TESTING SEGREGATION AND OTHER RHEOLOGICAL PROPERTIES OF SELF-CONSOLIDATING CONCRETE (SCC)

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DEDICATION

To my father, mother, and brothers for their love, support and encouragement made me through this work.

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ABSTRACT

Self-consolidating concrete (SCC) is a new type of high performance concrete that flows under its own weight, passes through intricate geometrical configurations, and fills the formwork without vibration and consolidation. Compared with normal concrete mixes, the composition and the rheological properties of SCC should be closely controlled in order to satisfy the fresh property requirements simultaneously. Moreover, the segregation resistance of self-consolidating concrete (SCC) is more sensitive to small variations of its properties. Segregation refers to movement of coarse aggregate relative to the mortar. Static segregation occurs when the concrete is at rest and the coarse aggregate sinks in the mortar. Dynamic segregation occurs when the concrete is flowing and the coarse aggregate lags behind the mortar. To study segregation and design an SCC mix, which is robust against small variations in raw materials, it is critical to be able to quickly quantify static and dynamic segregation and stability robustness. In this study, a modified Segregation Probe is introduced as a simple and fast method for testing static segregation and stability robustness of fresh concrete. On the other hand, Flow Trough was developed to measure dynamic segregation. It was found that mixture properties, such as higher paste volume, lower superplasticizer percentage by weight of cement, lower slump flow, smaller aggregate size, better gradation, and higher aggregate packing density may improve robustness and dynamic stability.

The effects of various aggregate properties on SCC rheology were investigated. It was found that lower superplasticizer dosage, higher aggregate volume, higher fine aggregate to coarse aggregate ratio, smaller aggregate size and lower aggregate packing density may increase yield stress of SCC mixture. Aggregate size had insignificant effect on plastic viscosity. Mixtures with Low slump flow (slump flow value less than 580 mm (23 in) in this study) exhibited anti-thixotropy manner, while mixtures with higher slump flow showed thixotropy manner.

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CHAPTER 1

INTRODUCTION

Self-consolidating concrete (SCC) is a new type of high performance concrete that flows under its own weight, passes through intricate geometrical configurations, and fills the formwork without vibration and consolidation. In 1986, Self-consolidating concrete was first introduced by Professor Hajime Okamura of Kochi University of Technology in Japan. Since then, the research and development of SCC have been spreading quickly around the world.

Some advantages of SCC include: a reduction in labor costs needed for manual consolidation, it is easily placed in elements with limited access; a decrease in noise emitted from mechanical equipment. The increased flowability and consolidation of SCC can also resulted in uniform surface finishes that are virtually free of imperfections

The three major fresh property requirements on fresh concrete for it to be considered self-consolidating concrete (SCC) are filling ability, passing ability, and stability (static and dynamic segregation resistance). Compared with ordinary concrete, the composition and the rheological properties of SCC should be closely controlled in order to satisfy the three fresh property requirements simultaneously.

1.1 OBJECTIVES

Segregation refers to movement of coarse aggregate relative to the mortar. Static segregation occurs when the concrete is at rest and the coarse aggregate sinks in the mortar. Dynamic segregation occurs when the concrete is flowing and the coarse aggregate lags behind the mortar. Segregation may cause lower flowability, aggregate blocking, higher drying shrinkage, and non-uniform compressive strength. To study segregation and design an SCC mix, which is robust against small variations in raw materials, it is critical to be able to quantify segregation and stability robustness quickly and accurately.

One of the disadvantages of SCC is its cost, associated with the usage of chemical admixtures and high volumes of Portland cement. One alternative to reduce the cost of

SCC is selecting aggregates with favorable characteristics such as higher packing density, which may minimize the paste volume while still maintaining favorable rheological properties.

The overall objective of this research project is to design new testing methods to measure segregation and to study the effects of aggregate properties on segregation and other rheological properties of SCC.

In chapter 2, a modified Segregation Probe is introduced as a simple and fast method for testing static segregation and stability robustness of fresh concrete. The effects of aggregate properties and concrete rheology on static segregation robustness of SCC mixtures using aggregate packing theories and rheological models have been studied in chapter 3. Chapter 4 includes a new test method that is rapid and reliable to better quantify dynamic segregation and the effects of aggregate properties and concrete rheology on dynamic segregation of SCC mixtures based on experimental tests and rheological models have been investigated. The main objective of the chapter 5 is to explore the effects of various aggregate properties on rheology of SCC. Chapter 6 concludes this work.

CHAPTER 2

STATIC SEGREGATION

2.1 BACKGROUND

The three major fresh property requirements for self-consolidating concrete (SCC) are flowing ability, passing ability, and stability (static and dynamic segregation resistance). Segregation is the separation of coarse aggregate from the mortar. The separation after SCC is placed is called static segregation, while the separation during the process of placement is called dynamic segregation [1].

Commonly used static segregation tests include Column Segregation [2], Penetration Test [3], V-Funnel test [4], Electrical Conductivity [5], Sieve Segregation Resistance Test [6], Hardened Visual Stability Index [7], and Image Analysis of Hardened Cylinder [8].

The V-funnel test is incorporated as a Japanese standard test, for static segregation. The V-shaped funnel is filled with about 12 lit (3 gal) of concrete. The V-funnel time (V- time) is the time taken for the concrete mix to flow out through the orifice. The V-time applicable for SCC is 10 s [4].

Electrical conductivity [5] method can measure static segregation by monitoring the difference in electrical conductivity along a concrete or mortar sample as a function of time. The variation in conductivity can then be related to changes in aggregate percentage to interpret segregation and bleeding.

To perform the Sieve Segregation Resistance Test [6], a sample of 10 liter (~2.6 gal) of concrete was allowed to rest for 15 min. Then, 2 liters was poured on a 4.75 mm sieve from a height of 500 mm, and percentage of sample passing the sieve was reported

The Hardened Visual Stability Test (HVSI) [7] gives a visual of the final coarse aggregate static settlement in SCC. The test consists of ratings based on the visual observations and criteria that can be subjective from person to person.

Among these tests, Column Segregation [2] and Penetration Test [3], are the standard testing methods for static segregation of SCC.

2.1.1 Column Segregation

Column segregation is used to measure static segregation. A sample of freshly mixed self-consolidating concrete is placed in a 200mm by 660 mm (8 by 26-inch) cylindrical column (Figure 2.1) with top and bottom sections 160 mm (6.5 inches) tall in one lift without tamping or vibration. The specimen is allowed to stand for 15 min. The mold is separated into three sections representing different levels of the cylindrical specimen (or column). Portions of concrete from the top and bottom section are washed on a 4.75 mm (No. 4) sieve, leaving the coarse aggregate on the sieve. The segregation index (SI), is calculated using the equation 2.1:

$$SI = 2\left[\frac{(CA_B - CA_T)}{(CA_B + CA_T)}\right] * 100 \quad , if\ \ CA_B > CA_T \qquad (2.1)$$

$$SI = 0 \quad , if\ \ CA_B \le CA_T$$

Where CA_T is the mass (weight) of coarse aggregate in the top section, and CA_B is the mass (weight) of coarse aggregate in the bottom section of the column. The smaller the deviation in total mass of collected aggregate between top and bottom sections of the column (SI<15%) is an indication of good stability, and minimal static segregation. Column segregation is a reliable and accurate test. However, the mold is big and not readily portable, and the test is time consuming and needs a big amount of concrete sample and water.

Figure 2.1- Column Segregation apparatus

2.1.2 Penetration Test

This test method is for the rapid assessment of the static segregation resistance of self-consolidating concrete and uses a penetration apparatus (Figure 2.2) and an inverted slump mold. The penetration head, consisting of a non-corrosive hollow cylinder and a metal rod, has a mass of 45$\pm$1 g. The inner diameter, wall thickness, and height of the hollow cylinder are 75$\pm$1 mm, 1.5$\pm$0.1 mm, and 50$\pm$1 mm, respectively.

A sample of freshly mixed self-consolidating concrete is placed in an inverted slump mold without tamping or vibration. The hollow cylinder attached to a metal rod (45±1 g) is aligned in the center of the inverted slump mold as shown in Figure 2.2. The hollow cylinder is then lowered until it touches the surface of the concrete and initial reading (d_1) is recorded. The concrete is allowed to stabilize for 80±5 sec, at which time the hollow cylinder is released to freely penetrate into the fresh concrete. After 30 sec, the penetration depth of the cylinder head is recorded (d_2) from the scale.

The penetration depth (P_d) is determined according to equation 2.2:

$$P_d = d_2 - d_1 \qquad (2.2)$$

Where d_1 is initial reading (mm) and d_2 is final reading (mm). Concrete has satisfactory segregation resistance if penetration depth is smaller than 10 mm, moderately resistant if P_d is between 10 and 25 mm, and SCC is not resistant if P_d is more than 25 mm.

Figure 2.2-Penetration Test [3]

2.1.3 Original Segregation Probe

Another test for static segregation is the Original Segregation Probe (Figure 2.3), which was developed by Shen et.al [9]. The basic procedure is summarized as follows:

1) Raw materials are mixed in a mixer according to standard procedure (Sand, coarse aggregate, and water were put in a drum mixer and mixed for 30 s. Then Cement and mineral admixture, if any, were put in the mixer and mixed for 3 min.

Mixer was stopped for 3 min. after that, Mixer was restarted, and superplasticizer and/or VMA were slowly poured and mixed for 2 min)

2) Fresh concrete is cast into a 150 x 300 mm cylinder with one lift and allowed to rest for 2 min before the test, during which time vibration of the cylinder is avoided.
3) The segregation probe is placed gently on the concrete surface and allowed to settle for 1 min.
4) The penetration depth is measured using the scale marked on the rod. This depth is used to determine the stability rating according to Table 2.1.

Table 2.1-Stability Rating for Segregation Probe (for concrete with ~300 mm thickness) (Data from [9])

Depth of Settlement mm	Stability Index, SI
< 4	0, highly stable
4 – <7	1, stable
7 – 25	2, unstable
> 25	3, highly unstable

Verified by image analysis of cut cylinders, the Segregation Probe was found to be able to measure the actual thickness of the paste/mortar layer on the top surface of a segregated mix [9].

It was found in several cases that when a mix is segregated the Segregation Probe might tilt during the relatively long settling process and cause incorrect readings. The tilted probe is mainly due to its asymmetric design around the vertical axis. As the probe settles, the unevenly distributed gravitational force and drag force from the paste may cause the probe to tilt, and the effect of unbalanced forces amplifies with lower paste viscosity and yield stress when the mix becomes unstable.

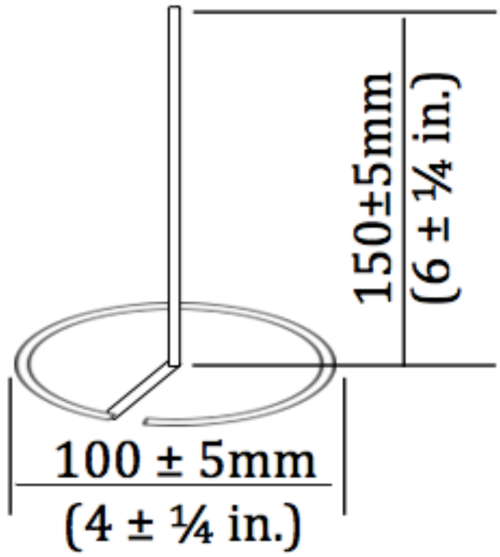


Figure 2.3-Original Segregation Probe (18 g) [9]

2.2 OBJECTIVES

The main objectives of the research in this chapter are: 1) to resolve the inclination issue by modifying the probe design, 2) to verify the design of the modified Segregation Probe theoretically based on mechanics analysis, 3) to verify the results of modified Segregation Probe with the original Segregation Probe, the Penetration Test, and the Column Segregation test, and 4) to check the reproducibility of the modified Segregation Probe.

2.3 EXPERIMENTAL PROGRAM

2.3.1 Details of materials

Type I Portland cement complying with ASTM C150/C150M-12 and type C fly ash complying with ASTM C618-12a were used. Coarse aggregate CA1 is crushed basalt rock, has maximum size of 19mm, bulk specific gravity of 2.56, bulk density of 1473 kg/m^3, and packing density of 0.55. Coarse aggregate CA2 is crushed basalt rock, has maximum size of 9.5mm, bulk specific gravity of 2.67, bulk density of 1491 kg/m^3, and packing density of 0.54. Fine aggregate FA1 has bulk specific gravity of 2.71, bulk density of 1460 kg/m^3, fineness modulus of 1.55, and packing density of 0.54. Fine aggregate FA2 is crushed basalt rock, has bulk specific gravity of 2.51, bulk density of 1677 kg/m^3, fineness modulus of 3.50, and packing density of 0.63. The properties and the gradation curve of coarse and fine aggregate are shown in Table 2.2 and Figure 2.4, respectively.

Table 2.2-Aggregate properties

Aggregate Name	Bulk Density (kg/m^3)	Bulk Specific Gravity	Fineness Modulus	Absorption Capacity (%)	Packing Density
CA1	1473	2.74	6.70	2.66	0.54
CA2	1491	2.70	5.95	3.61	0.54
FA1	1460	2.71	1.55	2.30	0.54
FA2	1675	2.64	3.50	5.16	0.63

A third-generation superplasticizer (SP, polycarboxylate-based) was used. It was a milky brown solution with a specific gravity of 1.06 and a solid content of 35%. The VMA (methyl-hydroxy-ethyl cellulose) used had a specific gravity of 1.00 and a solid content of 35%.

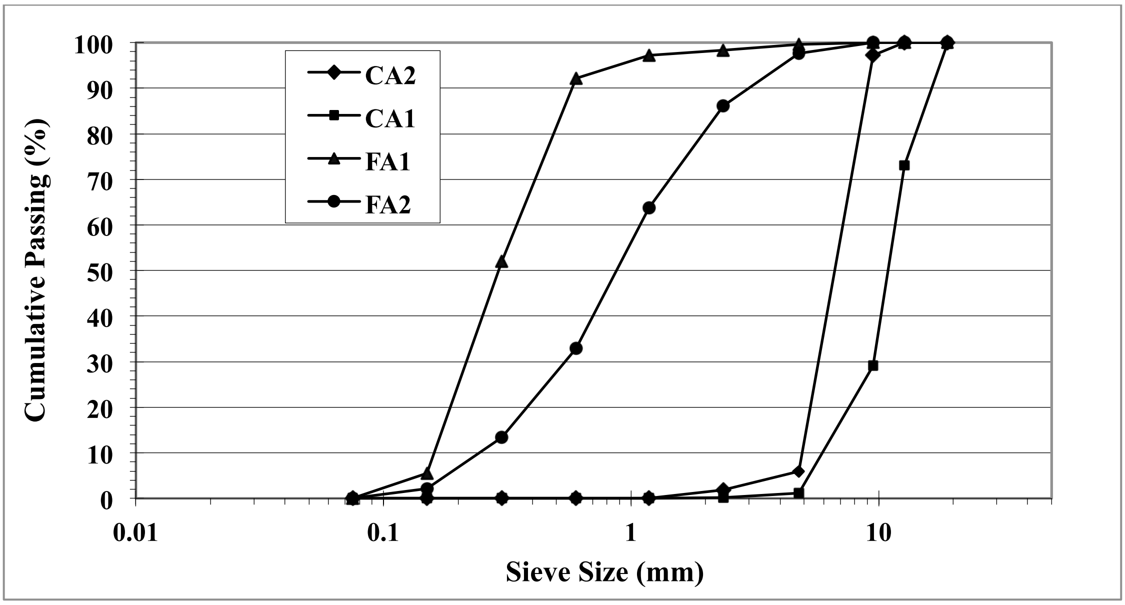


Figure 2.4-Gradation curves of coarse and fine aggregates

2.3.2 Mix Proportions

As shown in Table 2.3, a total of fifteen mixtures were tested. 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 may also be modified to explore the effects of these properties on robustness. 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 2.3-Mix proportions of SCC mixes

Mix Type	Mix ID	w/cm	Material kg/m3							Aggregate Properties				Admixture ml/m^3	
			Cement (Type I)	Fly Ash Class C	CA1	CA2	FA1	FA2	Water	%AGG	FA/CA	CA1%	Φm	SP	VMA
	GA	0.35	450	107	198	579	756		195	59	1.00	13	0.67	9707	0
Graded Aggregate	GA + 5 %P	0.35	506	120	181	530	692		219	54	1.00	13	0.67	7908	0
	GA -5 %P	0.35	394	94	214	629	821		171	64	1.00	13	0.67	11696	0
	MA	0.31	442	239	693		678		211	53	1.01	50	0.65	9299	0
Mineral Admixture	MA +5 %P	0.31	487	263	627	0	621		233	48	1.01	50	0.65	8804	0
	MA -5 %P	0.31	398	215	749		743	0	190	58	1.01	50	0.65	10501	0
	VMA	0.41	515		854		729		209	62	0.87	53	0.66	3051	1371
	VMA-LS	0.41	515		854	0	729		209	62	0.87	53	0.66	2370	1371
VMA	VMA +5 %P	0.41	582		783		670		236	57	0.87	53	0.66	2823	809
	VMA -5 %P	0.41	447		923		789		181	67	0.87	53	0.66	3497	881
	VMA-HP	0.41	585	0	468	593	585		238	59	0.56	28	0.71	8044	1360
	WB-SA	0.42	474		0	712	188	748	199	63	1.34	0	0.66	4090	1424
Well Balanced	WB1	0.42	502		533	115	222	743	211	61	1.53	33	0.74	3383	1131
	WB2	0.42	502		509	136	445	522	211	61	1.53	31	0.71	5007	1131
	WB3	0.36	502		534	142	467	547	181	64	1.53	31	0.71	6495	646

2.3.4 Mixing procedure

Each batch of concrete has a volume of about 43 liter (1.5 ft^3) and was prepared in a drum mixer with a capacity of 58 liter (2 ft^3). The following procedure was used:

1. Sand, coarse aggregate, and one third of water were put in a drum mixer and mixed for 30s.
2. Cement and mineral admixture, if any, were put in the mixer and mixed for 3 minutes and remaining water was slowly added during the first minute of mixing process.
3. Mixer was stopped for 3 minutes.
4. Mixer was restarted, and SP and/or VMA were slowly poured and mixed for 2 minutes before the slump flow, robustness, and/or rheology tests.

2.4 THE DESIGN OF MODIFIED SEGREGATION PROBE

As shown in Figure 2.5, the modified Segregation Probe has a 100-mm (4") diameter ring connected by three legs to a 125-mm (5") rod marked with a scale. The whole probe is made of 2.38-mm (3/32") diameter stainless steel wire and the total mass is 24±1 g.

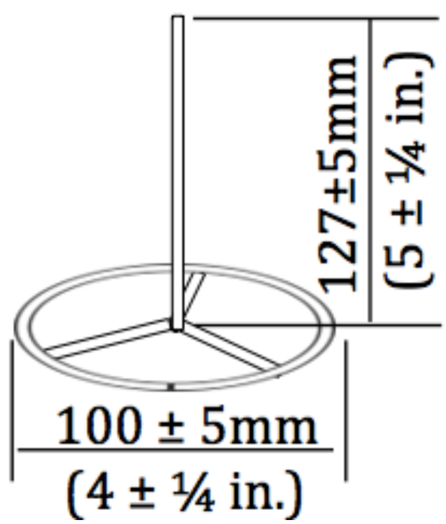


Figure 2.5-Modified Segregation Probe (24 g)

Because of its symmetric design, the modified Segregation Probe eliminates the cause of inclination in the original design. Figures 2.6 and Figure 2.7 compare the modified Segregation Probe and the original design.

Figure 2.6-Modified Segregation Probe (left) and tilted original design (right) in slump cones.

Figure 2.7-Modified Segregation Probe (left) and tilted original design (right) in a drum mixer.

The size, geometry, and weight of the modified Segregation Probe were designed based on mechanics analysis so that the probe can penetrate the mortar/paste layer, but sit on top of coarse aggregate. The modified Segregation Probe can be simplified as a long cylinder with a thickness of 2.38-mm. The probe in a fresh concrete mix experiences two opposing forces before it is released from rest, a buoyancy force B_F and a gravitational force G_F, as shown in Figure 2.8a. Since steel has a higher density than the concrete, the probe will start to settle vertically due to the unbalanced force ($G_F - B_F$) if the yield stress is not high enough to hold the probe.

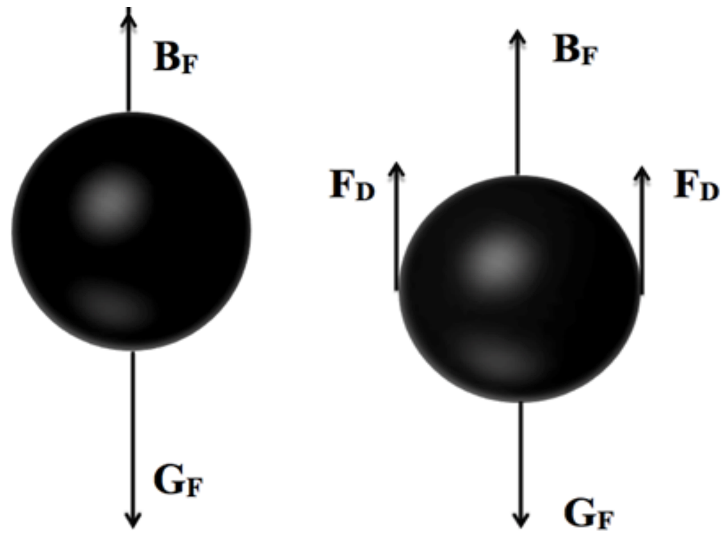


Figure 2.8-Forces acting on cross-section of modified Segregation Probe when it is a) at rest, and b) settling.

When the probe is settling downward, the suspension will provide another force called the drag force, F_D, as shown Figure 2-8b. Drag force F_D resists the settling of the probe, increases with higher speed, reduces the acceleration, and will eventually become equal to the original driving force ($G_F - B_F$) unless other forces break the balance. Then there are no unbalanced forces acting on the probe and it continues to travel at a constant settling velocity, u_∞.

According to fluid mechanics, the drag force F_D can be expressed as (Young et al 2004):

$$F_D = 0.5\rho \times u^2 \times A \times C_D \qquad (2.3)$$

where ρ is density of the suspension, u is settling speed, A is reference area (projected area perpendicular to the settling direction), which equals $d \times (\pi D + 1.5D)$—where d (0.00238 m) is the diameter of the wire cylinder cross section and D (0.1 m) is the diameter of the ring portion of the modified Segregation Probe, and C_D is drag coefficient. In low speed streamlined flow, which is the type of flow expected in this case, C_D can be estimated as [10]:

$$C_D = 8\eta/(d \times \rho \times u) \qquad (2.4)$$

where η is viscosity of suspension. Then drag force F_D can be rewritten as

$$F_D = 4(\pi + 1.5)\times u\times D\times\eta \quad (2.5)$$

The rheology of the cement paste/mortar can be described using the Bingham model:

$$\tau = \tau_0 + \dot{\gamma}\times\eta_{pl} \quad (2.6)$$

where τ is stress, τ_0 is yield stress, $\dot{\gamma}$ is shear rate, and η_{pl} is plastic viscosity. For a Bingham fluid, η in Eq 2.5 needs to be replaced by apparent viscosity ($\tau/\dot{\gamma}$); for a Bingham fluid this is:

$$\eta_{app} = \tau_0/\dot{\gamma} + \eta_{pl} \quad (2.7)$$

Replace the η value in Eq 2.5 with this expression for η_{app}, we can get the drag force F_D for a Bingham fluid

$$F_D = 4(\pi + 1.5)\times D\times u\times(\tau_0/\dot{\gamma} + n_{pl}) \quad (2.8)$$

Estimating the shear rate as velocity u divided by cylinder cross section diameter d changes Eq 2.8 to

$$F_D = 4(\pi + 1.5)\times D\times u\times\left(d\times\tau_0/u + \eta_{pl}\right) \quad (2.9)$$

As shown in Figure 2.8(a), the driving force for settlement is the difference between gravitational attraction and buoyancy force (G_F–B_F), which can be expressed as

$$(G_F - B_F) \simeq \frac{\pi d^2\times g\times[(\pi D+1.5D)\times(\rho_S-\rho_L)+H\rho_S]}{4} \quad (2.10)$$

where ρ_S is the density of solid (segregation probe), ρ_L is the density of suspension (paste/mortar/concrete), g is gravitational acceleration, and H (0.127 m) is the height of the vertical rod portion of the probe.

It has been discussed that F_D finally becomes equal to (G_F–B_F) and the particle travels at a constant settling velocity, u_∞. When that happens the right sides of Eqs 2.9 and 2.10 become equal:

$$4(\pi + 1.5)\times D\times u\times\left(d\times\tau_0/u + \eta_{pl}\right) = \frac{\pi d^2\times g\times[(\pi D+1.5D)\times(\rho_S-\rho_L)+H\times\rho_S]}{4} \quad (2.11)$$

Rearranging Eq 2.11 gives

$$u_\infty = \frac{\pi d^2\times g\times[(\pi D+1.5D)\times(\rho_S-\rho_L)+H\times\rho_S]-16(\pi+1.5)\times D\times d\times\tau_0}{16(\pi+1.5)\times D\times\eta_{pl}} \quad (2.12)$$

From Eq 2.12, it can be seen that if

$$\tau_0 \geq \frac{\pi d^2\times g\times[(\pi D+1.5D)\times(\rho_S-\rho_L)+H\times\rho_S]}{16(\pi+1.5)\times D\times d} \quad (2.13)$$

the segregation probe does not penetrate the suspension. Using ρ_S=7800 kg/m^3, and ρ_L=2000 kg/m^3, d=0.00238 m, and g=9.8 m/s^2 in Eq 2.13 gives τ_0 ≥36 Pa. This means the modified Segregation Probe penetrates only when the yield stress is less than 36 Pa. The typical yield stress of mortar of SCC ranged from 6 to 15 Pa [11] and the yield stress of SCC ranged from 50 to 200 Pa [12], which explains why the modified Segregation Probe penetrated cement paste and mortar but would not penetrate fresh concrete**.** Furthermore, the yield stress of the mortar and concrete were found to be 28 and 304 Pa for GA-5% mix, and 23 and 173 Pa for MA-5% mix in Table 2.3, which also indicates the modified Segregation Probe is being able to measure the mortar thickness.

2.5 THE PROCEDURE

The procedure of the modified Segregation Probe was slightly changed with reduced rest time of the concrete and shortened settling time of the probe. The new procedure is summarized as follows:

1) Raw materials are mixed in a mixer according to standard procedure;
2) Fresh concrete is cast into a 150 x 300 mm cylinder mold with one lift and allowed to rest for 1 min before the test, during which time vibration of the cylinder is avoided.
3) The segregation probe is placed gently on the concrete surface and allowed to settle for 30 sec.
4) The penetration depth is measured and the Stability Index is determined according to Table 2.1.

The reason for reduced concrete rest time (from 2min to 1 min) and shortened settling time (from 1 min to 30 sec) of the probe is based on numerous observations of real tests. In nearly all cases, probe stopped settlement well within 20 sec. Readings were found not be affected by shortened waiting times.

2.6 VERIFICATIONS

The results of Segregation Column [2] and modified Segregation Probe were compared in Figure 2.9. Since the segregation percentage limit for a stable mix is 15% for Segregation Column and 7 mm for modified Segregation Probe, points in Zone 3 and

4 indicates agreement and points in Zone 1 and 2 suggest disagreement. A good correlation was observed between Segregation Column test and modified Segregation Probe test because all data points are in Zone 3 and 4.

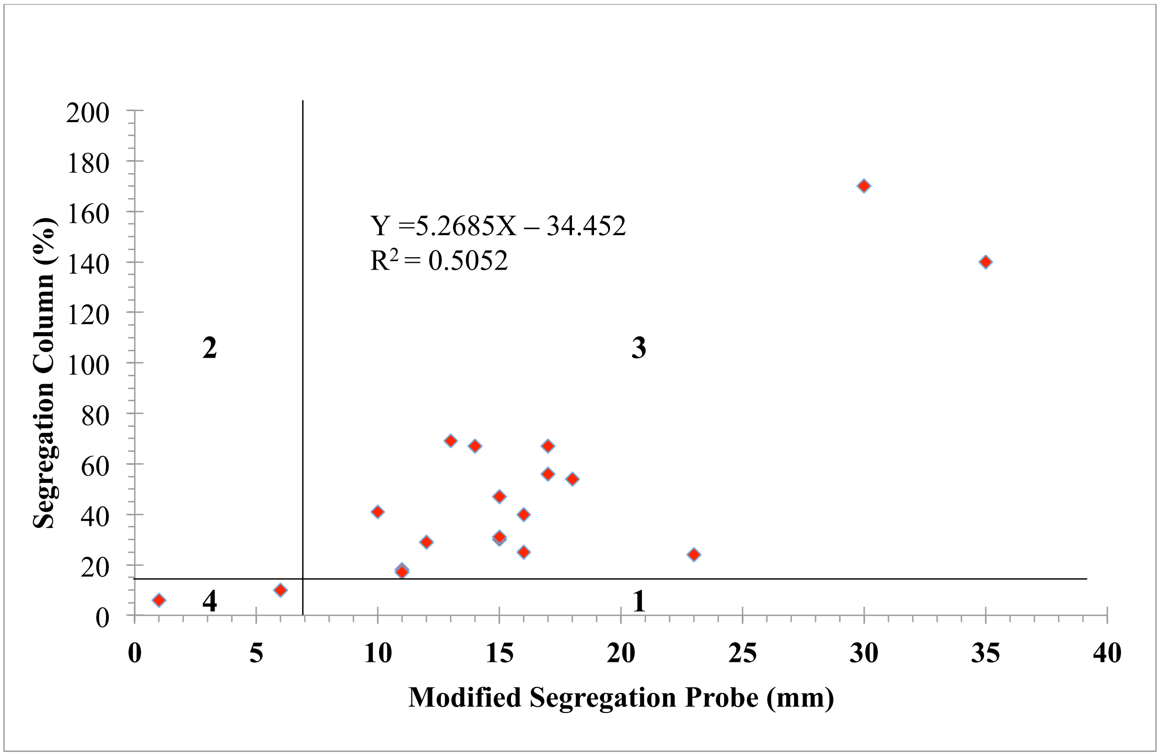


Figure 2.9-Results of Segregation Column (ASTM C1610/C1610M-10) and modified Segregation Probe

The results of Penetration Test [3] and modified Segregation Probe were compared in Figure 2.10. Because the penetration limit for a stable mix is 10 mm for Penetration Test and 7 mm for modified Segregation Probe, therefore, any point in Zone 3 and 4 indicates agreement between the two tests. Similarly, points in Zone 1 and 2 suggest disagreement. Clearly, there is a good correlation between Penetration Test and modified Segregation Probe test as almost all data points are in Zone 3 and 4.

