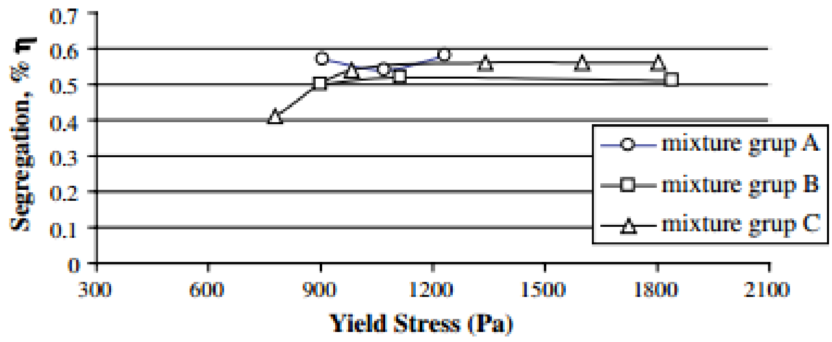

Figure 2-17 Relationship between yield stress and segregation for fresh concrete (CM mixture) (Bilgil et al., 2005)

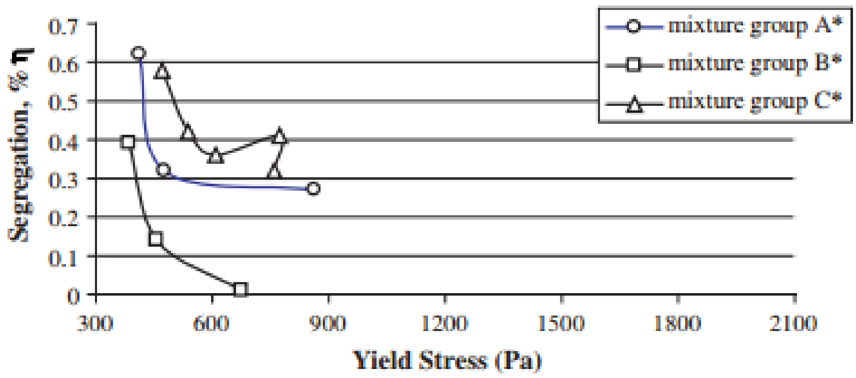

Figure 2-18 Relationship between yield stress and segregation for fresh concrete (CMS mixture) (Bilgil et al., 2005)

To sum up, the relationship between aggregate segregation and plastic viscosity/ yield stress do not follow a linear trend with the calculation from mathematical models. For fresh CM mixtures, no relation can be found between aggregate segregation and plastic viscosity or yield stress of fresh concrete. However, for CMS mixtures, aggregate segregation is decreased as plastic viscosity or yield stress increases. The different results between CM and CMS mixtures are due to super-plasticizer.

2) V.K.Bui et al.)

V.K.Bui et al. (2002) present a test method with a simple penetration test along with the L-box test to assess dynamic segregation. A penetration apparatus (PA) (Figure 2-19) was developed and used for testing the segregation resistance of SCC mixtures. Also a set of small cylinder moulds (Labled by the letter N) with a diameter of 80 mm and a height of 70 mm was employed to assess the segregation resistance of SCC mixtures in the horizontal direction (see Figure 2-20). PA consists of a penetration head with a mass of 54grams, a Frame F, Slot E, Reading scale M and Screw D.

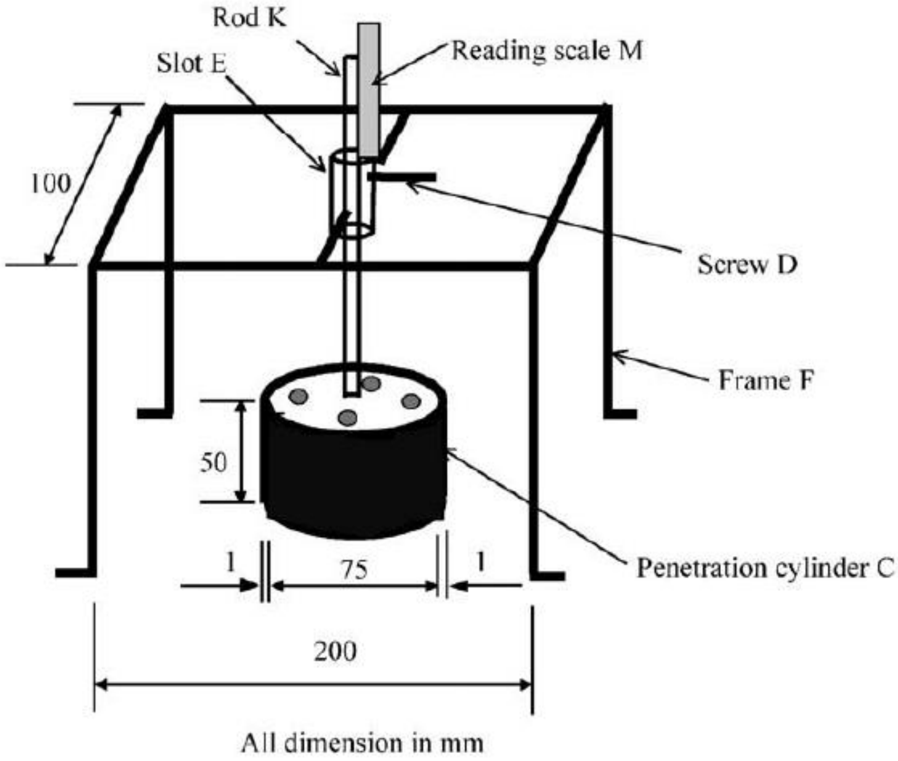

Figure 2-19 PA for segregation tests (Bui et al., 2002)

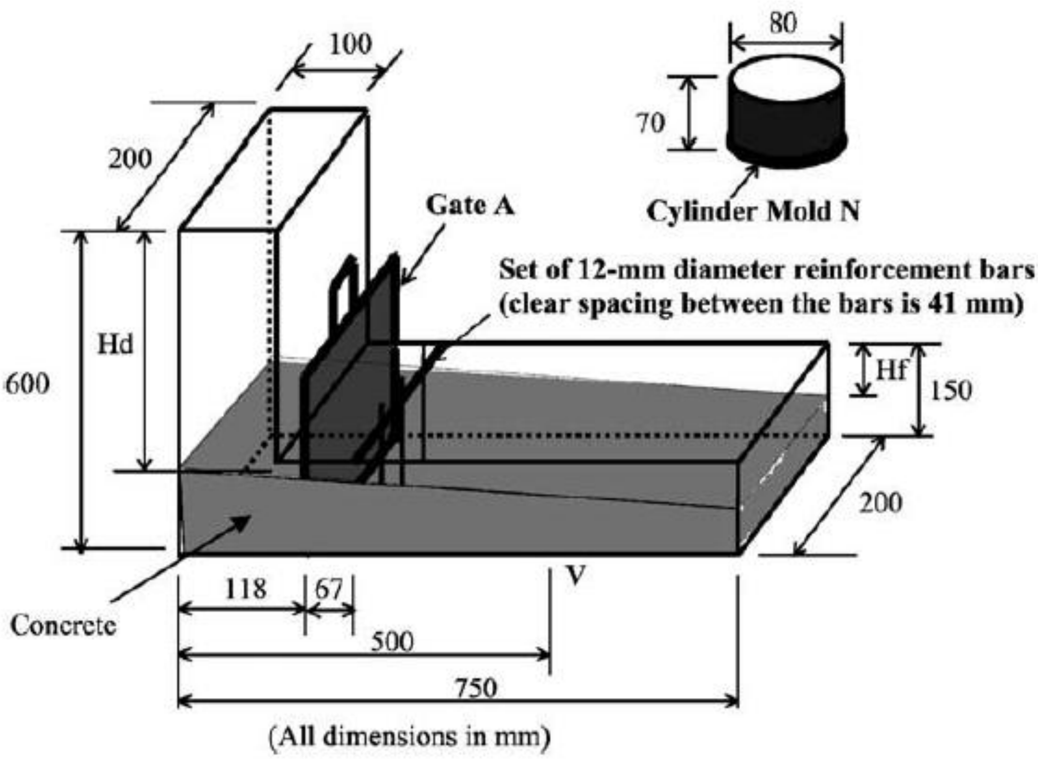

Figure 2-20 L-box apparatus and small cylinder mold N (Bui et al., 2002)

The testing procedure is carried out with the following steps:

(1) With gate A of the L-box closed, place concrete into the vertical leg of the L-box without any consolidation such as rodding or vibration. Level the top of the placed concrete immediately.

(2) After 2 min, locate the PA on the top of the vertical leg of the L-box, adjust the penetration cylinder to just touch the upper surface of concrete, then allow the cylinder to penetrate freely into the concrete. After 45 s, the Pd(penetration depth) of the cylinder head is recorded from the scale. The average Pd of three measurements at two sides and the center is calculated as the final Pd.

(3) Lift gate A in a vertical direction to allow the concrete to flow through the clear spacing between the reinforcement bars.

(4) When the concrete stops flowing, take fresh concrete from the region in front of the reinforcement set and fill it into a pair of small molds (Labled by the letter N). Similarly, take fresh concrete at the end of the horizontal leg of the L-box and again fill the concrete into the other pair of small molds (Labled by the letter N). Immediately, wash out the concrete from the small molds (Labled by the letter N), 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%.

(5) 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 test results obtained from the penetration device are verified with wet-sieving index, and the results from the horizontal direction are showed in Figures 2-21 to 2-24. According to these Figures, the specimens have a mass difference (Rh) of coarse aggregate less than 10% when the Pds is less than 9 mm. Conversely, the specimens with Pds larger than 9mm had a mass difference (Rh) of coarse aggregate larger than 10%. These findings were valid for different water – binder ratios, different paste volumes and different materials (namely, different types of cement, mineral admixtures and aggregates). So, segregation resistance of SCC can be assessed as follows:

- Concrete has satisfactory segregation resistance inhorizontal direction if Pd $\leq$ 9 mm,
- Concrete has poor segregation resistance in horizontal direction if Pd > 9 mm.

The test results showed that the proposed method and the developed apparatus are useful for the rapid evaluation of segregation resistance of concrete in both vertical and horizontal directions. The method can reduce testing time and laboratory work. However, no relationship could be found between the penetration depth (Pd) and the effect of mix proportions on dynamic segregation. In addition, the L-box device is not long enough to obtain enough information about dynamic segregation. Besides that, due to the L-box geometry, the segregation assessment cannot be considered as a pure segregation measurement as blocking occurred the same time.

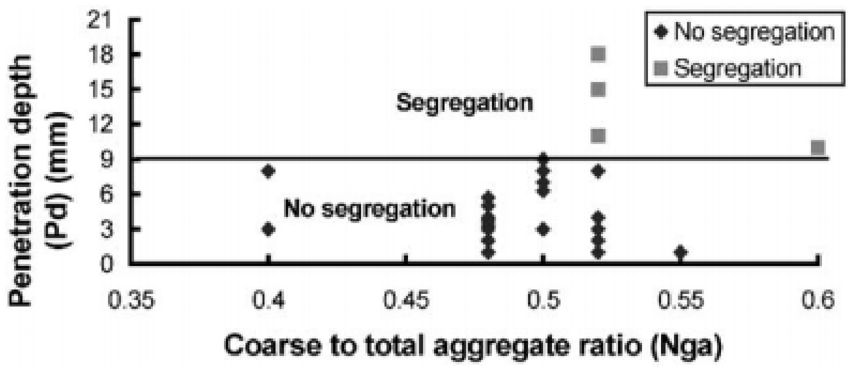

Figure 2-21 Pd with different coarse-total aggregate ratios and concrete segregation resistance in the horizontal direction (Bui et al., 2002)

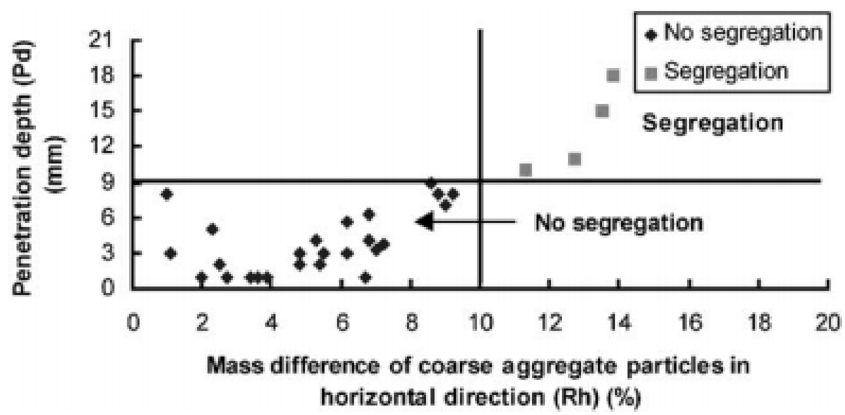

Figure 2-22 Pd and mass difference of coarse aggregate in the horizontal direction (Bui et al., 2002)

