THE EFFECTS OF AGGREGATE MOISTURE CONDITIONS ON RHEOLOGICAL BEHAVIORS OF HIGH-WORKABILITY MORTAR PREPARED WITH FINE RECYCLED-CONCRETE AGGREGATE

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LIST OF ACRONYMS

Acronyms	**Explanation**
FRCA	Fine Recycled-Concrete Aggregate
HRWRA	High Range Water Reducing Admixture
IW	Initial Free Water Content
IW/c	Initial Free Water to Cement Ratio
OD	Oven Dry
RCA	Recycled-Concrete Aggregate
rps	Rounds per Second
SCC	Self-Consolidating Concrete
SSD	Saturated Surface Dry
VMA	Viscosity Modifying Admixture
VSI	Visual Stability Index
w/c	Water to Cement Ratio

ABSTRACT

THE EFFECTS OF AGGREGATE MOISTURE CONDITIONS ON RHEOLOGICAL BEHAVIORS OF HIGH-WORKABILITY MORTAR PREPARED WITH FINE RECYCLED-CONCRETE AGGREGATE

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An ICAR rheometer was used in this study to measure the rheological behaviors of high-workability mortar (Self-Consolidating Concrete - SCC mortar). A mortar slump test and a mortar funnel test were also performed to evaluate the workability of SCC mortar. Fine recycled-concrete aggregate (FRCA) was used in this study in mixtures to replace natural aggregate at different degrees. Fine aggregates, both natural and recycled aggregates, were used to prepared SCC mortar in two moisture conditions, wet condition and dry condition. The change of workability and rheology of SCC mortar over time was investigated. It has been found that the fine recycled-concrete aggregate can be used to replace the natural aggregate in producing SCC mortar. The use of FRCA reduced both

the unit weight and the compressive strength of SCC mortar. It has also been found rheological parameters can be used to indicate the workability of SCC mortar.

CHAPTER I. INTRODUCTION

Background

Self-consolidating concrete (SCC), also referred to as self-compacting concrete is highly flowable and non-segregating concrete. The high flowability of SCC allows it to flow and consolidate into the framework and encapsulate the reinforcement under its own weight without mechanical consolidation. This characteristics makes it possible for placing concrete in difficult construction conditions such as heavily reinforce concrete members or complicated formwork (ACI Committee 237, 2007). To achieve high flowability, high-range water-reducing admixture (HRWRA) is usually used in SCC mixtures. On the other hand, to maintain the consistence of the mixtures, lower water to cement ratio is adopted and viscosity-modifying admixture (VMA) is used.

Tests such as slump flow, V-Funnel, J-Ring, L-Box, and column segregation were developed and used to measure the flowability, passing ability and segregation resistance of fresh SCC (ACI Committee 237, 2007). Rheology is another parameter used to evaluate the flowability of SCC mixtures, which provides a numerical description to the properties of SCC.

Recycled-concrete aggregate (RCA) was used in this research to replace the natural aggregate in different proportions. Many researchers have used recycled-concrete aggregate to produce both conventional concrete and SCC and the properties of the concrete with RCA were tested (Poon et al., 2004; Kou & Poon, 2009; Grdic et al., 2010).

It has been found with proper mix designs, concrete as well as SCC with good qualities can be produced with RCA.

The use of RCA benefits the ecology in both saving the natural raw materials and saving the energy and land used to dispose the demolished concrete. The production of concrete consumes a lot of natural aggregate which can hardly be used for any other purpose when the concrete structure is demolished. To dispose the old concrete, land is needed for burying purpose. In addition, transportation of the old concrete to the land increases the expenses of the disposal of the old concrete. If the old concrete can be used to produce new concrete, the construction cost can be reduced and the sustainability is achieved at the same time.

Statement of the Problem

The rheological behaviors of SCC have been studied and types of rheometers were invented to measure the rheological parameters of SCC (Hu, 2005). These parameters provide more accurate descriptions to SCC's properties at its fresh state than the conventional methods mentioned above. The rheological behaviors of SCC paste were also researched these years. It has been found that the rheology of cement paste can largely dictate the rheology of concrete (Ferraris, 2001; Martys, 2002). But the rheological behaviors of SCC mortar were still lack of study. It will be significant to measure the fresh SCC mortar's behaviors with the rheometer and compare the results with SCC.

On the other hand, recycled-concrete aggregate has been used to produce new concrete, including SCC. Most research focused on using coarse RCA to produce new concrete. Because the fine particles of recycled-concrete contain impurities and hardened cement paste, which increased the difficulty of the quality control of the new concrete. While right now research has been conducted to study SCC prepared with fine recycled-concrete aggregate (FRCA) (Kou & Poon, 2009). More studies need to be performed to research the usage of FRCA in SCC and mortar.

When FRCA is used in SCC, it should be noted that the moisture conditions of FRCA largely affect the workability of the mixtures due to its higher water absorption ability comparing to natural aggregate. When using dry condition FRCA to produce SCC, more water needs to be added to the mixture to prevent the quick reduction of workability. While it is still not clear how soon the workability reduces and how much the influence of aggregate moisture condition to the workability loss.

Objectives

This study focuses on several aspects stated as follow:

- Use FRCA to prepare qualified SCC mortar, which has good workability and stability;
- Measure fresh SCC mortar mixture with rheometer, and use the rheological parameters to explain the workability of the mixtures which are evaluated by conventional methods; and
- Investigate the effect of moisture conditions of fine aggregate on the workability change of SCC mortar mixtures.

CHAPTER II. LITERATURE REVIEW

Self-Consolidating Concrete

Introduction of Self-Consolidating Concrete

Self-consolidating concrete (SCC), also referred to as self-compacting concrete is highly flowable and non-segregating concrete. The high flowability of SCC allows it to flow and consolidate into the framework and encapsulate the reinforcement under its own weight without mechanical consolidation. This characteristics makes it possible for placing concrete in difficult construction conditions such as heavily reinforce concrete members or complicated formwork. (ACI Committee 237, 2007)

The concept of SCC was proposed by Okamura in 1986 to solve the problem of the reduction in the quality of concrete construction work which was caused by the lack of skilled workers in Japan. The development of SCC was carried out by Ozawa and Maekawa at the University of Tokyo. After the invention of SCC, it has been applied to construction industry. The production of SCC increased very fast and many researches related to SCC were also conducted. (Okamura & Ouchi, 2003)

Characteristics of SCC

SCC is a technology that has both economic and technological benefits, which were summarized by ACI Committee 237 (2007) as follow:

- Reduces labor and equipment since there is no need to vibrate to consolidation and no need to flatten surfaces;
- Consistent quality can be achieved regardless of the difference of the concrete workers skills;
- Faster casting and placing process leads to shorter construction duration;
- Reduces noise during the casting and placing process on the jobsite. This benefits the projects constructed in urban areas which usually need to be scheduled carefully when using conventional concrete to reduce the effect of vibration noise to the local community. Noise reduction also avoids paying for the premiums of insurance that is responsible for hearing-impaired workers;
- Simpler placing procedure and less equipments involvement result in lower possibility of worker injuries;
- Provides more flexibility for the reinforcement placement;
- Smooth surfaces can be easily achieved; and
- Reduces the use of materials such as underlayment used to level and prepare substrates for final flooring materials.

Besides the advantages, some other characteristics of SCC comparing to conventional concrete are summarized as follow. Brube and Richert (2001) found that SCC can be designed to have similar strength and durability as conventional concrete. However when SCC is not properly cured, it has higher plastic shrinkage cracking comparing to conventional concrete. High drying shrinkage can be observed in SCC which was due to the high water to cement ratio (ACI Committee 237, 2007). While when comparing SCC with conventional concrete which has similar compressive strength, SCC tends to have similar or even lower drying shrinkage (Persson, 1999; Sonebi & Bartos, 1999). It has also been found that SCC has similar drying shrinkage comparing to conventional concrete that has similar mixture proportions (Mortsell & Rodum, 2001).

Mix Design of SCC

SCC is a high flowable but stable mixture, and the mix design of SCC aims to find a balance of high flowability and good segregation resistance. A mix proportioning system for SCC was suggested by Okamura and Ozawa (1995). In this system, the coarse aggregate and fine aggregate contents are fixed separately at around 50 percent of the total solid volume and 40 percent of the mortar volume. The water to binder ratio and super plasticizer dosage are adjusted in order to obtain proper flowability. The water to powder ratio is around 0.9 to 1.0 by volume depending on the properties of the powder and the super plasticizer dosage. Some guidelines were also provided by other researchers to help design qualified SCC.

§ The volumetric ratio of aggregate to cementitious material should be reduced (Nagamoto & Ozawa, 1997; Khayat & Ghezal, 1999);

§ The paste volume and water to cement ratio should be increased (Nagamoto & Ozawa, 1997);

§ The total volume and the maximum particle size of coarse aggregate should be controlled (Nagamoto & Ozawa, 1997);

- Viscosity-modifying admixture (VMA) should be used (Nagamoto & Ozawa, 1997); and
- High-range water-reducing admixture (HRWRA) should be employed to obtain high deformability (Aggarwal et al., 2008).

Test Methods of SCC

Test methods, which focus on flowability, passing ability, and stability, were developed to measure and control the quality of SCC. The tests include slump flow test, T_{50} test, J-Ring test, L-Box test, V-Funnel test, column segregation test, and visual stability index (VSI) test. These tests are stated one by one in the rest part of this section. Some tests used in this study to measure the workability of SCC mortar were similar as the tests used in SCC. So it is helpful to understand to purpose and process of these tests.

Slump Flow Test

The slump flow test is used to measure the flowability and stability of SCC mixture by measuring the horizontal free-flow characteristics of SCC without obstructions. ASTM C1611 (Standard Test Method for Slump Flow of Self-Consolidating Concrete) provides a guide for this test. The flow distance of SCC mixture is measured in this test to illustrate the slump flow. Larger slump flow indicates better flowability of SCC. (ACI Committee 237, 2007)

T_{50} Test

T50 test can be performed at the same time of slump flow test. It is used to evaluate the viscosity of SCC mixture by measuring the time it takes for the mixture spreads and reaches to a circle with a diameter of 500 mm from the time the mold is lifted. Longer time indicates better viscosity of SCC. (ACI Committee 237, 2007)

Visual Stability Index Test

Daczko and Kurtz (2001) provided a method to determine the stability of SCC with the visual stability index (VSI) test. The index is shown in Table 2-1.

Table 2-1. Visual stability index (VSI) rating of SCC mixtures (Daczko & Kurtz, 2001)

VSI value	Criteria
0 = highly stable	No evidence of segregation in slump flow spread
1 = stable	No mortar halo or aggregate pile in the slump flow spread
2 = unstable	A slight mortar halo (< 10 mm) or aggregate pile, or both, in the slump flow spread
3 = highly unstable	Clearly segregating by evidence of a large mortar halo (>10 mm) or a large aggregate pile in the center of the concrete spread, or both.