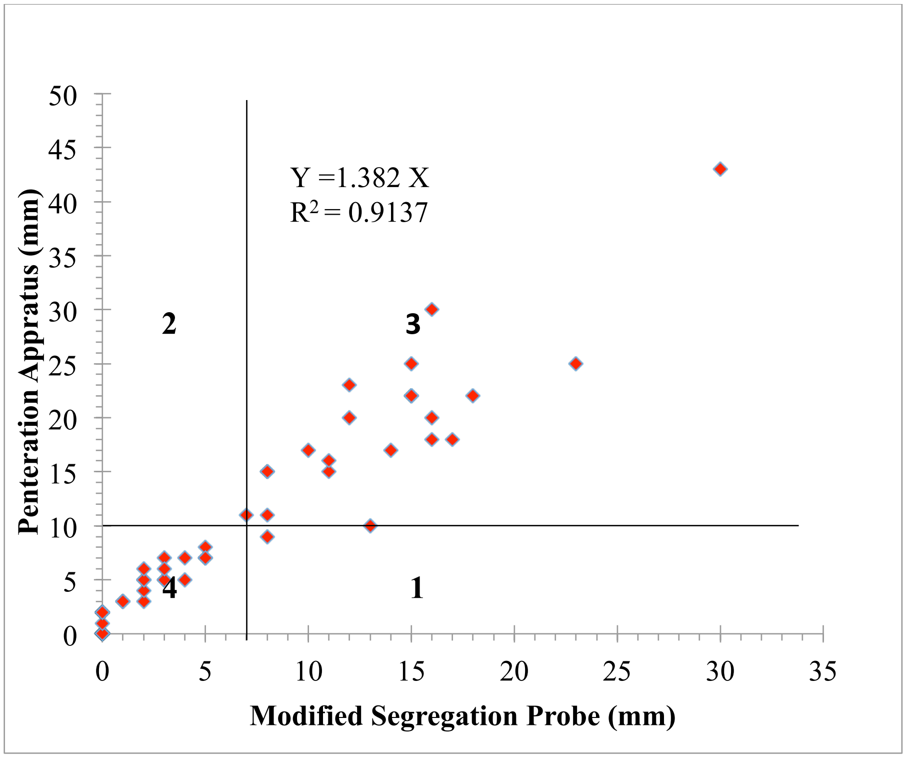


Figure 2.10-Results of Penetration Test (ASTM C1712-09) and modified Segregation Probe

Comparisons of modified Segregation Probe and the original design are illustrated in Figure 2.11. Each data point represents penetration depths for a specimen using the initial and the modified probe. Results from tilted original probe were regarded invalid and were shown as outliers and were not included in the comparison. The results of modified Segregation Probe had a linear relationship with the results of the original probe (Y= 0.902 X, with an R^2 value of 0.9833). Once again, these two sets of results also agreed well. Although the weight and geometry of the initial and modified probes are different, both can stop on top of coarse aggregate and measure the thickness of the mortar/paste layer. One possible reason for the lower values obtained by the modified version compared with the original probe is because the modified probe has more projected area than the original probe (3 legs versus 1 leg). Since the top surface of the coarse aggregate matrix is rough, more projected area means the probe may be stopped earlier with less settlement.

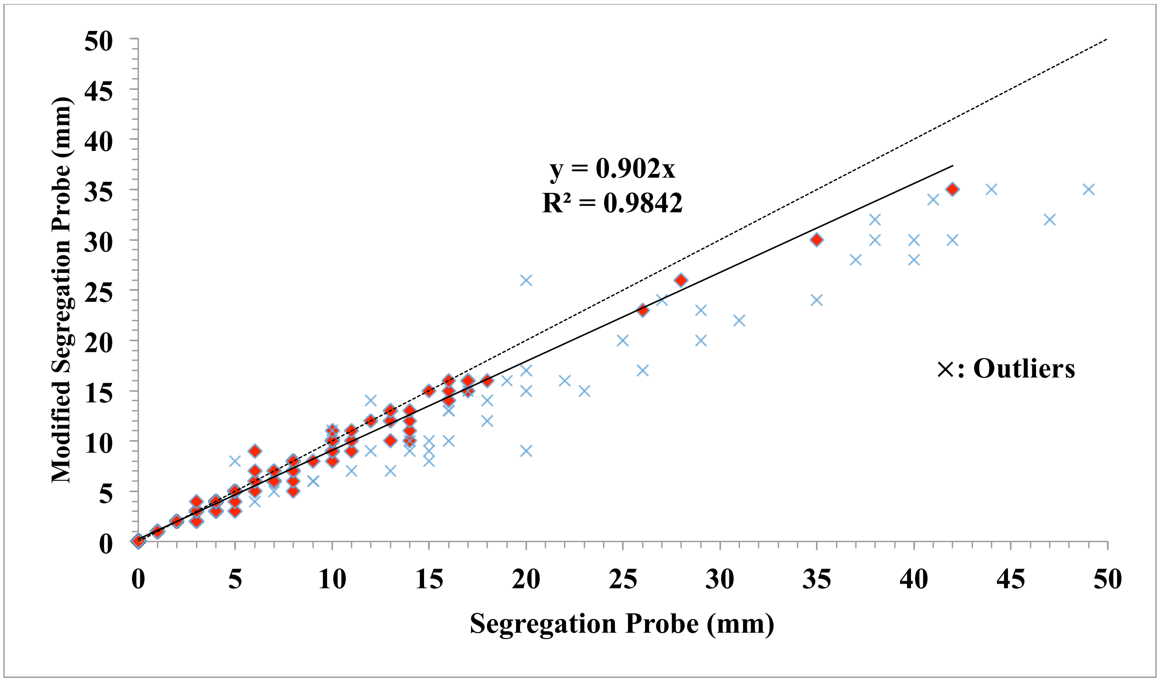
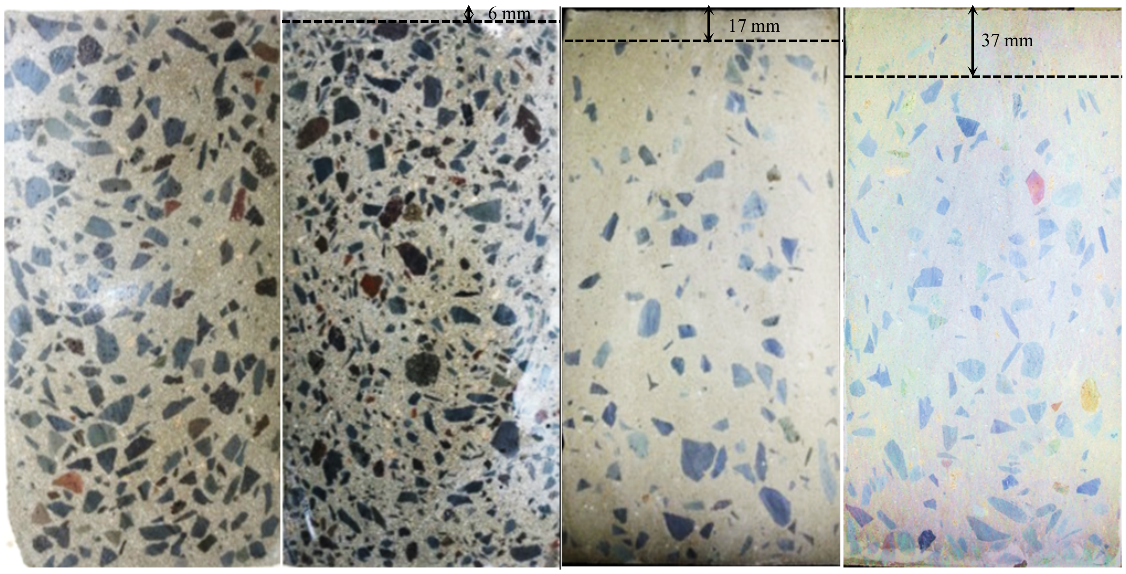


Figure 2.11-Results of original Segregation Probe and modified Segregation Probe.

Figure 2.12 shows photos of four cut hardened cylinders with Stability Index of 0, 1, 2, and 3. For each cylinder, the actual thickness of the paste/mortar layer was measured and compared with measurements from modified Segregation Probe. Specimen (a) has a measured mortar thickness of 0 mm and probe settlement of 0 mm, and both values give a Stability Index of 0. Similarly, the measured mortar thickness and probe settlement are very close for specimen (b), (c), and (d), indicating the modified Segregation Probe can measure the actual the mortar layer.



a b c d

Figure 2.12-Cut 150 mm x 300 mm Cylinders: (a) SI = 0, Measured Mortar Thickness = 0 mm, Probe Settlement =0 mm; (b) SI = 1, Measured Mortar Thickness = 6 mm, Probe Settlement =6 mm; (c) SI = 2, Measured Mortar Thickness = 17 mm, Probe Settlement =17 mm; (d) SI = 3, Measured Mortar Thickness = 38 mm, Probe Settlement =37 mm.

2.7 REPRODUCIBILITY

The reproducibility of modified Segregation Probe was checked for four mixes in Table 2.3: VMA+5%P, GA, MA, and MA-5%P. The Stability Index was controlled at 0, 1, 2, and 3 for VMA+5%P, GA, MA, and MA-5%P mix, respectively. For each mix, ten modified Segregation Probe tests were performed after freshly mixed concrete was filled into a 150 mm x 300 mm cylinder. The effect of hydration is regarded as minimal because the time duration to finish all ten tests is about 5 min. As shown in Figure 2.13, the variation was 1 mm (mean = 1.3 mm, % of error = -54% to 23%), 2 mm (mean = 5.9 mm, % of error = -19% to 15%), 3 mm (mean = 16.8 mm, % of error = -7% to 11%), and 5 mm (mean = 37.5 mm, % of error = -7% to 7%) for VMA+5%P (SI=0), GA (SI=1), MA(SI=2), and MA-5%P(SI=3) mix, respectively. The less stable the mix, the higher the penetration depth, and the higher the variation in results. Since all ten tests for each mix fell in the same Stability Index, the reproducibility can be considered acceptable.

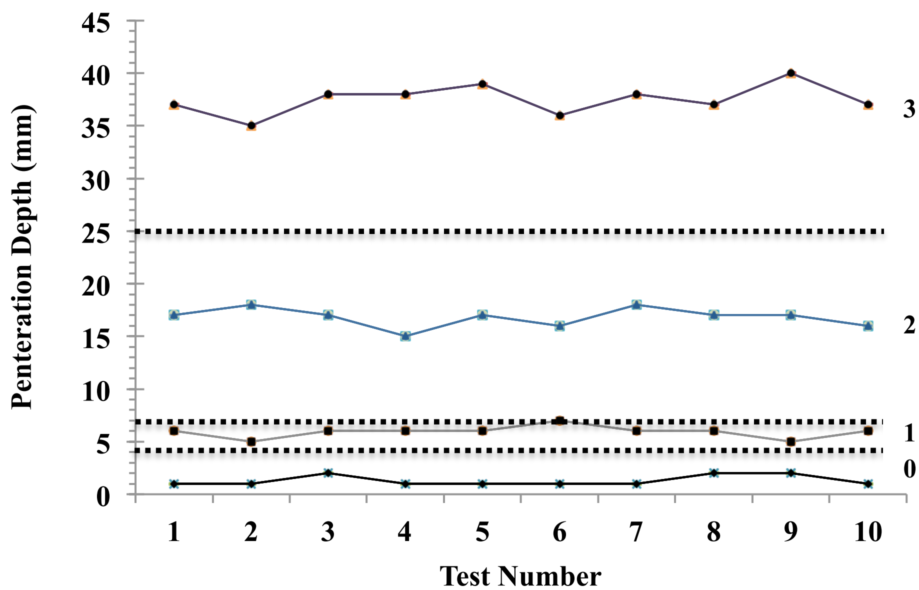


Figure 2.13-Reproducibility tests of modified Segregation Probe.

2.8 CONCLUSIONS

The following conclusions can be drawn from the results of modified Segregation Probe:

1) The symmetrical design of the modified Segregation Probe resolved the tilting problem of the original design in some segregated mixes.

2) The time to perform the modified Segregation Probe was shortened with reduced resting and settling periods.

3) The modified Segregation Probe is shown experimentally and theoretically to measure the thickness of the paste/mortar layer on top of instable SCC.

4) The results of modified Segregation Probe agreed well with the Penetration Test from ASTM C1712-09.

5) There is general agreement between the results of modified Segregation Probe and the Segregation Column test from ASTM C1610/C1610M-10.

6) The results of modified Segregation Probe agreed well with the original Segregation Probe when no tilting problem was presented.

7) The reproducibility of the modified Segregation Probe was acceptable for all Stability Indices.

CHAPTER 3

STABILITY ROBUSTNESS OF SELF-CONSOLIDATING CONCRETE

3.1 BACKGROUND

Compared with ordinary concrete, the composition and the rheological properties of SCC should be closely controlled in order to satisfy the three fresh property requirements simultaneously. Small fluctuations of the plastic viscosity and yield stress of paste, and the size, volume, gradation, as well as moisture content of the fine and coarse aggregates could adversely affect workability, composition, and durability [1].

Due to its sensitive nature, SCC typically requires a higher level of quality control. A lack of robust mixture is one of the main reasons limiting large scale production of SCC in the field, where external sources of variability are difficult to monitor and control [1]. Therefore, it is desired to have a robust SCC mixture, which is minimally affected by the variations in mix compositions [13]. As a matter of fact, robustness checking has been recognized as a critical step in mix design of SCC [14].

Previous researches have revealed that decreasing the water/cement ratio, increasing fine/total aggregate ratio, increasing total aggregate content, reducing aggregate size, as well as adding VMA (viscosity modifying admixture), fly ash, welan gum (rheology modifier), and condensed silica fume may improve robustness of SCC [5, 9, 11, 13,15-23].

Unfortunately, much of the research is empirical and the mechanism of how various aggregate properties and the rheology of cement paste and concrete affect robustness is still not well understood.

3.2 OBJECTIVES

The main objective of this chapter is to study the effects of aggregate properties and concrete rheology on static segregation robustness of SCC mixtures using aggregate packing theories and rheological models. The experimental method to assess robustness is based on modified Segregation Probe, which was introduced in chapter 2.

3.3 DETAILS OF MATERIALS AND MIX PROPORTIONS

Type I Portland cement complying with ASTM C150/C150M-12 and type C fly ash complying with ASTM C618-12a were used. Coarse aggregate CA1 is crushed basalt rock, has maximum size of 19mm, and coarse aggregate CA2 is crushed basalt rock, has maximum size of 9.5mm. The properties and the gradation curve of coarse and fine aggregate are shown in Table 3.1 and Figure 2.4, respectively.

Table 3.1-Aggregate properties

Aggregate Name	Bulk Density (kg/m^3)	Bulk Specific Gravity	Fineness Modulus	Absorption Capacity (%)	Packing Density
CA1	1473	2.74	6.70	2.66	0.54
CA2	1491	2.70	5.95	3.61	0.54
FA1	1460	2.71	1.55	2.30	0.54
FA2	1675	2.64	3.50	5.16	0.63

A polycarboxylate-based superplasticizer (SP) was used. It was a solution with a specific gravity of 1.06 and a solid content of 35%. The VMA (methyl-hydroxy-ethyl cellulose) used had a specific gravity of 1.00 and a solid content of 35%.

As shown in Table 3.2, a total of fifteen mixtures were tested to study the effects of slump flow, aggregate volume, size, gradation, and packing density, chemical admixtures, and concrete rheology on robustness. 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.

Table 3.2-Mix proportions of SCC mixes

Mix Type	Mix ID	w/cm	Material kg/m3							Aggregate Properties				Admixture ml/m^3	
			Cement (Type I)	Fly Ash Class C	CA1	CA2	FA1	FA2	Water	%AGG	FA/CA	CA1%	Φm	SP	VMA
Graded Aggregate	GA	0.35	450	107	198	579	756		195	59	1.00	13	0.67	9707	0
	GA + 5 %P	0.35	506	120	181	530	692		219	54	1.00	13	0.67	7908	0
	GA -5 %P	0.35	394	94	214	629	821		171	64	1.00	13	0.67	11696	0
Mineral Admixture	MA	0.31	442	239	693		678		211	53	1.01	50	0.65	9299	0
	MA +5 %P	0.31	487	263	627	0	621		233	48	1.01	50	0.65	8804	0
	MA -5 %P	0.31	398	215	749		743	0	190	58	1.01	50	0.65	10501	0
VMA	VMA	0.41	515		854		729		209	62	0.87	53	0.66	3051	1371
	VMA-LS	0.41	515		854	0	729		209	62	0.87	53	0.66	2370	1371
	VMA +5 %P	0.41	582		783		670		236	57	0.87	53	0.66	2823	809
	VMA -5 %P	0.41	447		923		789		181	67	0.87	53	0.66	3497	881
	VMA-HP	0.41	585	0	468	593	585		238	59	0.56	28	0.71	8044	1360
Well Balanced	WB-SA	0.42	474		0	712	188	748	199	63	1.34	0	0.66	4090	1424
	WB1	0.42	502		533	115	222	743	211	61	1.53	33	0.74	3383	1131
	WB2	0.42	502		509	136	445	522	211	61	1.53	31	0.71	5007	1131
	WB3	0.36	502		534	142	467	547	181	64	1.53	31	0.71	6495	646

Within each basic mixture type, the volume, gradation, packing density, maximum size of aggregate, as well as slump flow may also be modified to explore the effects of these properties on robustness of SCC. 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 size, 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.

3.4 THE PROCEDURE

Each batch of concrete has a volume of about 43 liter (1.5 ft^3) and was prepared in a drum mixer with a capacity of 58 liter (2 ft^3). The mixing procedure of concrete was explained in chapter 2.

3.4.1 Slump Flow Test

The slump flow test followed the procedure in ASTM C1611 [24] and was performed on a flat, smooth, and level steel plate with a size of 1m x 1m. After raw materials were thoroughly mixed in a drum mixer according to steps listed in section of mixing procedure, fresh concrete was transferred to a bucket and filled into an inverted slump cone in one lift without tamping. The top surface of the concrete was then trowelled flat and the slump cone was lifted carefully and vertically to allow the concrete to flow under its own weight. The slump flow was measured after concrete stopped as the average of the largest diameter of the concrete and the diameter measured perpendicular to the largest diameter (Figure 3.1).

Figure 3.1-Slump flow test

3.4.2 Robustness testing

To study robustness of SCC, it is essential to be able to quantify static segregation and robustness quickly and effectively. Compared with other static segregation tests such as Column Segregation (ASTM C1610/C1610M-10) [2], Penetration Test (ASTM C1712-09) [3], V-Funnel Test [4], Electrical Conductivity [5], Sieve Segregation Resistance Test [6], Hardened Visual Stability Index (AASHTO PP58-08) [7], and Image Analysis of Hardened Cylinder [8], the modified Segregation Probe is found to be especially suitable for the assessment of a mixture's robustness against fluctuations in mix proportions [25]. First of all, only the probe and a concrete mixer are needed during the robustness test. Setup frame, mold, slump cone, electrical devices, or even sampling are not required during the test. Secondly, robustness test can be performed directly in a pan or drum mixer as long as the depth of concrete is controlled at around 300mm (12"), making it convenient to slightly modify the mix proportions. Finally, a robustness test which including a series of mixing, Segregation Probe test, and remixing takes only around 15 minutes and the effects of thixotropy and hydration are minimized.

The robustness tests were performed directly in a drum mixer with a capacity of 58 liter. The volume of concrete (43 liter) was controlled so that the concrete thickness at the measuring point was around 300mm (12"). The following procedure was followed after raw materials were mixed in a drum mixer according to mixing procedure section:

1. After mixer was stopped, the modified Segregation Probe was gently placed on the concrete surface and allowed to settle until it stopped (in about 15 second).
2. The penetration depth was measured using the scale marked on the probe.
3. The w/cm was increased by 0.01 (or 0.02 for a highly stable mixture in order to save time) by adding water and mixing for 1 minute.
4. Steps 1–3 were repeated until clear evidence of excessive segregation was observed.

3.4.3 Concrete rheology test

Rheological properties were measured using a portable rheometer with vane geometry (Figure 3.2). After the mixture was prepared following the steps in the section of mixing procedure and transferred into the rheometer, a stress growth test was performed immediately to determine the static (at-rest) yield stress. A stress growth test involves rotating the vane at a low, constant speed of 0.025 rps while monitoring the build-up in torque and the maximum measured torque used to calculate yield stress.

Figure 3.2-Vane-type concrete rheometer

Then a flow curve test was performed immediately. The test protocol consisted of a 20 seconds pre-shear period at a constant speed of 0.50 rps followed by 7 flow curve points in descending order from 0.50 to 0.05 rps (Figure 3.3). The purpose of the pre-shear period is to minimize the effects of thixotropy and to provide a consistent shear history. The dynamic yield stress and plastic viscosity were calculated from the flow curve. The calculation of the Bingham model parameters of yield stress and plastic viscosity is based on the Reiner-Riwlin equation.

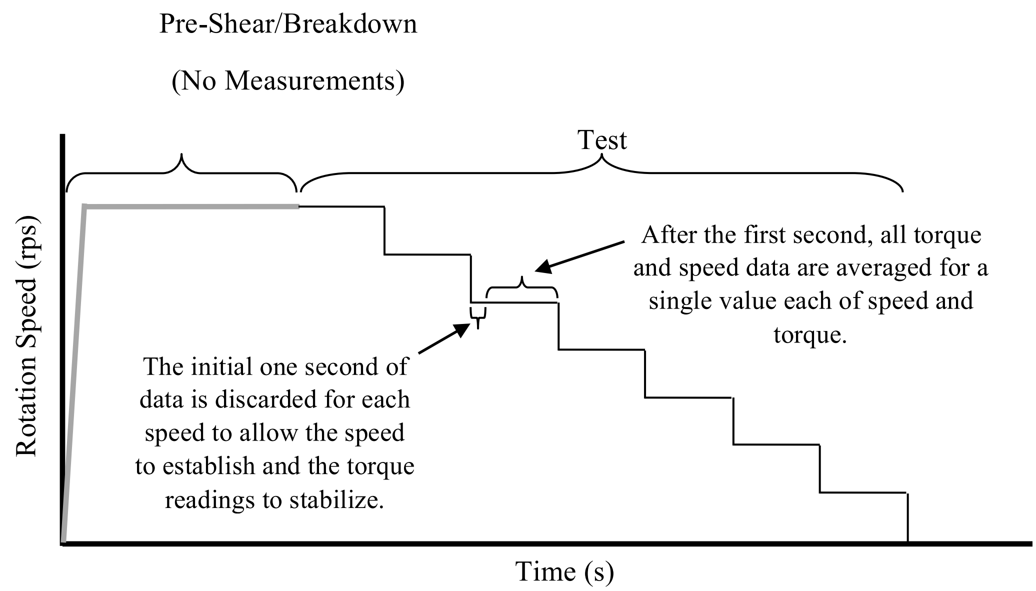


Figure 3.3-Rheological protocol to determine yield stress and viscosity of concrete for the vane-type rheometer.

3.5 RESULTS AND DISCUSSIONS

The experimental results of the fifteen SCC mixtures are summarized in Table 3.3. The effects of aggregate volume, size, gradation, FA/CA, packing density, slump flow, SP dosage, and concrete rheology on robustness will be discussed in details as follows.

Table 3.3-Experimental Results

Mix Type	Mix ID	Slump Flow mm	TMS0	TMS1	Static Yield Stress (Pa)	Dynamic Yield Stress (Pa)	Plastic Viscosity (Pa.S)
Graded Aggregate	GA	710	0.05	0.11	164	114	6
	GA + 5 %P	710	0.15	0.19	135	125	1
	GA -5 %P	710	0.00	0.00	304	234	6
Mineral Admixture	MA	710	0.03	0.04	189	65	15
	MA +5 %P	710	0.04	0.05	231	136	14
	MA -5 %P	710	0.02	0.03	173	9	31
VMA	VMA	710	0.06	0.13	433	107	27
	VMA-LS	580	0.16	0.18	NA	NA	NA
	VMA +5 %P	710	0.10	0.14	219	116	2
	VMA -5 %P	710	0.16	0.21	338	32	44
	VMA-HP	660	0.12	0.14	185	96	6
Well Balanced	WB-SA	660	0.17	0.21	380	306	7
	WB1	660	0.13	0.14	83	27	8
	WB2	660	0.17	0.20	198	30	33
	WB3	660	0.13	0.16	184	43	33

TMS1 is defined as the difference between the target w/cm and the w/cm corresponding to the limiting penetration depth of 7mm (Stability Index of 1 in Table 1). TMS0 is defined as the difference between the target w/cm and the w/cm corresponding to a penetration depth of 4mm (Stability Index of 0 in Table 1).

3.5.1 Effects of aggregate volume on robustness

Figure 3.4 shows the robustness curves of the GA, GA+5%P, and GA-5%P mixtures. Compared with the “GA” mixture, “GA+5%P” mixture had 5% more paste volume, and “GA-5%P” mixture had 5% less paste volume. Other mix proportions were virtually identical. The slump flow was controlled at 710 mm (28 in) for all three mixtures (by varying SP dosage).

Three parameters can be examined for quantifying and ranking the robustness of different mixtures: 1) the slope of the curve, 2) the Tolerable Moisture to Stability Index of 1 (TMS1), and 3) the Tolerable Moisture to Stability Index of 0 (TMS0).

The slope of the robustness curve may give a quick indication of how fast the stability decreases with higher water content. A flatter slope generally indicates higher robustness. The GA-5%P mixture has the steepest slope among the three mixtures in Figure 5, hence the least robust mixture. In some cases, the slopes of robustness curves are too close to compare and TMS1 and TMS0 can be used to further quantify the robustness.

Compared with a mixture with higher TMS1 and TMS0, a mixture with lower TMS1 and TMS0 can tolerate less moisture and admixture overdoses (due to daily aggregate moisture fluctuation, metering inaccuracies…) while maintaining its stable state. The TMS1s of GA, GA+5%P, and GA-5%P mixture were 0.11, 0.19, and 0.00, respectively. The TMS0s of GA, GA+5%P, and GA-5%P mixture were 0.05, 0.15, and 0.00, respectively. Clearly increasing paste volume had significant effect on improving robustness and the robustness ranking for GA type of mixtures is GA+5%P >GA> GA - 5%P.

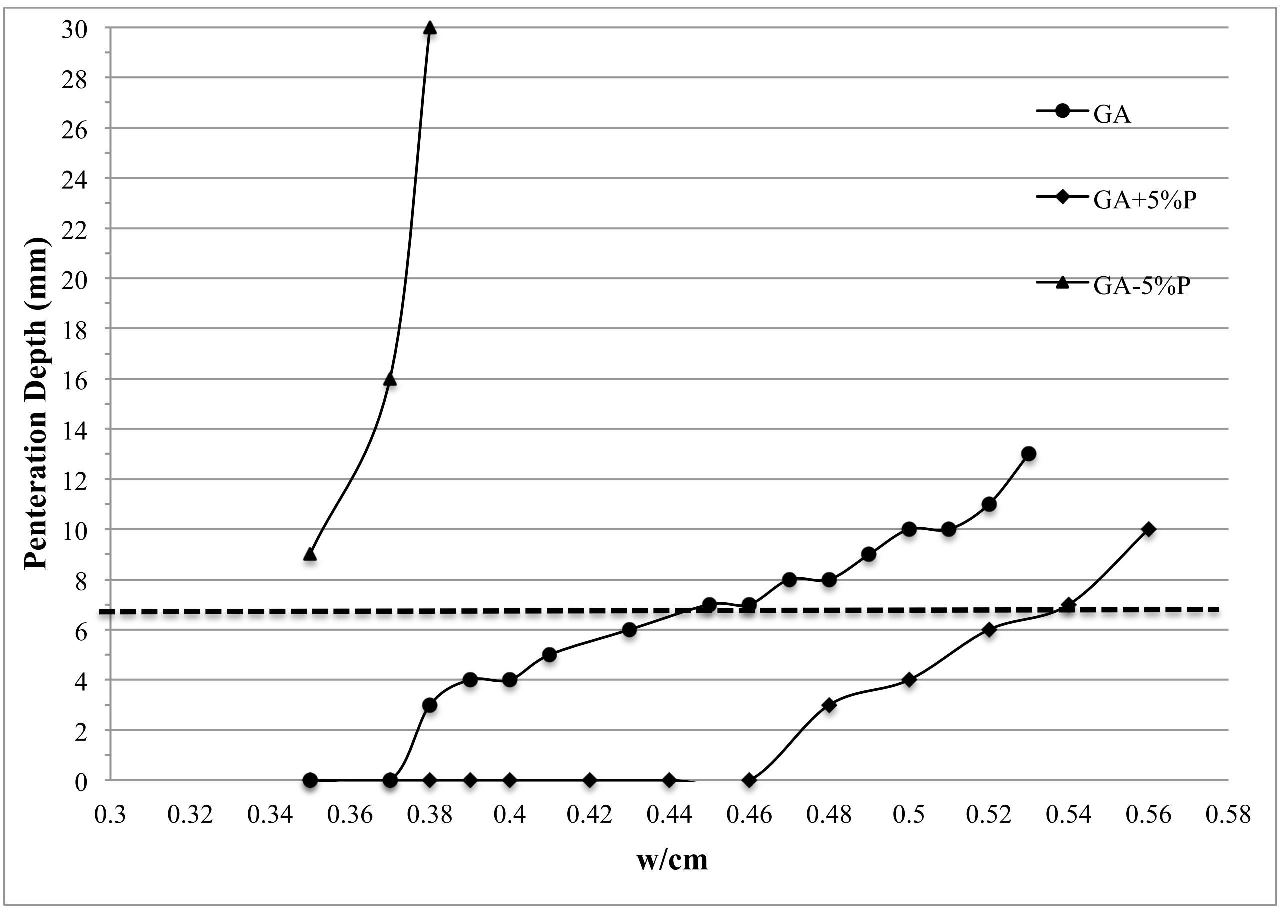


Figure 3.4-Effect of aggregate volume on robustness of graded aggregate mixtures. (TMS1 for GA, GA+5%P, and GA-5%P mixture: 0.11, 0.19, and 0.00; TMS0: 0.05, 0.15, and 0.00)

Figure 3.5 shows the robustness curves of the MA, MA+5%P, and MA-5%P mixtures. Compared with the "MA" mixture, "MA+5%P" mixture had 5% more paste volume, and "MA-5%P" mixture had 5% less paste volume. Other mix proportions were mostly the same. The slump flow was 710 mm (28 in) for all three mixtures. The slopes of the curves are too close to compare in this case. The TMS1s of MA, MA+5%P, and MA-5%P mixture were 0.04, 0.05, and 0.03, respectively. The TMS0s of MA, MA+5%P, and MA-5%P mixture were 0.03, 0.04, and 0.02, respectively. Similar to the graded aggregate mixtures, higher paste volume in mineral admixture mixtures also corresponded to improved robustness and the robustness ranking is MA+5%P >MA> MA -5%P.