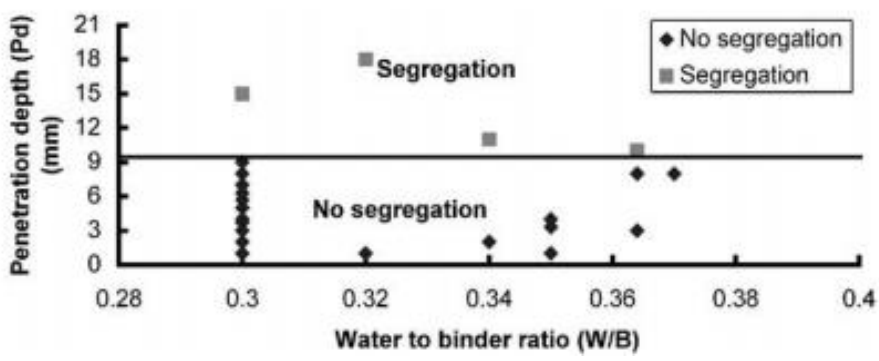

Figure 2-23Pd with different water-binder ratios and concrete segregation resistance in the horizontal direction ((Bui et al., 2002)

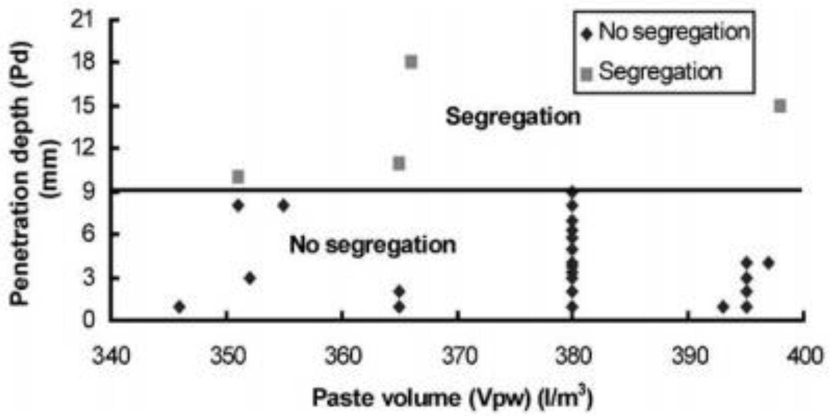

Figure 2-24 Pd with different paste volumes and concrete segregation resistance in the horizontal direction (Bui et al., 2002)

3) Hassan El-Chabib et al.)

This study proposed a similar penetration device to evaluate the segregation potential of a wide range of SCC mixtures. The apparatus used in the study consists of a modified penetration apparatus proposed by Bui et al (2002) and a PVC tube with a diameter of 150 mm (6 in.) and a height of 300 mm (12 in.). The tube is divided into three 150 mm ×100mm (6 in. × 12 in.) equal parts using leak-free joints that are hinged to a vertical steel rod for easy sliding [Figure 2-25(a)]. The modified version of the penetration apparatus consists of four penetration heads (instead of one) mounted on a steel frame. Each penetration head is approximately 25 g (≈1 oz) in mass and 20 mm (0.78 in.) in diameter with a semi-spherical end [Figure. 2-25(b)].

The average depth of the penetration heads is measured by allowing the heads to penetrate under their self-weight into concrete just after the cylinder is filled. The three parts of the cylinder are then separated after a rest period of approximately 30 minutes and concrete in each part is washed out over a 9.5 mm (3/8 in.) sieve. Coarse aggregates with particle sizes larger than 9.5

mm (3/8 in.) in each part of the cylinder are then retrieved and their masses are determined. The segregation index (SI) is taken as the coefficient of variation (COV) of the coarse aggregate content in all three parts and is calculated using the following equation

$$SI = \frac{1}{3}\sum_{i=1}^{3}\left|\frac{M_i - M_{avg}}{M_{avg}}\right| \times 100 \qquad \text{(Eqn.2-4)}$$

Where $M_{avg} = \frac{1}{3}\sum_{i=1}^{3} M_i$ and M_i equals the mass of coarse aggregate particles larger than 9.5 mm (3/8 in.) in each part of the cylinder. Results of SI are then correlated to the corresponding average penetration depth *Pd* of the penetration heads, which is a more rapid field-oriented test.

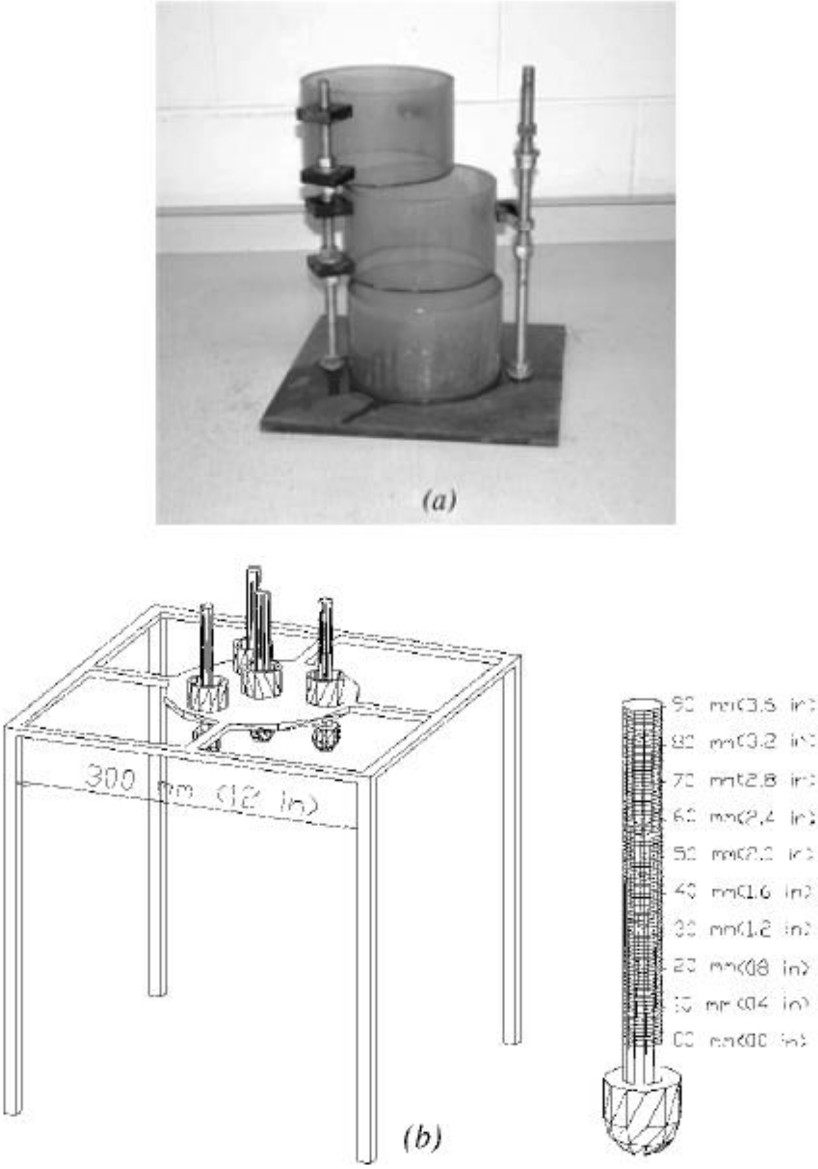

Figure 2-25 (a) Three-compartment hinged cylindrical mold; (b) modified penetration depth apparatus (El-Chabib and Nehdi, 2006)

A total of 123 SCC mixtures covering a large scope of mixture designs were made. Effects of various mixture design parameters on segregation resistance are reproduced from Hassan El-Chabib et al. study shown in Figure 2-26 to Figure 2-31.

Figure 2-26 shows that increasing the cementitious materials (w/cm=0.45) slightly increased the dynamic segregation in SCC mixtures which is unexpected. Results SI-Dynamic (Segregation Index) of Figure 2-27 show that increasing the cementitious materials slightly reduced dynamic segregation in SCC mixtures.

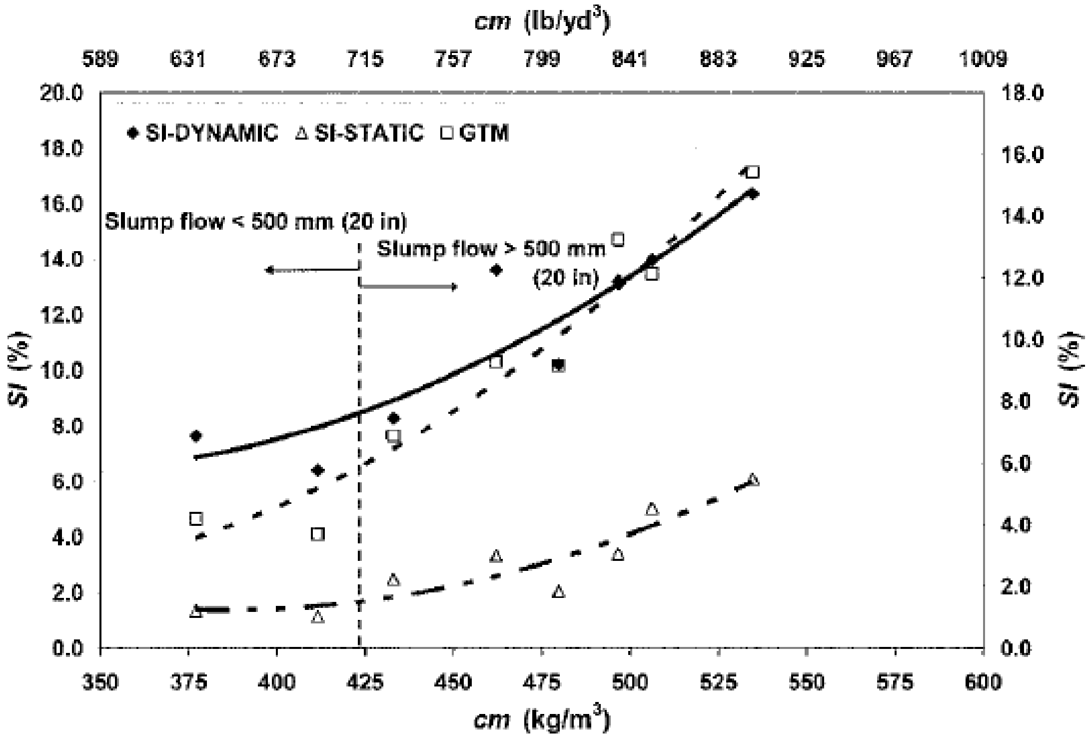

Figure 2-26 Effect of cementitious materials content on segregation resistance of SCC mixtures, w/cm=0.45 (El-Chabib and Nehdi, 2006)

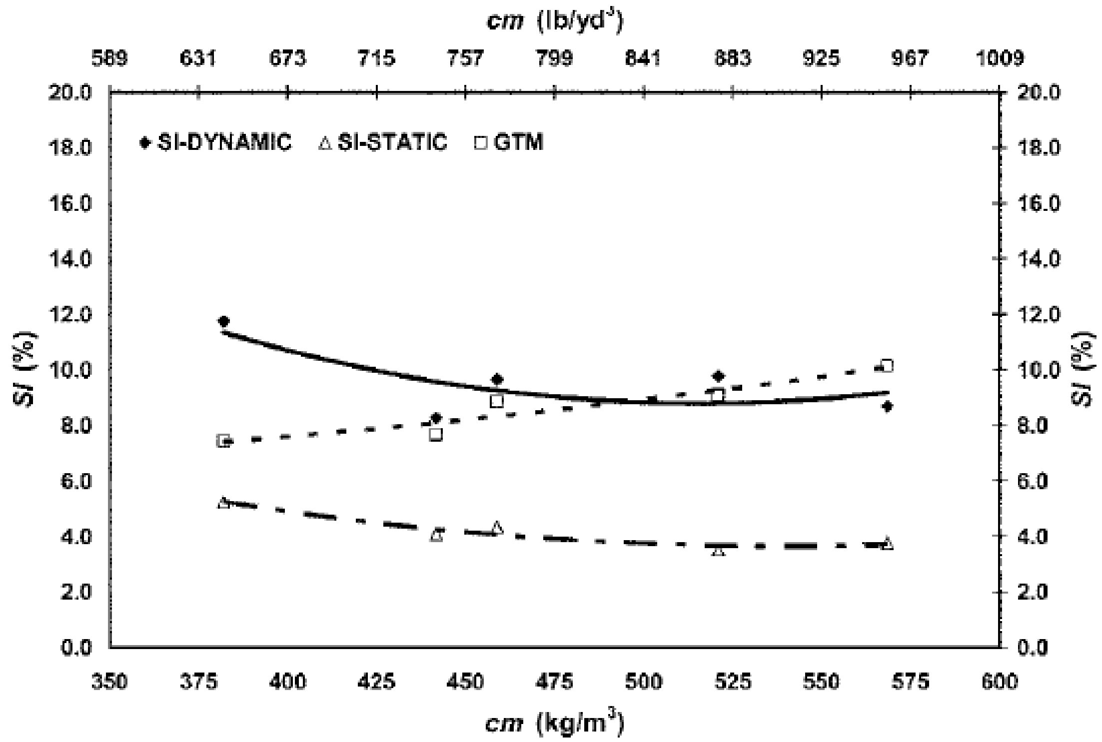

Figure 2-27 Effect of cementitious materials content on segregation resistance of SCC mixtures, w/cm=0.40 (El-Chabib and Nehdi, 2006)

Test results are shown in Figure 2-28 in which data from both methods show a similar trend for the effect of the *w/cm* on SI. Such an effect, however, was more pronounced in the case of SI-DYNAMIC for *w/cm* > 0.45. This is likely due to the effect of filling the concrete tubes using a free fall of SCC from a V-funnel, therefore increasing the possibility of coarse aggregate separation by subjecting the concrete to more severe placement conditions. Figure 2-28 also shows that for the particular dosages of HRWRA and VMA used, all test methods captured a significant increase in segregation for *w/cm* > 0.45, whereas for *w/cm* < 0.45, the rate of increase in segregation was less dramatic.