J-Ring Test

The J-Ring test is used to evaluate the passing ability of SCC mixture. ASTM C1621 (Standard Test Method for Passing Ability of Self-Consolidating Concrete by J-Ring) can be followed to perform this test. The higher J-Ring slump flow indicates better passing ability. (Sonebi & Bartos, 1999; Bartos et al., 2002)

V-Funnel Test

The purpose of V-funnel test is to measure the flowability, the passing ability and the stability of fresh concrete. A V shape funnel (V-funnel) is used in the test. After fill the funnel with concrete mixture, the gate at the bottom of the V-funnel is opened and t_0, which is the time for the concrete goes through the funnel, is measured. Fill the V-funnel again and let the concrete stand in it for 5 minutes and then open the gate to measure t_5, which is the time for the concrete goes through the V-funnel after 5 minutes stand. Comparing t_0 and t_5 the segregation of SCC can be estimated. (ACI Committee 237, 2007)

L-Box Test

L-box test aims at investigating the passing ability of the SCC. An L-box is used in the test. After filling the vertical part of the L-box, the door between vertical part and horizontal part is lifted and the concrete from the vertical part goes through the bars at the door and fill the horizontal part of the L-box. The time at which the concrete reaches 200 mm (1/4 length) of the horizontal box, 400 mm (1/2 length) of the horizontal box and the end of the box, t_{20}, t_{40}, and t_{final} are measured. By comparing the height of the concrete surfaces at both ends of the horizontal box, h_1 and h_2, the blocking ratio can be calculated. (ACI Committee 237, 2007)

Column Segregation Test

The column segregation test is performed to investigate the segregation resistance of the SCC. A column with three equal parts is needed for this test. The column is filled with concrete, after standing for 30 minutes, the concrete from top 1/3 part and the concrete from the bottom 1/3 part of the column are taken out separately, and then these two parts of concrete are washed and sieved with a #4 sieve. The remained aggregates from each parts of concrete are measured, with which the segregation ration is calculated flowing ASTM C1610. (ACI Committee 237, 2007)

Rheology

Rheology and Workability of SCC

One of the most important characteristics of fresh SCC is its high workability, which is often described by flowability, passing ability, and segregation resistance. The tests mentioned in last section were frequently used to measure the workability of SCC. Tests have also been developed to measure the SCC mortar’s workability, such as mortar slump test and mortar funnel test (D'Aloia, 2006). In addition to workability, rheology is used to characterize the properties of fresh SCC mixture. The flowability and the passing ability of the fresh concrete can be evaluated by the rheological parameters measured with a rheometer (Gjorv, 1998; Noguchi et al., 1999). The rheological parameters can also provide more stable results than other tests in describing the flowability of concrete (Yen et al., 1999). When comparing the data obtained from the rheology test, it was found that the results are in agreement with the results obtained from slump flow test, mortar slump test, and mortar funnel test of either SCC or SCC mortar (Reinhardt & Wüstholz, 2006; D'Aloia et al., 2006).

Yield Stress and Plastic Viscosity

Yield stress represents the shear stress required to initiate flow for concrete mixtures. Plastic viscosity reflects the resistance to flow after the yield stress has been surpassed. A qualified SCC mixture should have both high flowability and high segregation resistance. Therefore a high static yield stress is desirable because it improve the resistance to segregation. The plastic viscosity is also able to reduce segregation when concrete is flowing, and it provides cohesiveness at the same time. On the other hand, a low dynamic yield stress is necessary for ease of pumping, placement, and self consolidation. (Germann Instruments, Inc., 2007)

Bingham Model

Concrete at fresh state can be considered as a fluid, which means that it will flow under the action of shear stresses (Barnes et al., 1989). Many tests have been conducted to study the rheological properties of fresh concrete during the last decades, and a Bingham equation (Eq. (1)) was found can be used to describe the rheological properties of concrete (Tattersall, 1973; Tattersall, 1983).

$$\tau = \tau_0 + \mu \dot{\gamma} \quad (1)$$

Where:

τ: shear stress (Pa)

τ_0: yield stress (Pa)

μ: plastic viscosity (Pa s)

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

Ferraris and Brower (2000, 2003) verified the validity of this equation by utilizing different types of rheometers and different concrete compositions. This equation is also known as Bingham model (Figure 2-1).

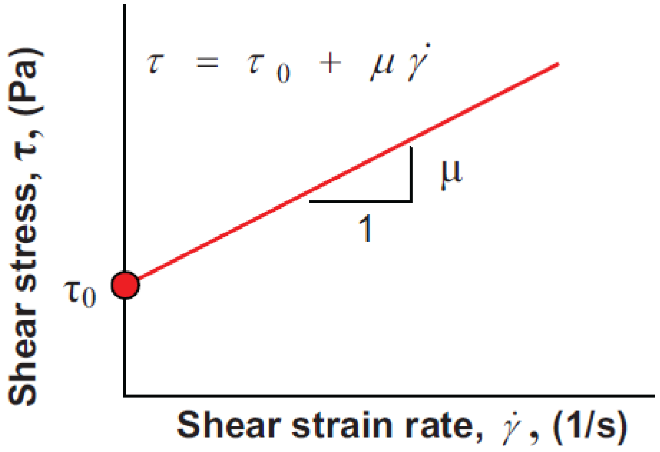


Figure 2-1. Bingham Model (Germann Instruments, Inc., 2007)

On the other hand, concrete cannot be simply considered as a fluid because of its thixotropic behavior. Thixotropic is a phenomenon that a higher shear stress can be observed during a period of no-flow condition, and the shear stress decreases to a lower shear stress which is able to maintain the flow of concrete once the flow has begun. Figure 2-2 illustrates this process. To use Bingham model to characterize concrete, thixotropic need to be eliminated by starting the test with a long period of pre-shearing period and then decreasing the shear rate during the test (Feysa et al., 2008).

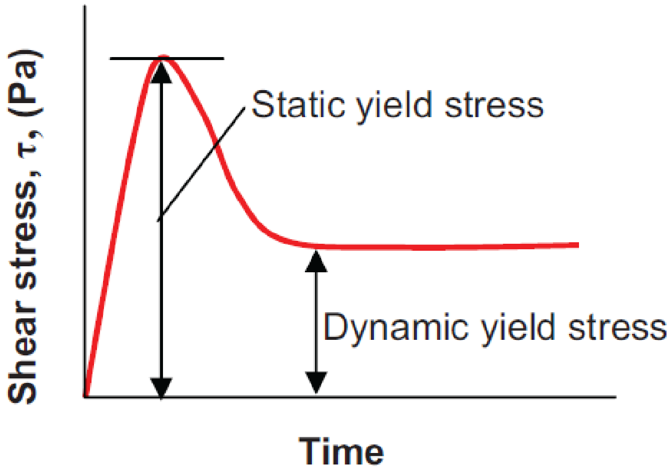


Figure 2-2. Shear stress of concrete (Germann Instruments, Inc., 2007)

Recycled-Concrete Aggregate

Properties of Recycled-Concrete Aggregate

The use of recycled-concrete aggregate (RCA) benefits the ecology in both saving the natural raw materials and save the energy and land used to dispose the demolished concrete (ECCO, 1999). RCA usually has a lower relative density than natural aggregate. The relative density decreases gradually as particle size decreases (Kosmatka, 2002). RCA also has higher water absorption in comparison to the natural aggregate (Zoran et al., 2010; Kwan, 2012). This results from the high absorption of porous mortar and hardened cement paste within the recycled concrete aggregate. The absorption values range from 3% to 10%, which are larger than the natural aggregate and smaller than the lightweight aggregate. Tam et al. (2008) tested 3 RCAs produced with demolished concrete which has different ages. It has been found that RCA produced from older concrete has higher water absorption. Tegguer (2011) found the particle size of RCA also has influence to the absorptions. RCA with smaller particle size tends to have high absorption than RCAs with larger particle size. It has also been found by Tegguer that after soaking RCA in the water for 24 hours, 60% and 70% of the total water absorption can be attained for RCA with 5 - 200 mm particle sizes.

Use of Recycled Concrete Aggregate in SCC

The SCC has been widely used in construction due to its advantages mentioned above. However, the use of SCC is still limited especially in the United States owing to the relatively high cost of this technology which results from the larger amount of cement and admixtures used in SCC (Vachon & Daczko, 2002). Many researches involved using industrial or agriculture by-products in order to reduce the cost of SCC have been conducted these years (Sahmaran et al., 2006; Memon et al., 2008). Recycled concrete aggregate has also been used to produce new SCC whose properties were tested. This section shows the findings of using recycled concrete aggregate in producing SCC from recently researches conducted by other researchers (Kou & Poon, 2009; Zoran et al., 2010).

Effects of RCA on Properties of Hardened SCC

SCC produced with RCA has several hardened properties:

- The density of SCC decreased up to 3.40% when increased the proportion of coarse RCA in the SCC (Zoran et al., 2010).
- The increase of the proportion of coarse RCA in SCC also led to a decrease of compressive strength up to 8.55%. While, high-performance concrete is still able to be obtained through using appropriate materials and mix designs (Zoran et al., 2010).

  When using FRCA to produce SCC, the compressive and tensile splitting strengths decreased with increasing FRCA content. The maximum compressive and tensile splitting strength were achieved by using 25–50% FRCA as a replacement of river sand (Kou & Poon, 2009).
- New concrete made from RCA or FRCA generally has good durability. It has been found that the carbonation, permeability, and freeze-thaw resistance were same or even better than concrete prepared with regular aggregate (Kou & Poon, 2009; Zoran et al., 2010).

§ The drying shrinkage increased with an increase in the FRCA content but it can be controlled by reducing the water to cement ratio (Kou & Poon, 2009).

Effects of RCA on Properties of Fresh SCC

Kou and Poon (2009) conducted a series of tests to study the properties of SCC at fresh state prepared with coarse and fine RCA. It has been observed that the increase of FRCA content led to an increase on the slump flow and blocking ratio of the SCC mixtures.

Kou and Poon (2009) also found that when using unsaturated RCA to produce SCC, a higher flowability was able to be observed at the early stage of SCC mixtures and the flowability decreased over time. This was caused by the higher absorption of RCA and FRCA. Zoran et al. (2010) suggested that the quantity of water should be increased when using RCA to prepare SCC. The required quantity of water can be compensated either by measuring of water absorption of RCA in first 30 minutes or by its saturation via a prior immersion, or experimentally, until the same concrete consistency is achieved.

Aggregate Moisture Condition and Concrete

Influence of Moisture Condition to Concrete

Poon et al. used natural and coarse RCA with different moisture conditions to prepare concrete. The effects of moisture condition on the properties of fresh concrete were investigated. It was found that the slump of fresh concrete was affected by the moisture condition. Dry aggregates led to a higher initial slump and quicker slump loss, while wet aggregates had normal initial slumps and slump losses. The initial slump of concrete was strongly dependent on the initial free water content of the concrete mixes (2004).

Water Absorption of RCA

The slump loss of concrete and the change of the slump flow of SCC are influenced largely by the high water absorption capacity of RCA. Researches were performed focused on measuring the water absorption of RCA and the absorption rate of RCA.

Tegguer (2012) found the water absorption of RCA for 24 h of soaking produced about 60% and 70% of the total water absorption obtained after 85 h and 110 h of soaking for 12.5–20 mm fraction and 5–12.5 mm fraction respectively (Figure 2-3). Tam et al. (2008) found that the water absorption was larger in the first 5 hours. This produced up to 80% of the total water absorption. Pereira et al. (2012) measured the absorption of FRCA over time, and the results are shown in Figure 2-4. After socking FRCA in water for 10 minutes, FRCA had absorbed 50% of its potential capacity of 24 hours.