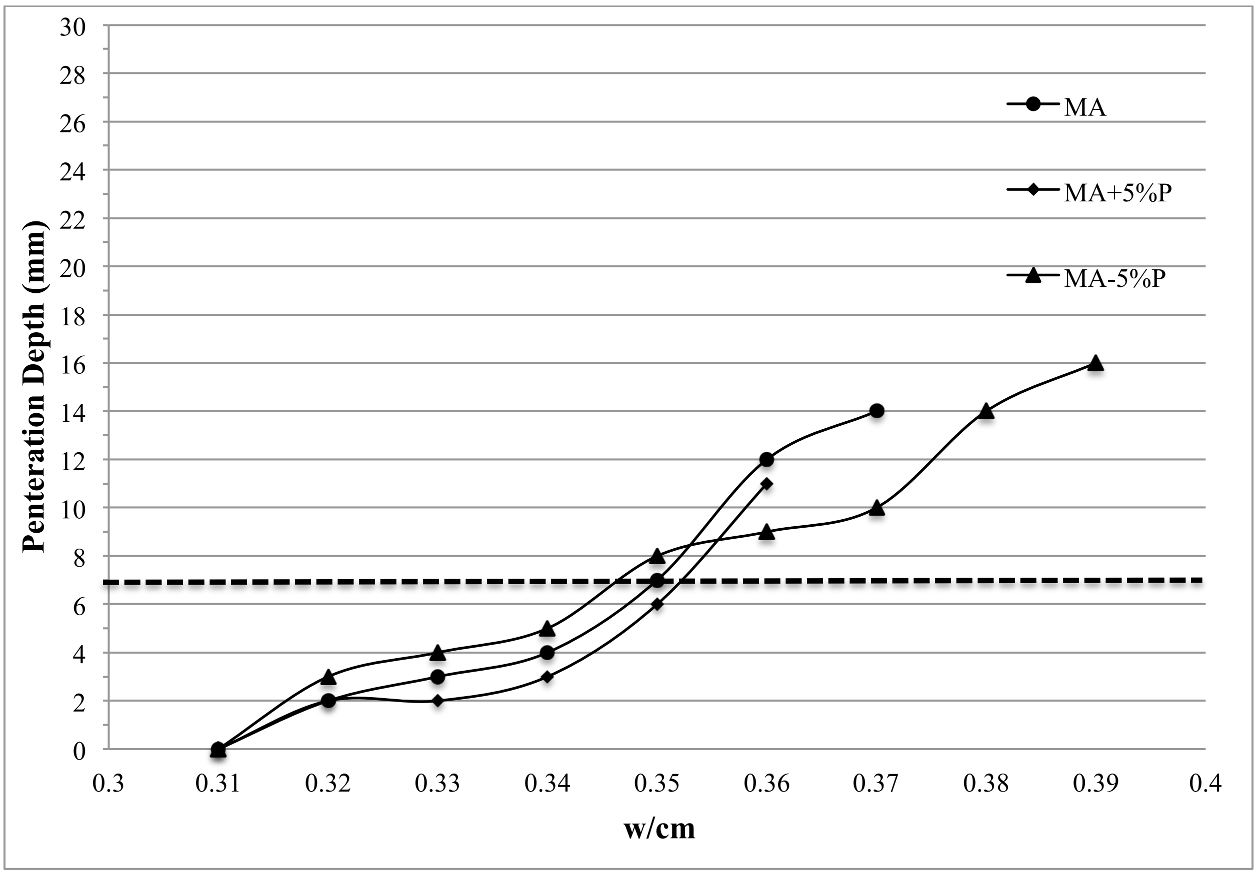


Figure 3.5-Effect of aggregate volume on robustness of mineral admixture mixtures. (TMS1 for MA, MA+5%P, and MA-5%P mixture: 0.04, 0.05, and 0.03; TMS0: 0.03, 0.04, and 0.02)

One factor that may help to explain the improved robustness for mixtures with higher paste volume is the dosage of SP and paste rheology. The SP dosages (solid % by weight of cementitious materials) of GA type of mixtures were 0.47% (GA+5%P), 0.65%

(GA), and 0.89% (GA-5%P). Also the SP dosages of MA type of mixtures were 0.44% (MA+5%P), 0.51% (MA), and 0.64% (MA -5%P). For each type of mixtures, lower SP dosage coincided with better robustness.

To further understand how SP dosage affects robustness, it may be helpful to examine the static segregation rate equation below [26],

$$u_a = u_s\left(1-\frac{\varphi}{\varphi_m}\right)^{5.18} = \frac{\left(\frac{(\rho_S-\rho_L)gd}{18}-\tau_0\right)d}{\eta_{pl}}\left(1-\frac{\varphi}{\varphi_m}\right)^{5.18} \quad (3.1)$$

Where u_a is the segregation rate of the entire set of aggregate (aggregate/paste interface), u_s is the segregation rate of a single representative particle, ϕ is the volume fraction of aggregate, ϕ_m is the packing density of aggregate, ρ_S is the density of aggregate, ρ_L is the density of paste, g is gravitational acceleration, d is the diameter of a representative aggregate, η_{pl} is paste plastic viscosity, and τ_0 is paste yield stress. According to Eqn (3.1), no segregation occurs when $\tau_0 \geq \frac{(\rho_S-\rho_L)gd}{18}$.

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 means higher yield stress and viscosity of cement paste and thus more moisture and SP can be absorbed until the yield stress and viscosity of paste are too low to hold off the coarse aggregate from settling.

From Eqn (3.1), it seems that mixture with lower aggregate volume should have higher segregation rate. However, this negative effect of lower aggregate volume on segregation rate will not play a role until the paste yield stress is too low ($\tau_0 < \frac{(\rho_S-\rho_L)gd}{18}$) to hold off the aggregate.

As will be discussed in the section of SP dosage on robustness (3.5.4), this reverse relationship of SP dosage and robustness is less obvious when different types of mixtures with various average aggregate size and packing densities are compared, which could also be expected from Eqn. (3.1).

3.5.2 Effects of target slump flow on robustness

Figure 3.6 compares the robustness curves of the VMA and VMA-LS mixtures. The two mixtures had the same proportion excepting the dosages of SP and VMA. The slump flow was 710mm (28 in) for the VMA mixture and 580 mm (26 in) for the VMA-LS mixture.

The TMS1s of VMA and VMA-LS mixtures were 0.13 and 0.18, and the TMS0s were 0.06 and 0.16, respectively. Obviously lower slump flow coincided with better robustness, which can still be explained by the higher paste yield stress and viscosity of the VMA-LS mixture. The SP dosage was 0.22% for the VMA mixture and 0.17% for the VMA-LS mixture. Again, according to Eqn. (3.1), less SP % means higher yield stress and viscosity of paste and a mixture can absorb more moisture and SP before segregation occurs.

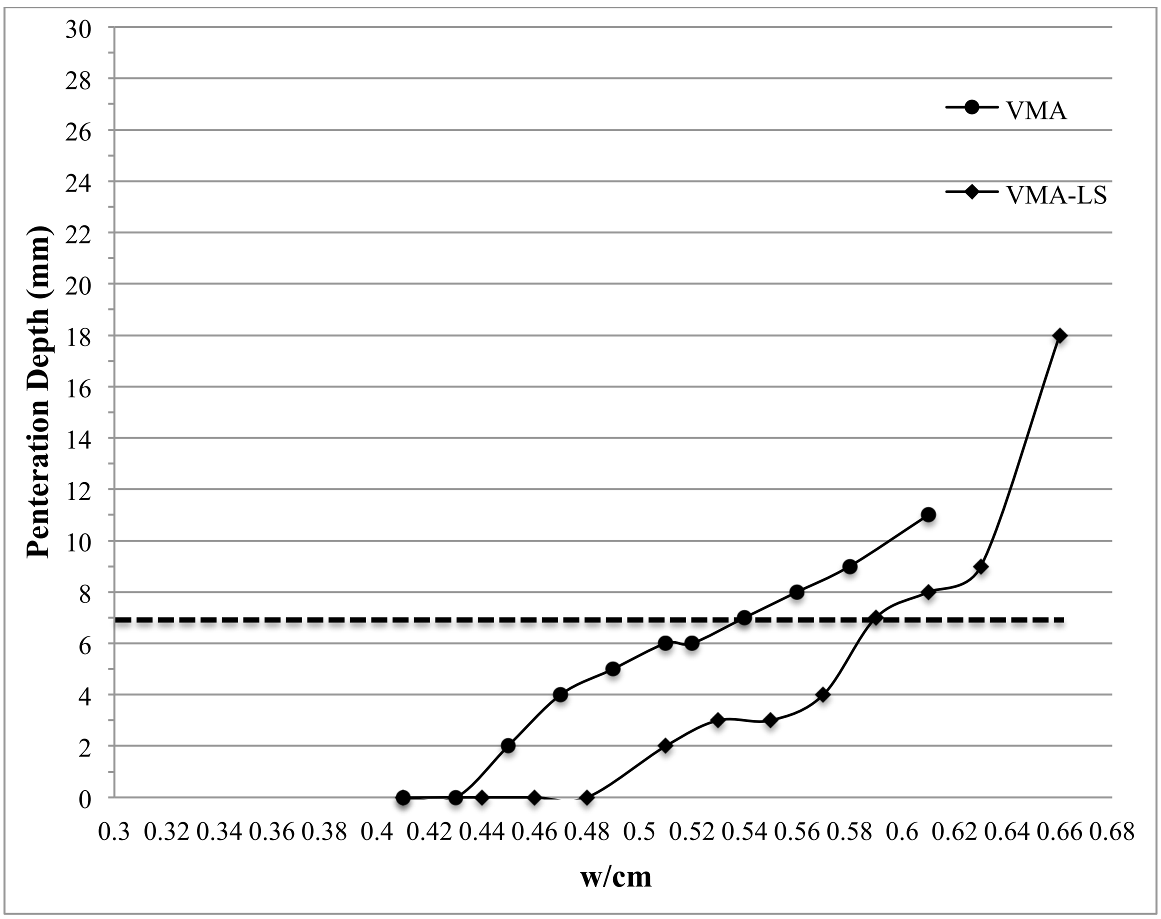


Figure 3.6-Effect of target slump flow on robustness of VMA mixtures. (TMS1 for VMA, and VMA-LS mixture: 0.13 and 0.18; TMS0: 0.06 and 0.16)

3.5.3 Effects of aggregate size, gradation, FA/CA ratio, and packing density on robustness

Figure 3.7 shows the combined effects of aggregate size and gradation on robustness. Compared with the VMA mixture, which had 19-mm coarse aggregate, the WB-SA mixture had smaller (9.5-mm) coarse aggregate and better gradation (two types of sand instead of one). The aggregate packing densities (ϕ_m) of two mixtures were the same. TMS1s for VMA and WB-SA mixture were 0.13 and 0.21, and TMS0s were 0.06 and 0.17, respectively. Clearly reducing aggregate size and improving gradation can improve robustness significantly.

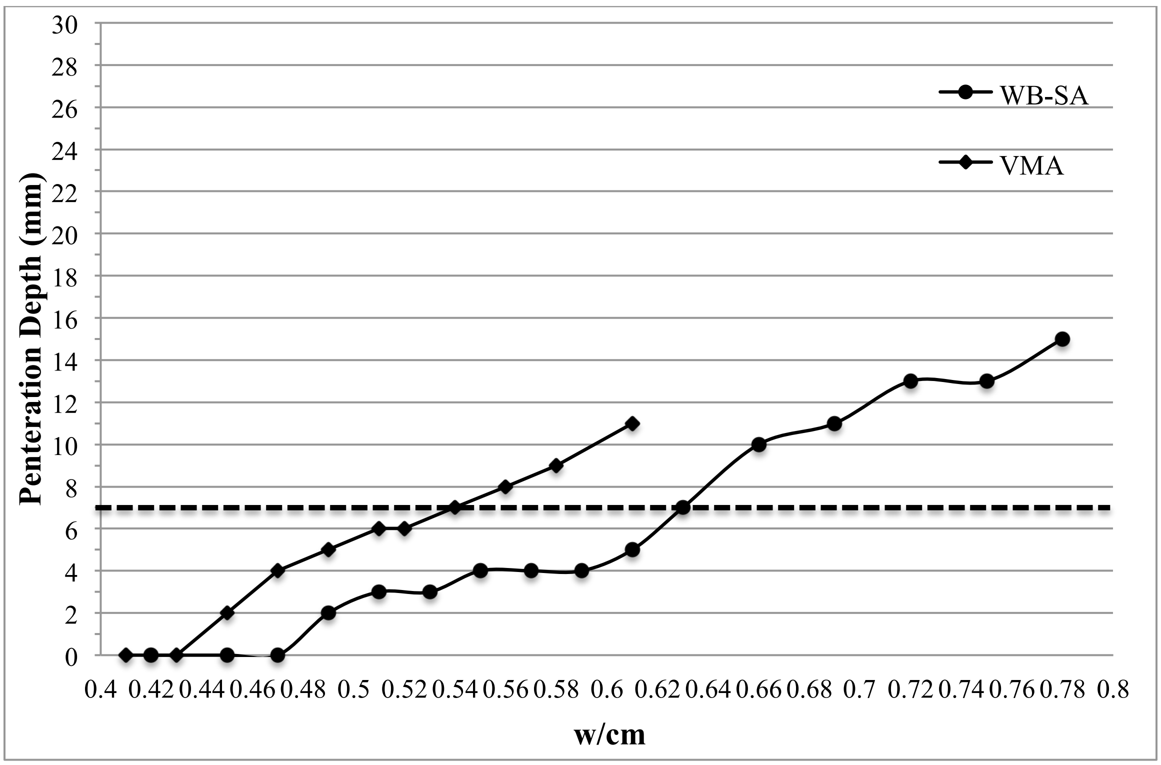


Figure 3.7-Effect of aggregate size and gradation on robustness. (TMS1 for VMA and WB-SA mixture: 0.13 and 0.21; TMS0: 0.06 and 0.17)

Figure 3.8 illustrates how robustness was influenced by aggregate size and packing density. The WB-SA mixture had only one coarse aggregate (9.5-mm) and a ϕ_m of 0.66. The WB1 mixture had both large (19-mm) and medium size (9.5-mm) coarse aggregate and a ϕ_m of 0.74. The WB2 mixture had both large (19-mm) and medium size (9.5-mm) coarse aggregate and a ϕ_m of 0.71. Compared with the WB1 mixture, WB2 mixture has smaller average aggregate size (less 19-mm coarse) and a lower ϕ_m. There is no other major difference in mix proportions of these mixtures. The TMS1s of WB-SA, WB1, and WB2 mixture were 0.21, 0.14, and 0.20; and TMS0s were 0.17, 0.13, and 0.17, respectively. It seems that reducing the aggregate size had a more significant effect on improving robustness compared with increasing ϕ_m.

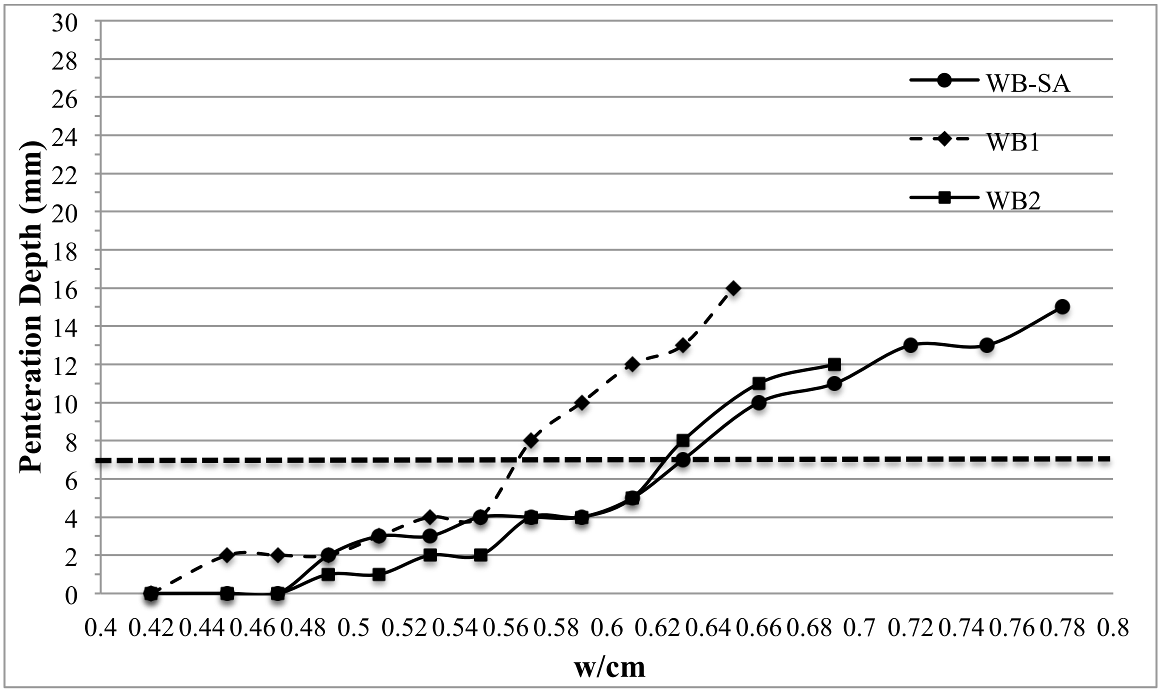


Figure 3.8-Effect of aggregate size and packing density on robustness. (TMS1 for WB-SA, WB1, and WB2 mixture: 0.21, 0.14 and 0.20; TMS0: 0.17, 0.13, and 0.17)

The improved robustness with smaller aggregate can also be explained based on Eqn (3.1). Since no segregation occurs when $\tau_0 \geq \frac{(\rho_S - \rho_L)gd}{18}$, smaller aggregate size d will reduce the minimum required yield stress of paste above which segregation will not occur. As a result, mixture with smaller aggregate can absorb more moisture and SP because it requires lower paste yield stress to hold off the coarse aggregate from settling. Furthermore, it can be observed from Eqn (3.1) that smaller d will also reduce the segregation rate after segregation starts. Compared with aggregate size, the relatively smaller effect of ϕ_m may be due to the fact that ϕ_m will not play a role until segregation occurs.

Figure 3.9 shows how FA/CA ratio and average aggregate size influencing robustness. Compared with the VMA-HP mixture, the WB2 mixture had a larger FA/CA ratio (1.53 vs. 0.56) and smaller average aggregate size. No other major differences between these two mixtures. Again, reducing aggregate size and increasing FA/CA ratio can improve robustness.

The higher FA/CA ratio has two effects on the mix proportion: 1) reduced average aggregate size, and 2) less required SP dosage due to the lubricant effects of sand particles between coarse aggregate. As discussed previously, both these effects will help improve robustness.

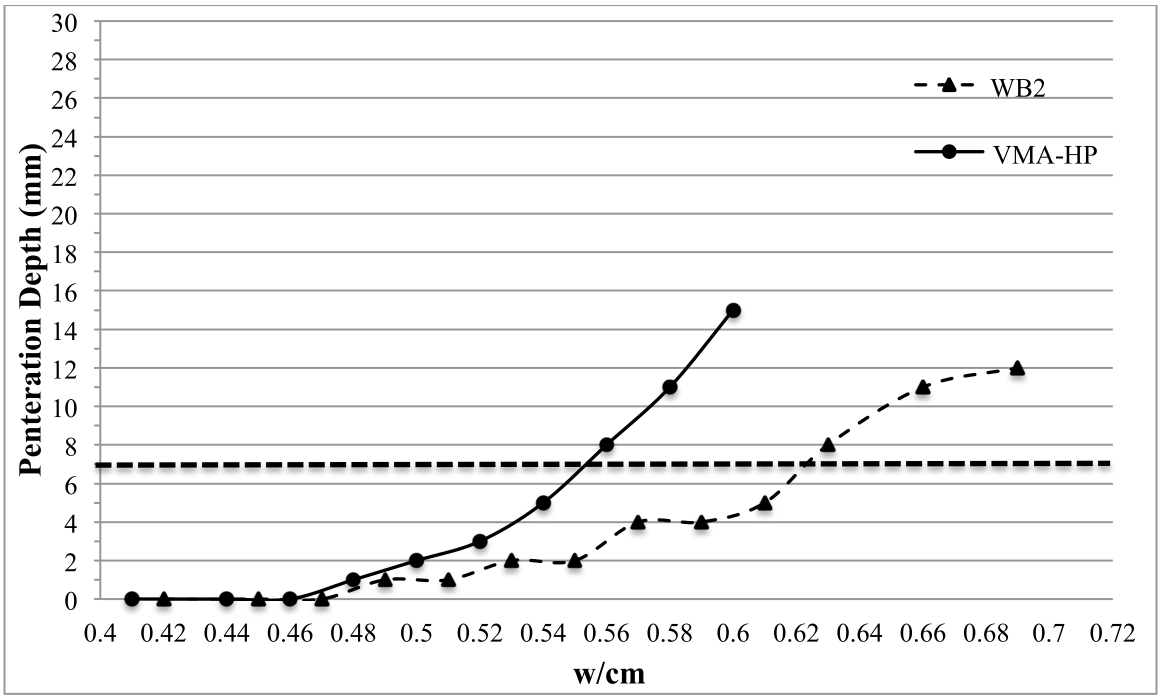


Figure 3.9-Effect of FA/CA ratio on robustness. (TMS1 for WB2 and VMA-HP mixture: 0.20 and 0.14; TMS0: 0.17 and 0.12)

3.5.4 Effects of SP dosage on robustness

It was found from the section of effect of aggregate volume on robustness (section 3.5.1) that there was a clear reverse relationship between SP dosage and robustness within the same type of mixture (GA, MA, e.g.): mixtures with less SP % by weight of cement showed better robustness. The reason is because less SP dosage means higher yield stress and viscosity of paste, and thus more moisture and SP can be absorbed until the paste yield stress and viscosity are too low to prevent the coarse aggregate from settling.

Figures 3.10 and 3.11 show how TMS1 and TMS0 were influenced by SP % by weight of cement when different types of mixtures were compared together. The slump flow was controlled at 710 mm (28 in) for all mixtures. The reverse relationship between SP dosage and robustness is less obvious when different types of mixtures with various aggregate properties are compared. Based on Eqn. (3.1), the segregation rate is a function of not only yield stress and viscosity of paste, but also aggregate size, volume, and packing density. The effect of paste rheology (via SP dosage) became less obvious when more variables were introduced.

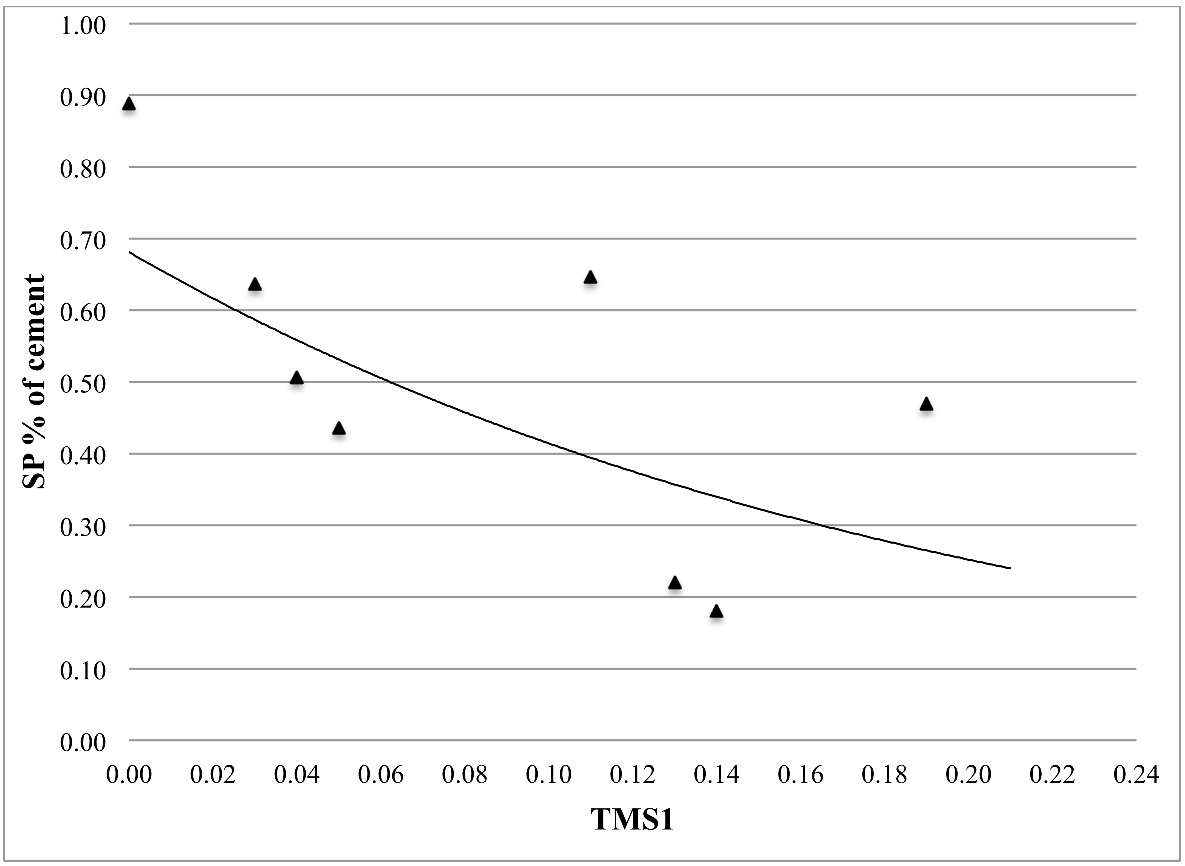


Figure 3.10-Effect of SP % by weight of cement on TMS1 for SCC mixtures with 710mm (28 in) slump flow.

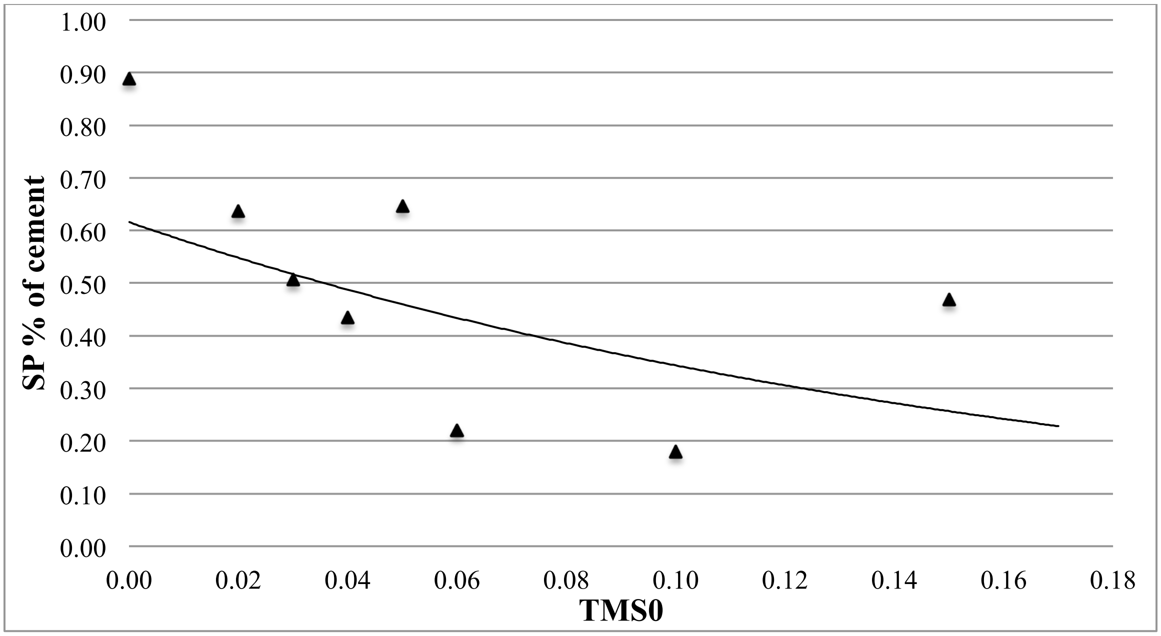


Figure 3.11-Effect of SP % by weight of cement on TMS0 for SCC mixtures with 710 mm (28 in) slump flow.

3.5.5 Effects of concrete rheology

Figures 3.12, 3.13 and 3.14 present how TMS1 was influenced by concrete static yield stress, plastic viscosity, and dynamic yield stress. No clear correlation was found in each case. Based on Eqn. (3.1), the controlling factors for static segregation rate and robustness are yield stress and viscosity of paste, and aggregate size, volume, as well as ϕ_m. Although concrete rheology is also influenced by paste rheology, aggregate volume, and $\phi_{m,}$ no direct relationship was observed between concrete rheology and robustness in this study.

The paste rheology of the mixtures in Table 3.2 is planned to be measured in future study of robustness.

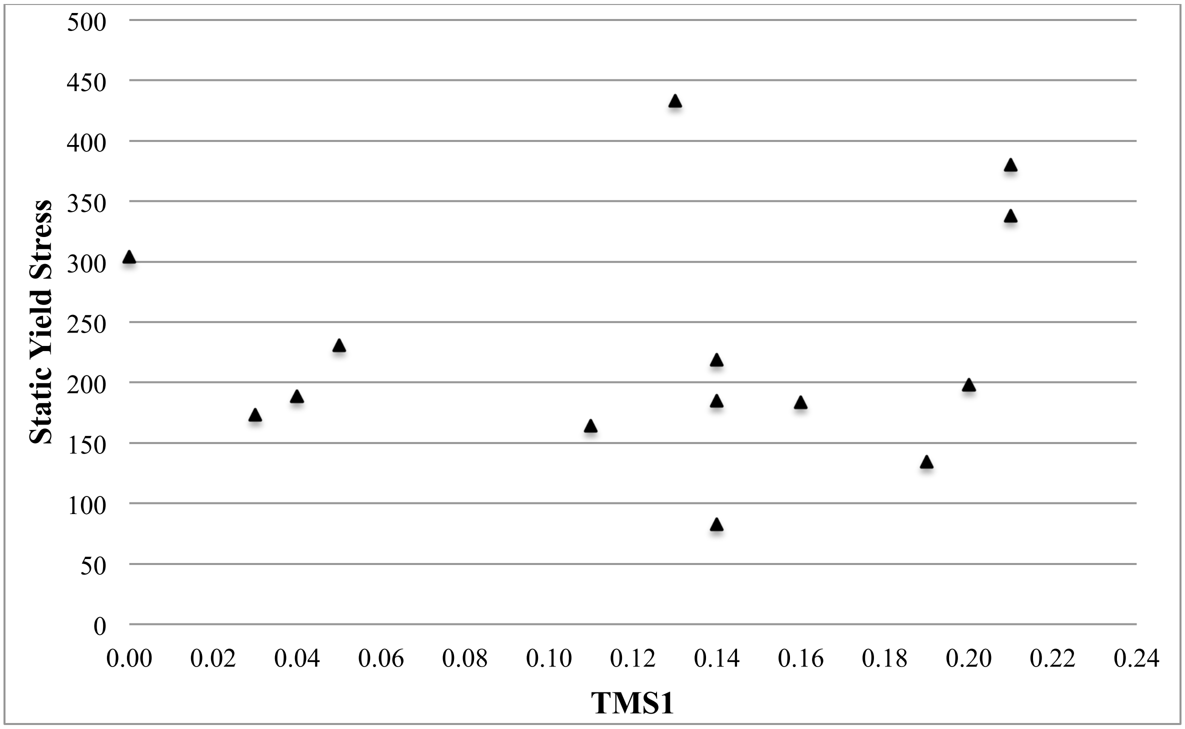


Figure 3.12-Effect of static yield stress of concrete on TMS1.