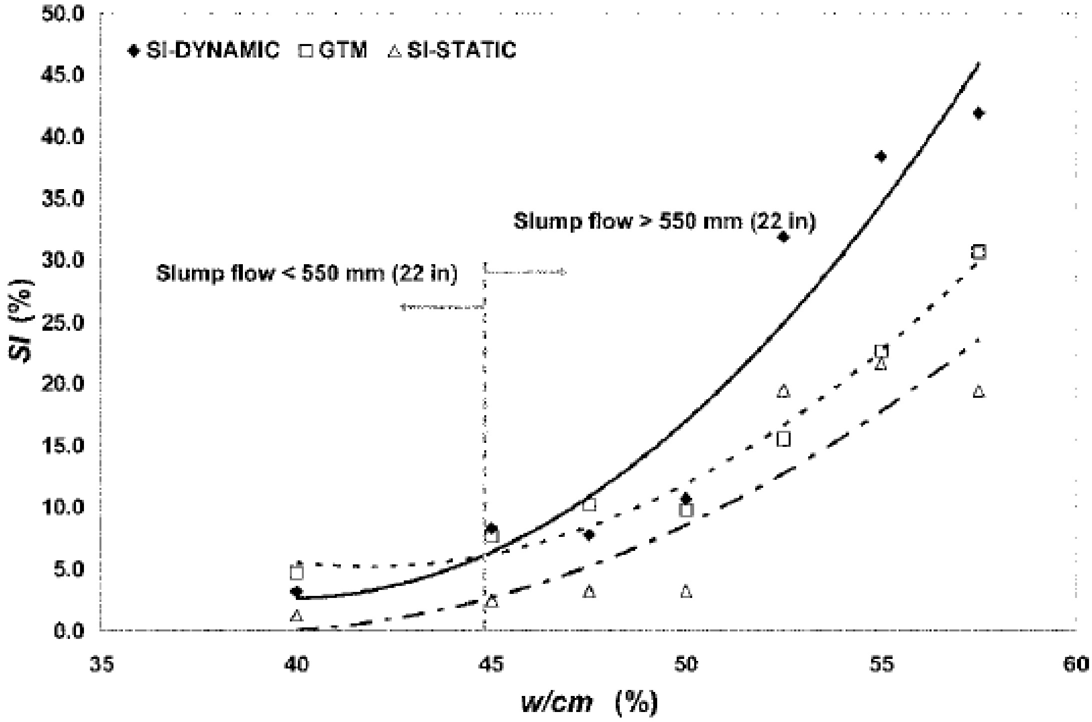

Figure 2-28 Effect of w/cm on segregation resistance of SCC (El-Chabib and Nehdi, 2006)

The effect of HRWRA and VMA dosages on the ability of SCC mixtures to resist segregation is shown in Figures 2-29 and 2-30, respectively. It is shown in Figure 2-29 that for constant *w/cm* and VMA content, the ability of SCC mixtures to resist segregation linearly decreased with increasing HRWRA dosage regardless of the test method used. Similar to the effect of the *w/cm*, higher HRWRA dosage tended to decrease the stability of SCC mixtures and this effect was more pronounced in the case of dynamic segregation. A reverse effect is exhibited by increasing the VMA dosage. Figure 2-30 shows that for constant *w/cm* and HRWRA dosage, higher VMA dosage increased the ability of SCC mixtures to resist segregation as expected. Such a trend is shown to be nonlinear (except for the GTM test) with a threshold VMA dosage beyond which the effect of VMA in decreasing segregation became significant for a constant dosage of HRWRA. Figures 2-29 and 2-30 also show that for SCC mixtures with low risk of segregation, the difference between SI values obtained using different test methods diminishes, showing that the test method proposed herein is reasonably sensitive to distinguish between static and dynamic segregation based on the placement conditions of SCC. In other words, measuring the SI of an SCC mixture having a moderate viscosity and low risk of segregation using either the static or dynamic condition should yield comparable values. It is important to note that the relationships shown in Figures 2-29 and 2-30 reflect the effect of admixtures used in this study, and that other types of admixtures might exhibit a different behavior.

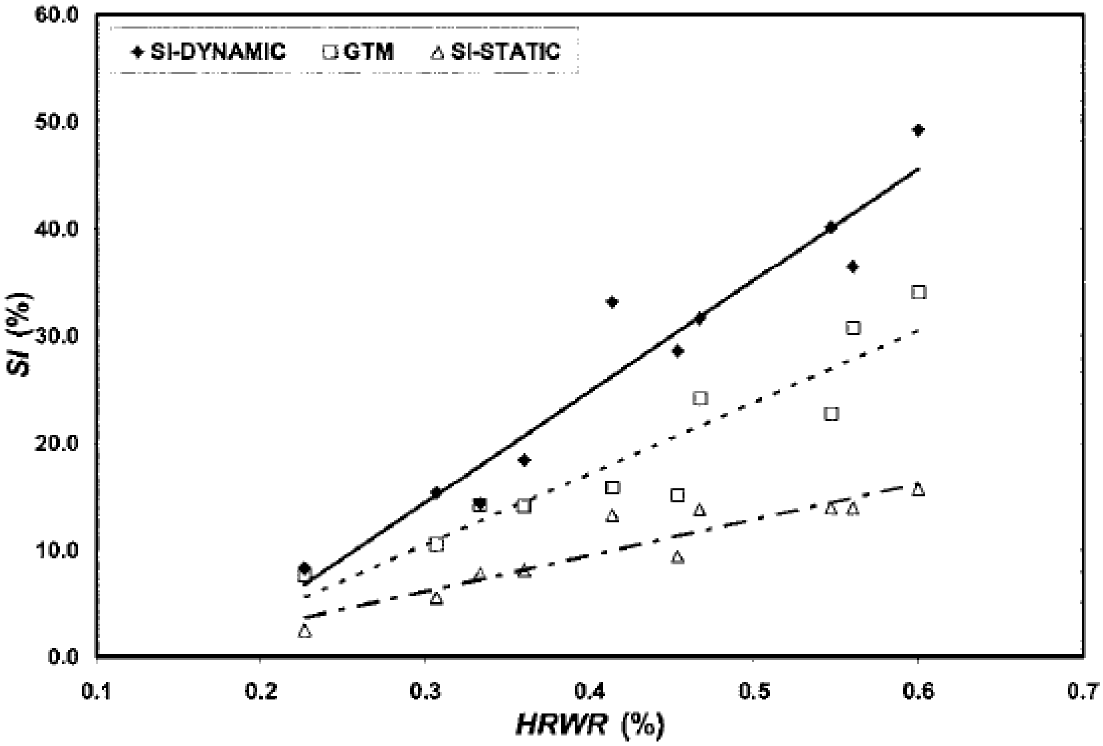

Figure 2-29Effect of HRWRA on segregation resistance of SCC mixtures (VMA= 0.01%, w/cm = 0.45) (El-Chabib and Nehdi, 2006)

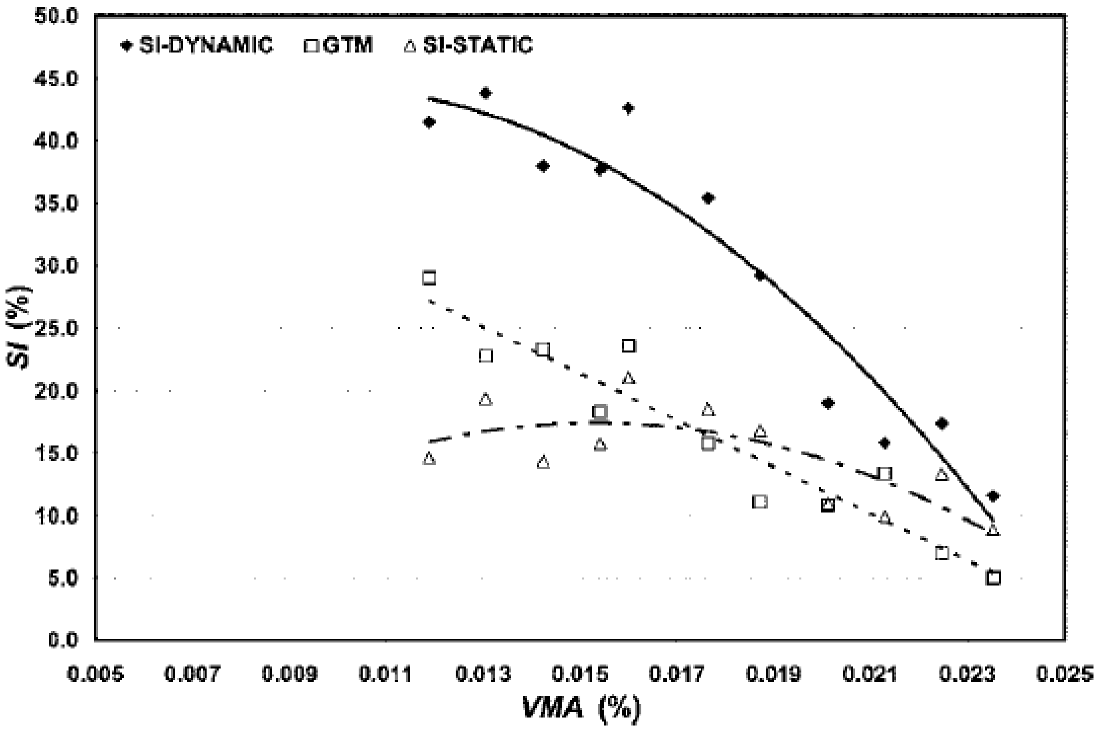

Figure 2-30 Effect of VMA on segregation resistance of SCC mixtures (VMA = 0.56%, w/cm = 0.45) (El-Chabib and Nehdi, 2006)

Results of coarse/total aggregate ratio on segregation resistance are shown in Figure 2-31, which indicates a slight to negligible increase in SI values obtained from all test methods over the range of aggregate ratio investigated. The figure also shows that the risk of dynamic segregation in SCC mixtures decreased when increasing the *CA*/*TA* ratio below a threshold value of approximately 0.45, and increased beyond that value. *CA*/*TA* ≈ 0.45 conforms to current recommendations regarding the coarse aggregate content in SCC mixture design.

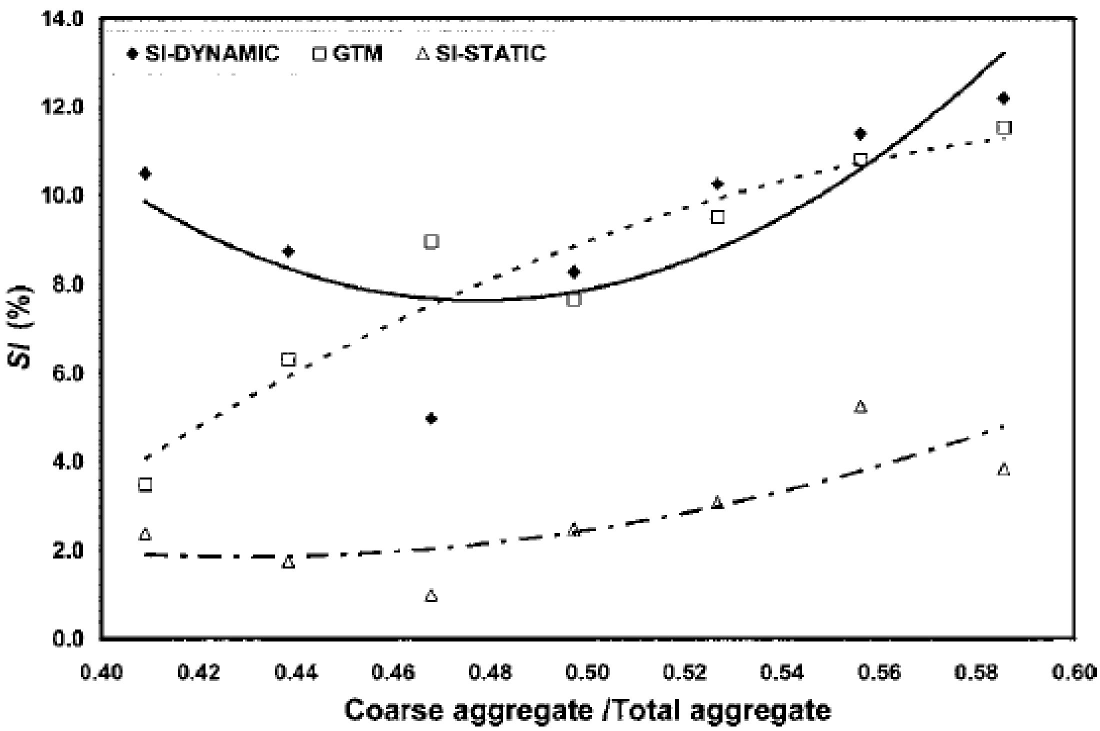

Figure 2-31Effect of coarse/total aggregate ratio on segregation resistance of SCC mixtures (constant volume of cementitious materials and w/cm = 0.45) (El-Chabib and Nehdi, 2006)

3 New Approach for Testing Dynamic Segregation

3.1 Dynamic Segregation

SCC should be able to flow through congested structural elements under its own weight, fill the formwork without segregation and with consolidate without any help of vibration. Therefore, adequate flow-ability, good passing abilities and good segregation resistance are essential properties of fresh SCC to ensure the quality of concrete placement, consolidation, and final product.