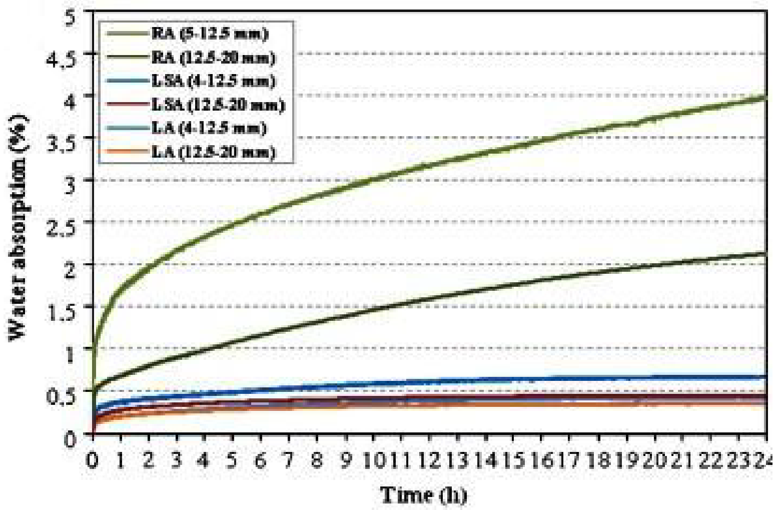


Figure 2-3. Absorption of aggregates over time (Tegguer, 2012)

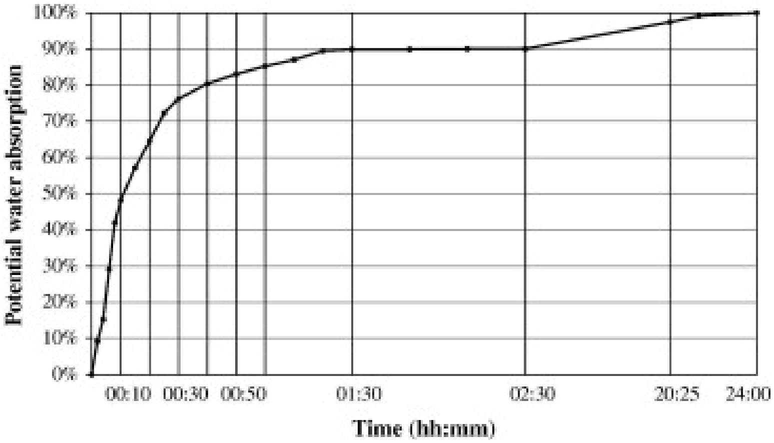


Figure 2-4. Absorption of FRCA over time (Pereira et al. 2012)

CHAPTER III. EXPERIMENTAL WORK

Material Properties

In this study Type I portland cement was used as cementitious material to produce mortar mixtures. Type I portland cement was produced by Texas Lehigh Cement Company, which confirms to requirements in ASTM C150.

Two types of natural fine aggregates, manufactured sand and silica sand (Figure 3-1), were used. Both of them were provided by a local aggregate plant, and meet the requirements in ASTM C33. The specific gravity and water absorption of manufactured sand and silica sand, which are measured following ASTM C128, are shown in Table 3-1. The manufactured sand and silica sand were used in a ratio of 5.75:1 by weight in mixtures. This ratio is adopted by local concrete plants to optimize the gradation of fine aggregate. Figure 3-2 shows the gradation of the fine aggregates.

Figure 3-1. Fine aggregates. (a). manufactured sand; (b). silica sand; and (c). FRCA

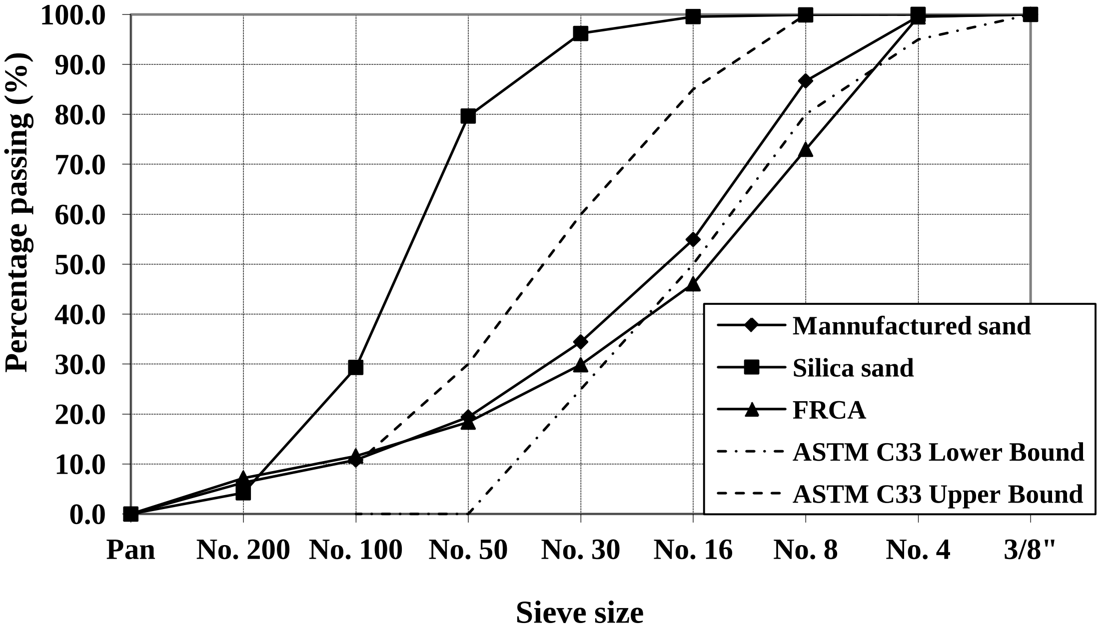


Figure 3-2. Fine aggregate gradation

Fine Recycled-Concrete Aggregate (FRCA), as shown in Figure 3-1, was used to substitute silica sand and manufactured sand with different percentages (25%, 50%, 75%, and 100%) in mortar mixtures. FRCA was achieved from recycled-concrete aggregate which was sieved with a 3/8 sieve. The recycled-concrete aggregate was obtained from a local recycled concrete plant. The gradation of FRCA is shown in Figure 3-2. The specific gravity and absorption of FRCA are shown in Table 3-1. OD means the specific gravity of aggregate in oven dry condition, and SSD means the aggregate is in saturated surface dry condition.

Table 3-1. Specific gravity and absorption of fine aggregate

	Specific gravity (OD)	Specific gravity (SSD)	Absorption
Manufacturing sand	2.42	2.50	3.24
Silica Sand	2.60	2.61	0.42
FRCA	1.95	2.16	10.74

One high-range water-reducing admixture (HRWRA), Glenium 7700, and a viscosity-modifying admixture (VMA), Rheomac VMA 362 were used in this study. The HRWRA was used to improve the flowability of SCC mortar and the VMA was used to maintain the uniformity of the SCC mortar.

Mix Proportions

Table 3-2 a and Table 3-2 b show ten mixes which were prepared in order to study the effect of moisture condition on the rheology of SCC mortar at fresh state. In the mix designs, FRCA replaced partial of the natural fine aggregate (manufactured sand and silica sand) with 25%, 50%, 75%, and 100% by weight. The mixes prepared with only natural aggregate were used as reference mixes (W0 and D0). Wet fine aggregate and dry fine aggregate were used separately in different mixes. The letters W and D in mix IDs separately indicate the fine aggregate was in wet condition or dry condition. The numbers in the mix IDs stand for the percentage by volume of the FRCA that was used in the mix as the substitution of natural fine aggregate, and 0 means only natural aggregate was used in the mixture. For example, W25 means there are 25% by volume of FRCA was used as replacement in the mix, and the fine aggregates were in wet condition; D75 means there are 75% by volume of FRCA was used to replace the natural fine aggregate in the mix, and the aggregates were in dry condition. In Table 3-2 a, the weights of fine aggregates are presented in saturated surface dry (SSD) condition. While in Table 3-2 b. the weight of fine aggregate is presented in oven dry (OD) condition. The total amount of water, which in clued free water and moisture in aggregate, maintained same between different mixes, so that the water to cement ratio (w/c) of each mix is same. But since FRCA has higher water absorption than natural aggregate, in W series, the initial free water content (IW) decreased when the amount of FRCA in the mixture increased; in D series, as all materials are in OD condition, the IW of each mix is same.

Table 3-2 a. Mortar mix proportions, wet aggregate

Mix ID	Cement (kg/m^3)	Water (kg/m^3)	Manufactured sand, SSD (kg/m^3)	Silica sand, SSD (kg/m^3)	FRCA, SSD (kg/m^3)	HRWRA (ml/kg)	VMA (ml/kg)	w/c	IW/c
W0	510.63	209.36	787.00	142.11	0.00	10.5	6.5	0.41	0.41
W25	511.75	196.80	591.54	106.81	195.22	10.5	6.5	0.38	0.38
W50	512.87	184.18	395.22	71.36	391.29	10.5	6.5	0.36	0.36
W75	514.00	171.51	198.05	35.76	588.23	10.5	6.5	0.33	0.33
W100	515.13	158.78	0.00	0.00	786.03	10.5	6.5	0.31	0.31

Table 3-2 b. Mortar mix proportions, dry aggregate

Mix ID	Cement (kg/m^3)	Water (kg/m^3)	Manufactured sand, OD (kg/m^3)	Silica sand, OD (kg/m^3)	FRCA, OD (kg/m^3)	HRWRA (ml/kg)	VMA (ml/kg)	w/c	IW/c
D0	505.34	231.33	778.84	140.63	0.00	10.5	6.5	0.41	0.46
D25	502.90	230.21	581.31	104.97	191.84	10.5	6.5	0.38	0.46
D50	500.48	229.10	385.67	69.64	381.84	10.5	6.5	0.36	0.46
D75	498.08	228.00	191.91	34.65	570.01	10.5	6.5	0.33	0.46
D100	495.71	226.92	0.00	0.00	756.39	10.5	6.5	0.31	0.46

Test procedures

Fine Aggregate Testing

Gradation Testing

The gradations of three types of fine aggregates were measured following ASTM C33 with the Rotary Lab Sifter which is as shown in Figure 3-3. Each time a 500 g of fine aggregate specimen was prepared following the method of reducing aggregate sample to test size stated in ASTM C702. The sieves used in this test were 3/8, #4, #8, #16, #30, #50, #100, and #200. The fine aggregate was spun and sieved in the Sifter for 10 minutes. The weight of aggregate from each sieve was measured with a scale and the results are shown in Figure 3-2.

Figure 3-3. Rotary Lab Sifter

Specific Gravity and Absorption Testing

The specific gravities and absorption capacities of three fine aggregates were tested following ASTM C128. The testing procedure is as follow: Fine aggregate was dried in oven at a temperature of 110 ± 5 °C for 24 hours. The sample then was moved out of the oven and cooled down at the room temperature for one hour until it went down to about 50°C so that the sample can be handled. The sample was then soaked in water for 24 ± 1 hour. To achieve SSD condition, sample was carefully dried with a testing dryer, which is shown in Figure 3-4.

Figure 3-4. Drying and stirring fine aggregates sample

There are two ways to measure the specific gravity and absorption of fine aggregate instructed in ASTM C128, which are gravimetric (pycnometer) procedure and volumetric (Le Chatelier flask) procedure. In this study, gravimetric procedure was used with a pycnometer as shown in Figure 3-5. As the fine aggregate specimen was properly prepared to SSD condition, a 500 g fine aggregate sample was measured following ASTM C702. The pycnometer was filled with some water and then put 500 g sample into the pycnometer. More water then was added to fill the pycnometer to approximately 90% full. The pycnometer was then agitated for about 20 minutes to remove the air bubbles in the sample. The pycnometer was then filled with water to its capacity and the total mass of the pycnometer, specimen, and water was measured. The fine aggregate and water was carefully removed to a container and were dried in the oven for 24 hours to constant mass. The dried fine aggregate was weighted. The pycnometer was filled with water to its capacity and the total mass of the pycnometer and the water was measured.