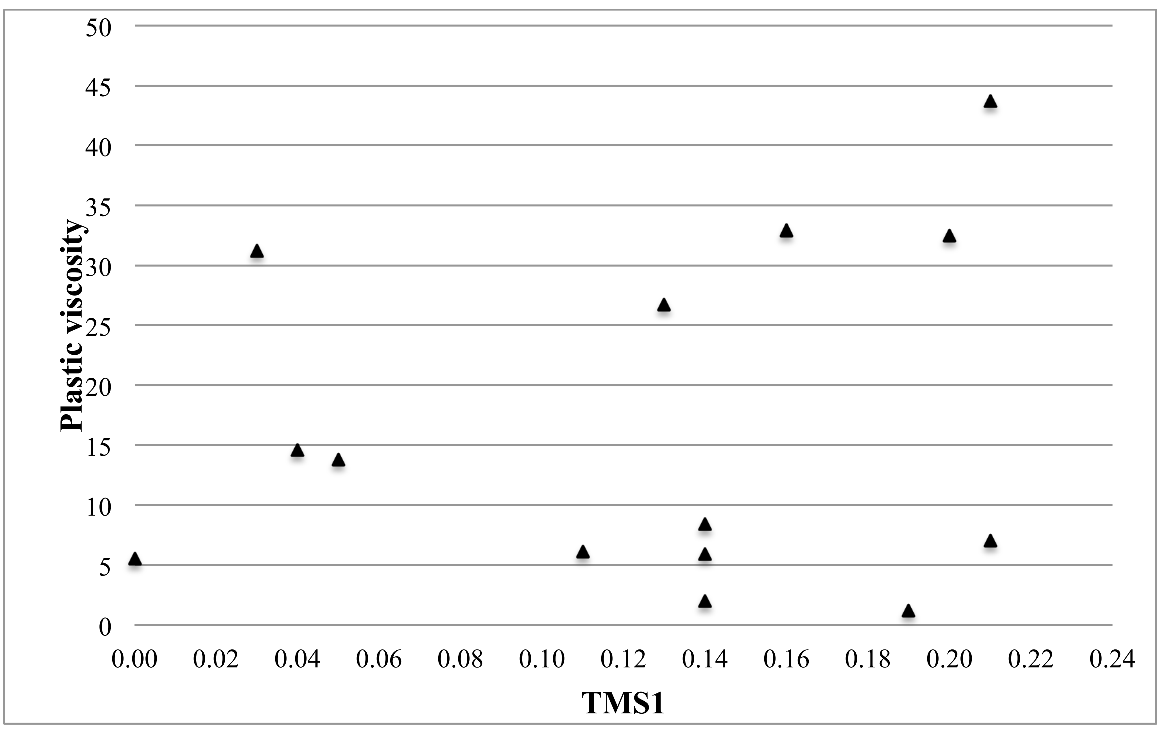


Figure 3.13-Effect of concrete plastic viscosity on TMS1.

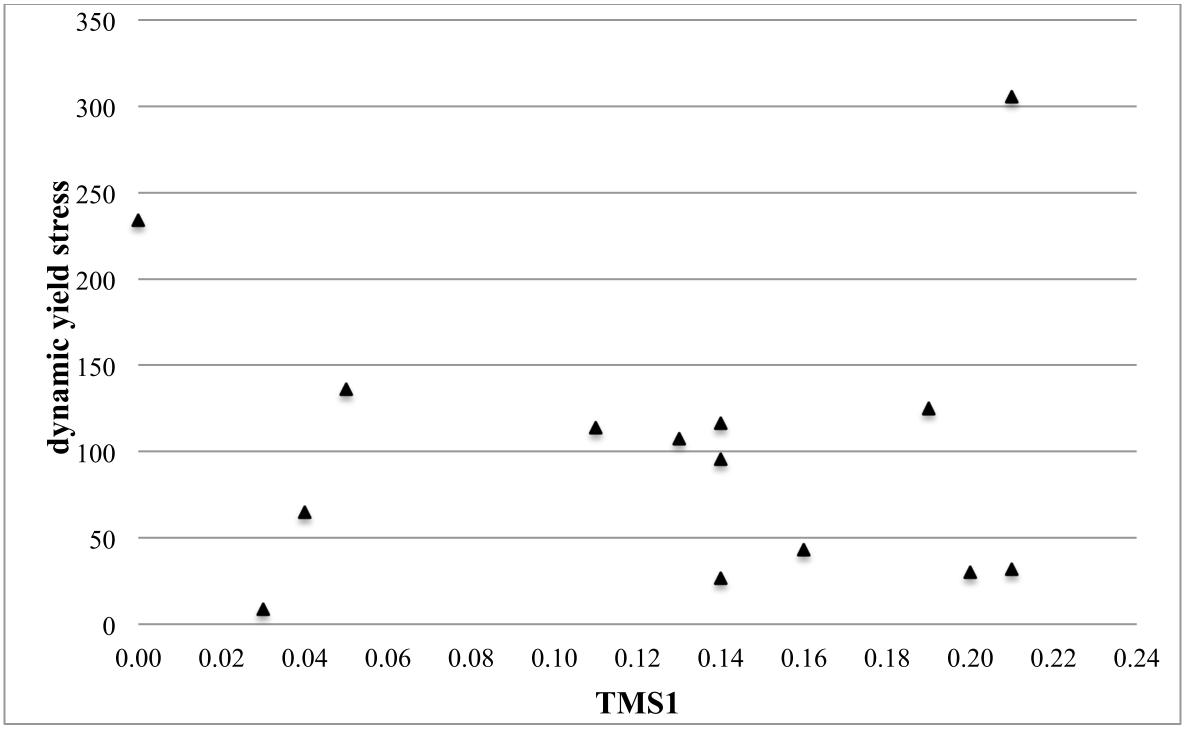


Figure 3.14-Effect of dynamic yield stress of concrete on TMS1.

3.6 CONCLUSION

The following conclusions can be drawn from the results and discussions of this chapter:

1) The robustness of SCC mixtures can be well quantified and compared based on the slope of robustness curves, TMS1, and TMS2.

2) The static segregation rate equation in Eqn. (3.1):

$$u_a = u_s\left(1-\frac{\varphi}{\varphi_m}\right)^{5.18} = \frac{\left(\frac{(\rho_s-\rho_L)gd}{18}-\tau_0\right)d}{\eta_{pl}}\left(1-\frac{\varphi}{\varphi_m}\right)^{5.18}$$

may be used to explain how various factors affect the robustness. However, caution should be taken when one factor affects multiple variables in the equation simultaneously.

3) Higher paste volume may improve robustness by reducing the required yield stress and viscosity of cement paste to maintain the same concrete slump flow.

4) The effects of aggregate volume and aggregate packing density on robustness will not play a role until the paste yield stress is too low to hold off the aggregate from settling.

5) Concrete with higher slump flow has reduced robustness due to lower paste yield stress and viscosity.

6) While smaller aggregate size, better gradation, and higher aggregate packing density can all improve robustness of SCC mixtures, smaller aggregate size and better gradation seem to have more significant impact on robustness than higher aggregate packing density.

7) Higher FA/CA ratio improves robustness due to: 1) reduced average aggregate size, and 2) less required SP dosage (and higher paste yield stress and viscosity) because of the lubricant effects of sand particles between coarse aggregate.

8) Lower SP % by weight of cement improves robustness by increasing yield stress and viscosity of paste.

9) As expected, no direct relationship was observed between concrete rheology and robustness in this study. The paste rheology of the mixtures will be measured in future study of robustness.

CHAPTER 4

DYNAMIC SEGREGATION

4.1 BACKGROUND

The main functional requirements for self-consolidating concrete (SCC) during the fresh state are flowing ability, passing ability, and segregation resistance. Segregation refers to movement of coarse aggregate relative to the mortar. It is useful to distinguish between two types of segregation, dynamic and static. Dynamic segregation occurs when the concrete is flowing and the coarse aggregate lags behind the mortar. Static segregation occurs when the concrete is at rest and the coarse aggregate sinks in the mortar. Segregation may cause lower flowability, aggregate blocking, higher drying shrinkage, and non-uniform compressive strength.

Segregation resistance in SCC is normally achieved by reducing free water content and adding a finely powdered material such as silica fume, fly ash, or limestone filler [27-29]. A viscosity-modifying admixture (VMA) is sometimes used to control segregation by increasing the capacity to retain free water and increasing the viscosity of the suspended liquid phase [11, 30, 31]. Decreasing slump flow (increasing concrete yield stress), w/cm, paste volume, aggregate size, increasing plastic viscosity, as well as using well-graded coarse aggregate may reduce dynamic segregation [32].

Regardless of these strategies, segregation problems are still commonly observed in SCC mixtures. And there is still a lack of understanding of the mechanism of how various aggregate properties and the rheology of cement paste and concrete affect dynamic segregation.

Accurate and reliable test methods are essential in order to study segregation of SCC. The V-funnel test [4], L-Box, U-Box and J-Ring tests [30,33] do not predict segregation directly, but are related to both static and dynamic segregation by considering the rheological properties measured by these tests [34].

The L-box test [30] consists of flow of concrete in an L-shaped container. The apparatus comprises a vertical section in which concrete is poured and a horizontal section through which the concrete flows when the trap door (located at the intersection of vertical and horizontal sections) is opened. The L-box test determines the ratio of concrete height in the horizontal section to the vertical section of the test apparatus.

To perform the J-ring test, the inverted slump cone is placed at the center of the J-ring apparatus (a 300 mm (12 in) diameter steel ring attached to vertical reinforcing bars at 60-mm (2.3 in) spacing) and the diameter of concrete spread is measured, and, then, is compared with the unconfined slump flow diameter.

The U-box test [33] is used to assess the passing ability of SCC. This test consist of apparatus, which has a 'U' shape and an opening with a sliding gate is fixed between the two compartments with vertical steel bars as obstructions. Concrete is made to flow through the obstructions and the difference in concrete height in the right section and left section of the container is reported.

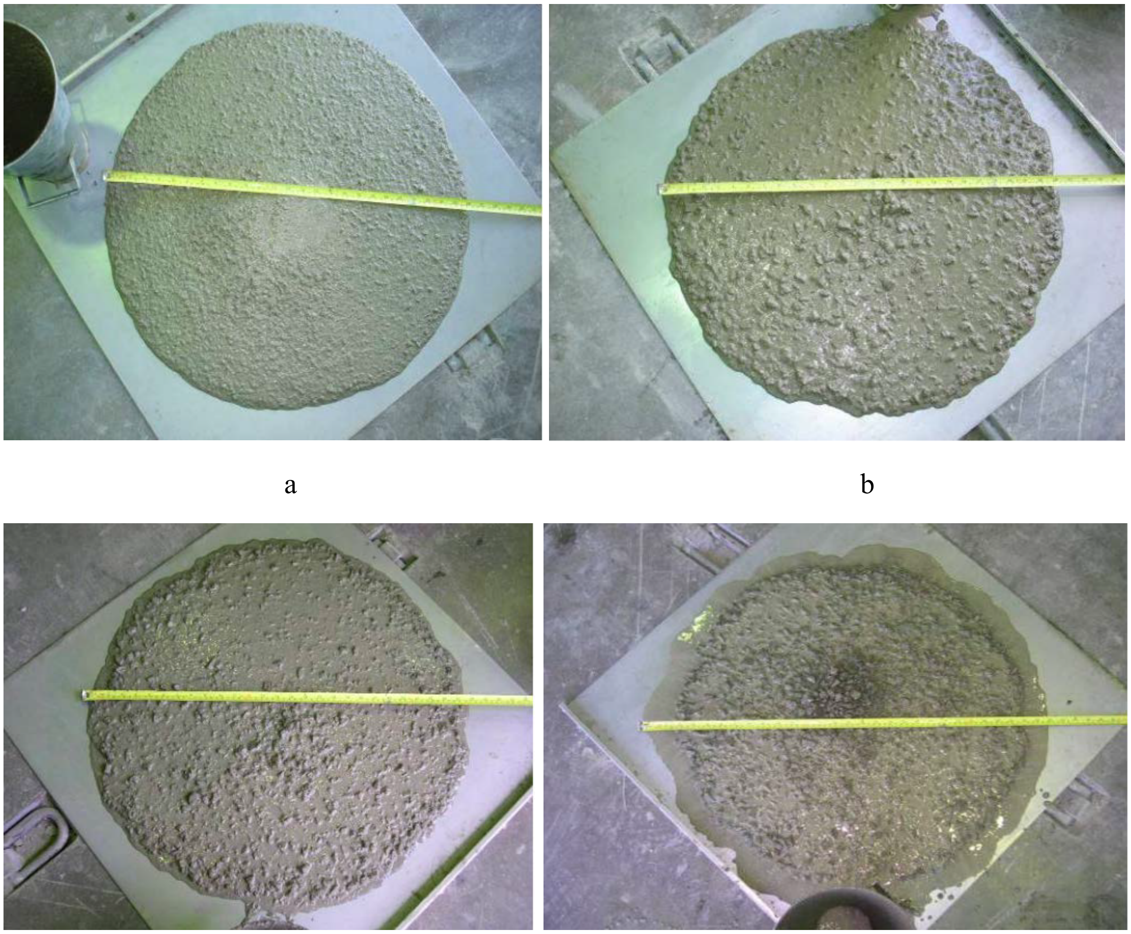
Currently, the only standard method for testing dynamic segregation of SCC is the visual stability index (VSI) [24]. Other methods such as the V-funnel [4], LCPC method [35], and sieve segregation resistance test [6] can also give useful information on predicting dynamic segregation, though these tests do not provide direct measurements of dynamic segregation.

4.1.1 Visual Stability Index (VSI) of Slump Flow Test

The stability of self-consolidating concrete can be observed visually by examining the concrete mass and therefore can be used for quality control of self-consolidating concrete mixtures [24]. The Visual Stability Index (VSI) Test is used to evaluate the dynamic segregation of SCC by observing coarse aggregate distribution at the border of the concrete after the slump flow test [24]. The VSI test is basically a visual ranking of the SCC sample on a scale of 0-3 with 0 being the highest stability. The concrete is inspected for segregation, bleeding and aggregate size distribution (figure 4-1) according to table 4.1. However, as will be discussed in following Sections, SCC with good VSI may have severe dynamic segregation problem especially over a long travel distance.

Table 4.1-Visual Stability Index Values [24]

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



a b

c d

Figure 4.1- Visual Stability Index (VSI) of Slump Flow Test, a)VSI=0; b) VSI=1; c) VSI=2; d) VSI=3

However, as will be discussed in following Sections, SCC with good VSI may have severe dynamic segregation problem especially over a long travel distance. To better quantify dynamic segregation and to understand the mechanisms responsible, a more reliable dynamic segregation test is urgently needed.

4.2 OBJECTIVES

The main objective of this chapter is to provide a new test for measuring dynamic segregation and study the effects of aggregate properties and concrete rheology on dynamic segregation of SCC mixtures based on experimental tests and rheological models.

This new test for measuring dynamic segregation is based on earlier work of Shen et al [36]. The test may be performed in the laboratory or in the field.

4.3 NEW DYNAMIC SEGREGATION TEST PROCEDURE

A laboratory test for dynamic segregation needs to satisfy several requirements. First, the test must be sensitive enough to detect meaningful differences in dynamic segregation. To that end, the flowing distance should be long enough to give useful information about dynamic segregation in typical field conditions. Typical flow distance of SCC in the field ranges from 2 to 10 m (6 to 33-ft). Obviously it is not practical to make a 10-m (33-ft) long apparatus for testing dynamic segregation. At the same time, a testing method with a short traveling distance may not be sensitive enough to reveal dynamic segregation in a long traveling distance. As discussed in later sections, SCC with a good visual stability rating from the slump flow test, in which the traveling distance is quite short, can exhibit severe dynamic segregation over a longer traveling distance. The second requirement is that the amount of sample concrete should be small enough to be easily handled in the laboratory. The testing apparatus should be portable and easy to construct. Finally, the test results must be sufficiently precise and accurate that results can be used with confidence.

To meet these requirements, the flow trough shown in Figure 4.2 was developed. It was made by assembling 25-mm (1-in) thick wood boards to form a 0.15-m by 0.15-m by 1.80-m (6-in by 6-in by 6-ft) trough. The 0.23-m (9-in) height difference between two ends gives a 7^{o} angle of inclination, which was the smallest slope that allowed the SCC to flow to the lower end based on previous experience of the authors. The surface of the trough was painted to make it water-resistant and easy to wash.

Using this trough, the test was performed according to the following procedure:

1. Before the test, the surface of trough was slightly wetted with water and superficial water was wiped off.
2. Fresh concrete was measured using a single lift into one 100-mm by 200-mm (4-in by 8-in) cylinder mold, one 150-mm by 300-mm (6-in by 12-in) cylinder mold, and a water-tight container having a volume of around 13.5 liter (~3.5 gallon).

3. The concrete in the 150-mm by 300-mm (6-in by 12-in) mold was poured onto the trough from the higher end as a priming step.
4. After the concrete stopped flowing, the trough was straightened up vertically for 30 sec to let the priming concrete flow off and leave a mortar layer on the trough surface.
5. The trough was then put back into initial inclined position and the concrete in 13.5-liter container was poured gradually and continuously on the trough from the higher end.
6. Another empty 100-mm by 200-mm (4-in by 8-in) mold was filled with the leading portion of concrete flowing through the trough.
7. Coarse aggregates were collected from the concrete samples in the two 100-mm by 200-mm (4-in by 8-in) molds, one collected at the beginning of the flow test (step 2) and the other collected at the end of the test (step 6), by washing the concrete samples over a 4.8-mm (0.19-in, #4) sieve.
8. Each coarse aggregate sample was weighed.
9. The dynamic segregation index (DSI) was then calculated as

$$DSI = (CA1-CA2)/CA1 \qquad (4.1)$$

where CA1 is the weight of coarse aggregate in the first 100-mm by 200-mm (4-in by 8-in) mold, collected at the beginning of the test, and CA2 is the weight of coarse aggregate in the second 100-mm by 200-mm (4-in by 8-in) mold, collected at the end of the test.

The priming step has two main advantages. First, it eliminates any variation in surface friction when different materials are used to construct the flow trough. Second, it more closely simulates the situation in formwork, where SCC is flowing over previously poured concrete except at the very beginning of the pour.

Figure 4.2. Flow trough for dynamic segregation. The trough dimensions are 0.15-m by 0.15-m by 1.80-m (6-in by 6-in by 6-ft)

4.4 VERIFICATION OF NEW DYNAMIC SEGREGATION TEST

4.4.1 Details of materials

Type I Portland cement complying with ASTM C150/C150M-12 and type C fly ash complying with ASTM C618-12a were used. Coarse aggregate "Coarse1" is crushed basalt rock, has maximum size of 19mm, bulk specific gravity of 2.56, bulk density of 1473 kg/m^3, and packing density of 0.55. Coarse aggregate "Coarse2" is crushed basalt rock, has maximum size of 9.5mm, bulk specific gravity of 2.67, bulk density of 1491 kg/m^3, and packing density of 0.54. Fine aggregate "Fine1" has bulk specific gravity of 2.71, bulk density of 1460 kg/m^3, fineness modulus of 1.55, and packing density of 0.54. Fine aggregate "Fine2" is crushed basalt rock, has bulk specific gravity of 2.51, bulk density of 1677 kg/m^3, fineness modulus of 3.50, and packing density of 0.63. The gradation curves of coarse and fine aggregates are shown in Figure 4.3.

A third-generation superplasticizer (SP, polycarboxylate-based) was used. It was a milky brown solution with a specific gravity of 1.06 and a solid content of 35%. The VMA (methyl-hydroxy-ethyl cellulose) used had a specific gravity of 1.00 and a solid content of 35%.

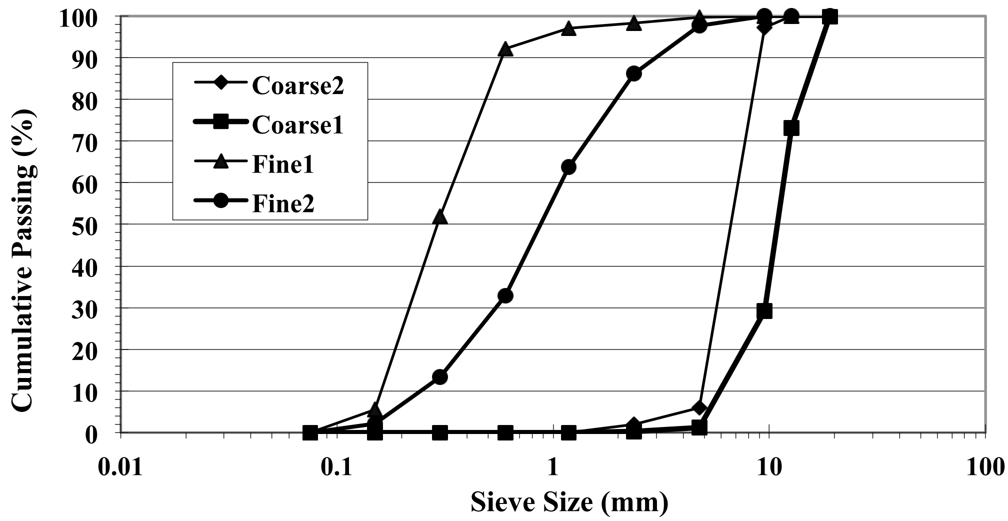


Figure 4.3-Gradation curves of coarse and fine aggregates.

4.4.2 Mix proportions and procedure

As shown in Table 4.2, a total of twenty-nine mixtures were tested to compare the results of the two dynamic segregation tests: flow trough and slump flow tests.

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.

Each batch of concrete has a volume of about 43 liter (1.5 ft^3) and was prepared in a drum mixer with a capacity of 57 liter (2 ft^3). The following procedure was used:

1. Sand, coarse aggregate, and one third of water were put in a drum mixer and mixed for 30s.

2. Cement and mineral admixture, if any, were put in the mixer and mixed for 3 minutes and remaining water was slowly added during the first minute of mixing process.

3. Mixer was stopped for 3 minutes.

4. Mixer was restarted, and SP and/or VMA were slowly poured and mixed for 2 minutes before the slump flow, flow trough, and/or rheology tests.

Table 4.2-Proportions of SCC mixtures

Mix Type	Mix ID	w/cm	Material kg/m3							Aggregate Properties				Admixture ml/m3	
			Cement (Type I)	Fly Ash Class C	Coarse1	Coarse2	Fine1	Fine2	Water	%AGG	FA/CA	Coarse1 %	ϕ_m	SP	VMA
	GA	0.35	450	107	198	579	756		195	59	1.00	0.13	0.67	9707	0
	GA-LS	0.35	450	107	198	579	756		195	59	1.00	0.13	0.67	3269	0
	GA-HS	0.35	450	107	198	579	756		195	59	1.00	0.13	0.67	10576	0
Graded Aggregate	GA + 5 %P	0.35	506	120	181	530	692		219	54	1.00	0.13	0.67	7908	0
	GA -5 %P	0.35	394	94	214	629	821		171	64	1.00	0.13	0.67	11696	0
	GA-A	0.38	405	96	193	989	557		190	64	0.47	0.11	0.70	8974	0
	GA-A	0.38	486	93	178	688	739		219	59	0.85	0.11	0.68	3481	0
	GA-A	0.46	372	88	208	650	844		213	63	1.00	0.12	0.73	5175	0
	MA	0.31	442	239	693		678		211	53	1.01	0.50	0.65	9299	0
	MF-LS	0.31	442	239	693		678		211	53	1.01	0.50	0.65	5000	0
	MA-HS	0.31	442	239	693	0	678		211	53	1.01	0.50	0.65	10692	0
Mineral Admixture	MA +5 %P	0.31	487	263	627		621		233	48	1.01	0.50	0.65	8804	0
	MA -5 %P	0.31	398	215	749		743	0	190	58	1.01	0.50	0.65	10501	0
	MA-A	0.39	393	212	168	647	683		234	56	0.85	0.11	0.71	9018	0
	MA-A	0.39	393	212	168	647	683		234	56	0.85	0.11	0.71	5881	1567
	MA-A	0.39	358	194	196	612	794		213	60	1.00	0.12	0.73	7906	0
	VMA	0.41	515		854		729		209	62	0.87	0.53	0.66	3051	1371
	VMA-LS1	0.41	515		854		729		209	62	0.87	0.53	0.66	2370	1371
	VMA-LS2	0.41	515		854		729		209	62	0.87	0.53	0.66	2716	1371
	VMA-HS	0.41	515		854	0	729		209	62	0.87	0.53	0.66	4807	1371
VMA	VMA +5 %P	0.41	582		783		670		236	57	0.87	0.53	0.66	2823	809
	VMA -5 %P	0.41	447		923		789		181	67	0.87	0.53	0.66	3497	881
	HP	0.41	585	0	468	593	585		238	59	0.56	0.28	0.71	8044	1360
	VMA-A	0.51	467		469	593	586		238	61	0.56	0.28	0.71	4651	1683
	VMA-A	0.51	457		186	718	759		234	62	0.85	0.11	0.71	5813	4809
	WB-SA	0.42	474		0	712	188	748	199	63	1.34	0.00	0.66	4090	1424
Well Balanced	WB1	0.42	502		533	115	222	743	211	61	1.53	0.33	0.74	3383	1131
	WB2	0.42	502		509	136	445	522	211	61	1.53	0.31	0.71	5007	1131
	WB3	0.36	502		534	142	467	547	181	64	1.53	0.31	0.71	6495	646

4.4.3 Flow trough and VSI of the slump flow test

Table 4.3 shows results of slump flow, Visual Stability Index (VSI) from the slump flow test, and Dynamic Segregation Index (DSI) from the flow trough test. The value of DSI varies between 2 and 31%, while the VSI ranges between 0 and 3, and slump flow values of the mixtures ranges between 580 and 760 mm (23 and 30 inch). DSI of mixture VMA-LS1 could not be measured due to very low slump flow.

Table 4.3-Comparison of flow trough and VSI from slump flow tests

Mix Type	Mix ID	w/cm	Slump Flow mm	VSI	DSI (%)
Graded Aggregate	GA	0.35	710	1	5
	GA-LS	0.35	610	1	15
	GA-HS	0.35	760	2	22
	GA + 5 %P	0.35	710	1	11
	GA -5 %P	0.35	710	1	14
	GA-A	0.38	660	3	10
	GA-A	0.38	670	1	8
	GA-A	0.46	710	0	7
Mineral Admixture	MA	0.31	710	0	3
	MA-LS	0.31	630	0	3
	MA-HS	0.31	760	3	10
	MA +5 %P	0.31	710	0	4
	MA -5 %P	0.31	710	2	21
	MA-A	0.39	740	3	21
	MA-A	0.39	740	1	7
	MA-A	0.39	710	2	26
VMA	VMA	0.41	710	1	15
	VMA-LS1	0.41	580	0	N/A
	VMA-LS2	0.41	630	0	6
	VMA-HS	0.41	760	1	12
	VMA +5 %P	0.41	710	1	13
	VMA -5 %P	0.41	660	1	2
	HP	0.41	660	1	12
	VMA-A	0.51	690	1	10
	VMA-A	0.51	690	1	16
Well Balanced	WB-SA	0.42	660	0	6
	WB1	0.42	660	2	31
	WB2	0.42	660	1	23
	WB3	0.36	660	2	22

In Figure 4.4, the data of Flow Trough test, expressed as Dynamic Stability Index (DSI), are plotted against the Visual Stability Index (VSI). For the 6 mixtures with a VSI of 0 (Stable), the DSI ranged from 3 to 7% with an average of 4.8%. For the 13 mixtures with a VSI of 1 (Stable), the DSI varied between 2 – 23% with an average of 11.4%. Majority of (75%) the DSI values were more than 10% when VSI was 1. A DSI rating of 10% means that 10% of the coarse aggregates were lost in the flowing distance of 1.8 m (6 ft). The loss of coarse aggregate could be worse in the field where concrete might easily flow 10 m (30 ft) or more. These results indicate that the flow trough is more sensitive to segregation than the slump flow method for some concrete. The finding of moderate dynamic segregation in mixtures with VSI of 1 is consistent with other research [34].

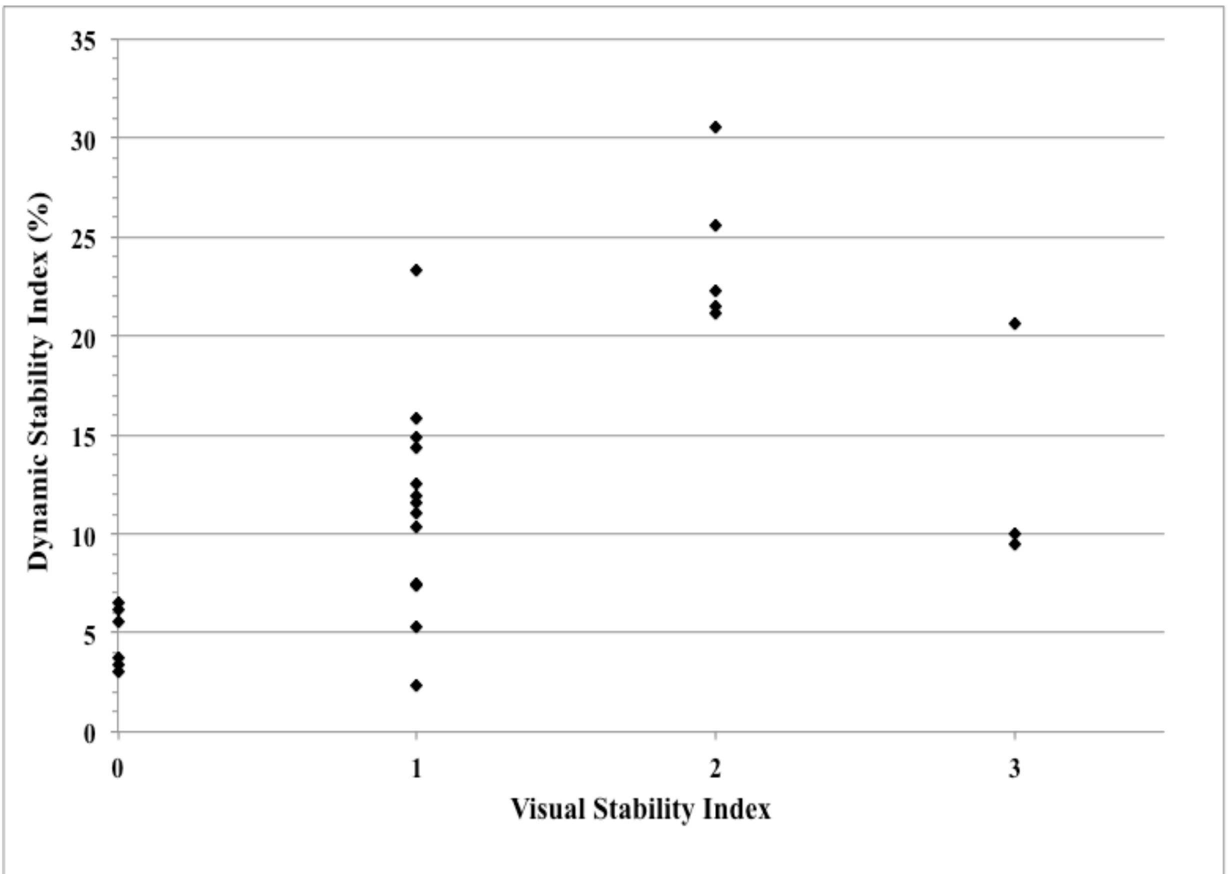


Figure 4.4-Results of Flow Trough test and Visual Stability index of Slump flow

For the 5 mixtures with a VSI of 2 (Unstable), DSI values ranged from 21-31% with an average of 24.4%. Interestingly, for the 3 mixtures with sever segregation (VSI = 3, Unstable), DSI values varied from 10 - 21% with an average of 13.7%. The reason why mixtures with VSI of 3 had lower DSI values than mixtures with VSI of 2 is likely due to extreme static segregation during the sampling process. In mixtures with sever segregation, coarse aggregates settled to bottom of the mixer and containers almost instantaneously. As a result, mortar will be poured first from the mixer to containers, and from containers to the flow trough, making uniform sampling nearly impossible. Therefore, for mixtures with a VSI of 3, the concrete will be rated unstable and no further flow trough test is needed.