The fresh properties of SCC can have significant impacts on the placement, segregation, and mechanical and physical properties of the final product. An SCC mix that is not evaluated correctly for segregation resistance, filling and passing abilities before its use for structural members can lead to substantial economic losses. However, sometimes the results of misevaluation can be more significant than economic losses. Poor passing and filling properties might be recognized during casting, but poor segregation tendency may not be easily recognized, which can result in structures with poor and non-uniform mechanical properties. Therefore, it is important to select reliable but simple testing methods to evaluate SCC fresh state properties (Erkmen, 2008).

Adequate segregation resistance means a homogeneous distribution of coarse aggregate at each level through the structure height and along the length of the structure. Weight and flow are the two main reasons leading to segregation. Weight can cause an uneven vertical distribution of the coarse aggregate, typically with more coarse aggregate found near the bottom of the form work. In addition, the flow of fresh SCC can cause an uneven horizontal distribution of the coarse aggregate which is dynamic segregation. This can occur in both free and obstructed flow. The presence of reinforcing obstacles increases resistance to concrete flow and can cause coarse aggregate blockage and separation from the paste (i.e., uneven distribution of coarse aggregate). Segregation has also been observed due to transportation and placement of the fresh concrete (Assaad et al., 2004), likely due to the introduction of energy into the system.

The effects of proportioning and application variables on segregation resistance were shown in Table 2-2.

Currently, the only standard test for dynamic segregation of SCC is the visual stability index (VSI), which is determined by observation of the periphery of SCC during the slump flow test. While the VSI is just an approximation to estimate dynamic segregation of SCC, it is also limited to a very small flow length. Therefore, a more reliable and precise test is urgently needed to quantify dynamic segregation of SCC.

3.2 Design and Test Procedure

A laboratory test to assess dynamic segregation of SCC needs to satisfy the following four requirements:

1. The flowing distance of SCC needs to be long enough so that the test could detect meaningful differences in dynamic segregation.

   Generally the range of flow distance of SCC in the field is from 3 meters to 9 meters (10 feet to 30 feet), but in some cases it could reach 30 meters (100 feet). A test method with a short traveling distance may not reveal enough information for dynamic segregation of SCC.

2. The amount of sampled SCC should be small enough to handle during the test.
3. The testing apparatus should be portable and easy to set up so that the test could be used in typical field conditions.
4. The test results should be sufficiently precise and accurate.

3.2.1 Test Device

The purpose of the test is to evaluate the resistance of SCC to dynamic segregation occurring because of flowing over a long distance. In order to satisfy the above four requirements, a flow trough testing method was developed. Figure 3-1 shows the testing device. It was constructed by assembling 25mm(1”) thick wood planks to build a 1.80m×0.15m×0.15m (6’ ×6”×6”) trough. The 0.23m (9") height difference between the upper end and the lower end gives a 7º angle of inclination, which was the smallest slope that allowed the SCC to flow from one end to the other end. All the wood planks were painted so that the trough is nonabsorbent. The test was performed with the following instruments:

1. A 1.80m×0.15m×0.15m(6’ ×6”×6”) flow trough
2. Three cylinder molds—the size of one is 0.15m × 0.3m(6"×12") and that of the other two are 0.1m × 0.2m(4” × 8”)
3. A bucket with capacity of 10~12 liters(2.6~3.2gallons)
4. Two No. 4 U.S. sieves

Figure 3-3-1 Flow Trough

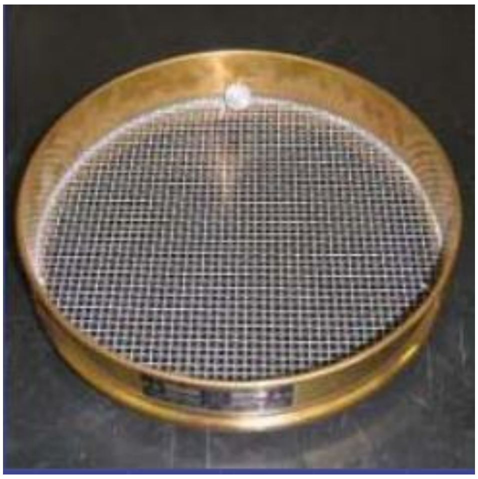

Figure 3-2 No.4 Sieve

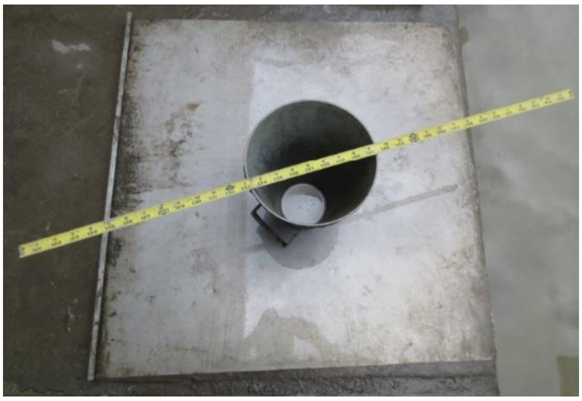

Figure 3-3 Slump flow test apparatus

Figure 3-4 4"×8" plastic cylinder

3.2.2 Test Procedure

The test was conducted with the following procedure:

1. Position the trough on flat ground, and fully dampen it.
2. Fresh SCC was measured using a single lift into one 0.1m×0.2m (4"×8") cylinder mold, one 0.15m × 0.3m(6"×12") cylinder mold, and a water-tight container having a volume of around 13.5 liters(around 3.6 gallon).
3. The concrete in the 0.15m × 0.3m(6"×12") mold was poured onto the upper end of the trough to prime the inner surface with paste.
4. When the concrete stopped flowing, the flow trough was straightened up vertically for 30 seconds to let the priming concrete flow off and leave a mortar layer on the trough surface.
5. The trough was then put back into the initial inclined position and the concrete in the 13.5-liter container was poured gradually and continuously on the trough from the higher end.
6. An empty 100-mm by 200-mm (4"×8") cylinder mold was filled with the preceding SCC flowing off the lower end of the flow trough.

7. Coarse aggregate contents were collected from two SCC samples, one is directly from mixer at the beginning the test, the other one is collected from the lower end of the flow trough at the end of the test, by washing SCC over a No.4 U.S. sieve.
8. Each coarse aggregate sample is weighed.
9. The dynamic segregation index (DSI) is then calculated with the equation below:

$$DSI = \frac{(CA1 - CA2)}{CA1} \qquad \text{(Eqn. 3-1)}$$

Where CA1 is the weight of coarse aggregate in the first mold, which is collected from the mixer, and CA2 is the weight of coarse aggregate in the second mold, collect from the lower end of the flow trough.

The purpose of the priming step is to eliminate variations in surface friction when different materials are used to construct the flow trough, and to better simulate the actual situation in the field, where SCC typically flows over previously poured concrete.

3.3 SCC Mix

3.3.1 Instruments and Materials

A Gilson Mixer Model No. 59015C was used to produce fresh SCC (see Figure 3-5), which spins at 22 revolutions per minute. Type I Portland Cement complying with ASTM C150/C150M-12 and Type C fly ash complying with ASTM C618-12a were used in this study.

The admixtures used for the mixes were Glenium 7500(super plasticizer, SP) and VMA 362, which were all produced by BASF (see Figure 3-6). The SP was a milky brown solution with a specific weight of 1.06 and a solid content of 26%. VMA used had a specific weight of 1.00 and a solid content of 35%.

Figure 3-5 Mixer

Figure 3-6 VMA and Super-plasticizer

The aggregates used for this thesis were originally from crushed basaltic rock which is native to the Island of Oahu. The basaltic rock is crushed into different sizes, therefore creating angular surfaces. Because the basaltic rock is very porous, both coarse and fine aggregates have high water demands. The physical properties of aggregates are shown in Table 3-1. Figure 3-7 presents the gradation curve of the aggregates used in this study.

The coarse and fine aggregates were prepared before one day of the mix. The moisture content (MC) of both types of aggregates were measured by drying their sample overnight untill the oven dry condition along with put sample submerge in the water overnight, and then calculated moisture content with the following three equations:

$$\text{Total Moisture(TM)} = \frac{W_{stock} - W_{OD}}{W_{OD}} \times 100\% \qquad \text{(Eqn. 3-2)}$$

$$\text{Absorption (A)} = \frac{W_{SSD} - W_{OD}}{W_{OD}} \times 100\% \qquad \text{(Eqn.3-3)}$$

$$\text{Moisture Content (MC)} = \frac{W_{stock} - W_{SSD}}{W_{SSD}} \times 100\% \qquad \text{(Eqn. 3-4)}$$

Where

W_{stock} = the weight of the aggregate in stockpile condition

W_{OD} = the weight of the aggregate in oven dry condition

W_{SSD} = the weight of the aggregate in saturated-surface-dry condition

Table 3-3-1 Aggregates Properties

	Maximum size(mm)	Bulk specific density	Bulk density(kg/m^3)	Packing density	Fineness Modulus
CA1	19.0	2.56	1473	0.55	-
CA2	9.5	2.67	1491	0.54	-
FA1	-	2.51	1677	0.63	3.50
FA2	-	2.71	1460	0.54	1.55

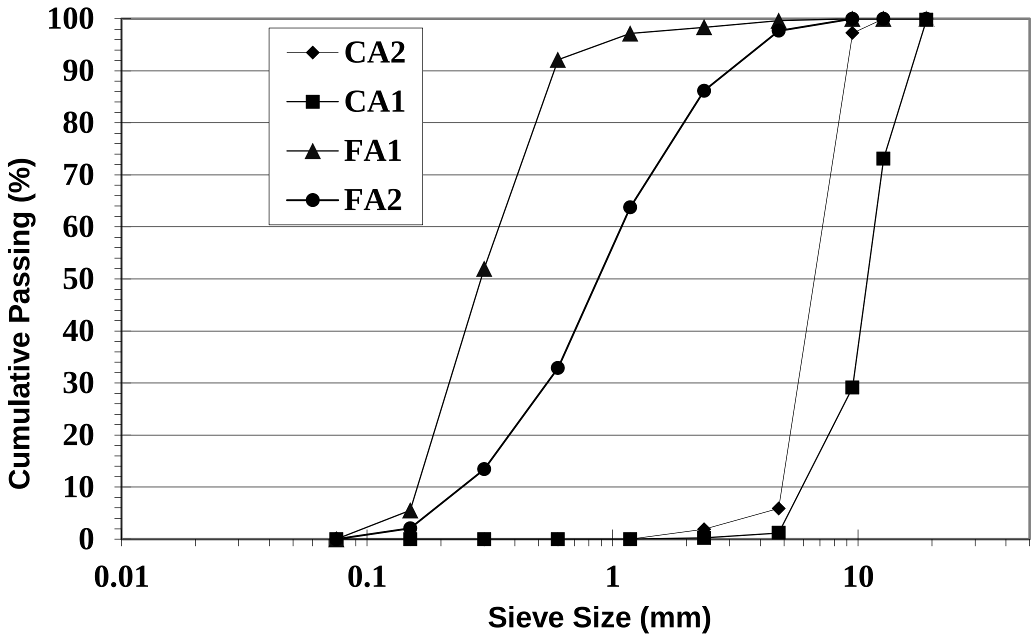

Figure 3-7 Gradation curves of coarse and fine aggregates

3.3.2 Mix Proportions

As shown in Table 3-2, a total of twenty-nine mixtures were tested to study the effects on dynamic segregation of paste volume, aggregate size and gradation, slump flow, and super plasticizer.

Four basic types of mixtures were designed: Graded Aggregate (GA), Mineral Admixture (MA), VMA, and Well Balanced (WB). Graded Aggregate mixtures had three types of aggregate, relatively high packing density, and a FA/CA ratio of 1. Mineral Admixture mixtures used fly ash to increase paste volume, had two types of aggregates and a FA/CA ratio of 1. VMA mixtures used VMA to improve the viscosity, had two types of aggregate, and a FA/CA ratio of 0.87. Well Balanced mixtures combined the benefits of VMA and Graded Aggregate mixtures. Within each basic mixture type, the volume, gradation, packing density, maximum size of aggregate, as well as slump flow also is modified to explore the effects of these properties on dynamic segregation.

Labels +5% P, -5% P, LS, HP, and SA indicate that compared with the basic mixture, a modified mixture has 5% more paste volume, 5% less paste volume, lower slump flow, higher aggregate packing density, and smaller coarse aggregate, respectively. For example, GA +5%P mixture has 5% higher paste volume than the basic GA mixture, and VMA-HP mixture has higher aggregate packing density than the basic VMA mixture.