Figure 3-5. Pycnometer (Humboldt Mfg. Co., 2012)

The specific gravity and the absorption were calculated following the formulas:

Specific gravity in OD condition = A / (B + S - C); (2)

Specific gravity in SSD condition = S / (B + S - C); (3)

Absorption, % = 100 [(S - A) / A], (4)

where:

A: mass of oven dry specimen, g

B: mass of pycnometer filled with water, to calibration mark, g

C: mass of pycnometer filled with specimen and water to calibration mark, g

S: mass of SSD specimen, g

The results of this test were listed in Table 3-1.

Preparation of Fine Aggregate in Wet and Dry Conditions

Fine aggregates were placed in the oven (Figure 3-6) at 110 ± 5 °C and dried for 24 hours until they achieved constant mass. To prepare the fine aggregates used for mixes that used dry fine aggregates (D series), fine aggregates were weighted before the mixture were produced. One hour is given for aggregates to cool down after they were moved out of the oven. While the fine aggregates should be used to produce mixture within one and half hours to avoid the absorption of too much moisture.

For mixes used wet fine aggregates (W series), the dry aggregates were soaked in water for 24 hours in a bucket which was sealed carefully in order to reduce the moisture loss. In this study, half of amount of water was used to soak fine aggregate which was enough to have fine aggregates achieve wet condition. The remaining half of the water was added to the mixture during the mix of mortar mixtures.

Figure 3-6. Fine aggregates in the oven

Mix Procedures

The mixtures were mixed with a 20 Quart Planetary Mixer as shown in Figure 3-7.

Figure 3-7. 20 Quart Planetary Mixer

After the mixer was set up and materials were prepared, water, HRWRA (Glenium 7700), and cement were put into the mixer bowl and mixed for 30 seconds at a slow speed which was 140 ± 5 r/min. When the mixer stopped, paste on sides of the bowl was scraped down to the bowl. Fine aggregate, VMA (Rheomac VMA 362), were added into the bowl. The mix was restart at the slow speed for 30 seconds and then at a medium speed which was 285 ± 10 r/min for another 30 seconds. HRWRA and VMA were diluted with water before added into the mixture. After the mixture was stopped, the mixture was stood in the bowl for 90 seconds and the paste on sides of the bowl was scraped down within 15 seconds. After the mixture was remixed for 60 seconds at the medium speed, the mixture was ready to be tested.

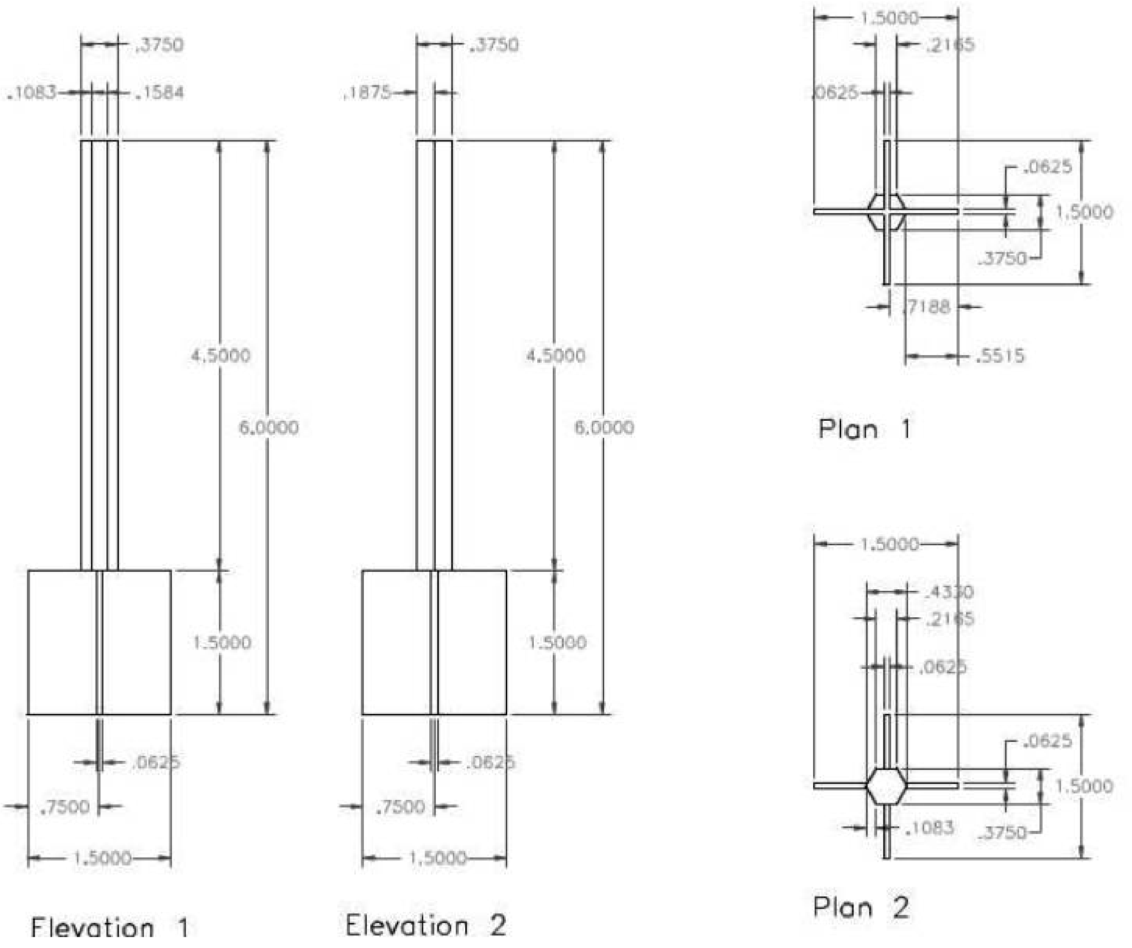
Fresh Mortar Testing

Due to the lack of standards that can be followed to test the workability and the rheology of mortar mixtures, the tests performed in this section were either followed the equipment manual (ICAR rheometer test) or followed similar tests performed on fresh concrete mixtures (mortar slump test, mortar funnel test, and mortar column segregation test).

ICAR Rheometer Test

An ICAR rheometer (Figure 3-8) was used in this test. A plastic cylinder with inside diameter of 100 mm and height of 200 mm was used as the container for fresh mortar mixture. A paddle was designed with the dimensions shown in Figure 3-9.

Figure 3-8. ICAR Rheometer



3-9. Detention of rheometer paddle

A program installed in the computer which connected to the rheometer was used to control the test. The parameters were set up in the software before the test, as shown in Figure 3-10. For the stress growth test, the test speed was set up as 0.025 rounds per second (rps). For the flow curve test, it was 10 seconds at a speed of 0.5 rps. The vane spun at an initial speed of 0.5 rps and gradually reduced to a final speed which was 0.05 rps. During this procedure, there were 10 points at which the speed was remained for 5 seconds and the torque was measured. The shear rate change over time of stress growth test and flow curve test were shown in Figure 3-11. Figure 3-12 illustrated the working procedure of ICAR rheometer.

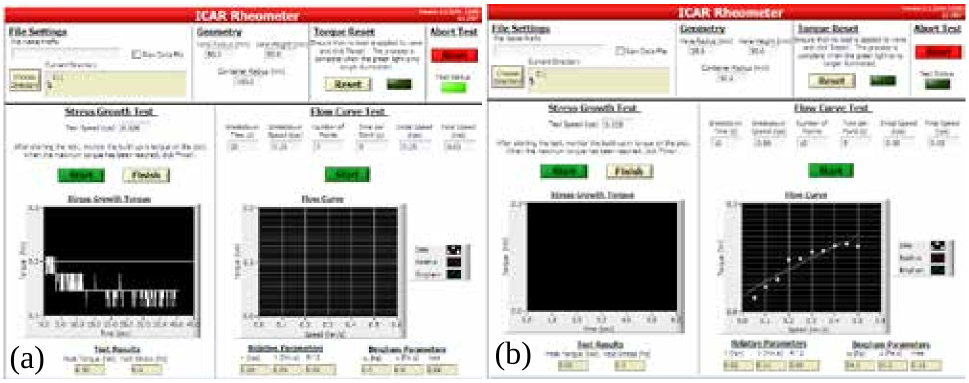


Figure 3-10. Interface of program controls ICAR rheometer.
(a) stress growth test; (b) flow curve test

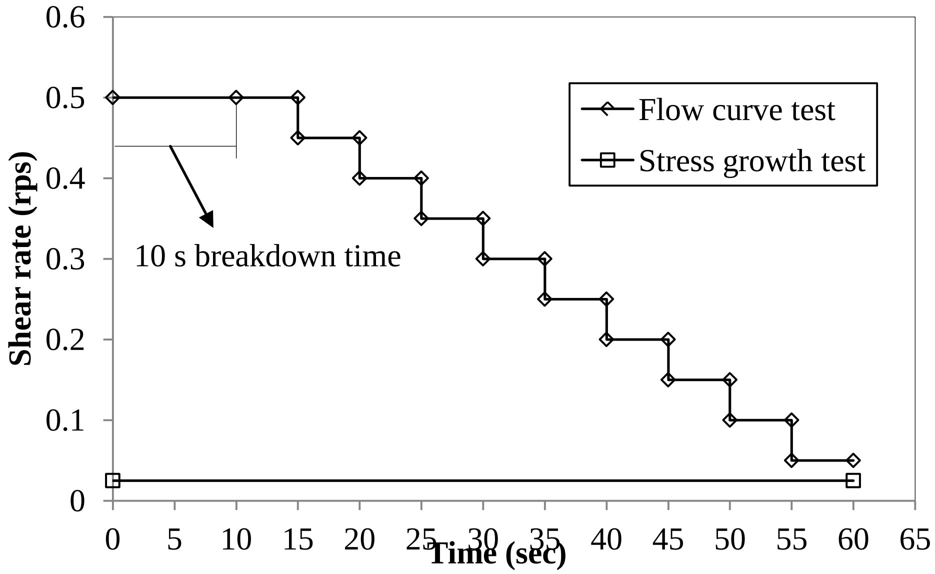


Figure 3-11. Shear rate change over time

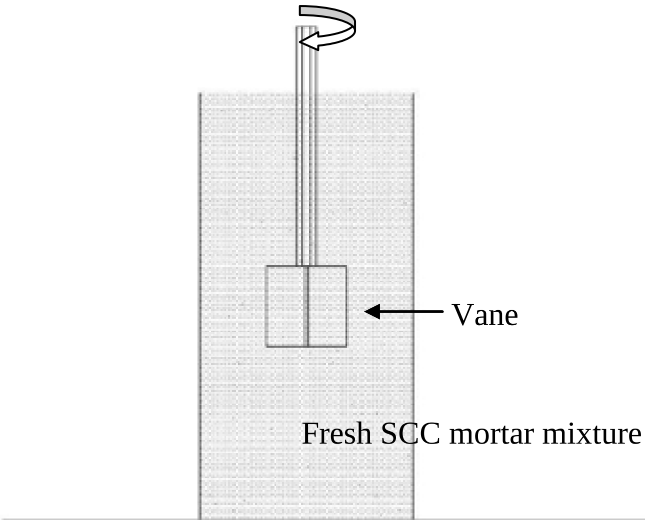


Figure 3-12. Working procedure of ICAR rheometer under

This test was used to measure the rheology of fresh SCC mortar which includes static yield stress, dynamic yield stress, and plastic viscosity. The dynamic yield stress was measured by capturing the largest resistance from the vane during the stress growth test, which in Figure 3-10 (a) is the peak (initial point) of the curve. The dynamic yield stress is measured in the flow curve test, where the largest resistance on the vane was used as the dynamic yield stress. During the flow curve test, the torque and speed of the vane at each point were measured, and slope of the linear regression line was calculated by the software and was used as the plastic viscosity (Figure 3-13).