4.4.4 Reproducibility

To check the reproducibility of the flow trough, three tests were performed on the same mixture (VMA mixture in Table 4.2). The slump flow was 790 mm (31 in). The DSI values were 0.18, 0.19, and 0.18, which indicate good precision.

In another check of reproducibility, the flow trough was used to test two SCC batches (MA mixture in Table 4.2). The slump flow values were 600 and 610 mm (23.5 and 24 in), and the DSI values were 0.01 and 0.03, respectively, also indicating good reproducibility.

4.5 THE EFFECTS OF AGGREGATE PROPERTIES ON DYNAMIC SEGREGATION OF SCC

As shown in Table 4.5, a total of twenty-nine mixtures were tested to study the effects of aggregate volume, size, gradation, and packing density, mineral and chemical admixtures, and concrete viscosity and yield stress on dynamic segregation. The test methods to assess dynamic segregation included the VSI and Flow Trough test that was explained in 4.4.1 and 4.3, respectively. Basic rheological parameters were obtained with ICAR Rheometer, which is a portable rheometer with vane geometry. Concrete rheology test was explained in chapter 3.

4.5.1 Details of materials and mix proportion

Type I Portland cement complying with ASTM C150/C150M-12 and type C fly ash complying with ASTM C618-12a were used. Coarse aggregate CA1 is crushed basalt rock, has maximum size of 19mm, and Coarse aggregate CA2 is crushed basalt rock, has maximum size of 9.5mm. The properties of coarse and fine aggregate are shown in Table 4.4.

Four basic types of mixtures were designed: graded aggregate (GA), mineral admixture (MA), VMA, and well balanced (WB). Within each basic mixture type, the volume, gradation, packing density, maximum size of aggregate, as well as slump flow may also be 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 size, 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 4.4-Aggregate properties

Aggregate Name	Bulk Density (kg/m^3)	Bulk Specific Gravity	Fineness Modulus	Absorption Capacity (%)	Packing Density
CA1	1473	2.74	6.70	2.66	0.54
CA2	1491	2.70	5.95	3.61	0.54
FA1	1460	2.71	1.55	2.30	0.54
FA2	1675	2.64	3.5	5.16	0.63

Table 4.5-Proportions of SCC mixtures

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

4.5.2 Results and discussions

The experimental results of the twenty-nine SCC mixtures are summarized in Table 4.6. The effects of aggregate volume, size, gradation, slump flow, SP dosage, and concrete viscosity and yield stress on dynamic segregation will be discussed in details as follows.

Table 4.6-Experimental results of SCC mixtures

Mix Type	Mix ID	w/cm	Slump mm	VSI	DSI(%)	Static Yield Stress (Pa)	Dynamic Yield Stress (Pa)	Plastic Viscosity (Pa.S)
Graded Aggregate	GA	0.35	710	1	5	164.1	113.9	6.1
	GA-LS	0.35	610	0	15	NA		
	GA-HS	0.35	760	2	22	5.8	0.1	21.9
	GA + 5 %P	0.35	710	1	11	134.7	125.0	1.2
	GA -5 %P	0.35	710	1	14	304.0	234.0	5.5
	GA-A	0.38	660	3	10	NA		
	GA-A	0.38	670	1	8			
	GA-A	0.46	710	0	7			
Mineral Admixture	MA	0.31	710	0	3	188.8	64.8	14.6
	MF-LS	0.31	630	0	3	NA		
	MA-HS	0.31	760	3	10			
	MA +5 %P	0.31	710	0	4	230.9	135.9	13.8
	MA -5 %P	0.31	710	2	21	173.2	8.6	31.2
	MA-A	0.39	740	3	21	NA		
	MA-A	0.39	740	1	7			
	MA-A	0.39	710	2	26	204.0	40.7	12.3
VMA	VMA	0.41	710	1	15	433.3	107.4	26.7
	VMA-LS1	0.41	580	0	N/A	NA		
	VMA-LS2	0.41	630	0	6			
	VMA-HS	0.41	760	1	12	313.5	129.2	10.4
	VMA +5 %P	0.41	710	1	13	219.0	116.3	2.0
	VMA -5 %P	0.41	660	1	2	338.0	31.8	43.7
	HP	0.41	660	1	12	185.0	95.5	5.9
	VMA-A	0.51	690	1	10	145.0	76.1	2.3
	VMA-A	0.51	690	1	16	159.0	104.0	3.1
Well Balanced	WB-SA	0.42	660	0	6	380.4	305.6	7.0
	WB1	0.42	660	2	31	82.7	26.7	8.4
	WB2	0.42	660	1	23	197.9	30.0	32.5
	WB3	0.36	660	2	22	184.0	43.0	32.9

4.5.2.1 Effects of aggregate volume on dynamic segregation

Figure 4.5 shows the DSI of the GA series mixtures and the MA series mixtures. Compared with the "GA" mixture, "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 slump flow was controlled at 710 mm (28 in) for all six mixtures (by varying SP dosage).

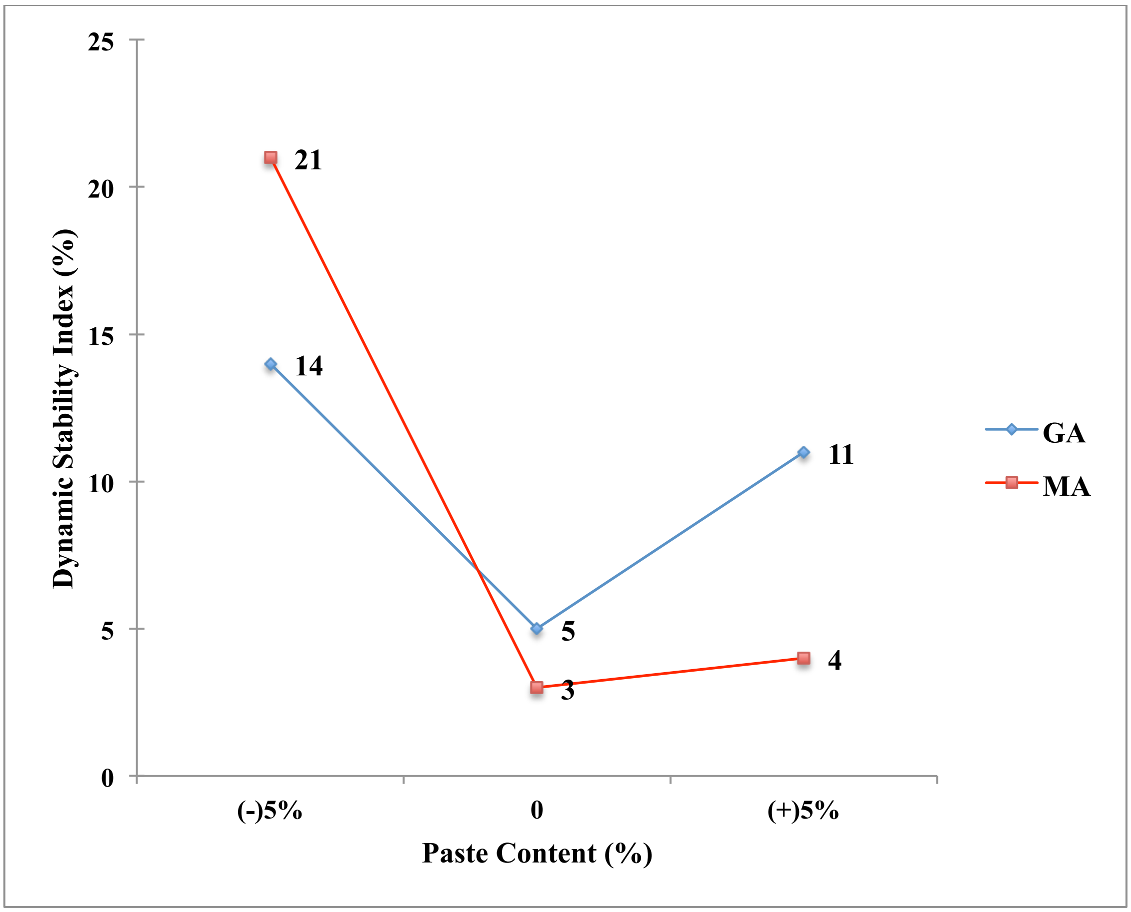


Figure 4.5-Effects of aggregate volume on dynamic segregation

The DSI for GA, GA+5%P, and GA-5%P mixture were 5%, 11%, and 14%, respectively. And the DSI for MA, MA+5%P, and MA-5%P mixture were 3%, 4%, and 21%, respectively. It seems 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).

One factor that may help to explain the higher dynamic segregation for mixtures with less paste volume is paste rheology controlled by the dosage of SP. The SP dosages (solid % by weight of cementitious materials) of GA type of mixtures were 0.58% (GA+5%P), 0.80% (GA), and 1.10% (GA-5%P). And the SP dosages of MA type of mixtures were 0.67% (MA+5%P), 0.78% (MA), and 0.98% (MA -5%P). For each type of mixtures, the mixture with highest SP dosage coincided with highest dynamic segregation.

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 a SCC mixture [37]. The drag force acting by the paste on the aggregate, F_A, can be expressed as

$$F_A = abc\left(9\eta_{pl}\Delta V\left(\frac{\phi_1}{r_1^2}+\frac{\phi_2}{r_2^2}+\frac{\phi_3}{r_3^2}\right)+\pi^2\tau_0\frac{21}{4}\left(\frac{\phi_1}{r_1}+\frac{\phi_2}{r_2}+\frac{\phi_3}{r_3}\right)\right) \quad (4.2)$$

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 (4.2), 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 (4.2), 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 section 4.5.2.4, this relationship between SP dosage and dynamic segregation is not obvious when different series of mixtures with various average aggregate size and gradation are compared, which could also be expected from Eqn. (4.2).

It should be noted that all the observations discussed above were performed right after the mixing procedure was stopped. The effects of factors such as hydration, admixture adsorption, and thixotropy on dynamic segregation will be studied in future tests.

4.5.2.2 Effects of slump flow on dynamic segregation

Figure 4.6 shows how the slump flow is related to dynamic segregation of the GA, MA, and VMA series of mixtures. Within the same series of mixtures, the slump flow was varied by changing dosage of superplasticizer while other mix proportions were virtually identical.

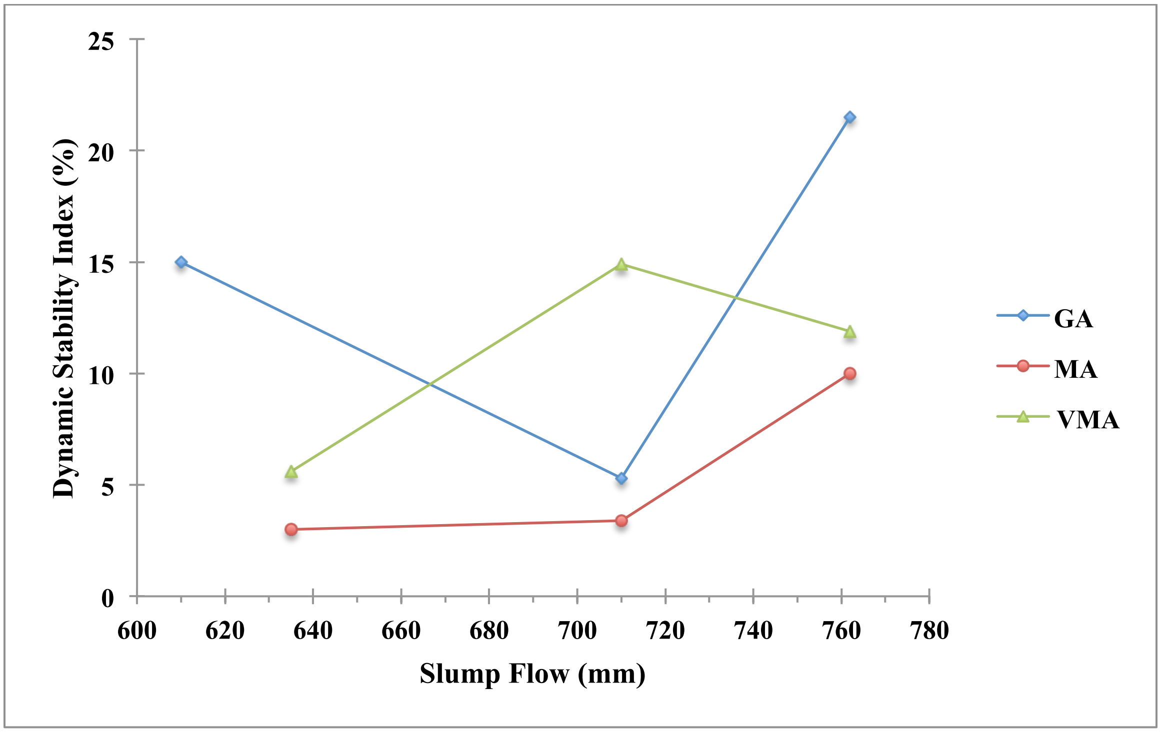


Figure 4.6-Effects of slump flow on dynamic segregation

For the GA series, the DSI of mixtures with slump flow of 610 mm (24 in), 710 mm (28 in), and 760 mm (30 in) were 15%, 5%, and 22%, respectively. For the MA series, the DSI of mixtures with slump flow of 630 mm (25 in), 710 mm (28 in), and 760 mm (30 in) were 3%, 3%, and 10%, respectively. And for the VMA series, the DSI of mixtures with slump flow of 635 mm (25 in), 710 mm (28 in), and 762 mm (30 in) were 6%, 15%, and 12%, respectively. For each series, the mixture with lowest slump (610 mm or 630 mm) always showed less dynamic segregation than the mixture with highest slump (760 mm), which indicates reducing slump flow could reduce dynamic segregation. The trend of higher DSI with higher slump flow was also observed when superplasticizer was added in a single mixture and slump flow and DSI were monitored [38].

The reason why lower slump flow coincided to better resistance to dynamic segregation may also be justified by higher paste yield stress and viscosity. The SP dosages of the GA type of mixtures were 0.27% (610-mm slump flow, 15% DSI) and 0.87% (760-mm slump flow, 22% DSI). The SP dosages of the MA type of mixtures were 0.42% (630-mm slump flow, 3% DSI) and 0.90% (760-mm slump flow, 10% DSI). And the SP dosages of the VMA type of mixtures were 0.20% (630-mm slump flow, 6% DSI) and 0.35% (760-mm slump flow, 12% DSI). Again, according to Eqn. (4.2), less SP % means higher paste yield stress, higher drag force to carry the coarse aggregate forward, and thus less dynamic segregation.

4.5.2.3 Effects of aggregate size and gradation on dynamic segregation

Figure 4.7 illustrates how dynamic segregation was influenced by aggregate size and gradation. The WB-SA mixture had only medium size (9.5-mm) coarse aggregate and packing density of 0.66, while the WB1 and WB2 mixtures had both large (19-mm) and medium size (9.5-mm) coarse aggregate and higher packing density (0.74 for WB1 and 0.71 for WB2). Compared with the WB1 mixture, WB2 mixture has smaller average aggregate size (less 19-mm coarse). There is no other major difference in mix proportions between these mixtures. The DSI of WB-SA, WB1, and WB2 mixture were 6%, 31%, and 23%. It seems that reducing the aggregate size had a more significant effect on improving dynamic segregation resistance compared with better gradation and higher aggregate packing density.

The improved dynamic segregation resistance with smaller aggregate can still be explained by Eqn (4.2). The reduction in DSI is mainly attributed to increased drag force provided by cement paste on smaller aggregates (smaller r_1, r_2, and r_3), which have higher surface area/mass ratios. Another possible factor is static segregation, concrete with larger aggregates is more likely to experience static segregation, and when more aggregates settle to the bottom and the frictional force provided to the aggregate by the underlying surface increases, dynamic segregation increases [37].

One may also analyze dynamic stability using other analytical methods such as the LCPC Box test. For example, the LCPC Box test [35] can use spread length and shape to calculate concrete yield stress, which in turn affects dynamic segregation.

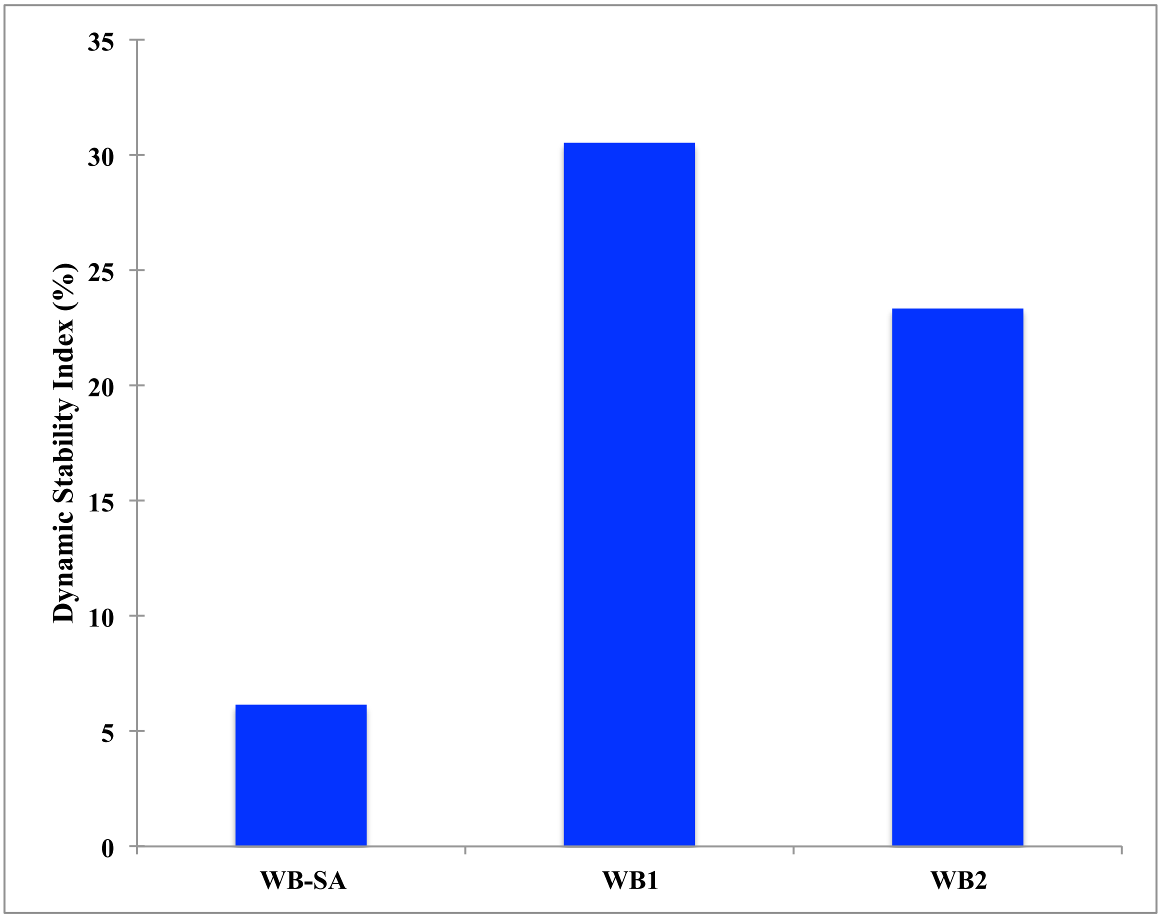


Figure 4.7-Effects of aggregate size and gradation on dynamic segregation

4.5.2.4 Effects of SP dosage on dynamic segregation

It was found from section 4.5.2.1 that higher SP dosage increases dynamic segregation within the same type of mixture (GA, MA, VAM e.g.). The reason is because less SP dosage means higher paste yield stress, and thus higher drag force is available for the paste to carry the coarse aggregate forward, which in turn results in less dynamic segregation.

Figures 4.8 shows how dynamic segregation index was influenced by SP % by weight of cement when different series of mixtures were compared together. The w/cm was controlled at around 0.41 for all mixtures. No clear correlation between SP dosage and dynamic segregation was observed when mixtures with various aggregate properties are compared. Based on Eqn. (4.2), the drag force is a function of not only yield stress and viscosity of paste, but also aggregate size, volume, and gradation. Furthermore, rheological properties of paste also depend upon early hydration phases and anions, which varies between difference series of mixtures. The effect of paste rheology (via SP dosage) became less obvious when more variables were introduced. The paste rheology is going to be measured in future test to further validate the theory.

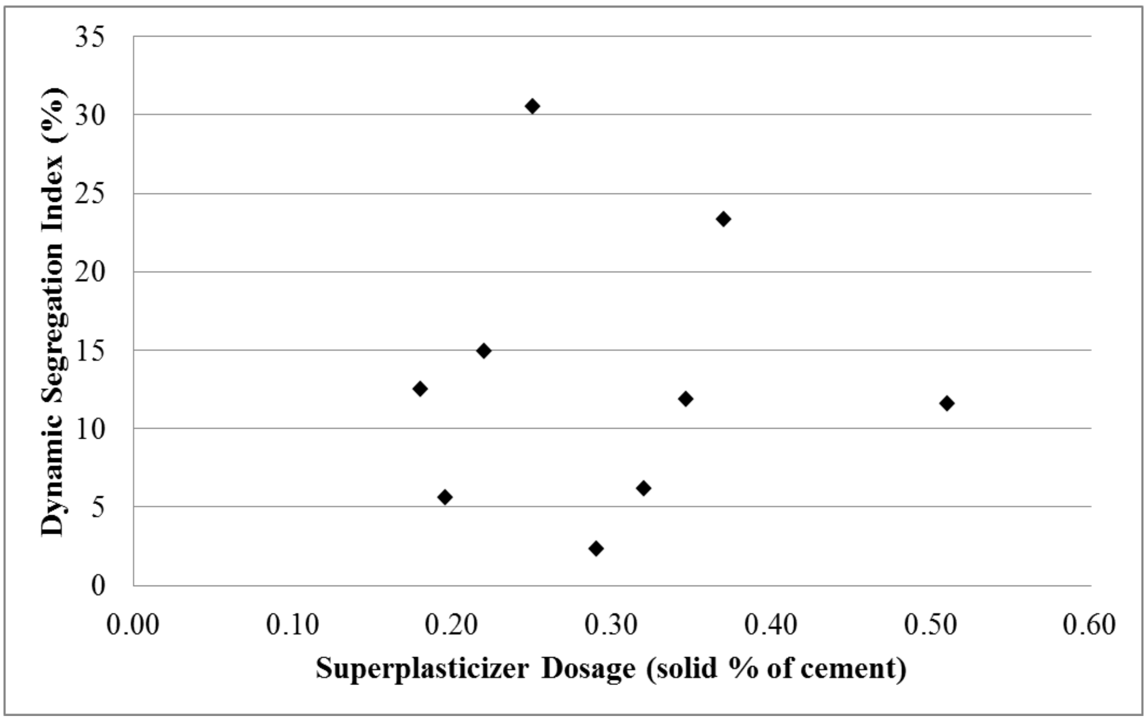


Figure 4.8-Effects of SP% by weight of cement on dynamic segregation (all mixture had w/cm of around 0.41)

4.5.2.5 Effects of concrete rheology on dynamic segregation

Figure 4.9 shows how DSI was affected by dynamic yield stress of mixtures. It was found that when the dynamic yield stress was higher than 50 Pa, most DSI values (11 of 12, or 92%) were less than 15%; while the dynamic yield stress was less than 50 Pa, most DSI values (6 of 7, or 86%) were higher than 20%, indicating severe dynamic segregation.

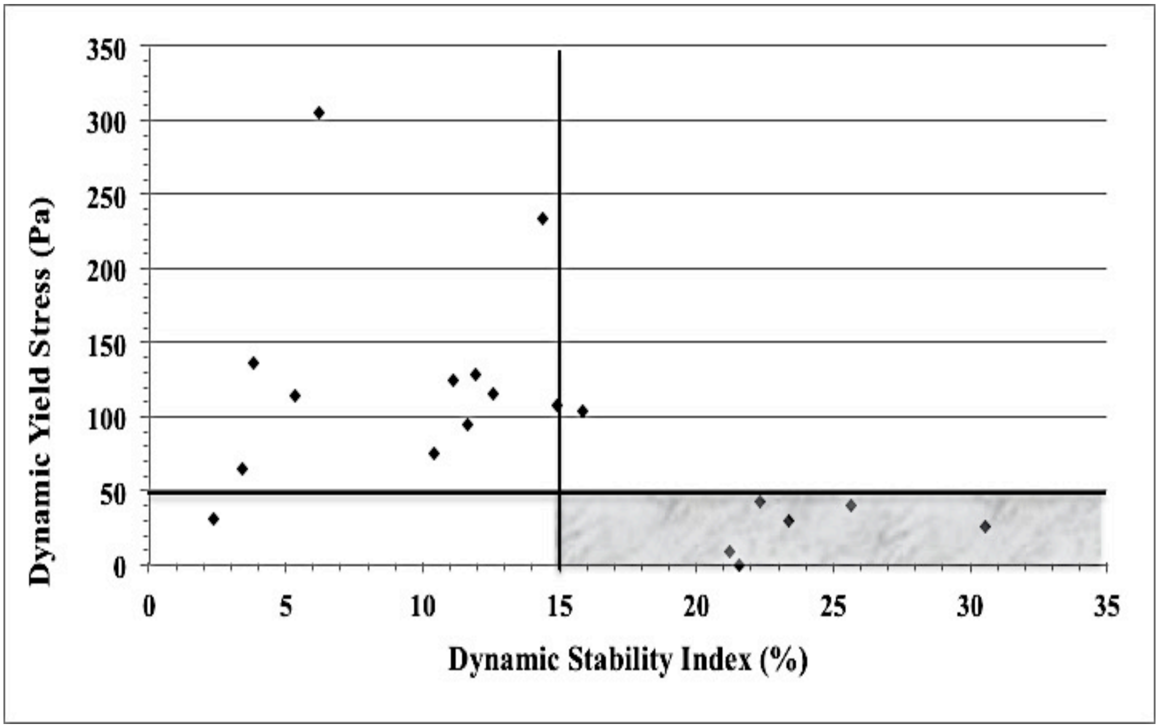


Figure 4.9-Effect of concrete dynamic yield stress on Dynamic Segregation Index

Figure 4.10 illustrates how VSI was influenced by dynamic yield stress. For mixtures with VSI of 0 and 1, there is a wide range of dynamic yield stress values and no clear correlation was found. For mixtures with VSI of 2, all dynamic yield stress values (5 of 5, or 100%) are less than 50 Pa.

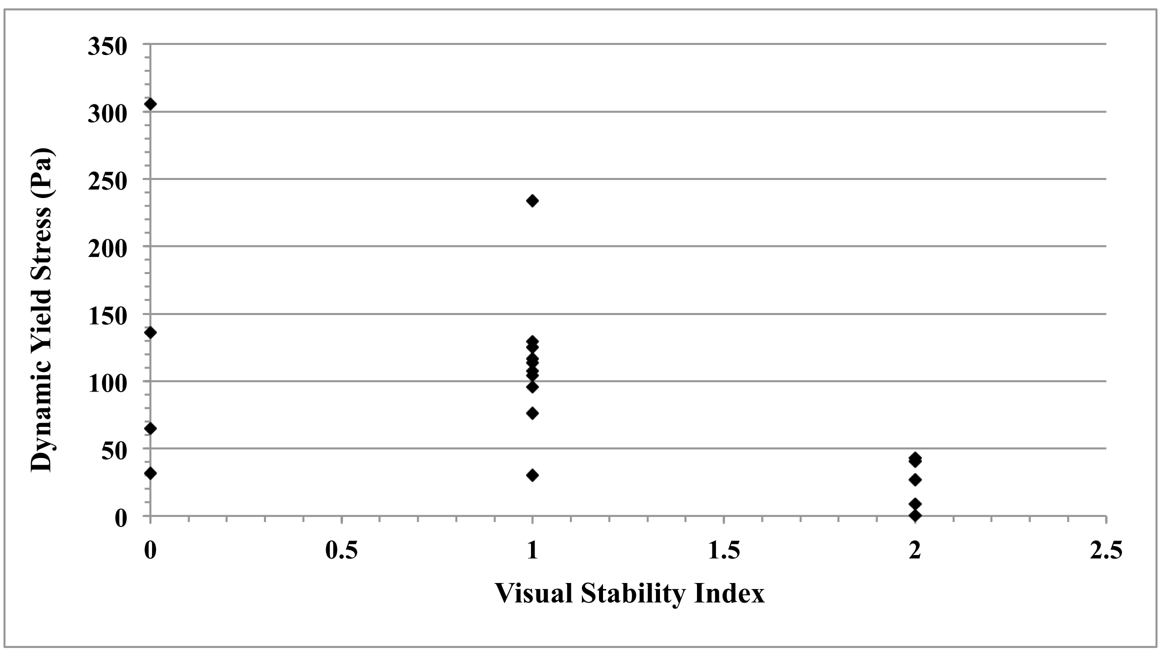


Figure 4.10-Effect of concrete dynamic yield stress on Visual Stability index

Figure 4.11 plots the relationship between concrete static yield stress and DSI. All mixtures (5 of 5, or 100%) with static yield stress of 250 Pa or higher had DSI values of 15% or less, while all mixtures (2 of 2, or 100%) with static yield stress of 100 Pa or lower had DSI value of 20% or higher. For mixtures with static yield stress between 100 to 250 Pa, the DSI values are highly variable.

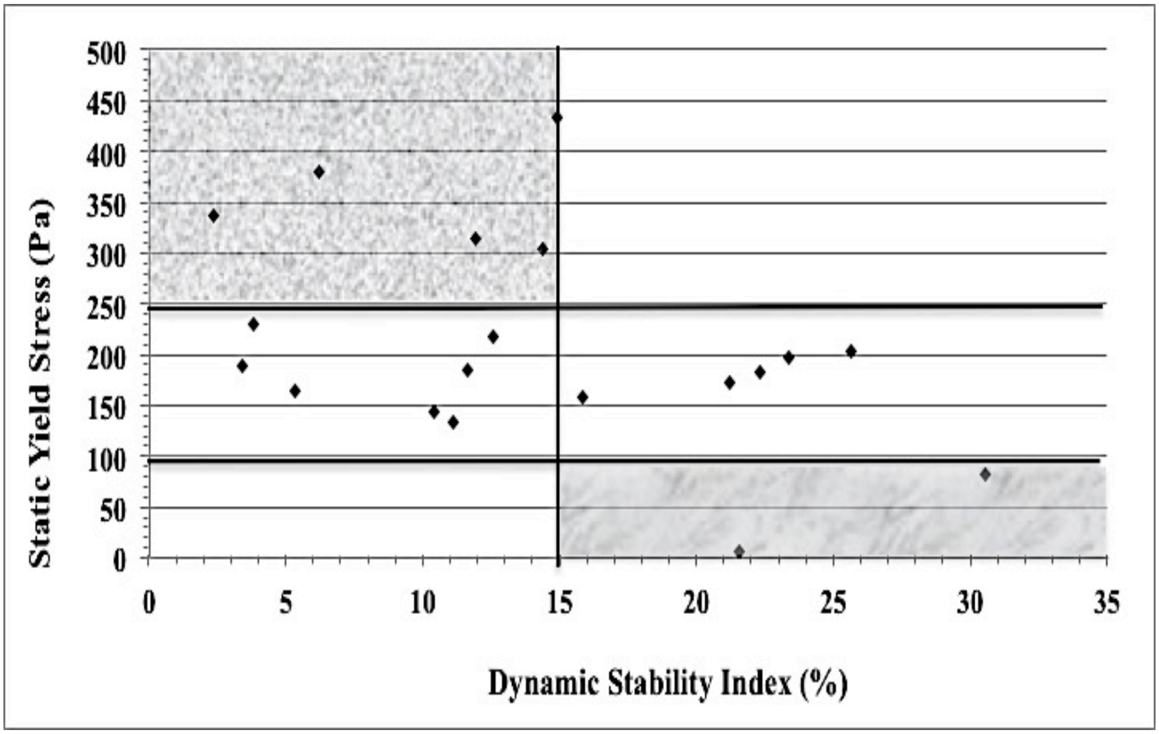


Figure 4.11-Effect of concrete static yield stress on Dynamic Segregation Index

Figure 4.12 shows the correlation between static yield stress and VSI. All mixtures (5 of 5, or 100%) with static yield stress of 250 Pa or higher had VSI of 0 or 1 (stable), while all mixtures (2 of 2, or 100%) with static yield stress of 100 Pa or lower had VSI of 2 (unstable). For mixtures with static yield stress between 100 to 250 Pa, the VSI values are variable.