Table 3-2 Proportions of SCC Mixtures

Mix	Mix Type	Mix ID	w/cm	Material kg/m3							Aggregate Properties				Admixture ml/m3		Slump
				Cement (Type I)	Fly Ash (C)	CA1	CA2	FA1	FA2	Water	%AGG	FA/CA	CA1%	Φm	SP	VMA	mm
1		GA	0.35	450	107	198	579	756		195	59	1.00	0.13	0.67	9707	0	710
2		GA-LS	0.35	450	107	198	579	756		195	59	1.00	0.13	0.67	3269	0	610
3		GA-HS	0.35	450	107	198	579	756		195	59	1.00	0.13	0.67	10576	0	762
4	Graded	GA + 5 %P	0.35	506	120	181	530	692		219	54	1.00	0.13	0.67	7908	0	710
5	Aggregate	GA -5 %P	0.35	394	94	214	629	821		171	64	1.00	0.13	0.67	11696	0	710
6		GA-A	0.38	405	96	193	989	557		190	64	0.47	0.11	0.70	8974	0	660
7		GA-A	0.38	486	93	178	688	739		219	59	0.85	0.11	0.68	3481	0	686
8		GA-A	0.46	372	88	208	650	844		213	63	1.00	0.12	0.73	5175	0	710
9		MF	0.31	442	239	693		678		211	53	1.01	0.50	0.65	9299	0	710
10		MF-LS	0.31	442	239	693		678		211	53	1.01	0.50	0.65	5000	0	635
11		MF-HS	0.31	442	239	693	0	678		211	53	1.01	0.50	0.65	10692	0	762
12	Mineral	MF +5 %P	0.31	487	263	627		621		233	48	1.01	0.50	0.65	8804	0	710
13	Filler	MF -5 %P	0.31	398	215	749		743	0	190	58	1.01	0.50	0.65	10501	0	710
14		MF-A	0.39	393	212	168	647	683		234	56	0.85	0.11	0.71	9018	0	737
15		MF-A	0.39	393	212	168	647	683		234	56	0.85	0.11	0.71	5881	1567	737
16		MF-A	0.39	358	194	196	612	794		213	60	1	0.12	0.73	7906	0	710
17		VMA	0.41	515		854		729		209	62	0.87	0.53	0.66	3051	1371	710
18		VMA-LS1	0.41	515		854		729		209	62	0.87	0.53	0.66	2370	1371	585
19		VMA-LS2	0.41	515		854	0	729		209	62	0.87	0.53	0.66	2716	1371	635
20		VMA-HS	0.41	515		854		729		209	62	0.87	0.53	0.66	4807	1371	762
21	VMA	VMA +5 %P	0.41	582		783		670		236	57	0.87	0.53	0.66	2823	809	710
22		VMA -5 %P	0.41	447		923		789		181	67	0.87	0.53	0.66	3497	881	660
23		HP	0.41	585	0	468	593	585		238	59	0.56	0.28	0.71	8044	1360	660
24		VMA-A	0.51	467		469	593	586		238	61	0.56	0.28	0.71	4651	1683	686
25		VMA-A	0.51	457		186	718	759		234	62	0.85	0.11	0.71	5813	4809	686
26		WB-SA	0.42	474		0	712	188	748	199	63	1.34	0.00	0.66	4090	1424	660
27	Well Balanced	WB1	0.42	502		533	115	222	743	211	61	1.53	0.33	0.74	3383	1131	660
28		WB2*	0.42	502		509*	136	445	522	211	61	1.53	0.31	0.71	5007	1131	660
29		WB3*	0.36	502		534*	142	467	547	181	64	1.53	0.31	0.71	6495	646	660

3.3.3 SCC Mix Procedure

On the day of the mix, 3.5 cubic feet of SCC were made for the batch of each mix. The batch of each mix was conducted as follows.

1. Damp the entire internal surface of mixer.
2. Add coarse aggregate and one quarter of the total volume of water, and turn on mixer for about 1minute.
3. Add fine aggregate and cement, mixing for 1 minute.
4. Add the remaining water and continue mixing for 3 minutes.
5. Turn the mixer off and let the concrete still for 3 minutes.
6. Start the mixer and add the designed amount of high range water reducer (HRWR) - Super-plasticizer, mixing for about 1.5 minutes.
7. Add the designed amount of VMA (viscosity-modifying admixture) if necessary, mixing for half minute.
8. Stop the mixer and perform the slump flow test. If the slump flow is greater than 26 inches then perform the flow trough test and record the visual stability index (VSI).
9. If the slump flow is less than 26 inches, then add to proper amount of Super-plasticizer until the slump flow is greater than 26 inches and repeat step 8.

3.3.4 Visual Stability Index (VSI) (ASTM C-1611)

VSI rates the segregation of SCC visually on a scale from 0 to 3 with increment of 0.5, with 0 rating represents no segregation and 3 indicating severe segregation.

VSI = 0 indicates that concrete mass is homogenous and no evidence of bleeding.

VSI = 1 shows slight bleeding, observed as a sheen on the surface of SCC.

VSI = 2 refers to the evidence of a mortar halo and water sheen.

VSI = 3 shows concrete of coarse aggregate at the center of concrete mass and presence of a mortar halo.

Figure 3-8 VSI =0(left) and VSI =1 (right)

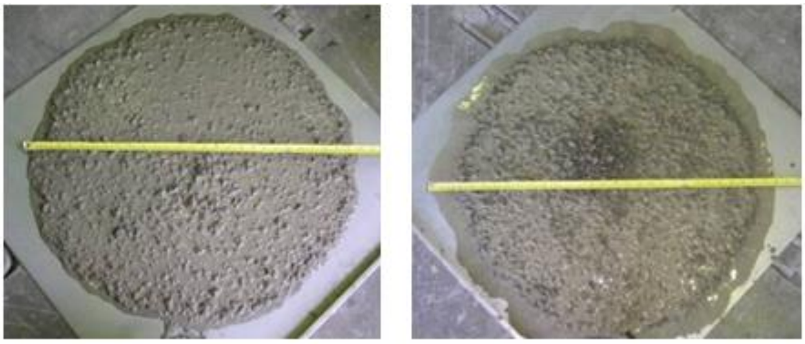

Figure 3-9 VSI =2 (left) and VSI =3 (right)

A VSI value larger than 2.0 indicates evidence of segregation and/or excessive bleeding and is not acceptable for typical SCC applications.

3.4 Flow Trough Test

Based on the designed flow trough test procedure in 3.2.2, 29 flow trough tests on 29 SCC mixes were performed to assess the sensitivity of the test.

Finally, 58 mass values of coarse aggregate were recorded, and 29 dynamic segregation index values were computed with the following equation:

$$DSI = \frac{(CA1-CA2)}{CA1}$$

Where

CA1 is weight of coarse aggregate from the sample of original SCC.

CA2 is weight of coarse aggregate from the sample collected at the bottom of the flow trough.

Figure 3-10 to 3-15 show the main components of the flow trough test.

Figure 3-10 Slump flow test

Figure 3-11 Prime the flow trough

Figure 3-12 SCC flowing on the flow trough

Figure 3-13 4"×8" Sample from flow trough

Figure 3-14 Wash Aggregate in No.4 sieve

Figure 3-15 Aggregate in No.4 Sieve

3.5 Test result

In total, twenty-nine SCC mixes were developed and batched using locally available aggregates. All of them were batched in small quantities and evaluated at the University of Hawai'i at Manoa Structures Laboratory.

The test results for this study are presented in Table 3-3. The results include Dynamic Segregation Index (DSI) from the flow trough test, slump flow, and Visual Stability Index (VSI) from the slump flow test. A wide range of workability characteristics, namely slump flow (585 to 762mm) and DSI (2% to

31%), was covered by this study. Such variations were achieved by altering super-plasticizer dosages, finely powder materials, and water-to-cement ratio.

Table 3-3 Test results of Mixes1 through Mix29

Mix	Mix Type	Mix ID	w/cm	Slump (mm)	VSI	DSI(%)
1	Graded Aggregate	GA	0.35	710	1	5
2		GA-LS	0.35	610	0	15
3		GA-HS	0.35	762	2	22
4		GA+5%P	0.35	710	1	11
5		GA-5%P	0.35	710	1	14
6		GA-A	0.38	660	3	10
7		GA-A	0.38	686	1	8
8		GA-A	0.46	710	0	7
9	Mineral Filler	MF	0.31	710	0	3
10		MF-LS	0.31	635	0	3
11		MF-HS	0.31	762	3	10
12		MF+5%P	0.31	710	0	4
13		MF-5%P	0.31	710	2	21
14		MF-A	0.39	737	3	21
15		MF-A	0.39	737	1	7
16		MF-A	0.39	710	2	26
17	VMA	VMA	0.41	710	1	15
18		VMA-LS1	0.41	585	0	NA
19		VMA-LS2	0.41	635	0	6
20		VMA-HS	0.41	762	1	12
21		VMA+5%P	0.41	710	1	13
22		VMA-5%P	0.41	660	1	2
23		HP	0.41	660	1	12
24		VMA-A	0.51	686	1	10
25		VMA-A	0.51	686	1	16
26	Well Balanced	WB-SA	0.42	660	0	6
27		WB1	0.42	660	2	31
28		WB2	0.42	660	1	23
29		WB3	0.36	660	2	22

Note: Blue cells show VSI=0; Yellow cells show VSI=1;
Green cells show VSI=2; Purple cells show VSI =3.

3.6 Analysis

3.6.1 Comparison of DSI and VSI

The flow trough DSI values were compared with the VSI values from the current standard test for dynamic segregation, see Figure 3-16.

According to Figure 3-16, for the stable situation of VSI=0, all flow trough DSI values were less than 7% (non-segregated), both values of VSI and DSI agreed reasonably well. For the less stable situation of VSI rating of 1, most DSI values fell in the reasonable range of 2% to 15%, only two DSI values 16% and 23% represented segregation .The DSI rating-23 means that 23 percent of the coarse aggregates were lost in the flowing distance of 1.8 m (6 feet). The loss of coarse aggregates could be worse in the field where concrete might easily flow 6 meters to 9 meters (20 to 30 feet). These results indicate that the flow trough is more sensitive to segregation than the slump flow method for SCC.
For the unstable situation of VSI rating of 2, all flow trough DSI values were more than 20% which indicated dynamic segregation. Both values of VSI and DSI agreed reasonably well.

In cases of severe segregation (VSI=3) there are variations in DSI value. This error may due to improper uniform sampling. With severe segregation, coarse aggregates immediately settled to the bottom of the mixer and cylinders. As a result, when the concrete in the mixer is poured into cylinders, and the concrete in the cylinder is poured on the trough, mortar is poured first and fills the cylinders. This event makes almost uniform sampling nearly impossible. Therefore, to avoid misleading results of DSI in severe segregation, there is no need to perform flow trough. Visual inspection of slump flow test is sufficient in this case.

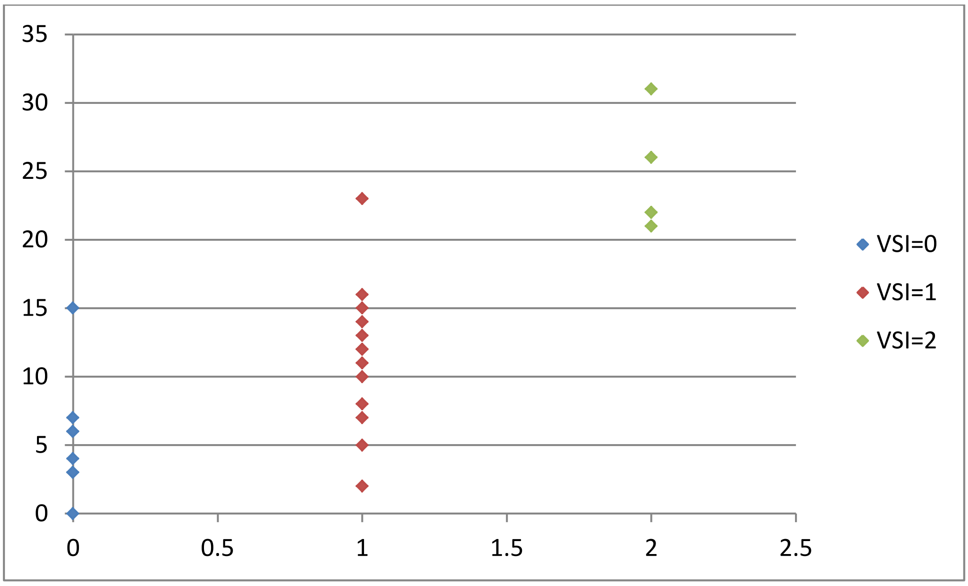

Figure 3-16 VSI versus DSI

3.6.2 Relationship between Slump Flow and Dynamic Segregation

Slump flow reflects the ability of SCC to flow under its own weight. The measurement of slump flow reflects the yield stress and viscosity of the SCC. Higher yield stress and viscosity corresponds to increased resistance to flow. The VSI value provides a fast but approximate indication of the stability of the mixture; however, an acceptable VSI does not ensure adequate stability. Therefore, the relationship between slump flow and DSI needs to be assessed.