In this study, down curve was used during the flow curve test. Down curve means the shear rate reduced from the highest to the lowest. The purpose of using down curve instead of up curve, which is to start the with the lowest shear rate and increases to the highest shear rate, is to eliminate the effect of thixotrophy of mortar mixtures.

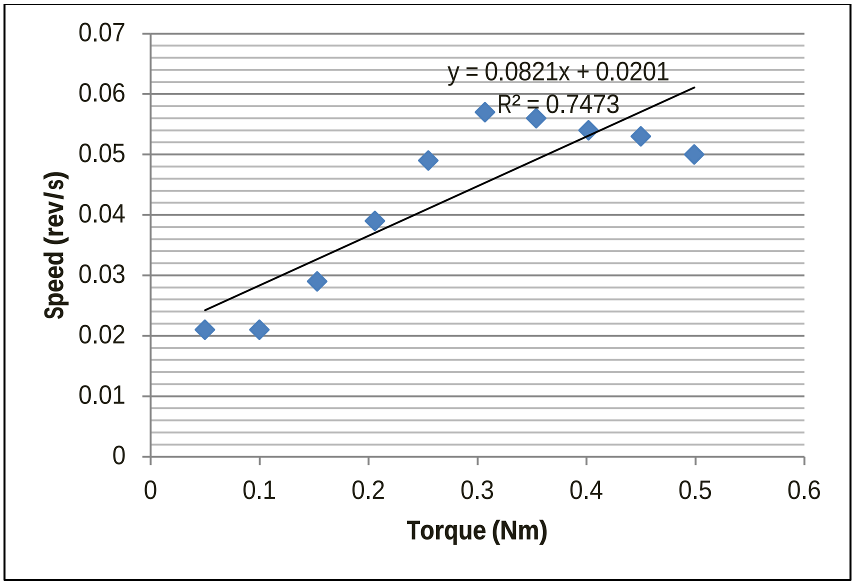


Figure 3-13. Plastic viscosity, D100 30 min (Pa s)

In this study, mortar mixture was measured with the ICAR rheometer every 30 minutes for 9 times, and the mixture was remixed for 30 seconds before each testing. The timeline of the test was presented in the flowing section. This test was also performed to the samples in mortar column segregation test to compare the difference of sample from the top of the column and the bottom of the column.

Mortar Slump Test

The mortar slump test was used to measure the flowability of SCC mortar. The mortar slump test was used in testing the flowability of SCC mortar or high flowable cement past (Schwartzentruber et al., 2006; Nunes et al., 2011). In this study a plastic cone with dimensions as shown in Figure 3-14 was used. The cone was placed on a plastic board with smooth and flat surface, and the smaller opening of the cone was on the top. The cone was filled with fresh SCC mortar (Figure 3-15), and then was vertically lifted. The mortar mixture spread on the plastic board. The diameter of the spread was measured at 4 different directions (Figure 3-15). The results were presented in diameter in next chapter.

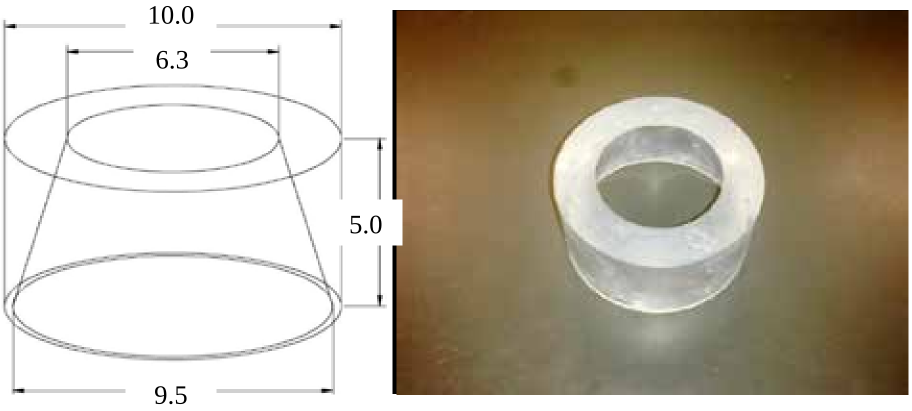


Figure 3-14. Dimension of mortar slump cone (cm)

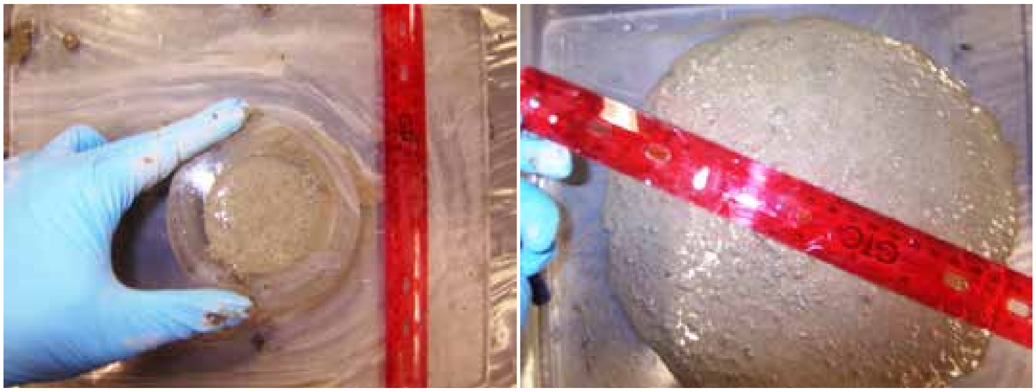


Figure 3-15. Mortar slump test

Mortar Funnel Test

The mortar funnel test is similar as the V-funnel test used in SCC test. This test was used to measure the flowability of the SCC mortar mixtures. A plastic funnel with dimensions shown in Figure 3-16 was used in this test. SCC mortar was filled into the funnel to 20 mm under the top opening. The mixture was filled into the funnel from about 1 cm height of the funnel opening. The bottom of the mortar funnel was blocked by fingers at the same time. When the fingers removed from the bottom, the time that mortar dropped out of the funnel was counted with a stopwatch with the accuracy of 0.1 second. A stopwatch was stopped at the moment when clear space was visible through the bottom opening of the funnel (Figure 3-17).

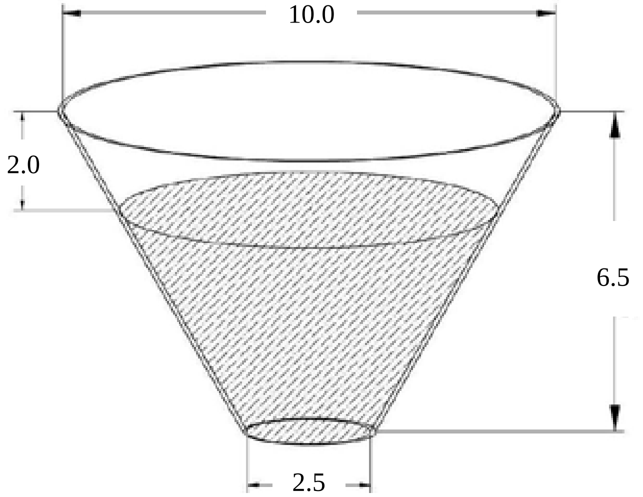


Figure 3-16. Dimension of mortar funnel (cm)

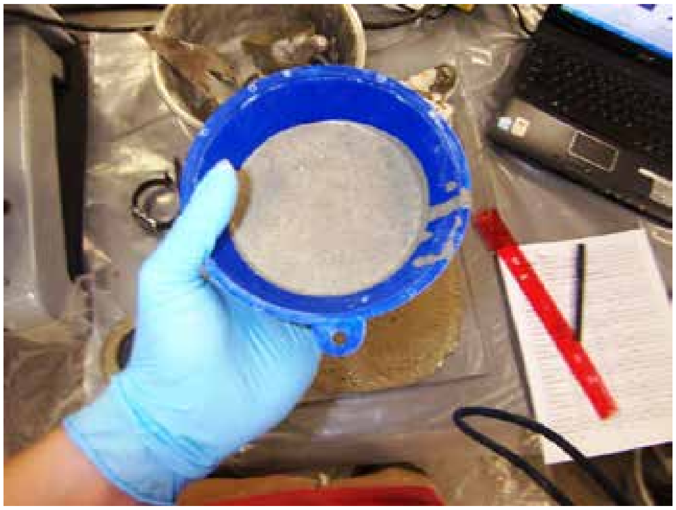


Figure 3-17. Mortar funnel test

Mortar Column Segregation Test

The mortar column segregation test was used in this study to measure the segregation of SCC mortar so that the consistency of the SCC mortar mixture can be evaluated. Two plastic cylinders with inside diameter of 100 mm and height of 200 mm were used. The cylinders were filled with SCC mortar. One of the cylinders was covered with a plate and then was placed upside down on to another cylinder, as shown in Figure 3-18. When the openings of two cylinders were matched, the plated was removed slowly. The cylinders were then sealed with tape (Figure 3-18).

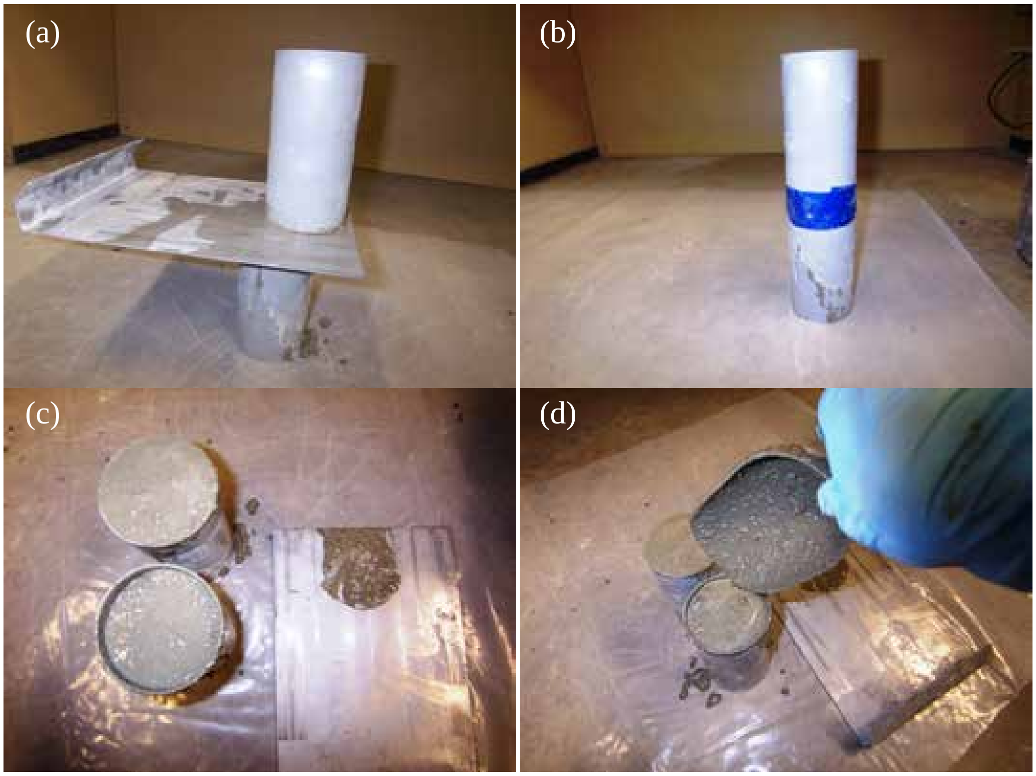


Figure 3-18. Mortar column segregation test

The cylinders were stood for 30 minutes, then the tape was removed and the cylinders were separated with the help of the plate (Figure 3-18). The top cylinder was filled with mortar to level up with the bottom cylinder (Figure 3-18).