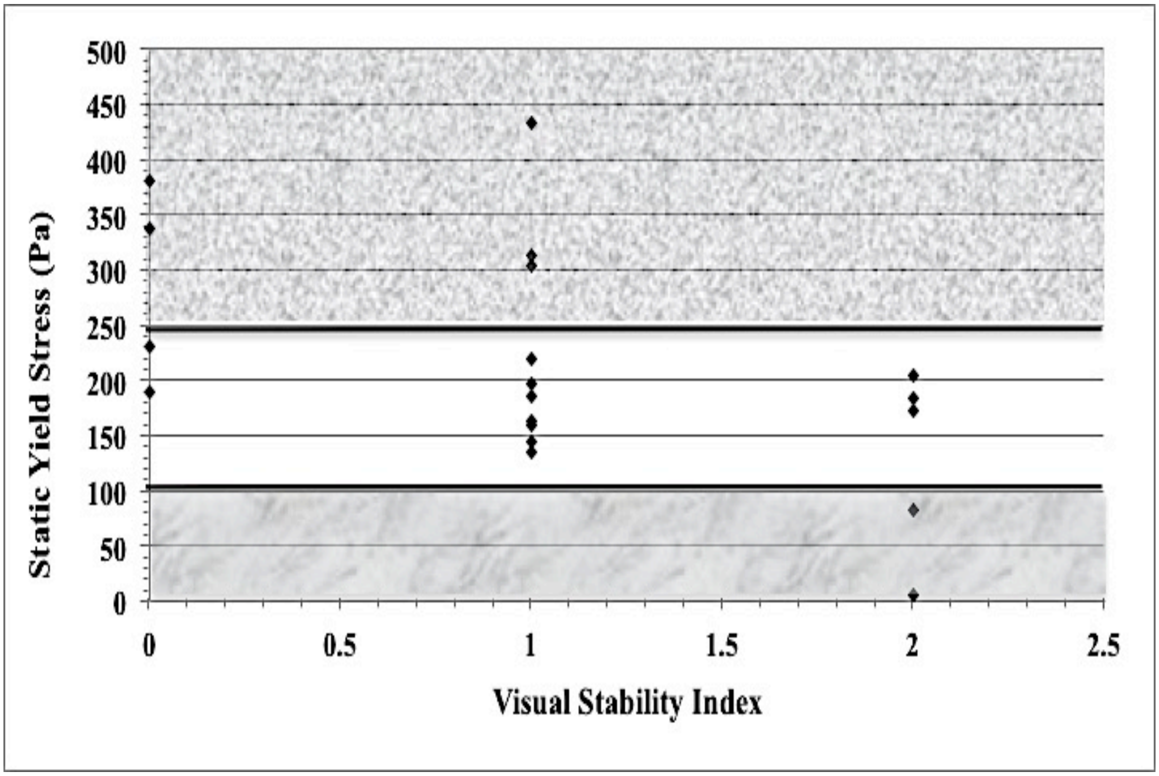


Figure 4.12-Effect of concrete static yield stress on Visual Stability index

Figure 4.13 and 4.14 show how DSI and VSI were influenced by concrete plastic viscosity. No clear correlation was found.

The paste rheology of the mixtures in Table 4.2 is planned be measured in future research of dynamic segregation.

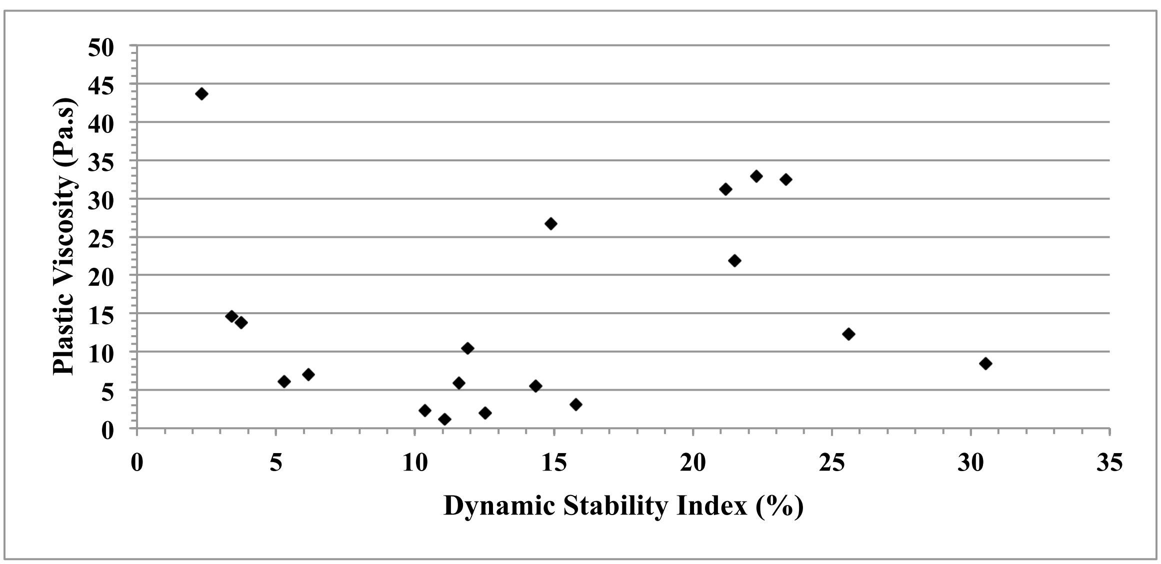


Figure 4.13-Results of concrete plastic viscosity and Flow Trough test

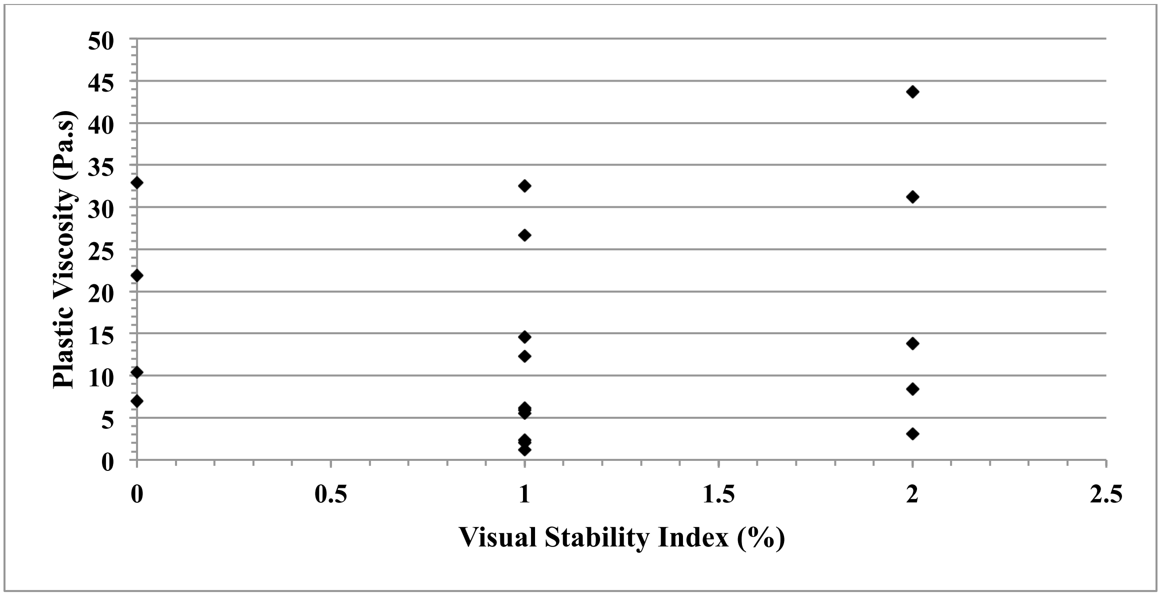


Figure 4.14-Results of concrete plastic viscosity and Visual Stability index

4.6 CONCLUSIONS

From the results obtained from this chapter, the following conclusions can be drawn:

1) The flow trough test was found to provide a measure of dynamic segregation of SCC with acceptable precision and accuracy.
2) The visual stability rating from the slump flow test did not always provide a suitable measure of dynamic segregation.
3) The drag force equation in Eqn. (4.2) and other rheological analysis such as the one used in the LCPC box [35] design 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.
4) 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.
5) Lower slump flow may reduce dynamic segregation due to higher paste plastic viscosity and yield stress.

6) Smaller coarse aggregate may improve dynamic segregation resistance due to higher aggregate surface area/mass ratio (result in higher drag force and higher concrete plastic viscosity), and possibly less static segregation.
7) While both smaller aggregate size and better gradation can improve dynamic segregation resistance of SCC mixtures, smaller aggregate size seems to have more significant effect compared with better gradation.
8) No clear relationship between SP % by weight of cement and dynamic segregation was observed when mixtures with various aggregate properties are compared. This is because the drag force is a function of not only yield stress and viscosity of paste, but also aggregate size and volume. The effect of paste rheology (via SP dosage) became less obvious when more variables were introduced.
9) Most mixtures with dynamic yield stress higher than 50 Pa had DSI less than 15%, and mixtures with the dynamic yield stress less than 50 Pa typically had DSI higher than 20%.
10) Most mixtures with VSI of 2 or higher had dynamic yield stress less than 50 Pa, while mixtures with VSI of 0 and 1 exhibited a wide range of dynamic yield stress values.
11) Most mixtures with static yield stress of 250 Pa or higher had DSI values of 15% or less and VSI of 0 or 1 (stable), and most mixtures with static yield stress of 100 Pa or lower had DSI value of 20% or higher and VSI of 2 (unstable) or 3 (unstable). For mixtures with static yield stress between 100 to 250 Pa, the DSI and VSI values are highly variable.
12) No direct relationship was observed between concrete plastic viscosity and dynamic segregation (DSI and VSI).

CHAPTER 5

RHEOLOGY OF SCC

5.1 BACKGROUND

The hardened properties and long-term behavior of SCC are significantly affected by its fresh properties [27, 39, 40]. Compared with ordinary concrete, the rheological properties of SCC should be closely controlled in order to satisfy flowability, passing ability, and segregation resistance requirements. Rheology of concrete is normally described by yield stress (the minimum shear stress required to initiate flow) and plastic viscosity (the ease of concrete flow) using the Bingham model [41,42]. SCC rheology can be affected by nearly every aspect of mix proportions and material characteristics, as well as mixing conditions such as time and temperature.

The effects of some properties such as characteristics of cement, chemical admixtures, supplementary cementitious materials, and construction conditions were extensively investigated by many researchers [43-52]. However, limited study was found in the literature related with the effects of aggregate characteristic on the rheological properties of SCC.

Some researchers [53-60] have studied the influence of the aggregates on the rheological properties of conventional concrete. However, it may not be fully applicable to modern highly flowable concrete such as SCC containing less coarse particles, one or more mineral and chemical admixtures, and where friction between the grains is negligible [61].

The effects of coarse particle volume fraction and shape on the rheological properties of SCC have been studied by Geiker et al. [16], and it was found that the aspect ratio, angularity, and surface texture of aggregates influence the viscosity and yield stress.

Koehler and Fowler [62] reported that in general, natural aggregates, well shaped manufactured sands, and well shaped crushed coarse aggregates resulted in low interparticle friction, low HRWRA demand, and low plastic viscosity.

One of the disadvantages of SCC is its cost, associated with the usage of chemical admixtures and high volumes of Portland cement [44]. One alternative to reduce the cost of SCC is selecting aggregates with favorable characteristics such as higher packing density, which may minimize the paste volume while still maintaining favorable rheological properties.

5.2 OBJECTIVES

The main objective of the research in this chapter was to explore the effects of various aggregate properties on rheology of SCC, which include aggregate volume (φ), fine aggregate to coarse aggregate ratio (FA/CA), coarse aggregate volume (CA1%), maximum aggregate size, aggregate packing density (φ_m), and aggregate gradation.

5.3 DETAILS OF MATERIALS AND MIX PROPORTIONS

Type I Portland cement complying with ASTM C150/C150M-12 and type C fly ash complying with ASTM C618-12a were used. Coarse aggregate CA1 is crushed basalt rock, has maximum size of 19mm, and Coarse aggregate CA2 is crushed basalt rock, has maximum size of 9.5mm. The properties and the gradation curve of coarse and fine aggregate are shown in Table 5.1 and Figure 5.1, respectively.

Table 5.1-Aggregate properties

Aggregate Name	Bulk Density (kg/m^3)	Bulk Specific Gravity	Fineness Modulus	Absorption Capacity (%)	Packing Density
CA1	1473	2.74	6.70	2.66	0.55
CA2	1491	2.70	5.95	3.61	0.54
FA1	1460	2.71	1.55	2.30	0.54

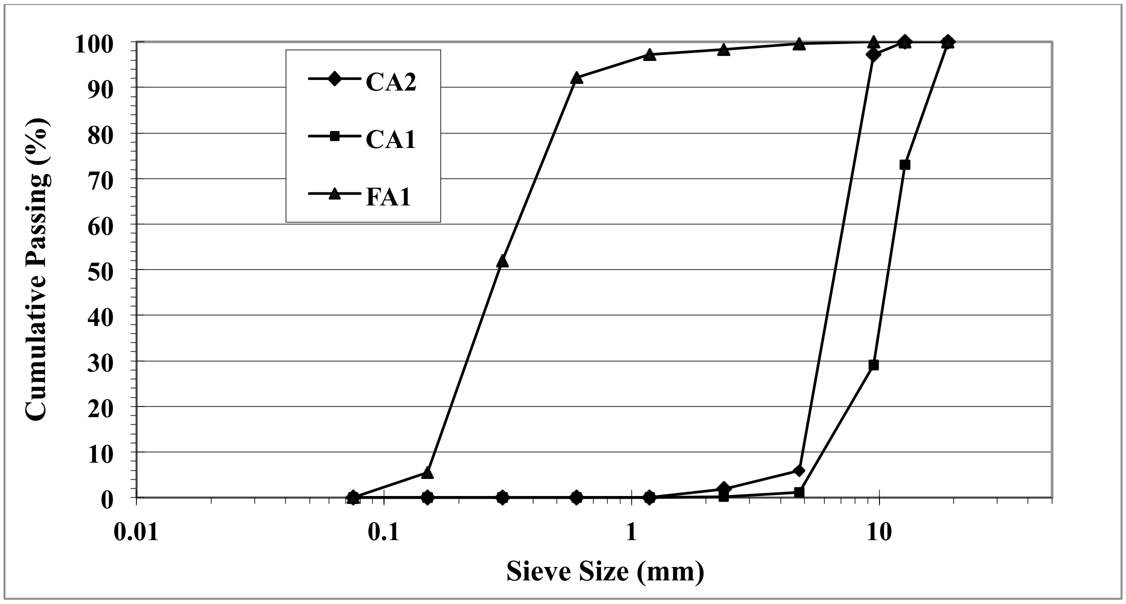


Figure 5.1-Gradation curves of coarse and fine aggregates

A polycarboxylate-based superplasticizer (SP) , with a specific gravity of 1.06 and a solid content of 35% was used. The VMA (methyl-hydroxy-ethyl cellulose) used had a specific gravity of 1.00 and a solid content of 35%.

As shown in Table 5.2, a total of twenty-five mixtures were tested to study the effects of aggregate volume (φ), fine aggregate to coarse aggregate ratio (FA/CA), coarse aggregate CA1 volume (CA1%), aggregate size, aggregate packing density (φ_m), and aggregate gradation on rheology of SCC.

Table 5.2-Proportions of SCC mixtures

Mix Type	Mix ID	w/cm	Material kg/m3						Aggregate Properties				Admixture	
			Cement (Type I)	Fly Ash Class C	CA1	CA2	FA1	Water	%AGG	CA1%	FA/CA	ϕ_m	SP (% of cement)	VMA (% of water)
Graded Aggregate	GA	0.35	450	107	198	579	756	195	59	0.13	1.00	0.674	0.35	0
	GA-HSP	0.35	450	107	198	579	756	195	59	0.13	1.00	0.674	0.46	0
	GA -5 %ϕ	0.35	506	120	181	530	692	219	54	0.13	1.00	0.674	0.35	0
	GA -2%ϕ	0.35	450	107	186	512	682	195	57	0.13	1.00	0.674	0.35	0
	GA +3 %ϕ	0.35	450	107	217	636	834	195	62	0.13	1.00	0.674	0.35	0
	GA +5 %ϕ	0.35	394	94	214	629	821	171	64	0.13	1.00	0.674	0.35	0
	GA/LFA	0.35	450	107	217	636	682	195	59	0.14	0.80	0.684	0.35	0
	GA/HFA	0.35	450	107	186	512	834	195	59	0.12	1.20	0.662	0.35	0
	GA/HCA1	0.35	450	107	777	0	756	195	59	0.30	1.00	0.676	0.35	0
	GA/HCA1$_2$	0.35	450	107	460	317	756	195	59	0.50	1.00	0.673	0.35	0
	GA/SA	0.35	450	107	0	777	756	195	59	0	1.00	0.671	0.35	0
	GA/SA-HSP	0.35	450	107	0	777	756	195	59	0	1.00	0.671	0.46	0
	GA/ϕm_{63}	0.35	450	107	171	372	985	195	59	0.11	1.86	0.630	0.35	0
	GA/ϕm_{64}	0.35	450	107	667	341	531	195	59	0.14	0.25	0.640	0.35	0
	GA/ϕm_{71}	0.35	450	107	211	1049	252	195	59	0.43	0.54	0.710	0.35	0
VMA	VMA	0.41	530	0	198	579	756	217	59	0.13	1.00	0.670	0.22	0.23
	VMA/LFA	0.41	530	0	217	636	682	217	59	0.14	0.80	0.684	0.22	0.23
	VMA/HFA	0.41	530	0	186	512	834	217	59	0.12	1.20	0.662	0.22	0.23
	VMA/HCA1	0.41	530	0	777	0	756	217	59	0.30	1.00	0.676	0.22	0.23
	VMA/HCA1$_2$	0.41	530	0	460	317	756	217	59	0.50	1.00	0.673	0.22	0.23
	VMA/SA	0.41	530	0	0	777	756	217	59	0	1.00	0.671	0.22	0.23
	VMA/ϕm_{63}	0.41	530	0	171	372	985	217	59	0.11	1.86	0.630	0.22	0.23
	VMA/ϕm_{64}	0.41	530	0	667	341	531	217	59	0.14	0.25	0.640	0.22	0.23
	VMA/ϕm_{69}	0.41	530	0	211	1049	252	217	59	0.14	0.42	0.690	0.22	0.23
	VMA/ϕm_{71}	0.41	530	0	211	843	462	217	59	0.43	0.54	0.710	0.22	0.23

Two basic types of mixtures were designed: graded aggregate (GA) and VMA. Graded aggregate mixtures had water to binder ratio (w/b) of 0.35 and used fly ash to increase paste volume, while VMA mixtures had w/b ratio of 0.41 and used VMA to improve the viscosity.

Within each basic mixture type, the volume, gradation, packing density, maximum size of aggregate, as well as slump flow may also be modified to explore their effects on concrete rheology. Labels +5% φ, -5% φ, HSP, HFA, LFA, HCA1, φ_{mi}, and SA indicate that compared with the basic mixture, a modified mixture has 5% more aggregate volume, 5% less aggregate volume, higher SP%, higher FA/CA ratio, lower FA/CA ratio, higher coarse aggregate CA1 volume, different aggregate packing density, and smaller coarse aggregate size, respectively. For example, GA +5%φ mixture has 5% higher aggregate volume than the basic GA mixture, and VMA/φ_{m71} mixture has higher aggregate packing density than the basic VMA mixture.

5.4 PROCEDURES

5.4.1 Mixing procedure

Each batch of concrete had a volume of about 30 liters (1.1 ft^3) and was prepared in a drum mixer with a capacity of 58 liters (2 ft^3). The following procedure was used:

1. Sand, coarse aggregate, and one third of water were put in a drum mixer and mixed for 30s.
2. Cement and mineral admixture, if any, were put in the mixer and mixed for 3 minutes and remaining water was slowly added during the first minute of mixing process.
3. Mixer was stopped for 3 minutes.
4. Mixer was restarted, and SP and/or VMA were slowly poured and mixed for 2 minutes before the slump flow, and rheology tests.

5.4.2 Slump Flow test

The slump flow test followed the procedure in ASTM C1611 [24] and was explained in details in chapter 3. In addition to the diameter, the time for concrete to flow to a diameter of 500 mm (T_{50}), and the time to reach final diameter (T_f) were also measured.

5.4.3 Concrete rheology test

Rheological properties were measured using the ICAR rheometer, which is a controlled-rate rheometer (Figure 5.2). The rheometer features a 4-bladed vane (127 mm in diameter and height) that is rotated axially in the center of the container. The vane, which acts as the inner cylinder of a coaxial cylinders rheometer, is utilized because of its compact design and the elimination of slippage. The container includes vertical strips to prevent slippage of the concrete against the container walls. The container size is selected based on the maximum aggregate size. The gap between the vane and concrete specimen boundaries should be at least 4 times the maximum aggregate size. For a 19mm maximum aggregate size, the 76mm gap is required. This distance is measured horizontally from the vane to the edges of the vertical strips on the container. Vertically, it is measured from the vane to the free surface and from the vane to the bottom of the container. This minimum gap size is necessary to ensure a sufficient degree of homogeneity in the concrete specimen [63].

After the mixture was prepared following the steps in the section of mixing procedure and transferred into the rheometer, a stress growth test and flow curve test were performed. The rheometer electronics control the speed of the vane and record the torque acting on the vane as it rotates in concrete.

The stress growth test is used to determine the static (at-rest) yield stress, while the flow curve test is used to measure the relationship between shear stress and shear rate and to compute the Bingham parameters of yield stress and plastic viscosity. The yield stress measured with the flow curve test is the dynamic yield stress because it is measured after the breakdown of the effects of thixotropy [62].

Figure 5.2-Vane-type concrete rheometer

5.4.3.1 Stress growth test

In a stress growth test, the stress in the material is gradually increased until flow beings. A stress growth test involves rotating the vane at a low, constant speed while monitoring the build-up in torque. The optimum test speed depends on the material being tested. For concrete, a value of 0.025 rps has been found to be appropriate for many concrete materials [63]. The maximum torque corresponds to the yield stress. The stress growth test is highly dependent on the shear history of the sample.

A typical stress growth plot is shown in Figure 5.3. For the stress growth test, the software automatically selects the maximum-recorded torque. The yield stress is computed with Equation 5.1:

$$\tau_o = \frac{2T}{\pi D^3\left(\frac{H}{D} + \frac{1}{3}\right)} \qquad (5.1)$$

Where τ_o is the yield stress, T is the maximum torque, D is the diameter of the vane, and H is the height of the vane. In this equation, the shear stress is assumed to be evenly distributed on the side and ends of the vane [63].

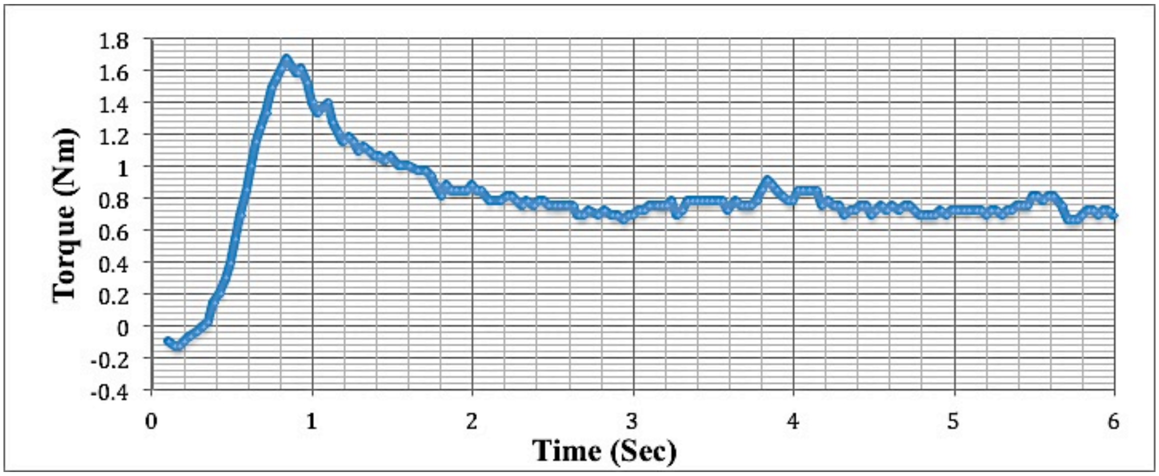


Figure 5.3-A typical Stress Growth Test

5.4.3.2 Flow curve test

A flow curve tests consists of a breakdown, or pre-shear period, followed by a series of flow curve points (Figure 5.4). The purpose of the pre-shear period is to minimize the effects of thixotropy and to provide a consistent shear history. The pre-shear period consists of a single, constant speed, typically equal to the maximum test speed. No measurements are made during the pre-shear period. After the pre-shear period, the flow curve is immediately started. A single test consists of a specified number of points in ascending or descending order. The software equally divides the speed points between the initial and final speed points [63].

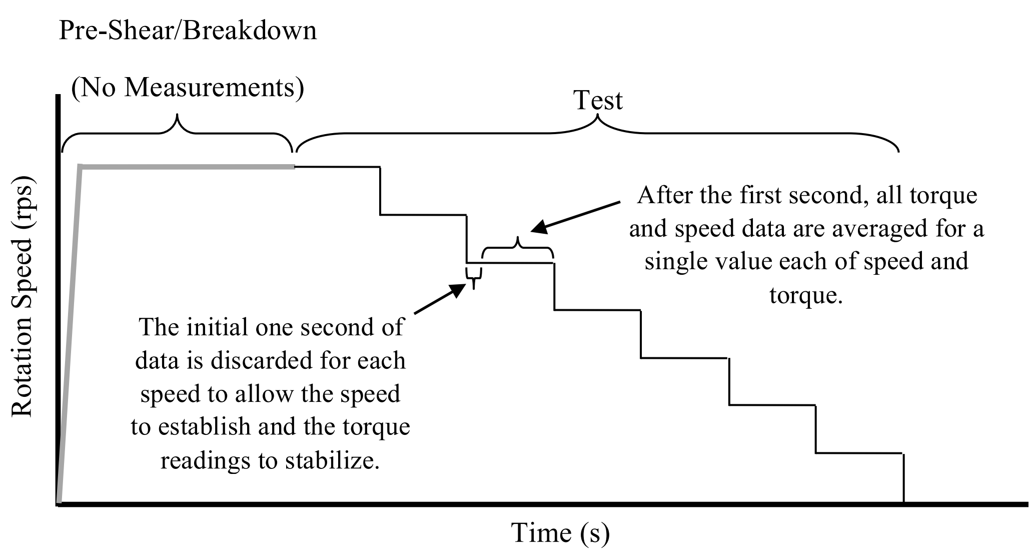


Figure 5.4-A typical Flow Curve Test [63]

The flow curve test results are computed both in relative and fundamental units. To compute relative units, a straight line is fit to the torque versus rotation speed data. The intercept is denoted as the Y-value (Nm) and the slope is denoted as the V-value (Nm.s). The Y-and V-values are related to, but not equal to, yield stress and plastic viscosity, respectively. For fundamental units, results are computed based on the Bingham model in terms of the yield stress (Pa) and plastic viscosity (Pa.s) [63].

The calculation of the Bingham model parameters of yield stress and plastic viscosity is based on the Reiner-Riwlin equation, which is expressed in Equation 5.2.

$$\Omega = \frac{T}{4\pi h \mu}\left(\frac{1}{R_1^{\ 2}} - \frac{1}{R_2^{\ 2}}\right) - \frac{\tau_0}{\mu}\ln\left(\frac{R_2}{R_1}\right) \tag{5.2}$$

Where Ω is the rotation speed (rad/s), T is torque (Nm), h is the vane height (m), R_1 is the vane radius, and R_2 is the outer container radius [63].

It is worth to mention that the fresh concrete performance data right after mixing may not be representative for the concrete performance after a while and over the course of time. Therefore, In order to examine the changes in rheological values of the concrete over time, the concrete rheology was measured 0, 5, 10, and 15 minutes after completion of mixing on the same sample. The samples were stored in the same conditions as the concrete mixtures.

It should be noted that different concrete rheometers adopt different geometries and significant difference could exist between rheological parameters obtained from different rheometers.

5.5 RESULTS AND DISCUSSIONS

The experimental results of the twenty-five SCC mixtures are summarized in Table 5.3. The effects of SP dosage, aggregate volume, size, gradation, and packing density on rheology of SCC will be discussed in details as follows.

Table 5.3-Experimental results of SCC mixtures

Mix Type	Mix ID	w/cm	Slump flow			Rheology (at t=0)		
			Slump (mm)	T_{50} (s)	T_f (s)	Static Yield Stress (Pa)	Dynamic Yield Stress (Pa)	Plastic Viscosity (Pa.S)
Graded Aggregate	GA	0.35	660	2.2	7.0	213.0	113.0	18.7
	GA-HSP	0.35	737	2.8	12.0	48.0	4.3	18.9
	GA -5 %ϕ	0.35	737	2.0	11.2	44.1	12.9	10.8
	GA -2%ϕ	0.35	685	3.0	7.0	73.9	35.8	14.7
	GA +3 %ϕ	0.35	585	2.6	5.0	267.6	150.0	28.0
	GA +5 %ϕ	0.35	585	2.8	5.5	435.0	311.0	31.7
	GA/LFA	0.35	685	3.0	9.0	99.3	52.7	24.4
	GA/HFA	0.35	585	2.5	5.0	543.8	330.2	23.7
	GA/HCA1	0.35	685	3.0	8.6	161.8	74.6	23.2
	GA/HCA1_2	0.35	737	3.6	9.5	119.8	36.2	37.0
	GA/SA	0.35	585	5.0	10.0	412.0	260.0	26.4
	GA/SA-HSP	0.35	685	4.2	7.0	39.6	0.1	25.1
	GA/ϕm_{63}	0.35	558	2.8	11.5	617.5	459.0	16.3
	GA/ϕm_{64}	0.35	660	4.5	7.5	N/A	N/A	N/A
	GA/ϕm_{71}	0.35	710	3.0	10.0	107.7	101.1	14.7
VMA	VMA	0.41	660	2.6	5.0	172.5	124.2	6.8
	VMA/LFA	0.41	635	3.2	5.5	158.0	91.6	10.1
	VMA/HFA	0.41	558	2.6	3.8	340.1	245.0	5.3
	VMA/HCA1	0.41	685	2.0	5.6	231.2	87.7	8.6
	VMA/HCA1_2	0.41	635	2.4	4.5	123.8	73.2	9.9
	VMA/SA	0.41	585	2.2	3.5	235.0	157.1	8.0
	VMA/ϕm_{63}	0.41	558	4.5	5.0	353.1	213.9	13.6
	VMA/ϕm_{64}	0.41	635	4.0	7.0	N/A	N/A	N/A
	VMA/ϕm_{69}	0.41	685	2.4	7.0	82.5	59.8	13.7
	VMA/ϕm_{71}	0.41	710	2.0	5.5	77.4	73.2	18.2

5.5.1 Effects of SP Dosage on rheology of SCC

Figure 5.5 shows how superplasticizer affects rheology of SCC. The SP dosages of the GA and GA/SA type of mixtures were 0.35% and the SP dosages of the GA-HSP and GA/SA-HSP type of mixtures were 0.46%.