Figure 3-17 shows how the slump flow affects dynamic segregation of GA, MA, and VMA series of mixtures. Super-plasticizer content was adjusted to keep the three mixtures slump flow of 610mm or 635mm, 710mm, and 762 mm while other mix proportions were virtually identical.

For GA series, the DSI values of mixtures with slump flow of 610mm, 710mm, and 762mm were 15%, 5%, and 22%, respectively. For the MA series, the

DSI values of mixtures with slump flow of 635mm, 710mm, and 762mm were 3%, 3%, and 10%, respectively. And for the VMA series, the DSI values of mixtures were 6%, 15%, and 12%, respectively. According to the three series mixtures, the mixture with lowest slump (610mm or 635mm) always showed less dynamic segregation than the mixture with highest slump (762mm), which indicates reducing slump flow could reduce dynamic segregation. Even though the 9 data do not offer sufficient information, it can be considered as part of the dynamic segregation evaluation.

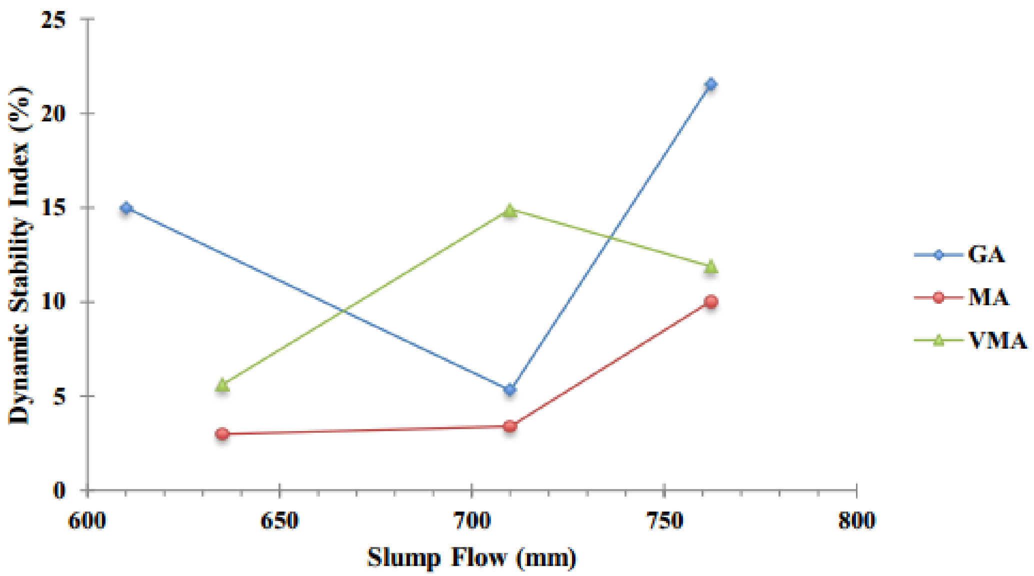

Figure 3-17 Effects of slump flow on dynamic segregation

3.6.3 Effect of Paste Volume on Dynamic Segregation

DSI values of the GA series mixtures and the MA series mixtures were presented in Figure 3-18. Compared with the "GA" mixtures, "GA+5%P" mixture had 5% more paste volume, and "GA-5%P" mixture had 5% less paste volume. Similarly, "MA+5%P" mixture had 5% more paste volume and "MA-5%P" mixture had 5% less paste volume compared with the "MA" mixture. Other mix proportions were virtually identical within the same series of mixtures. The super-plasticizer content was adjusted to maintain a slump flow of 710mm for all six mixtures.

The DSI values of GA, GA+5%P, and GA-5%P mixtures were 5%, 11%, and 14%, respectively. The DSI values for MA, MA+5% P and MA-5% P were 3%, 4%, and 21%. Based on Figure 3-18, it can be concluded that reducing paste volume may increase dynamic segregation, as the highest DSI occurred in the mixture with the least paste volume for each series (GA-5%P and MA-5%P mixture).

To further understand how SP dosage affects dynamic segregation, it may be helpful to examine the drag force acting on the aggregate by the paste during the flowing process of an SCC mixture (Shen et al 2009). The drag force acting by the paste on the aggregate, F_A, can be expressed as

$$F_A = ABC(9\eta_{pl}\Delta V\left(\frac{\phi_1}{r_1^2}+\frac{\phi_2}{r_2^2}+\frac{\phi_3}{r_3^2}\right)+\pi^2\tau_0\frac{21}{4}\left(\frac{\phi_1}{r_1}+\frac{\phi_2}{r_2}+\frac{\phi_3}{r_3}\right)) \quad \text{(Eqn. 3-5)}$$

Where a, b, and c are dimensions (height, width, and length) of the concrete sample, ϕ_1, ϕ_2, ϕ_3 are volume fractions of different types of aggregates, η_{pl} is paste plastic viscosity, r_1, r_2, r_3 are the radii of the aggregates, ΔV is velocity difference between aggregate and paste, calculated from the initial conditions and forces, and τ_0 is paste yield stress.

According to Eqn. 3-5, higher paste plastic viscosity and yield stress correspond to higher drag force by the paste to carry the aggregate forward, and thus reduce the chance and extent of dynamic segregation. Because the slump flow was kept constant for the mixtures under comparison, mixtures with higher paste content (lower aggregate volume) had less inter-particle friction and required less SP to achieve the same slump flow. Less SP % by weight of cementitious materials increases paste yield stress and viscosity, raises the drag force, and thus reduces dynamic segregation.

From Eqn. 3-5, it seems that a mixture with higher aggregate volume (ϕ_1, ϕ_2, ϕ_3) should have higher drag force and thus less dynamic segregation. However, it should be noted that higher aggregate volume also corresponds to higher aggregate mass and the acceleration due to drag force, F_A/mass, will not change significantly because of higher aggregate volume and mass. As will be discussed in the section of SP dosage on dynamic segregation, this relationship between SP dosage and dynamic segregation is not obvious when different series of mixtures with various average aggregate sizes and gradations are compared, which could also be expected from Eqn.3-5.

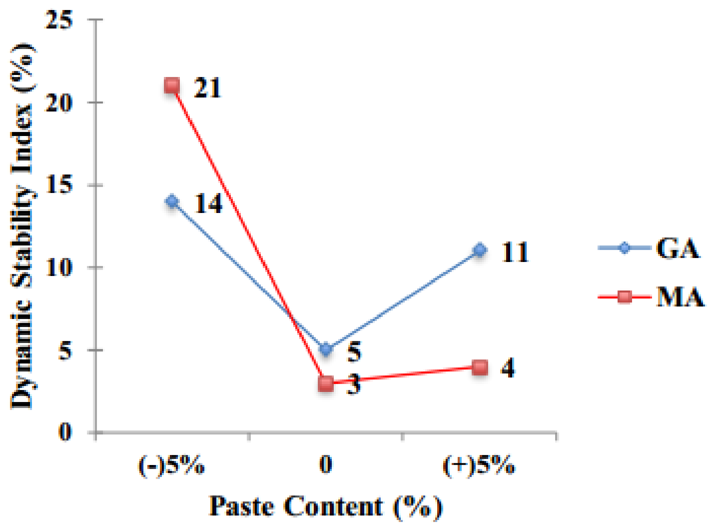

Figure 3-18 Paste volume versus DSI

3.6.4 Effect of Super plasticizer on Dynamic Segregation

Super plasticizer is indispensable for producing SCC, and it can significantly affect the cost of SCC. Therefore, it is essential to investigate the relationship between super plasticizer dosage and dynamic resistance.

The effect of super plasticizer on dynamic segregation is presented in Figures 3-19 to 3-21. Three groups of SCC mixtures were prepared with all parameters kept constant except super plasticizer dosages. The first group was graded aggregate type of SCC mixture which included mix 1 to mix 3; the second group was a mineral filler type of SCC mixture which included mix 9 to mix 11; the last one was a VMA type of SCC mixture which included mix 17 to mix 20. The three figures show that increasing super plasticizer dosage increases dynamic segregation.

The main purpose of super plasticizer is to impart a high degree of flow-ability; however, the higher dosage generally associated with SCC could result in a high degree of dynamic segregation. Higher dosage means less paste yield stress and viscosity, therefore smaller drag forces are available for the paste to carry the coarse aggregate forward leading to higher dynamic segregation.

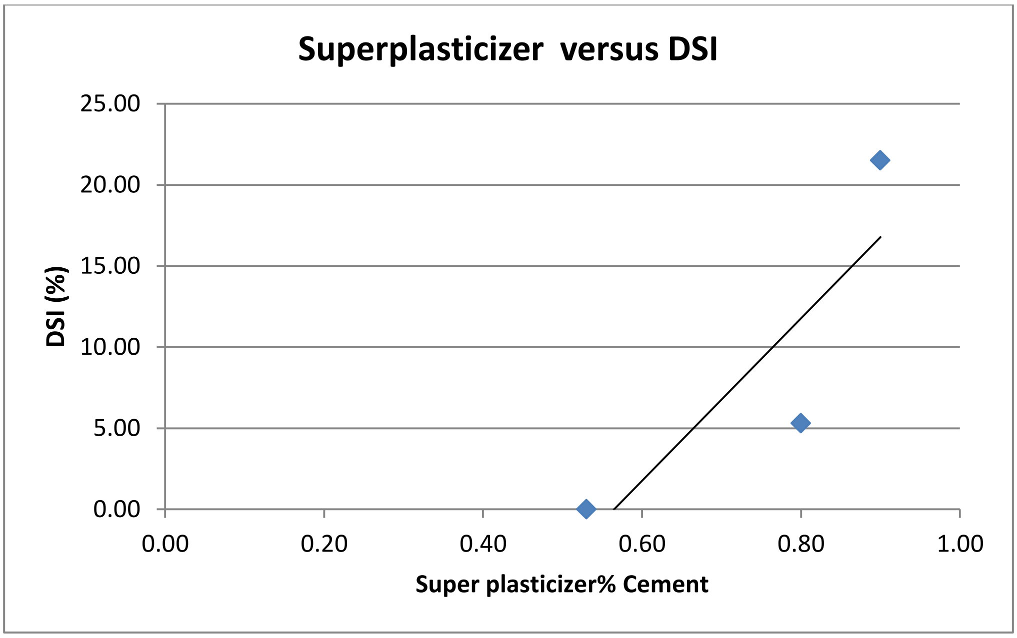

Figure 3-19 Super plasticizer versus DSI (Graded Aggregate type)

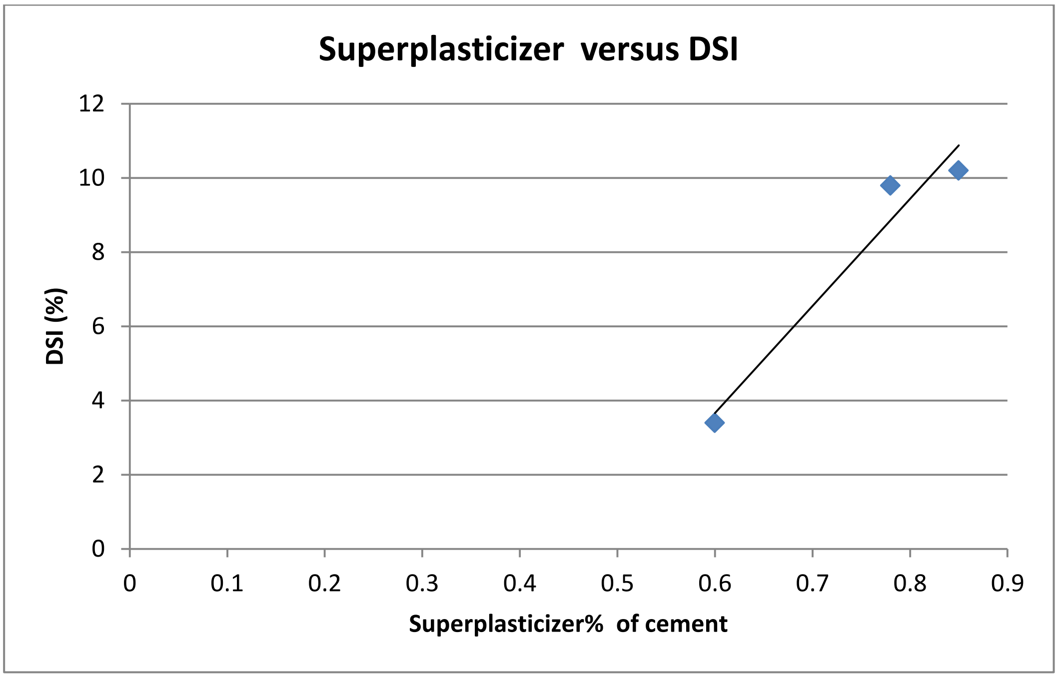

Figure 3-20 Super plasticizer versus DSI (Mineral Filler type)