The mortar from the top and the bottom of the cylinders was placed in two containers and was washed with water (Figure 3-19). The containers were labeled well. From Figure 3-19, the container with bottom mortar contained more cement paste and was darker than the top one.

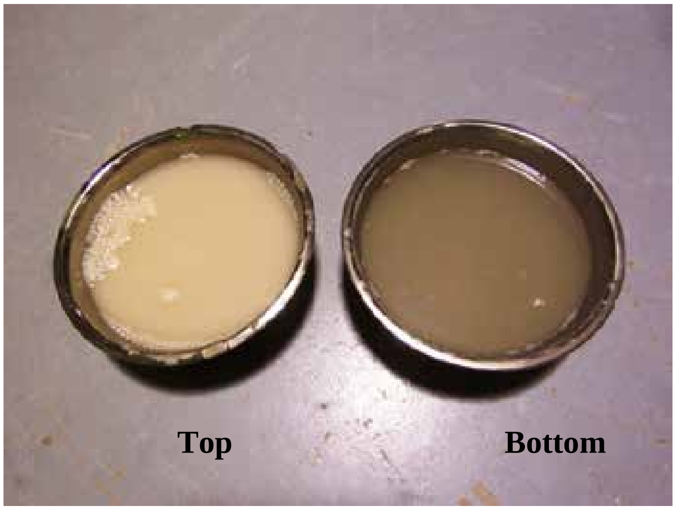


Figure 3-19. Mortar mixtures in water

The paste in the mortar from top and bottom were was washed away separately with a #8 sieve as shown in figure 3-20. The aggregate was then placed in the oven at a temperature of 110 ± 5 °C for 24 hours. The aggregates were sieved with a #8 sieve and then the particles that didn’t pass the sieve were measured with a scale. The segregation rate was calculated following the equation:

$$S = 2\left[\frac{(A_B - A_T)}{(A_B + A_T)}\right] \times 100, if\ A_B > A_T \tag{5}$$

$$S = 0, if\ A_B \leq A_T \tag{6}$$

where:

S = static segregation, percent

A_T = mass of fine aggregate which is larger than 2.36 mm (#8 sieve) in the top cylinder

A_B = mass of fine aggregate which is larger than 2.36 mm (#8 sieve) in the bottom cylinder

Figure 3-20. Sieving aggregates

The ICAR rheometer was also used to test the rheology of SCC mortar in top and bottom cylinders. This test is performed after the cylinders were separated following 30 minutes stand time and before the mortar was removed from the cylinders.

Experiment Timeline

This study focused on the effect of moisture condition of aggregate on the workability of SCC mortar. The workability of mortar changed along with the process of the absorption of fine aggregate and the hydration of the mortar. It was important to follow a certain procedure for all mixes, which was to perform certain test following a fixed timeline. The procedure is as shown in Figure 3-21.

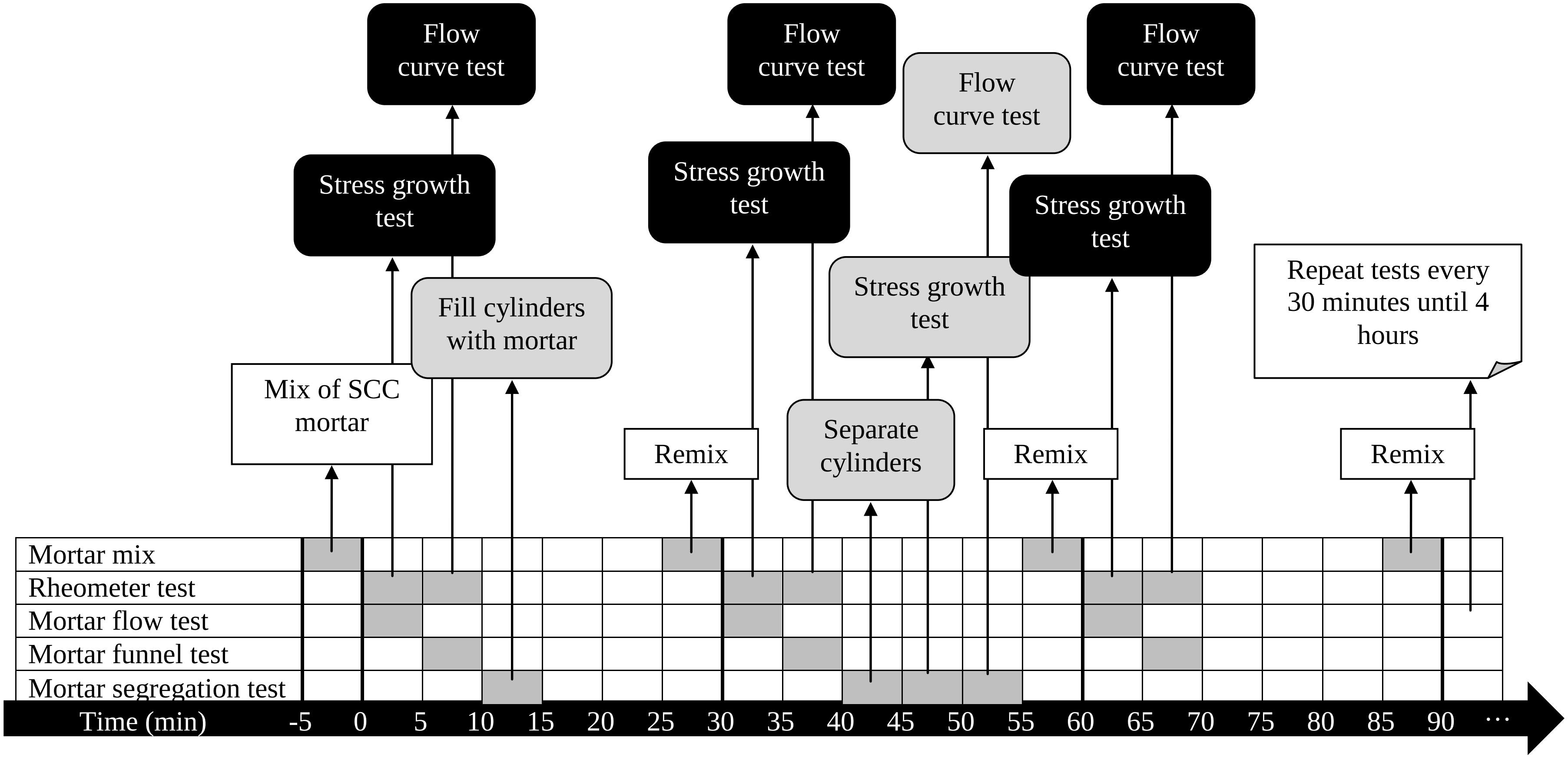


Figure 3-21. Test timeline

The ICAR rheometer test was performed right after the mortar mix was mixed. During the rheometer was running, the mortar flow test and the mortar funnel test were performed. Mortar was also placed into the cylinders for the mortar segregation test. The mortar from the ICAR rheometer test, mortar slump test, and mortar funnel test, was put back to the mixing bowl after the test. After 30 minutes from the mixture was mixed, the ICAR rheometer test, mortar flow test, and mortar funnel test were repeated. Following these three tests, the cylinders for the mortar column segregation test were separated, and the rheology of the top and bottom mortar was measured. The aggregate was then washed and sieved with water. The ICAR rheometer test, mortar flow test, and mortar funnel test were repeated every 30 minutes for 4 hours (9 times including the initial measurement).

Hardened Mortar Test

Three 50 × 50 mm mortar cubes from each mix design were prepared following ASTM C109. The cubes were cured one day in the molds and then removed from the molds and cured in a curing chamber (ASTM C155) until 7 days. The compressive strengths of 7 day were then tested following ASTM C109 with a Test Mark CM400 machine (Figure 3-22).

Figure 3-22. Test Mark CM400

CHAPTER IV. TEST RESULTS AND DATA ANALYSIS

Fresh SCC Mortar Test Results and Data Analysis

ICAR Rheometer Test

Two tests were performed and three parameters were measured with the ICAR rheometer. The static yield stress was measured with the Stress Growth test, and the dynamic yield stress and the plastic viscosity were measured with the Flow Curve test. The data and 3-D charts are shown in Appendix.

Static yield stress, dynamic yield stress, and plastic viscosity of W series (using wet fine aggregate) and D series (using wet fine aggregate) changed over elapse time and have similar trend separately. Static yield stress, dynamic yield stress, and plastic viscosity maintained consistent until around 120 minutes and grew dramatically after that. Two major reasons caused the growth of the parameters. One is the cement hydration, and the other is the reduction of the initial free water content in the mixtures. In W series, because the aggregate used in all five mixtures was saturated, there was no change of water content during 240 minutes and the growth of yield stress and plastic viscosity was caused only by the cement hydration process. In W series, due to the higher absorption of FRCA, when more FRCA was used to replace the natural aggregates, lower free water was in the mixtures. As a result, W100 which used FRCA as the only aggregate has the lowest initial free water content and W0 has the highest free water content, which resulted the differences in parameter changes. Lower initial free water content leads to higher yield stress and plastic viscosity, and these parameters increased earlier in mixtures with lower initial free water content than that in mixtures with more free water. In D series, since all five mixes have same initial free water content in the mixtures, the different of yield stress and plastic viscosity growth were caused mainly by the change of free water content. Since FRCA has higher absorption capacity, mixtures with more FRCA lost its free water faster and the yield stress and plastic viscosity grew faster. The reason why the parameters maintained stable for 120 or 150 minutes is the because of the usage of HRWRA, which is able to lengthen the setting time of the cement mortar (BASF Corporation, 2010).

In the rest of the chapter, the parameters will be compared to each other to find the correlations and relationships. The parameters will also be compared between mixtures with different free water content. The trends of parameters over time will be studies too.

Relationship between Static Yield Stress, Dynamic Yield Stress and Plastic Viscosity

Figure 4-1 shows the relationship between static yield stress and dynamic yield stress. Both in W series and D series, they are highly correlated. In W series, as the initial free water content remained constant, the dynamic yield stress and the static yield stress increased with a similar rate, and they have a linear relationship. While the dynamic yield stress in D series, where the free water decreased over time, increased slower than the static yield stress. This may indicate that the reduction of free water has more effect on dynamic yield stress than on static yield stress.