As expected, increasing superplasticizer dosage decreased both static and dynamic yield stress. The change in static yield stress over time is a function of thixotropy and workability loss. However, increased static yield stress in mixtures with high dosage of superplasticizer (GA-HSP and GA/SA-HSP) maybe mainly due to thixotropy as slump loss was insignificant (dynamic yield stress in both mixtures did not vary noticeably with time).

For both GA and GA/SA mixture, increasing Superplasticizer dosage did not noticeably enhance initial plastic viscosity (t=0); however, at later time of 5, 10, and 15 minutes, plastic viscosity increased with higher superplasticizer dosage (Fig. 5.5c).

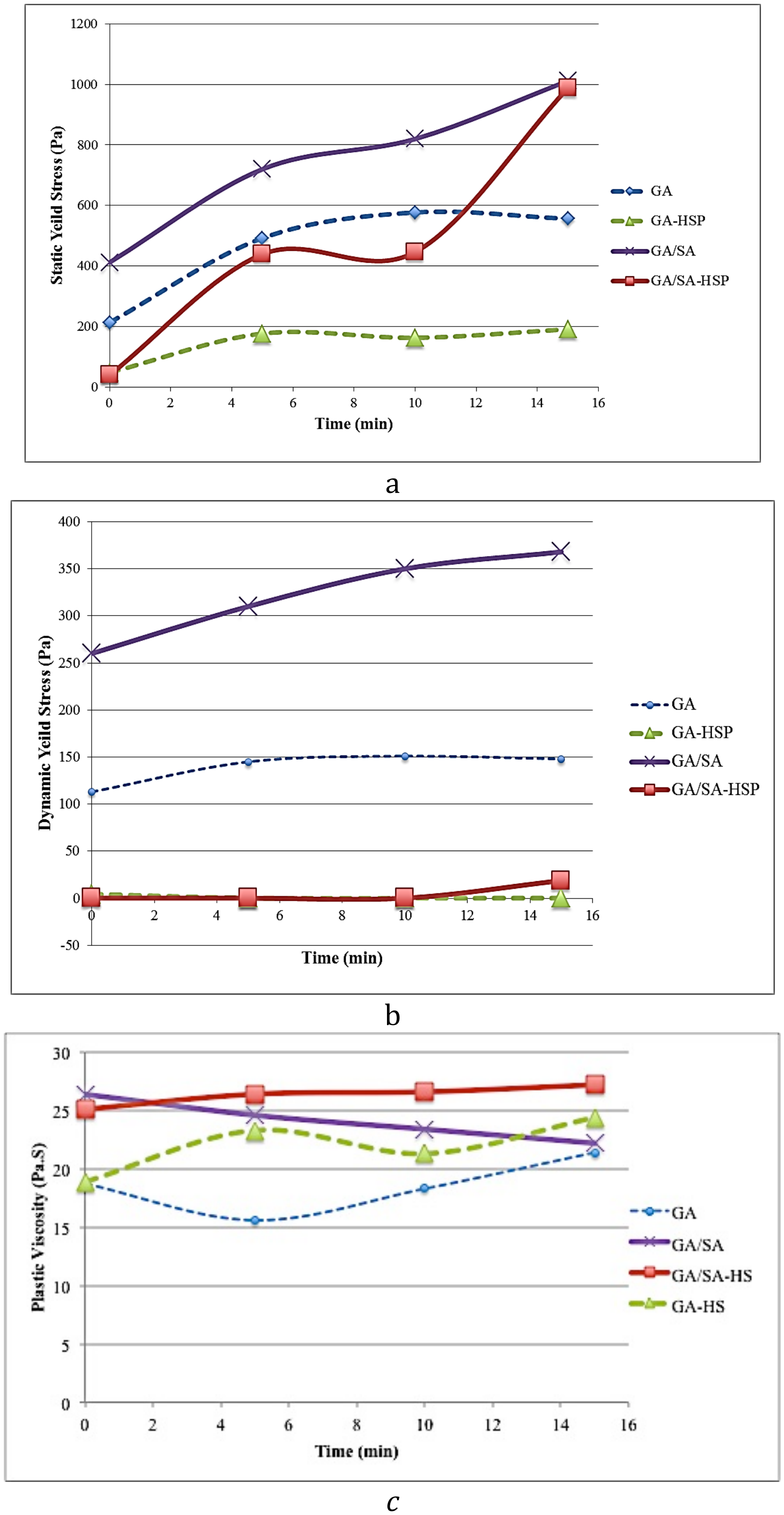
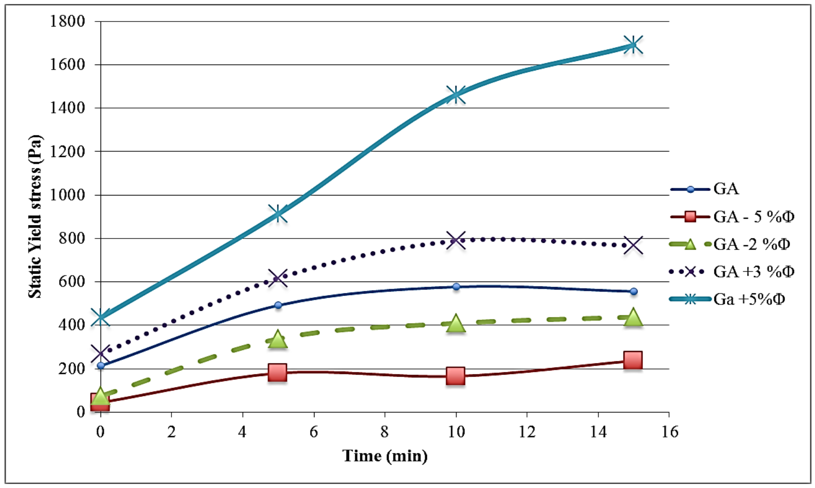


Figure 5.5-Effect of Superplasticizer on yield stress and plastic viscosity of SCC mixture. a) Static Yield Stress b) Dynamic Yield Stress c) Plastic Viscosity

5.5.2 Effect of aggregate volume on Rheology of SCC

Fig 5.6 illustrates the rheological curves of the GA, GA+5%ϕ, GA+2%ϕ, GA-3%ϕ, and GA-5%ϕ mixtures over time. Compared with the GA mixture, GA +5%ϕ mixture had 5% more aggregate volume, and GA-5%ϕ mixture had 5% less aggregate volume.



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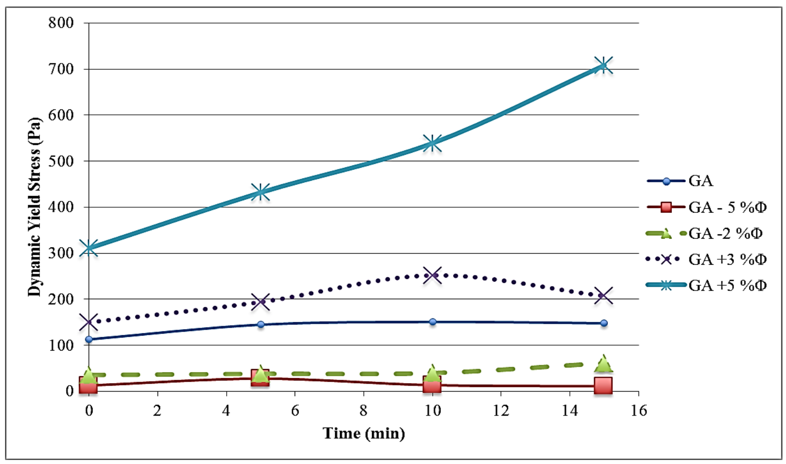

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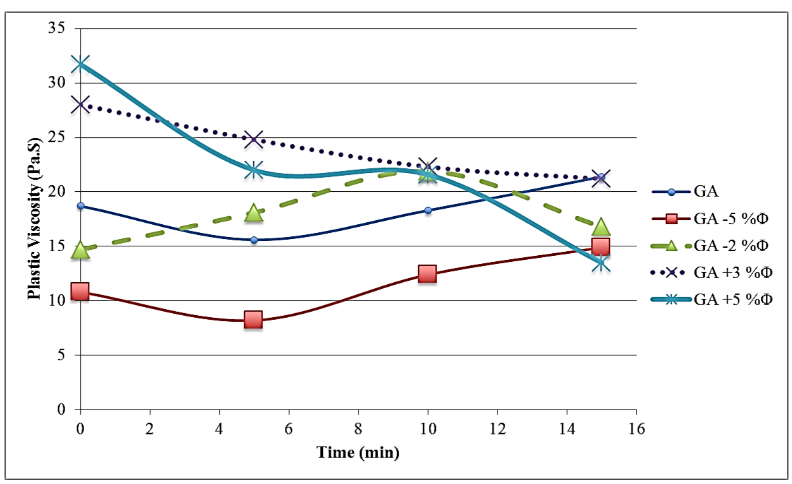


c

Figure 5.6-Effect of aggregate volume on Rheology of graded aggregate mixtures a) Static Yield Stress b) Dynamic Yield Stress c) Plastic Viscosity

Clearly, higher aggregate volume corresponded to higher static and dynamic yield. Coussot [64] studied rheology of suspension and developed a model relating the mixture yield stress to the yield stress of suspending fluid.

$$\tau_m = \tau_f \left(1 - \frac{\phi}{\phi_m}\right)^{-m} \qquad (5.3)$$

Where τ_m is yield stress of mixture, τ_f is yield stress of suspending fluid, ϕ_m is the maximum packing density of particles and m is a coefficient. The value of m is 1 when particle volume fractions (ϕ) is lower than 0.6. Coussot model can be applied in SCC by considering cement paste as the suspending fluid and aggregate as the suspended particles. According to equation 5.3, since the suspending fluid and ϕ_m were similar in all mixtures above (similar paste properties in all mixture), increasing aggregate volume increases yield stress of mixtures. We can only note without comment that there were significant increases in yield stress by increasing aggregate volume from +3%ϕ to +5%ϕ (Fig. 5.6a and 5.6b).

Figures 5.6c also shows that at t=0, plastic viscosity decreased with lower aggregate volume. The Krieger-Dougherty equation [65] may be useful to describe the relationship between viscosity and volume fraction in concrete.

$$\eta_c = \eta_p \left(1 - \frac{\phi}{\phi_m}\right)^{-[\eta]\phi_m} \qquad (5.4)$$

where η_c is the apparent viscosity of the suspension, η_p is the apparent viscosity of the solution, ϕ is the volume fraction of particles, ϕ_m is the maximum packing density of particles, and $[\eta]$ is the intrinsic viscosity of the particles. The value of $[\eta]$ is 2.5 for ideal spherical particles and is more than 2.5 for non-spherical or highly charged particles. According to Eqn (5.4), higher aggregate volumes correspond to higher viscosity (η_p is similar in all mixture), which is the case for t=0. However, based on the results in this study, it seems this equation cannot be applied in other time (t>0) as plastic viscosity of mixtures have different trends. GA+3%ϕ, GA+5%ϕ decrease with time and GA-5%ϕ, GA-2%ϕ increase with time. At t=15, mixtures have different ranking on magnitude of plastic viscosity compare to t=0. Decreased plastic viscosity with increasing time for GA+3%ϕ and GA+5%ϕ mixtures could be due to the higher shear rate of paste for mixture with higher aggregate volume.

5.5.3 Effects of FA/CA Ratio, Aggregate Size, and Packing Density on Rheology of SCC

As can be seen in Figure 5.7a-d, increasing fine aggregate to coarse aggregate (FA/CA) ratio (while, keeping the total aggregate volume constant) increased static and dynamic yield stress. Higher yield stress of mixture with higher FA/CA ratio could be attributed to greater surface area to volume ratio of the fine aggregates, which increases the effective aggregate volume. As paste properties and volume are constant in all mixture, with increasing FA/CA ratio, larger aggregate surface need to be coated with paste in order for the SCC to be workable.

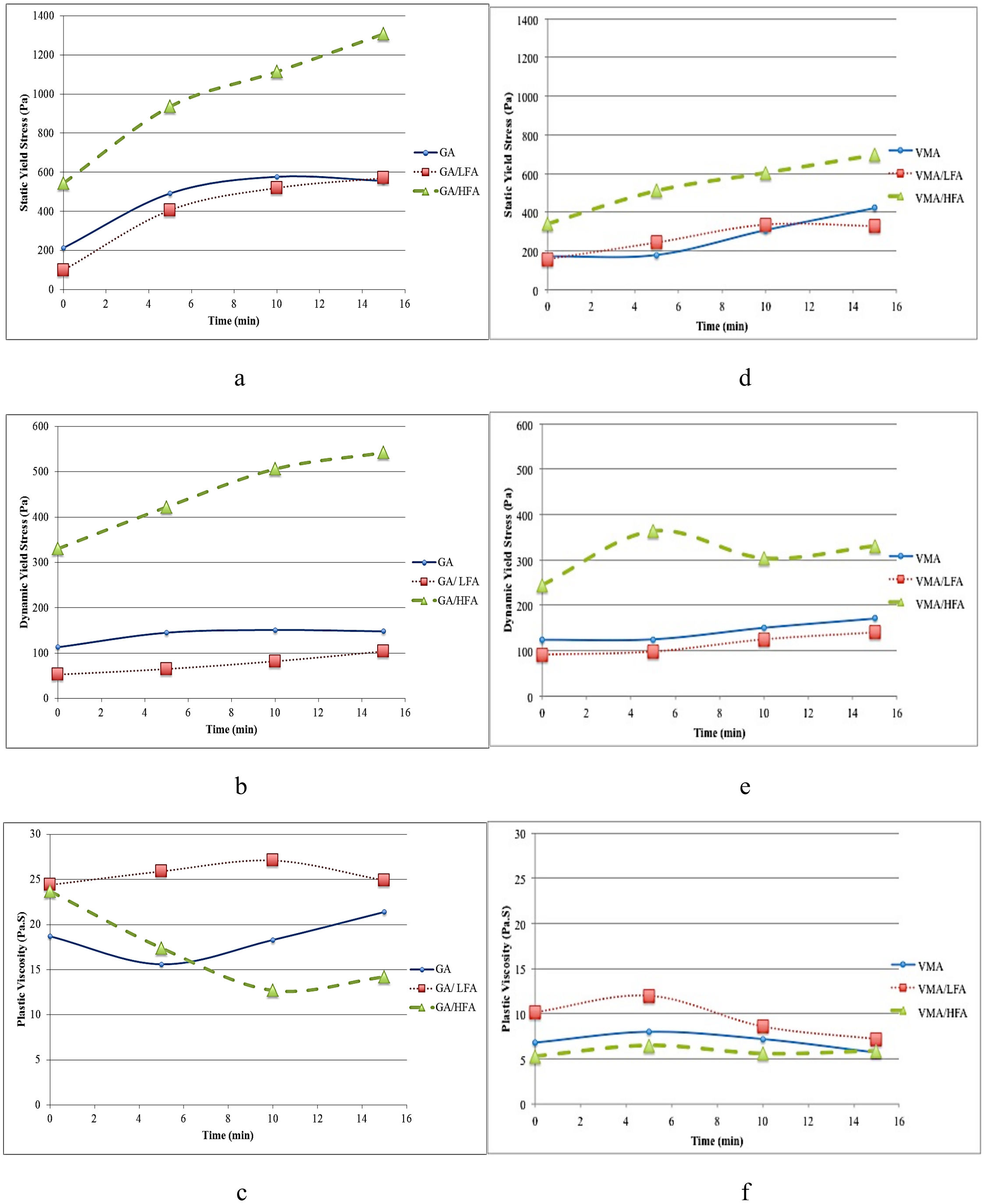
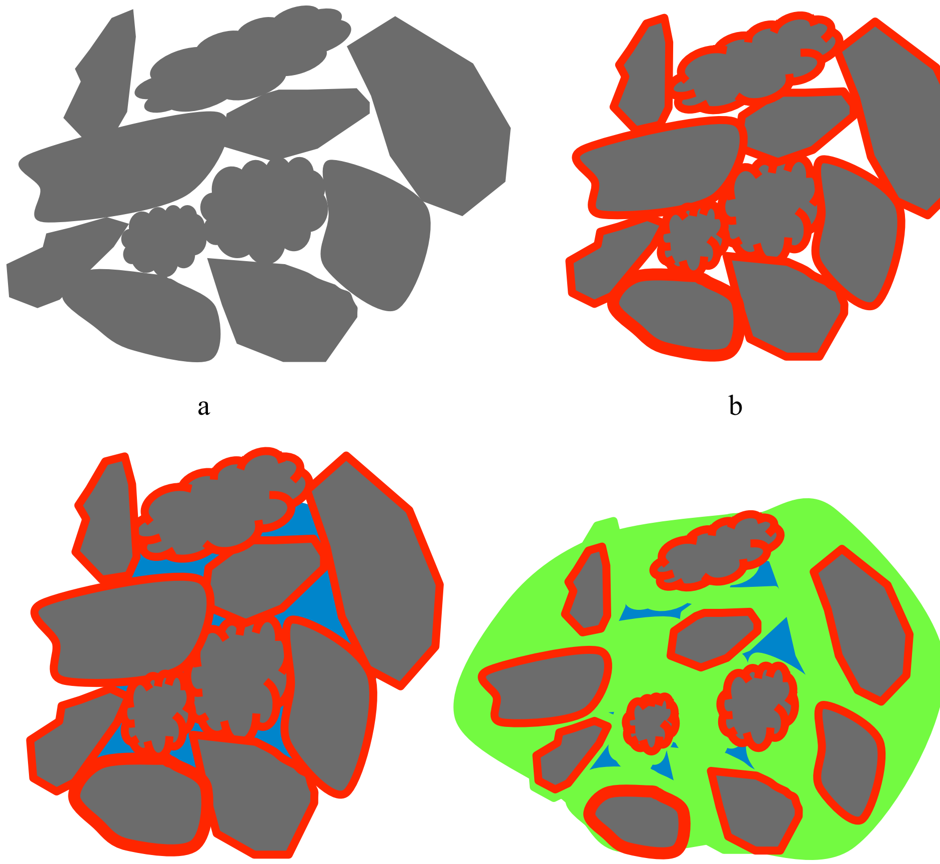


Figure 5.7-Effect of FA/CA ratio on rheology of SCC, (a-c) are for GA series and (d-f) are for VMA series

It should be noted that the amount of paste required to produce a workable mixture is greater than the volume of voids between aggregates. The required paste volume should cover aggregates surface, fill inter particles gaps between aggregates, and increase aggregates particle spacing to achieve desired slump (see Figure 5.8).



a b

c d

Figure 5.8- Three functions of paste, a: Packed aggregates; b: Required paste to cover aggregate surface; c: Required paste to fill inter-particle gaps; d: Required paste to increase particle spacing and achieve desired slump

At t=0, in GA series, both GA/LFA and GA/HFA have higher plastic viscosity compare to GA mixture but in other time (t>0), with decreasing plastic viscosity of GA/HFA and increasing plastic viscosity of GA mixture, different ranking can be observed. In VMA series, in all time VMA/HFA have lower plastic viscosity and VMA/LFA ratio have higher plastic viscosity compare to VMA mixture (Fig. 5.7f).

Left column of Figure 5.9 shows the rheology curves of the GA, GA/HCA1, and GA/HCA1$_2$ mixtures and right column of figure 8 shows rheology curves for VMA series. Compared with the GA mixture, the GA/HCA1 mixture had 17% more CA1 volume, and GA/HCA1$_2$ mixture had 37% more CA1 volume (0% of CA2 Volume). Other mix proportions were mostly the same.

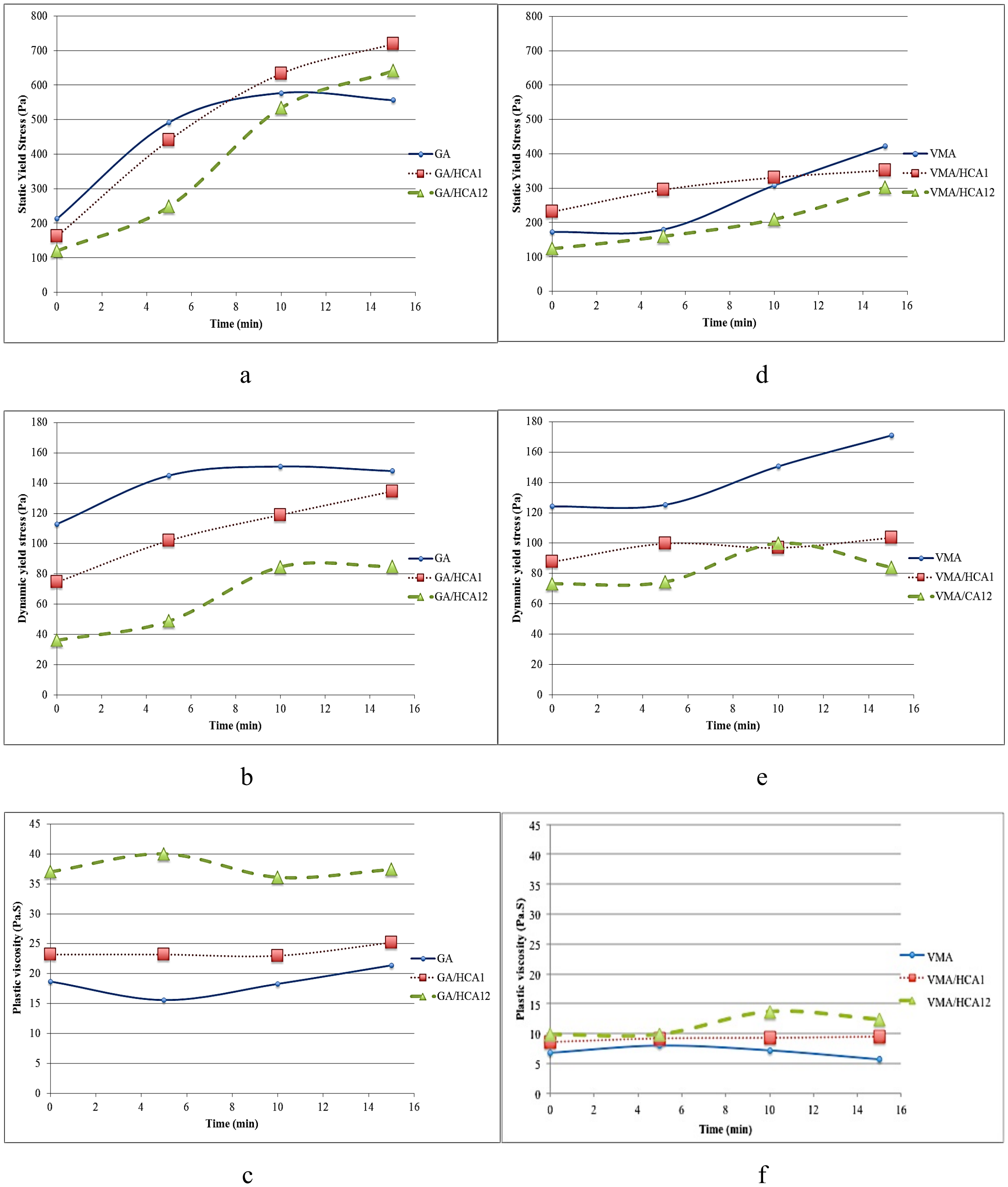


Figure 5.9- Effect of CA1% on rheology of SCC, (a-c) are for GA series and (d-f) are for VMA series

Static yield stress of GA mixtures with higher percentage of CA1 increased significantly over time and at t=15 both GA/HCA1 and GA/HCA1$_2$ had higher static yield stress than GA mix. Similar trend could not be observed in VMA series.

It can be seen from Figure 5.9c-d that increasing CA1% ratio reduced dynamic yield stress of SCC mixtures. This could be related to lower surface area to volume ratio of the CA1 compare to CA2, which in turn decreased absorption of paste on aggregate surface. Therefore, there was more paste volume available to fill voids and increasing aggregates particle spacing.

Plastic viscosity of both GA And VMA mixtures increased with higher percentage of CA1. It should be considered that as CA1 percentage increased, CA2 percentage decreased. Lower volume of intermediate aggregate (CA2) could increase interlocking between coarser aggregates (CA1) and therefore increase plastic viscosity of SCC. Westerholm et al [66] found that lowest fines content in mortar corresponded with the highest viscosity, which was due to the lack of enough fines to fill the voids between the larger aggregate particles.

The differences in rheological trends over time between GA and VMA mixtures could be attributed to different paste compositions. Issues like delayed adsorption of SP could be different in presence of VMA and/or fly ash. The paste rheology of the mixtures in Table 5.2 is planned be measured in future research to further validate the theory.

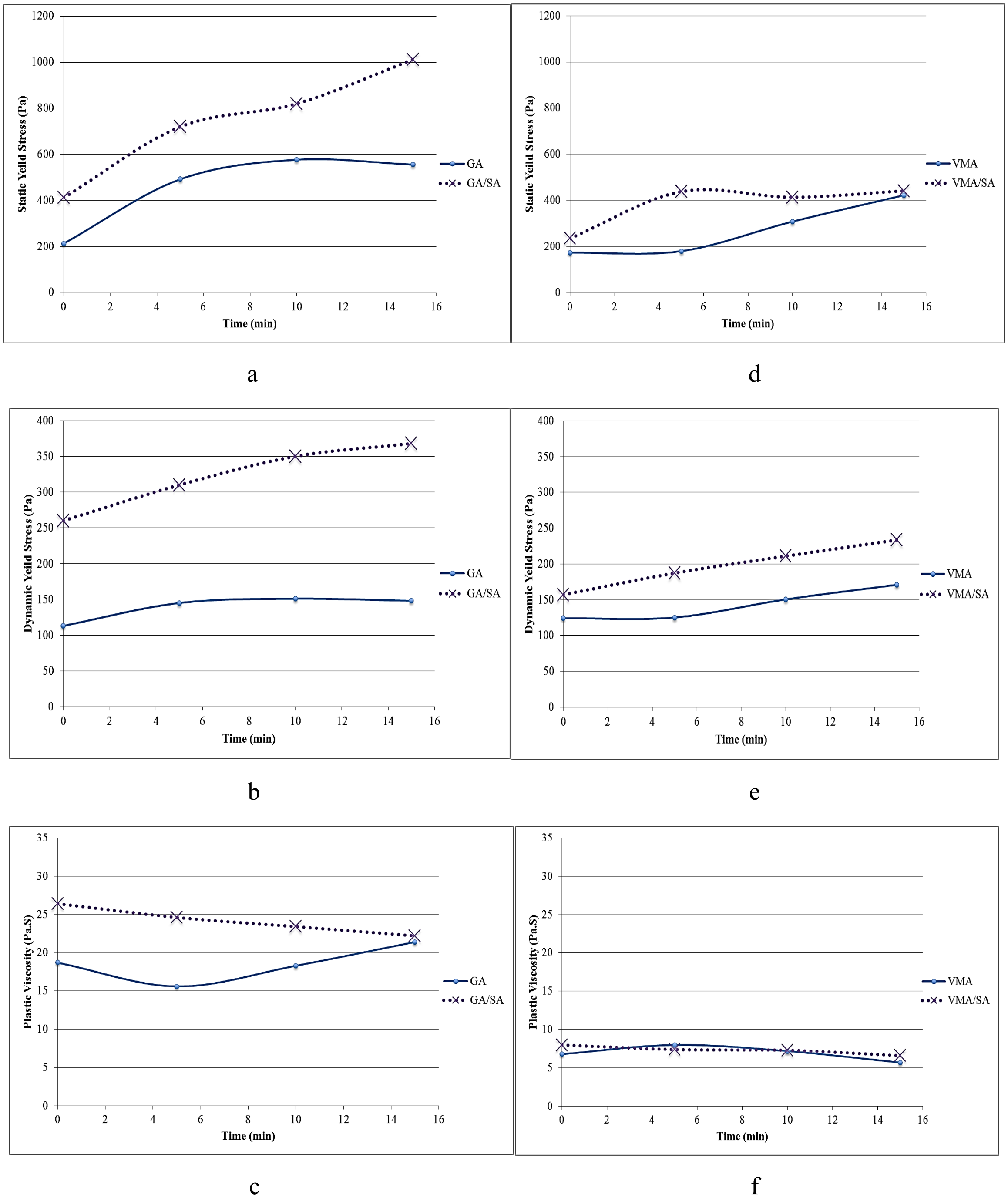
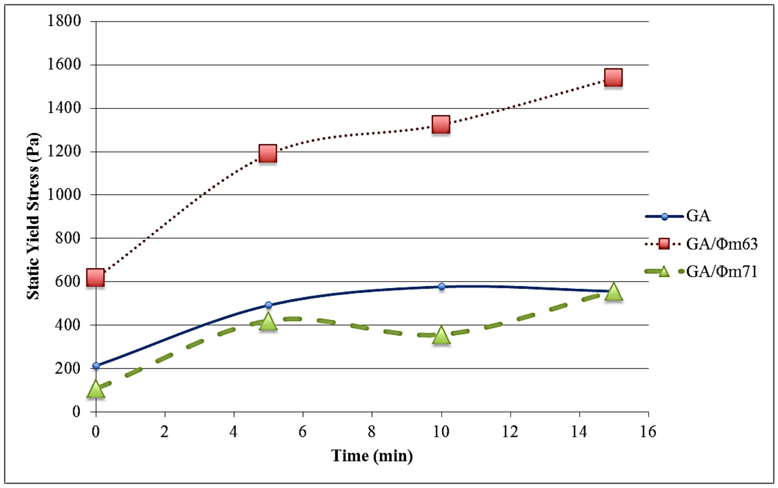


Figure 5.10-Effect of aggregate size on rheology of SCC, (a-c) are for GA series and (d-f) are for VMA series

Figure 5.10 shows how aggregate size affects yield stress and plastic viscosity of SCC mixtures. Compared with the GA and VMA mixtures, which had 19-mm coarse aggregate, the GA/SA and VMA/SA mixtures had smaller (9.5-mm) maximum coarse aggregate size.

Clearly, reducing aggregate size increased static and dynamic yield stress for both GA and VMA series and this trend is more noticeable in GA series. The increased yield stress with smaller aggregate can also be explained based on the higher aggregate surface area of smaller aggregate size compared to larger aggregate size.