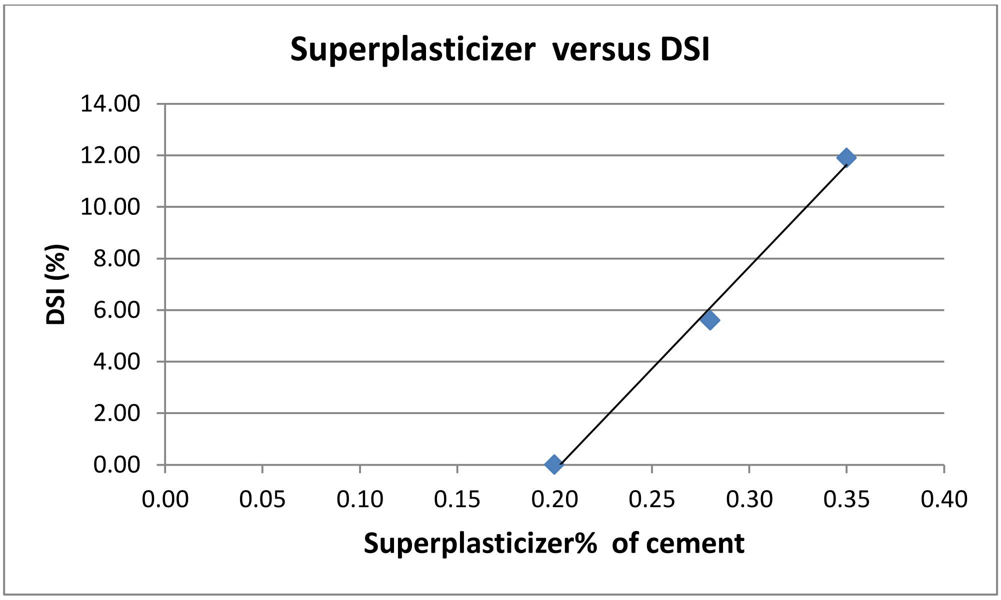

Figure 3-21 Super plasticizer versus DSI (VMA type)

3.6.5 Aggregate size and gradation

The effects of aggregate size and gradation on dynamic segregation are presented in Figure 3-22. Mixes 26, 27, and 28 were prepared with different coarse aggregate sizes and gradations but their mix proportions were kept the same. They represent

WB-SA, WB1 and WB2 mixtures. The WB-SA mixture only had medium size coarse aggregate (with maximum size 9.5mm), while WB1 and WB2 mixtures had both large (with maximum size of 19mm) and medium size coarse aggregate. The DSI values of the three mixtures were 6%, 31%, and 23%. It can be concluded that reducing the aggregate size had a more significant effect on improving dynamic segregation resistance compared with better gradation.

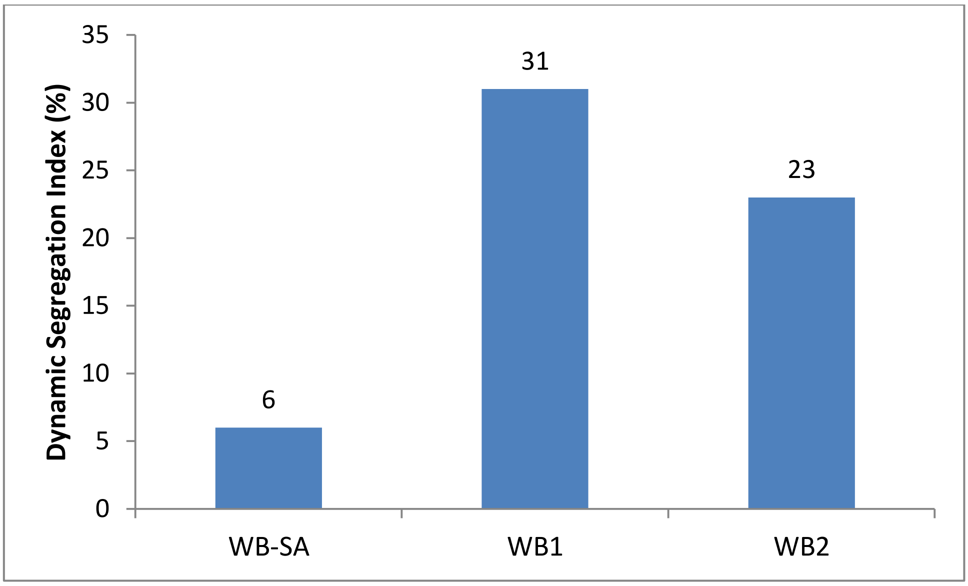

Figure 3-22 Effects of aggregate size and gradation on dynamic segregation

3.6.6 Further discussion

A practical way to prevent dynamic segregation is to set a maximum traveling distance for a given SCC mixture. This can be done by simplifying the results of dynamic segregation analysis and performing the flow trough test. From both the analysis and experimental work, it was noticed that although the DSI values varied from mix to mix, the shape of the travel distance-DSI curves did not change dramatically (Shen et al 2009 B). In other words, for a certain travel distance, the ratio of the DSI at that distance to the DSI at 1.8 m (6 feet) does not change substantially from mix to mix. Based on this observation, the maximum traveling distance can be set based on requirements such as maximum cement factor.

Assuming SCC has "a" kg/m^3 cementitious material, w/cm ratio of "b", air void of "c"%, and the bulk density of cementitious material is "d" g/cc, for the cement content to be lower than "e" kg/m3, the maximum allowable DSI can be calculated as:

$$DSI_{max} = 1 - \frac{1000 - 10c - b \times e - \frac{e}{d}}{1000 - 10c - a \times b - \frac{a}{d}} \qquad (Eqn. 3-6)$$

If the DSI value is larger than DSI$_{max}$, the cement factor will be larger than e.

The procedure to set the maximum traveling distance is shown as follows. Firstly, the flow trough test is performed and the DSI at 1.8m (DSI$_{1.8}$) is obtained. Secondly, the DSI$_{max}$ is calculated using Eqn. 3-6 and mix proportions. Thirdly, the ratio of DSI$_{max}$/ DSI$_{1.8}$ is calculated. Finally, the maximum traveling distance is found by using DSI$_{max}$/ DSI$_{1.8}$ and Figure 3-23.

For example, Hawaii Department of Transportation requires that the maximum cement factor does not exceed 7.05 cwt/ yd^3 (418 kg/m^3) so e is 418 kg/m^3. Assuming concrete has 360 kg/m^3 cement (a=360), 0.38 w/c ratio (b=0.38), air void 7% (c=7), and bulk density of cement material is 3.15 g/cc (d=3.15), the DSI$_{max}$ is calculated as 0.06. If the DSI$_{1.8}$ from flow trough test is 0.04, the value of DSImax/ DSI$_{1.8}$ is 1.5. By using Figure 3-23, the maximum traveling distance is found to be around 3 meters.

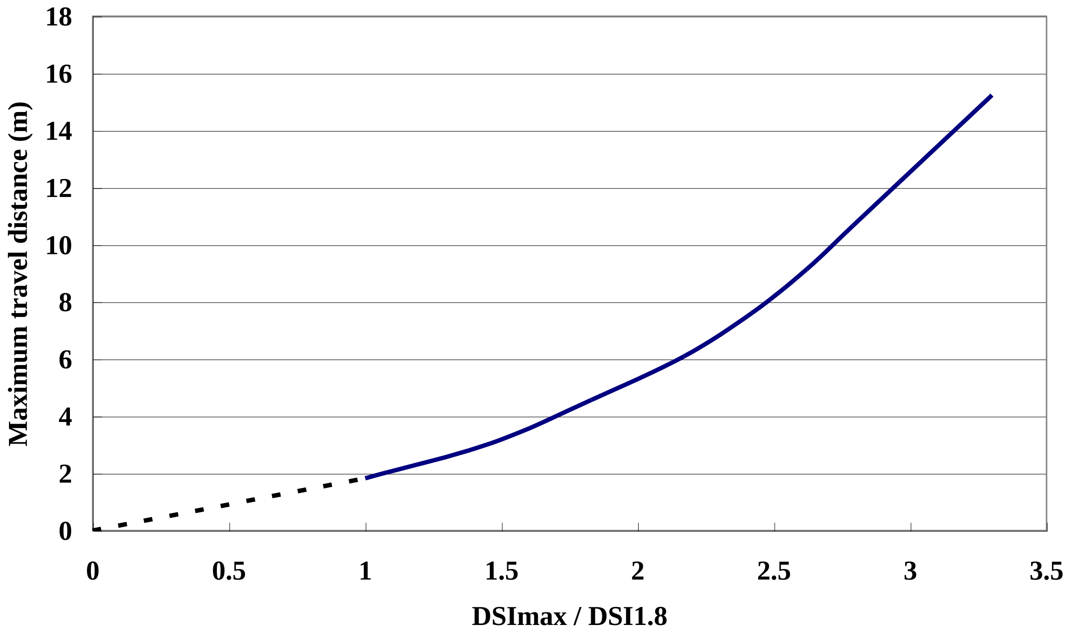

Figure 3-23 Estimation of maximum travel distance

4. Conclusion

The purpose of the study was to develop a new test method to assess dynamic segregation of SCC and detect the effect of various parameters on dynamic segregation. According to this study, the following conclusions were drawn.

- The flow trough test was found to provide a measure of dynamic segregation of SCC with acceptable precision and accuracy.
- The visual stability rating from the slump flow test did not always provide a suitable measure of dynamic segregation.
- The drag force equation 3-5 can be used to explain how various factors affect the dynamic segregation. Nevertheless, caution should be taken when one factor affects multiple variables in the equation simultaneously.
- Higher paste volume may reduce dynamic segregation by requiring less SP% by weight of cementitious materials to maintain the same slump flow. Less SP dosage causes higher paste plastic viscosity and yield stress, higher drag force provided by the paste to carry the aggregate forward, and thus less dynamic segregation.
- Lower slump flow may reduce dynamic segregation due to higher paste plastic viscosity and yield stress.
- Smaller coarse aggregate may improve dynamic segregation resistance due to higher aggregate surface area/mass ratio and higher drag force, and possibly less static segregation.

- While both smaller aggregate size and better gradation can improve dynamic segregation resistance of SCC mixtures, smaller aggregate size seem to have more significant effect compared better gradation.

5. Future Work Recommendation

The followings could be helpful in providing more insight into dynamic segregation phenomenon and determining the parameters that affect it.

- There exist more parameters that could affect dynamic segregation and they are worth being studied. Such parameters include packing density of aggregates (lattice effect), aggregates shapes, aggregate density, and rebar spacing in the formwork.
- The utilization of SCC in the United States has grown substantially recently. The benefits of SCC draw the attention of engineers and practitioners. To keep the good reputation of SCC, three attractive properties of SCC must be maintained at the same time. For the research on dynamic segregation, coming up with new strategies to control segregation is a good direction.
- In addition to good material selection, the mix design of SCC requires securing a proper balance between fresh properties necessary for the successful final production. To establish the correlations between contradictory workability characteristics of SCC, new models are good ways to estimate the performance of fresh SCC.

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7. Appendix A: Aggregate Properties

Basalt Sand Properties

Sieve No.	Sieve Size (in.)	Weight of Sieve (g)	Weight of Sieve and Aggregate (g)	Mass of Agg Retained on Each Sieve (g)	Percent of Mass Retained on Each Sieve (%)	Cumulative Percent Retained (%)	Percent Fine (%)
No. 4	0.187	1351	1433	82.1	8.2	8.2	91.8
No. 8	0.099	1259.5	1511.5	252	25.2	33.5	66.5
No. 16	0.0469	749.9	976.7	226.8	22.7	56.2	43.8
No. 30	0.0232	1069.3	1241	171.7	17.2	73.3	26.7
No. 50	0.0117	790.1	921.8	130.9	13.1	86.5	13.5
No. 100	0.0059	898.1	960.8	62.7	6.3	92.7	7.3
Total		7007.8	8006.6	998.8	100.0		

Bulk Specific Weight	2.55
SSD Specific Weight	2.67
Apparent Dry Specific Weight	2.90
Absorption Capacity (%)	5.10
Fineness Modulus	2.99
Bulk Density (lb/ft^3)	104.70
Packing Density	0.66

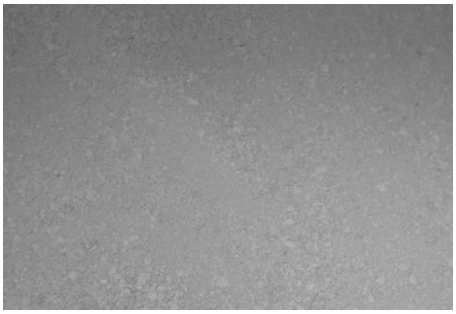

Figure 7-1 Basalt sand

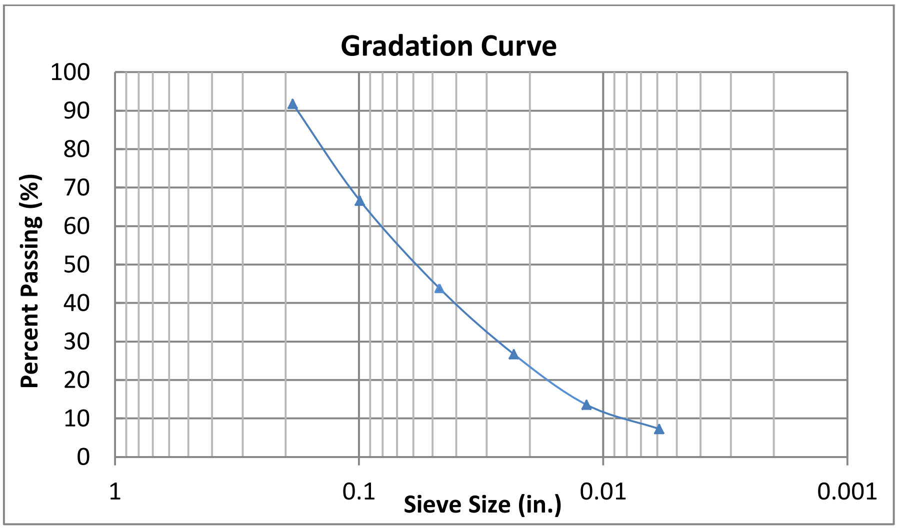

Figure 7-2 Basalt sand gradation Curve

Halawa 3F Coarse Aggregate Properties

Sieve No.	Sieve Size (in.)	Weight of Sieve (g)	Weight of Sieve and Aggregate (g)	Mass of Agg Retained on Sieve (g)	Percent of Mass Retained on Sieve (%)	Cumulative Percent Retained (%)	Percent Fine (%)
3/4"	0.75	1220.6	1223.1	2.5	0.1	0.1	99.9
1/2"	0.50	1184.1	2261.2	1077.1	21.5	21.6	78.4
3/8"	0.38	1174.1	2726.4	1552.3	31.1	52.6	47.4
No. 4	0.187	1350.3	3308.2	1957.9	39.2	91.8	8.2
No. 8	0.099	835.7	1176.9	341.2	6.8	98.6	1.4
Total		6597.7	11596.9	4999.2	100.0		