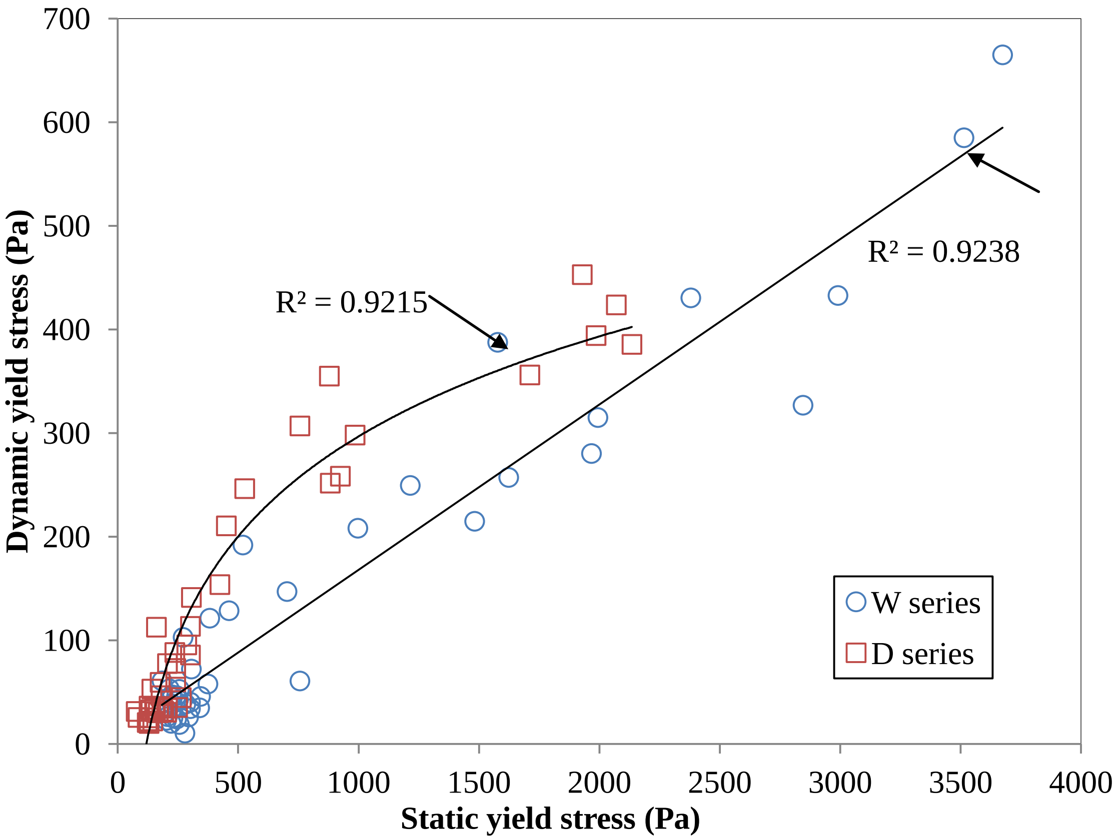


Figure 4-1. Relationship between static yield stress and dynamic yield stress

There is also a linear relationship between dynamic yield stress and plastic viscosity as shown in Figure 4-2. Dynamic yield stress growth led to plastic viscosity growth.

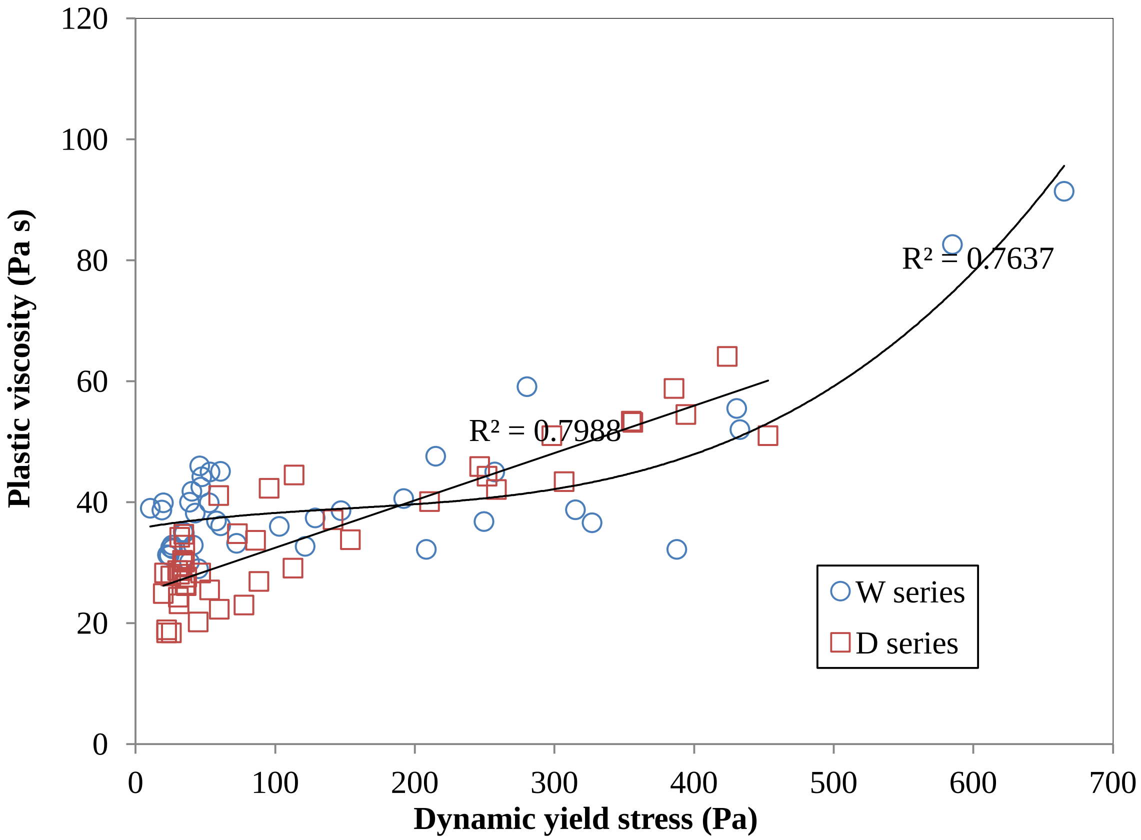


Figure 4-2. Relationship between dynamic yield stress and plastic viscosity

Change of Dynamic Yield Stress and Plastic Viscosity over Time

Figure 4-3 and 4-4 present dynamic yield stress and plastic viscosity of all the mixes over time. These figures show that the difference of initial free water content in mixtures doesn’t have significant effect on the initial dynamic yield stress and plastic viscosity, and the dynamic yield stress of both W series and D series was below 100 Pa. As mentioned before, this is owing to the usage of HRWRA, Glenium 7700, which lengthened the setting time of the mixture (BASF Corporation, 2010). However, in W series, when FRCA content increased in the mixture, the dynamic yield stress increased faster. This is due to FRCA contains cement paste powders which accelerates the hydraulic procedure of the cement and shortens the setting time. While in D series, the difference of the change of dynamic yield stress between different mixes was not significant. Because in D series, the amount of initial free water content in different series was same.