In GA Series, reducing maximum aggregate size slightly increases plastic viscosity at t=0 but this enhancement decreases with time (Fig. 5.10e). In VMA series, however, there is no noticeable increase in plastic viscosity with smaller maximum aggregate size. Some researchers reported that in the case of suspensions of single-size spheres, plastic viscosity does not depend on the size of the particles and for binary systems of spheres, the influence of the size distribution being contained in the packing density [67, 68]. As both mixtures had almost the same packing density, it can be expected that reducing maximum aggregate size doesn’t affect viscosity of SCC. However this assumption is not always valid for particle systems with a large range of sizes and different shapes.



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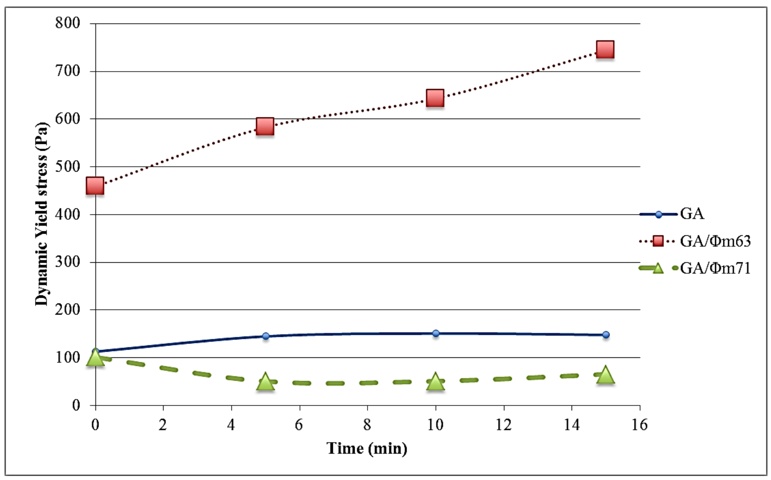

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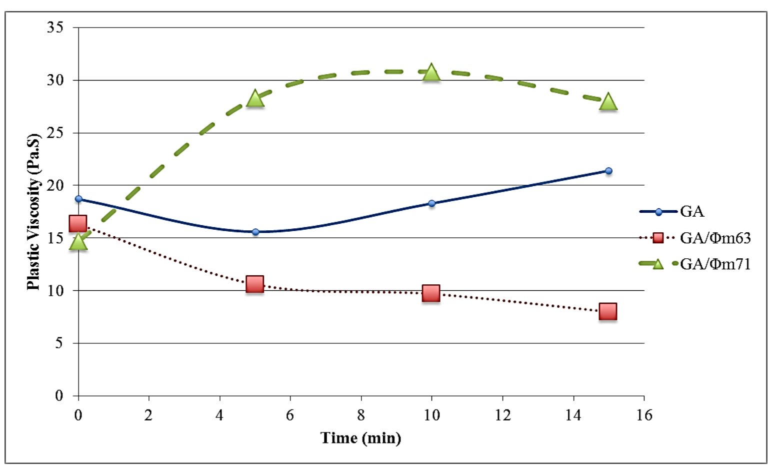


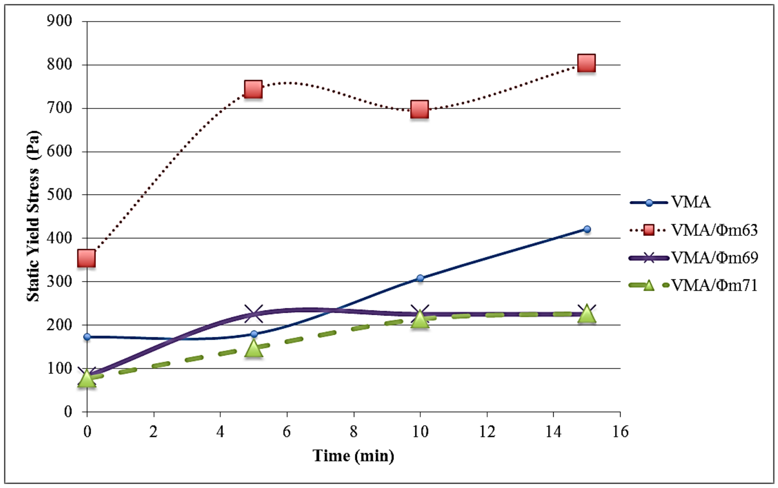
c

Figure 5.11-Effect of packing density on Rheology of SCC (GA series)
a) Static Yield Stress b) Dynamic Yield Stress c) Plastic Viscosity

Figure 5.11 illustrates how concrete rheology was influenced by aggregate packing density. The GA, GA/φ_{m63} and, GA/φ_{m71} mixtures had packing density (φ_m) of 0.67, 0.63 and 0.71, respectively.

As can be seen in figure 5.11a and 5.11b, decreasing packing density increased static and dynamic yield stress significantly. The higher yield stress for mixtures with lower packing density can be explained by Eqn (5.3). Since the suspending fluid and ϕ were similar in all three mixtures, decreasing aggregate packing density increases yield stress of mixtures.

As mentioned earlier, required paste to achieve desired slump will cover aggregates surface, fill inter particles gaps between aggregates, and increase aggregates particle spacing. As the paste volume was constant, mixtures with higher aggregate packing density (lower inter particles gaps) had larger spacing between aggregates and reduced interparticle friction, and consequently lower plastic viscosity. On the other hand, GA/φ_{m71} had lower percentage of fine aggregate that resulted in increased interlock between coarse aggregate. At t=0, it seems reduced interparticle friction was more pronounced and with period of time, increased interlock between coarse aggregate become more pronounced. Similarly, GA/φ_{m63} had higher percentage of fine aggregate and thus decreased interlock between coarse aggregate and resulted in lower viscosity.



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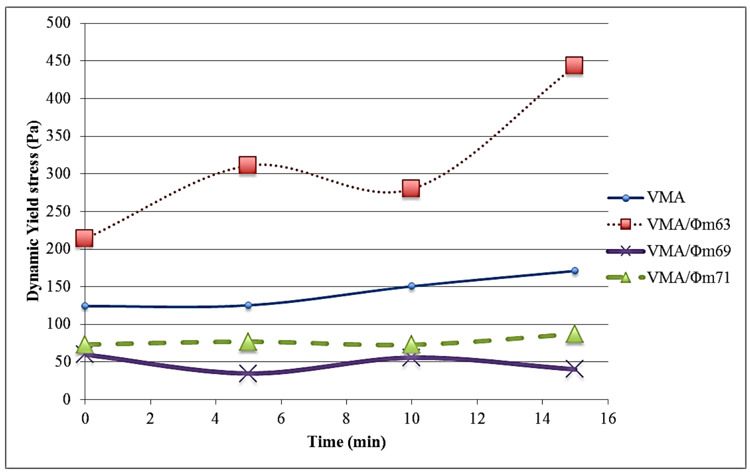

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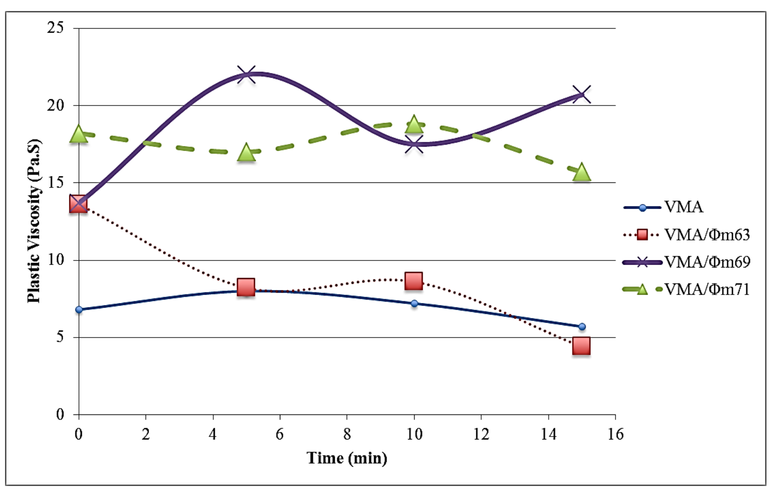


c

Figure 5.12-Effect of packing density on Rheology of SCC (VMA series)
a) Static Yield Stress b) Dynamic Yield Stress c) Plastic Viscosity

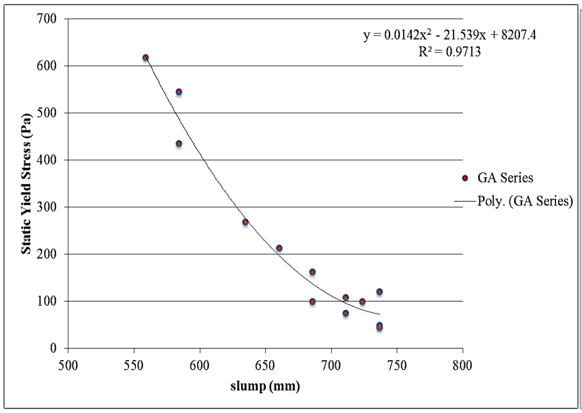
The VMA mixture had φ_m of 0.67 and VMA/φ_{m63}, VMA/φ_{m69}, VMA/φ_{m71} had packing density (φ_m) of 0.63, 0.69, and 0.71 respectively (see figure 5.12). It is worth mentioning that VMA/φ_{m64} with a packing density of 0.64 and FA/CA ratio of 0.25 was segregated and its rheological parameters were not included in the analysis. The reason is because yield stress and plastic viscosity measurements can be distorted by segregation [68].

As shown in Figure 5.12 (VMA series), similar to GA series, mixtures with higher packing density had lower static and dynamic yield stress and higher plastic viscosity.

Comparing VMA/φ_{m71} and VMA/φ_{m69}, it is implied that yield stress is controlled by a combined effect of packing density and sand content as VMA/φ_{m69} (aggregate packing density of 0.69 and sand content of 30%) had lower dynamic yield stress than VMA/φ_{m71} (maximum aggregate packing density φ_m=0.71 and sand content of 0.35%). Struble et al found that the yield stress of concrete had its minimum at 40% sand, about the same value as the maximum in volume fraction [57]. So, it could be suggested that the sand content should be included in The Coussot equation.

5.5.4 Relationship between Concrete rheology test and slump flow test

It can be seen from Figure 5.13 that there is a polynomial relationship between yield stress and slump tests and the correlation coefficients are basically larger than 0.97 in GA series and larger than 0.81 in VMA series, which indicates that yield stress of SCC may be estimated by measuring slump flow. However, this statement holds true only when the paste proportions were constant. In figure 5.14, rheological data are plotted against slump test for all mixtures with different paste and aggregate properties. No reasonable relationship was observed between concrete rheology and slump flow under this condition.



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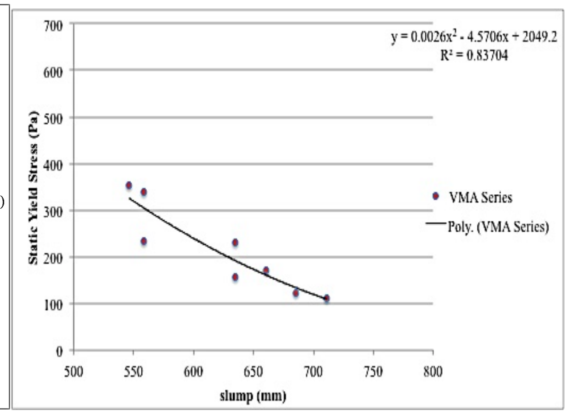

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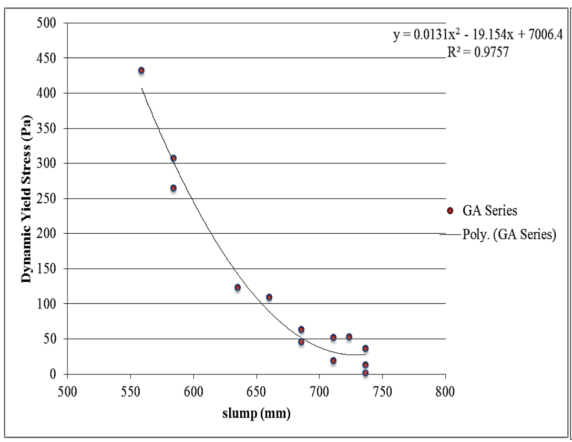

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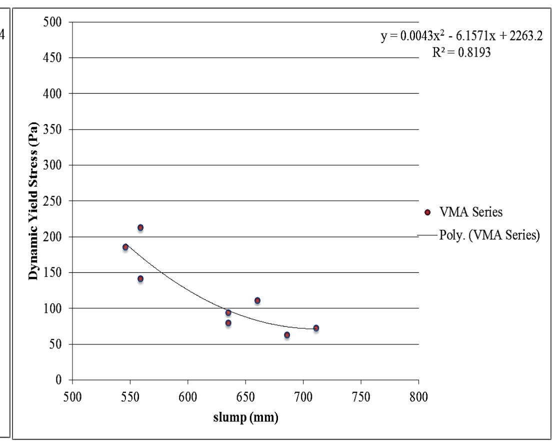
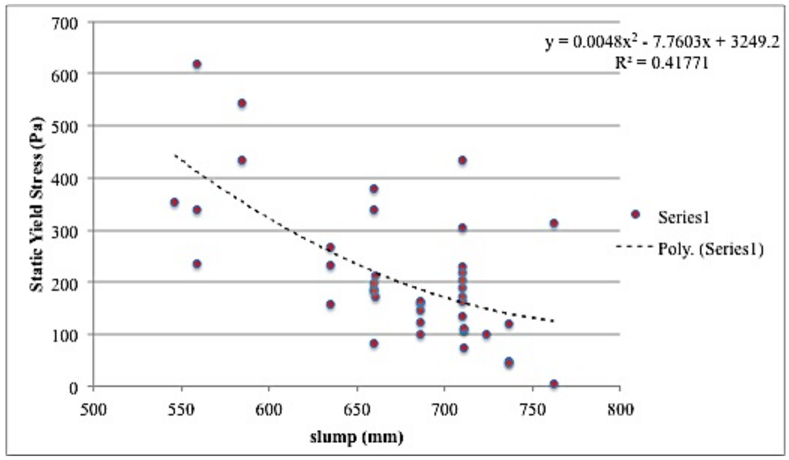


d

Figure 5.13-Relationship between yield stress and slump for SCC mixtures, (a and b) are for GA series and (c and d) are for VMA series (constant paste properties with different aggregate properties).



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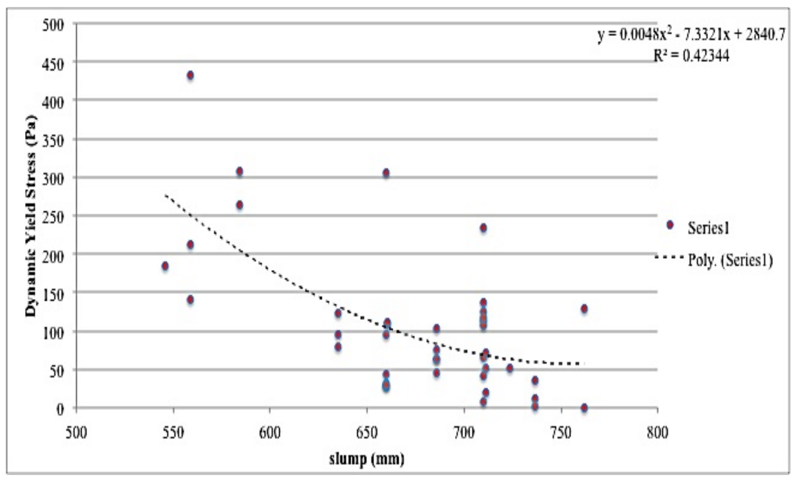
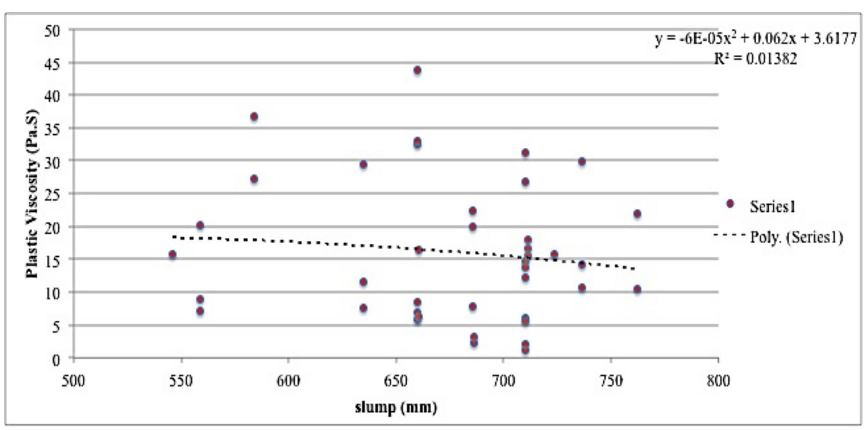


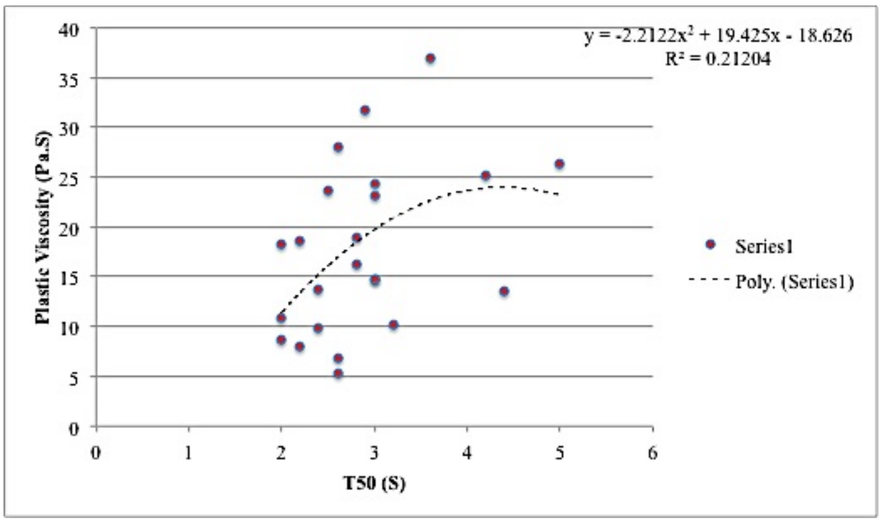
b



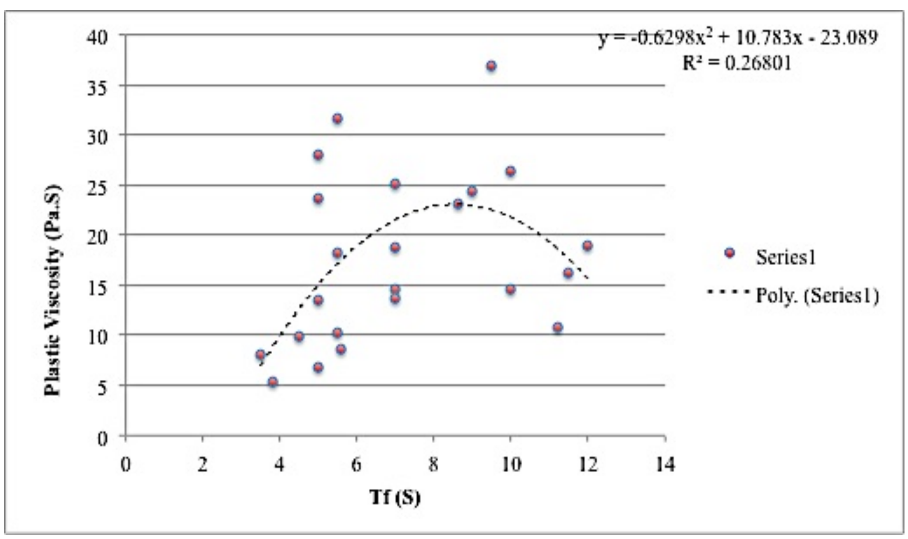
c

Figure 5.14-Relationship between Rheology parameters and slump for all mixtures (different paste and aggregate properties) (Extra Data form Previous work [38])

Figure 5.15a shows how plastic viscosity correlated to T_{50} from slump test. As the slump is used to estimate of the yield stress, the T_{50} is often measured in the field to estimate the viscosity of the concrete [30]. However, no direct relationship was observed between plastic viscosity and T_{50} in this study. This could be partially due to the limited range of T_{50} (2- 5 sec) in this study. Tregger et al [34] found that the time to reach a final diameter (T_f) was more indicative of viscosity than T_{50}. However, no clear relationship was observed between T_f and viscosity in this study (Fig. 5.15b).



a



b

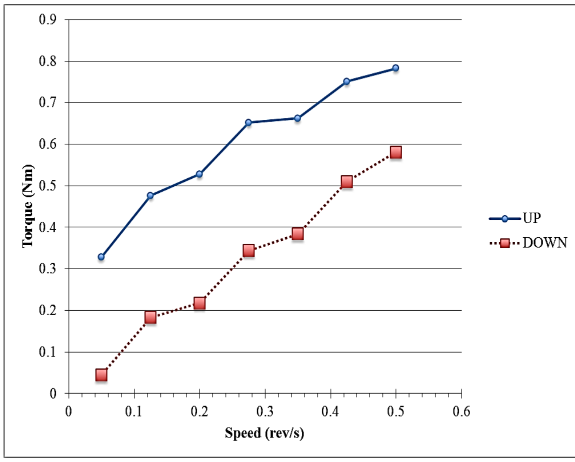
Figure 5.15-Relationship between plastic viscosity and T_{50} (a) and T_f (b) for SCC mixtures.

The flow curves of SCC mixtures with different slump obtained with the ICAR rheometers are shown in Figure 5.16a–f.

Thixotropy was measured by performing a loop test in a rheometer. In this test, the shear rate is increased from minimum to a maximum value and returned to minimum. The area between the up and down curve is indication of thixotropy. For all thixotropic materials, the up-curve will be above the down-curve. Conversely, the down-curve will be above the up-curve for anti-thixotropic materials [69].

As can be seen in Figure 5.16, SCC mixture with slump of 560 mm (22 in) and 580 mm (23 in) showed anti-thixotropic manner; however, SCC mixture with higher slump showed thixotropic manner. Thixotropy should not be confused with shear-thinning behavior, which describes the decrease in viscosity as a function of increasing shear rate, not shearing over time. Thixotropy typically occurs in shear-thinning fluids whereas anti-thixotropy, or the reversible, time dependent increase in viscosity during constant shearing, typically occurs in shear-thickening fluids [70].

As the data set used in this chapter is relatively small and these phenomena have not been observed in literature, further data needs/ to be collected to definitively establish the existence of relation between Slump flow value and thixotropy/anti-thixotropy manner of SCC concrete.



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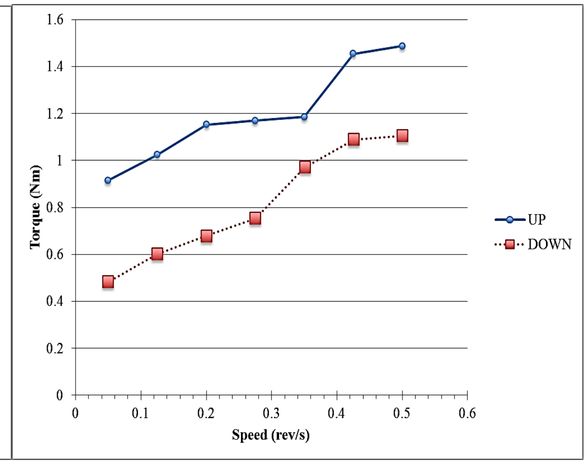

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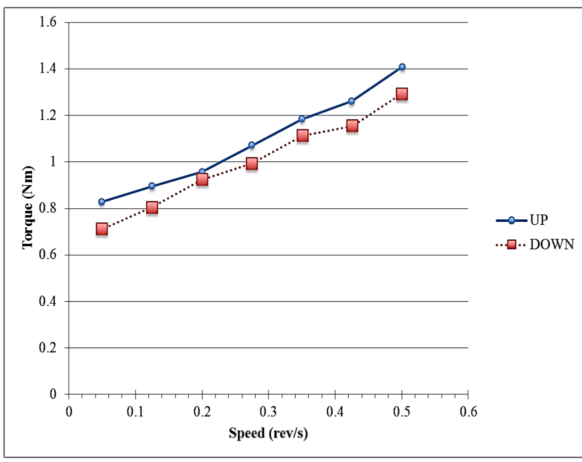

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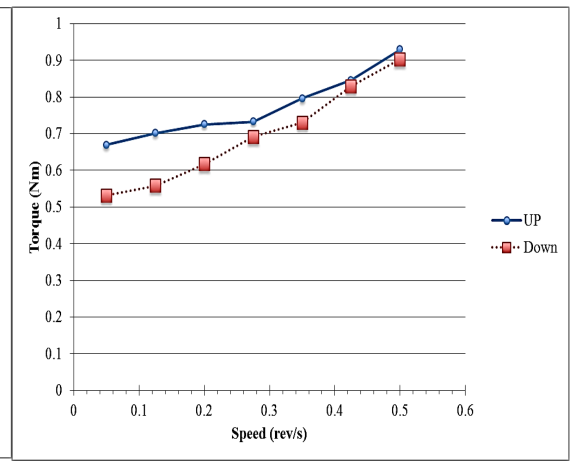

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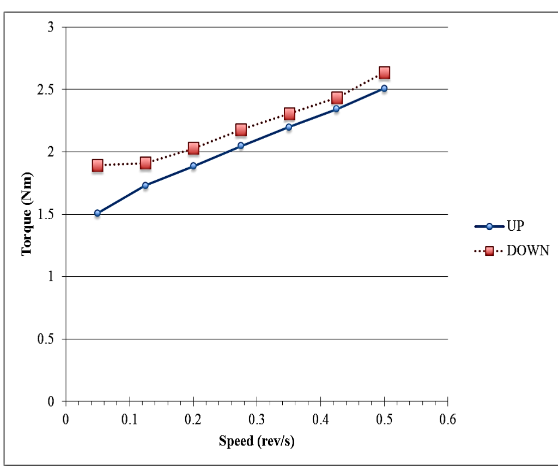
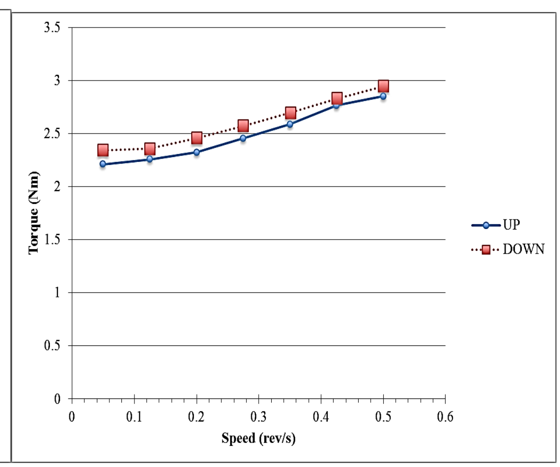


e



f

Figure 5.16-Flow curves of SCC mixtures with different slump (a: 740 mm (29 in), b: 710 mm (28 in), c: 660mm (26 in), d: 610 mm (24 in), e: 580 mm (23 in) f: 560 mm (22 in))

5.6 CONCLUSION

From the results obtained from this study (limited range of 25 mixtures), the following conclusion can be drawn:

1) Increasing aggregate volume increases yield stress and viscosity of mixtures. The Krieger-Dougherty equation can be used to explain how aggregate volume affects the plastic viscosity.

2) Higher yield stress of mixture with higher FA/CA ratio could be attributed to greater surface area to volume ratio of the fine aggregates, which increases the effective aggregate volume.

3) Increasing CA1% ratio reduced dynamic yield stress of SCC mixtures due to lower aggregate surface area/mass ratio.

4) Reducing maximum aggregate size slightly increases plastic viscosity.

5) Mixtures with higher packing density had lower static and dynamic yield stress and higher plastic viscosity. The Coussot model can be used to explain how aggregate packing density affects the yield stress.

6) A polynomial relationship between yield stress and slump tests was observed when the paste proportions were constant.

7) No direct relationship was observed between plastic viscosity and T_{50} and T_f in this study.

8) SCC mixture with slump flow diameter of 560 mm (22 in) and 580 mm (23 in) showed anti-thixotropic manner; however, SCC mixture with higher slump showed thixotropic manner.

CHAPTER 6

CONCLUSION

From all the results and discussion in previous chapters, the following conclusions are drawn:

1) The symmetrical design of the modified Segregation Probe resolved the tilting problem of the original design in some segregated mixes.

2) The modified Segregation Probe is shown experimentally and theoretically to measure the thickness of the paste/mortar layer on top of instable SCC.

3) The results of modified Segregation Probe agreed well with the Penetration Test from ASTM C1712-09.

4) There are general agreement between the results of modified Segregation Probe and the Segregation Column test from ASTM C1610/C1610M-10.

5) The robustness of SCC mixtures can be well quantified and compared based on the slope of robustness curves, TMS1, and TMS2.

6) The static segregation rate equation in Eqn. (3.1):

$$u_a = u_s\left(1-\frac{\varphi}{\varphi_m}\right)^{5.18} = \frac{\left(\frac{(\rho_s-\rho_L)gd}{18}-\tau_0\right)d}{\eta_{pl}}\left(1-\frac{\varphi}{\varphi_m}\right)^{5.18}$$

can be used to explain how various factors affecting the robustness. However, caution should be taken when one factor affects multiple variables in the equation simultaneously.

7) Higher paste volume may improve robustness by reducing the required yield stress and viscosity of cement paste to maintain the same concrete slump flow.

8) While smaller aggregate size, better gradation, and higher aggregate packing density can all improve robustness of SCC mixtures, smaller aggregate size and better gradation seem to have more significant impact on robustness than higher aggregate packing density.

9) Higher FA/CA ratio improves robustness due to: 1) reduced average aggregate size, and 2) less required SP dosage (and higher paste yield stress and viscosity) because of the lubricant effects of sand particles between coarse aggregate.

10) The flow trough test was found to provide a measure of dynamic segregation of SCC with acceptable precision and accuracy.

11) The visual stability rating from the slump flow test did not always provide a suitable measure of dynamic segregation.

12) The drag force equation in Eqn. (4.2) and other rheological analysis such as the one used in the LCPC box [35] design can be used to explain how various factors affecting the dynamic segregation. Nevertheless, caution should be taken when one factor affects multiple variables in the equation simultaneously.

13) 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.

14) 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 with better gradation.

15) Most mixtures with dynamic yield stress higher than 50 Pa had DSI less than 15%, and mixtures with the dynamic yield stress less than 50 Pa typically had DSI higher than 20%.

16) Increasing aggregate volume increases yield stress and viscosity of mixtures. The Krieger-Dougherty equation can be used to explain how aggregate volume affects the plastic viscosity.

17) Higher yield stress of mixture with higher FA/CA ratio could be attributed to greater surface area to volume ratio of the fine aggregates, which increases the effective aggregate volume.

18) Reducing maximum aggregate size slightly increases plastic viscosity.

19) Mixtures with higher packing density had lower static and dynamic yield stress and higher plastic viscosity. The Coussot model can be used to explain how aggregate packing density affects the yield stress.

20) A polynomial relationship between yield stress and slump tests was observed when the paste proportions were constant.

21) SCC mixture with slump of 560 mm (22 in) and 580 mm (23 in) showed anti-thixotropic manner; however, SCC mixture with higher slump showed thixotropic manner

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