Bulk Specific Weight	2.61
SSD Specific Weight	2.67
Apparent Dry Specific Weight	2.84
Absorption Capacity (%)	3.71
Bulk Density (lb/ft^3)	90.2
Packing Density	0.58

Figure 7-3 Halawa 3F

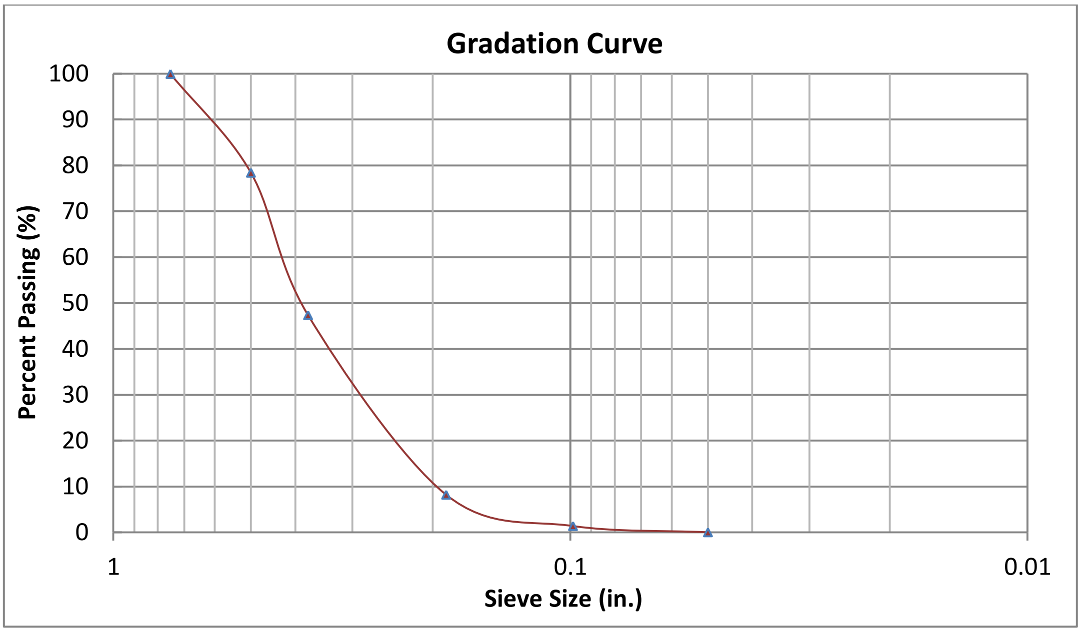

Figure 7-4 Halawa 3F Gradation Curve

Maui Dune Sand Properties

Sieve No.	Sieve Opening (in.)	Weight of Sieve (g)	Weight of Sieve and Aggregate (g)	Mass of Agg Retained on Each Sieve (g)	Percent of Mass Retained on Each Sieve (%)	Cumulative Percent Retained (%)	Percent Fine (%)
No. 4	0.187	736.1	739.8	3.7	0.4	0.4	99.6
No. 8	0.099	470.5	483.3	12.8	1.3	1.6	98.4
No. 16	0.0469	438.5	450.5	12	1.2	2.8	97.2
No. 30	0.0232	464.6	515.1	50.5	5.0	7.9	92.1
No. 50	0.0117	322.5	724.4	401.9	40.2	48.1	51.9
No. 100	0.0059	334.8	799.5	464.7	46.4	94.5	5.5
Pan	0	289.6	344.8	55.2	5.5	100.0	0.0
Total		3056.6	4057.4	1000.8	100.0		

Bulk Specific Weight	2.63
SSD Specific Weight	2.71
Apparent Dry Specific Weight	2.82
Absorption Capacity (%)	2.30
Fineness Modulus	1.55
Bulk Density (lb/ft^3)	91.13
Packing Density	0.54

Figure 7-5 Maui Dune Sand

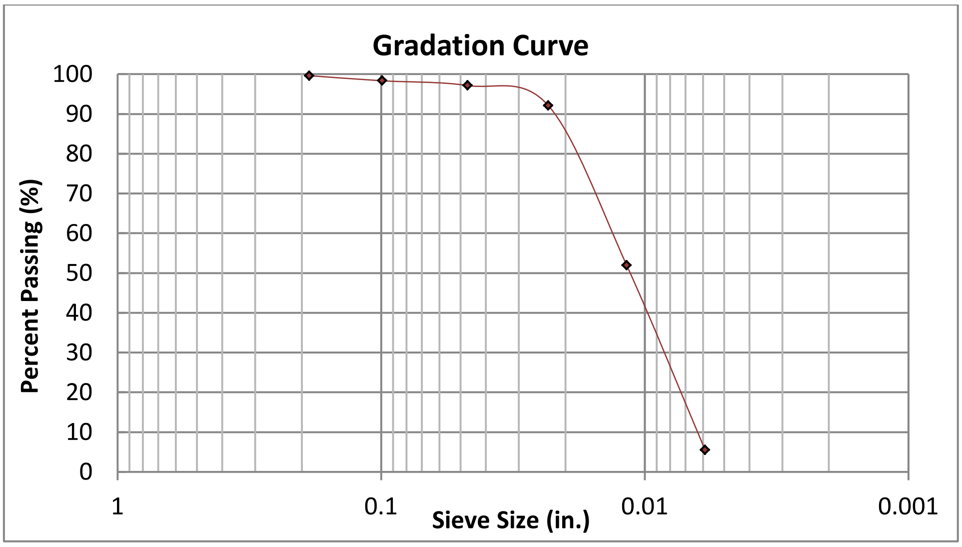

Figure 7-6 Maui Dune Sand Gradation Curve

Kapa'a Chips Properties

Sieve No.	Sieve opening (in.)	Weight of Sieve (g)	Weight of Sieve and Aggregate (g)	Mass of Agg Retained on Each Sieve (g)	Percent of Mass Retained on Each Sieve (%)	Cumulative Percent Retained (%)	Percent Fine (%)
3/4"	0.75	1220.6	1220.6	0	0.0	0.0	100.0
1/2"	0.50	1184.1	1185.3	1.2	0.0	0.0	100.0
3/8"	0.38	1174.2	1309.9	135.7	2.7	2.7	97.3
No. 4	0.187	1349.8	5918.1	4568.3	91.4	94.1	5.9
No. 8	0.099	835.4	1035.5	200.1	4.0	98.1	1.9
Total		6597.3	11597.9	5000.6	100.0		

Bulk Specific Weight	2.61
SSD Specific Weight	2.70
Apparent Dry Specific Weight	2.88
Absorption Capacity (%)	3.61
Fineness Modulus	2.95
Bulk Density (lb/ft^3)	90.53
Packing Density	0.54

Figure 7-7 Kapa'a Chips

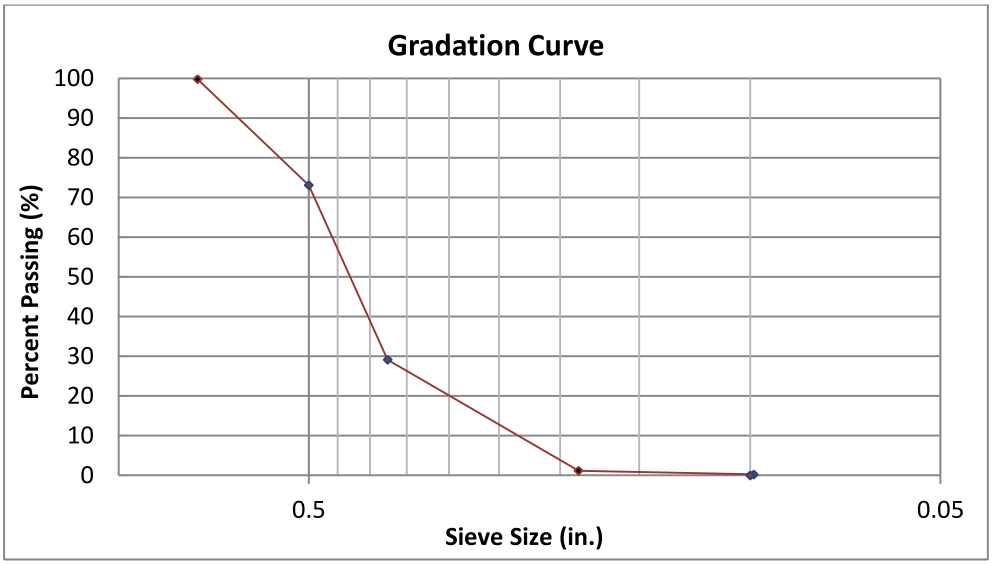

Figure 7-8 Kapa'a Chips Gradation Curve

Halawa 3F 2 Properties

Sieve No.	Sieve Opening (in.)	Weight of Sieve (g)	Weight of Sieve and Aggregate (g)	Mass of Agg Retained on Each Sieve (g)	Percent of Mass Retained on Each Sieve (%)	Cumulative Percent Retained (%)	Percent Fine (%)
3/4"	0.75	1221	1270.7	50	1.0	1.0	99.0
1/2"	0.50	1184.1	3065.2	1881.1	37.6	38.6	61.4
3/8"	0.38	1174	2787.4	1613.1	32.3	70.9	29.1
No. 4	0.187	1350.2	2711.7	1361.5	27.2	98.1	1.9
No. 8	0.099	835.3	917.2	81.9	1.6	99.7	0.3
Total		6597.8	11598	5000.2	100.0		

Bulk Specific Weight	2.64
SSD Specific Weight	2.72
Apparent Dry Specific Weight	2.86
Absorption Capacity (%)	2.88
Fineness Modulus	4.08
Bulk Density (lb/ft^3)	92.53
Packing Density	0.55

Figure 7-9 Halawa 3F 2

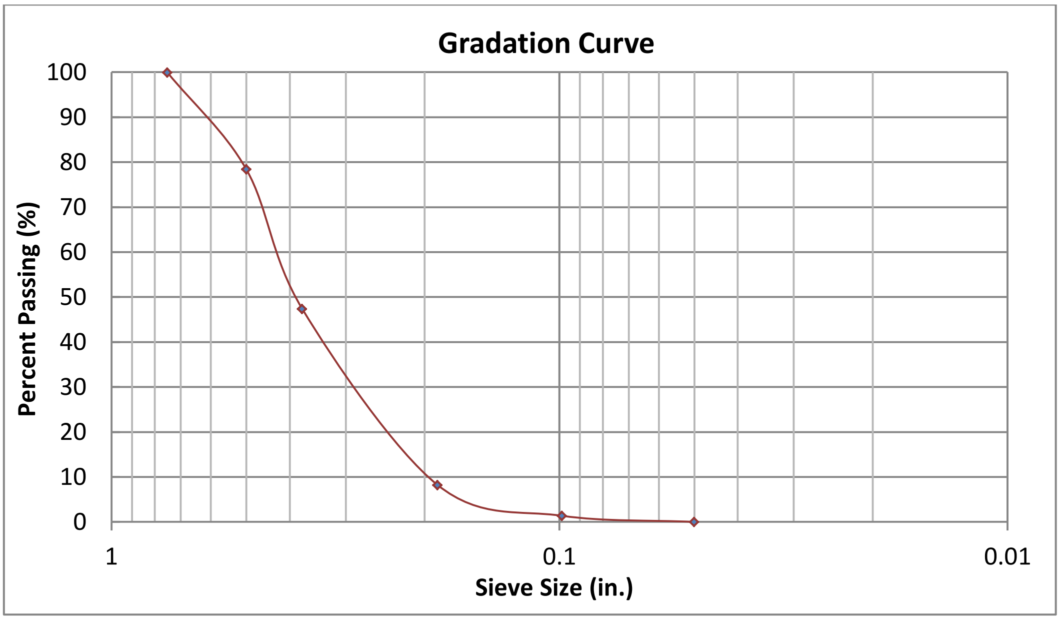

Figure 7-10 Halawa 3F 2 Gradation Curve