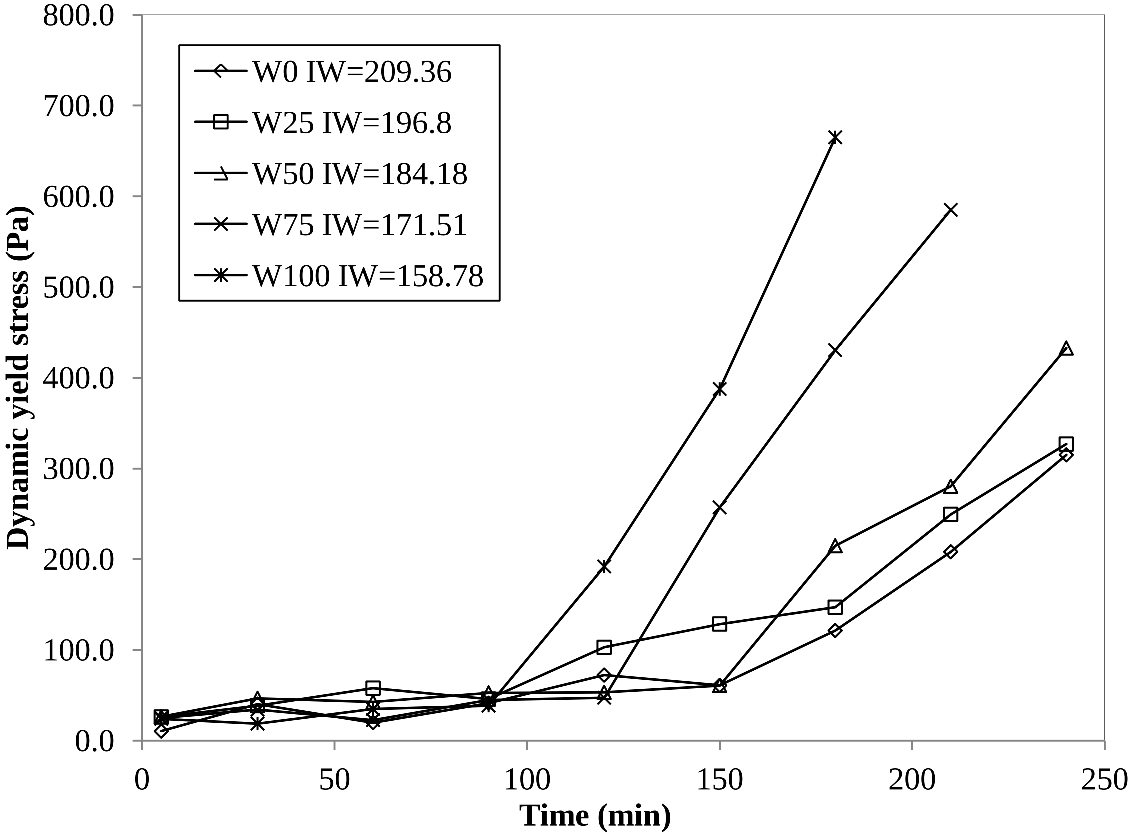


Figure 4-3 a. Change of dynamic yield stress of W series over time

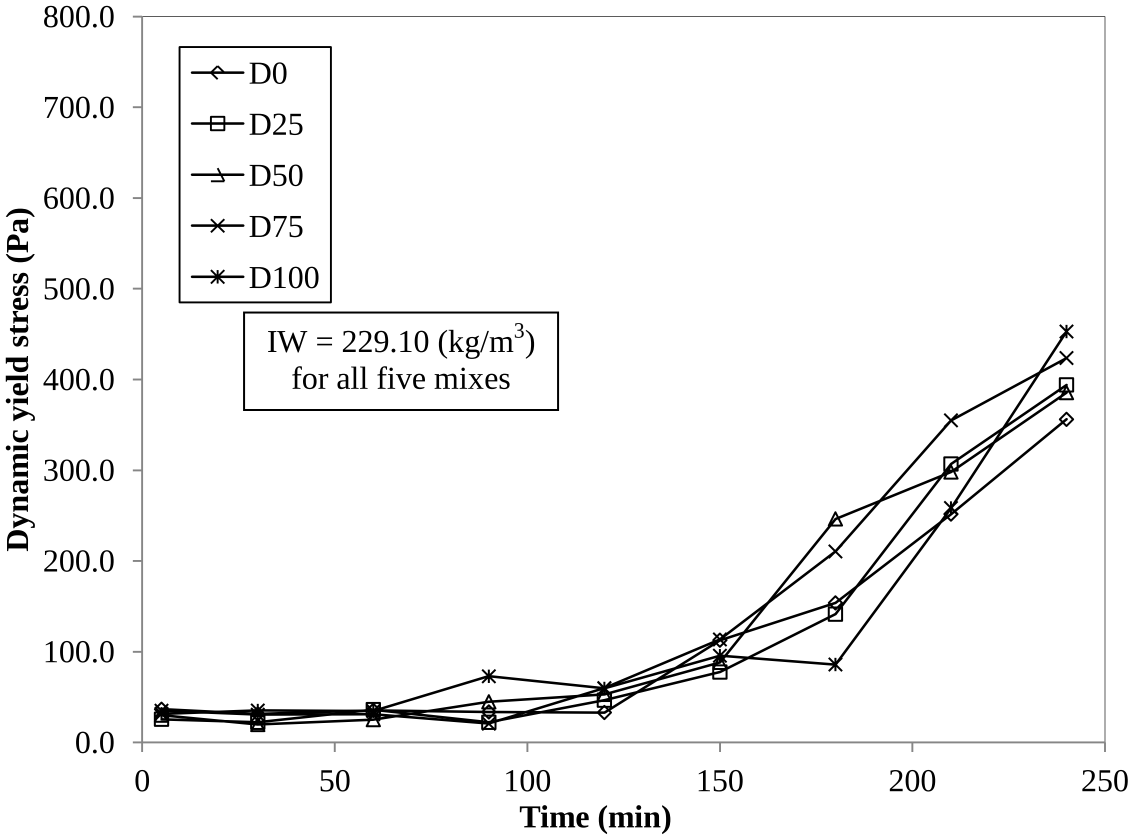


Figure 4-3 b. Change of dynamic yield stress of D Series over time

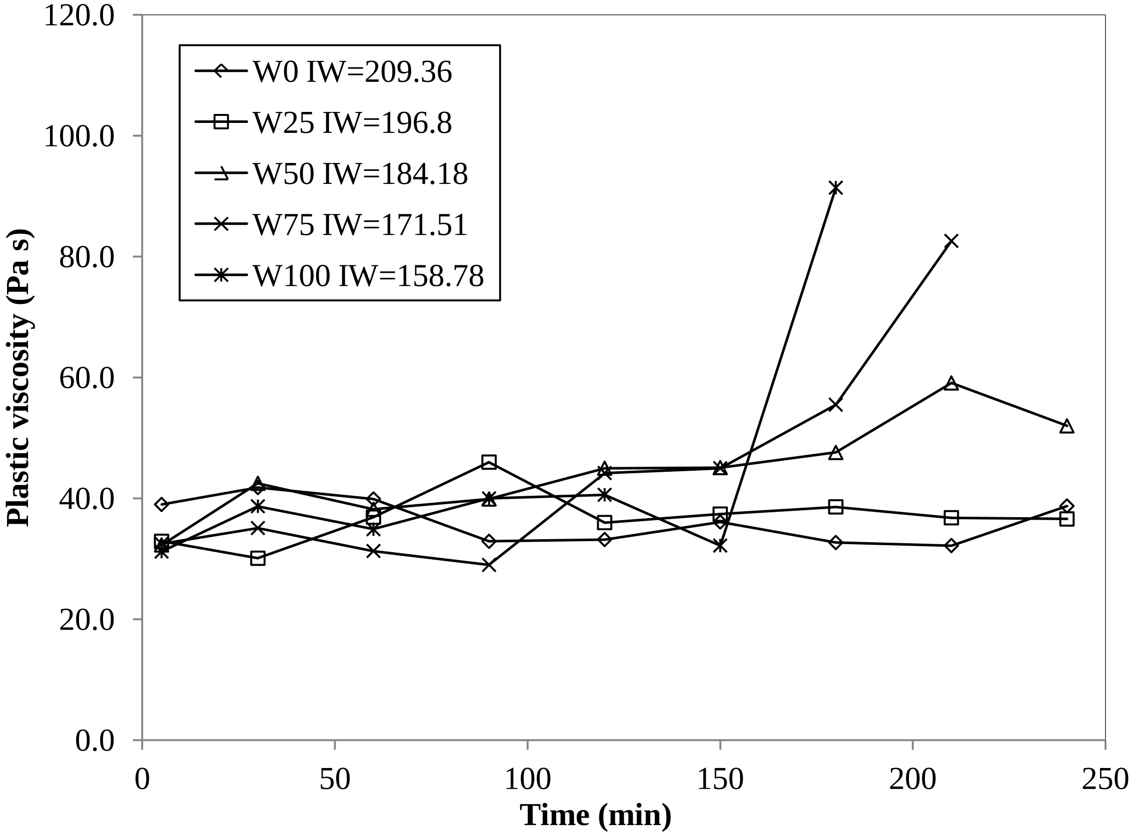


Figure 4-4 a. Change of plastic viscosity of W series over time

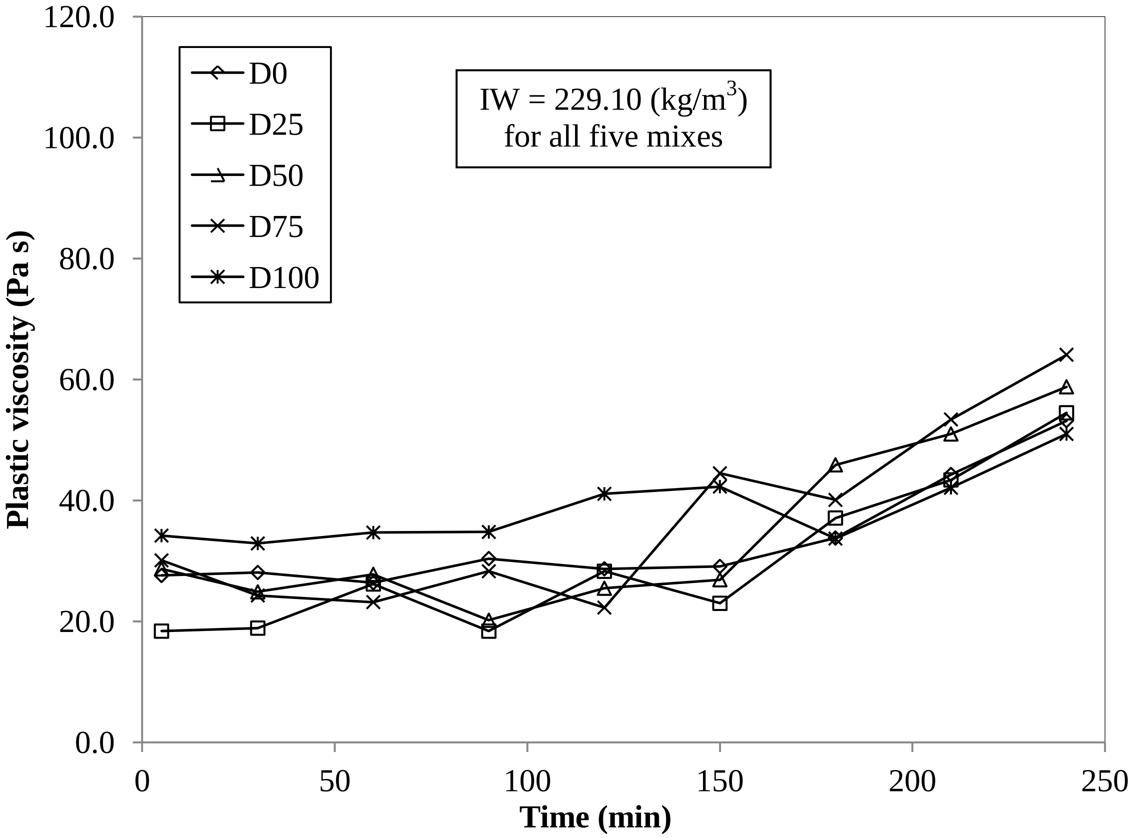


Figure 4-4 b. Change of plastic viscosity of D series over time

Mortar Slump Test and Mortar Funnel Test

The results of mortar slump test and mortar funnel test and the plotted 3-D charts are presented in Appendix. W series mixtures have lower initial slump but less slump loss over time compared to mixtures in D series.

Figure 4-5 a and b show the slump loss of all ten mixtures over time. The initial slump was influenced mainly by the initial free water content. In W series, the initial slump was between 10 to 15 cm, and more free water leads to higher slump. The slump loss in W series were caused by the cement hydration process, and all five mixes have similar trends of slump loss. In D series, the slump loss was caused by both the cement hydration and the absorption process of aggregate. Because FRCA has higher water absorption capacity, mixes with more FRCA lost the slump faster.

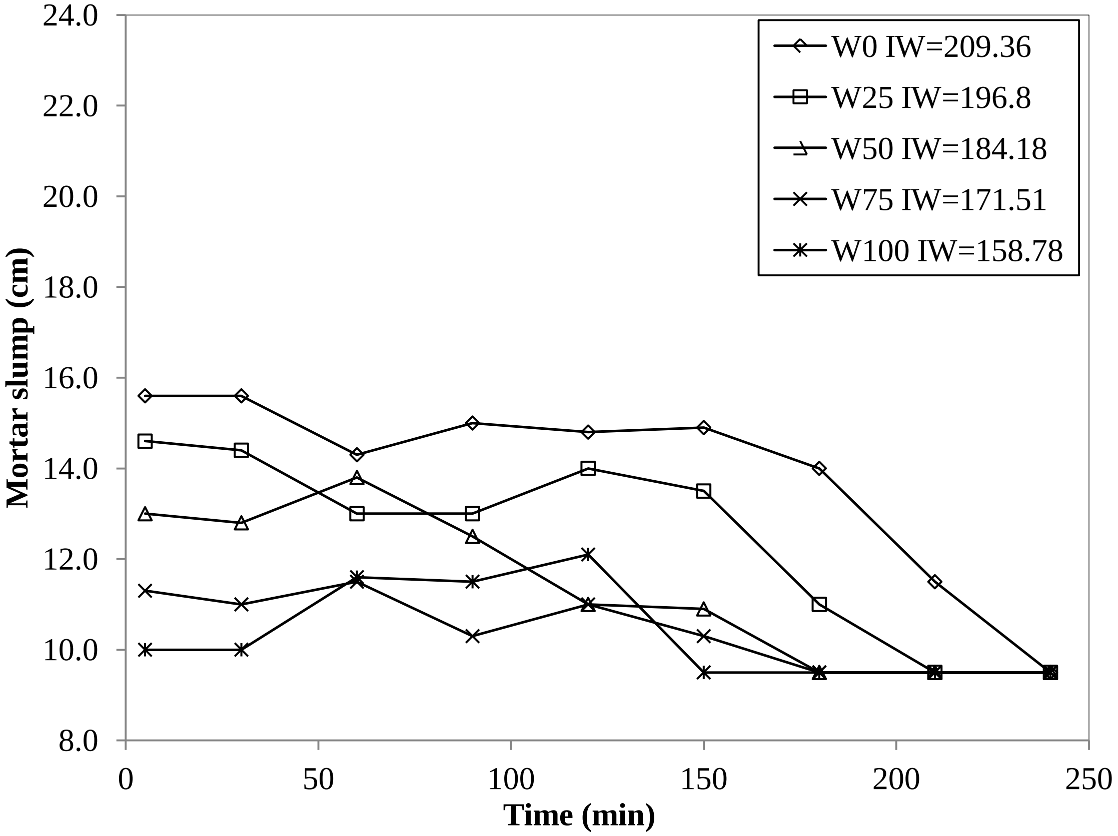


Figure 4-5 a. Change of mortar slump diameter of W series over time

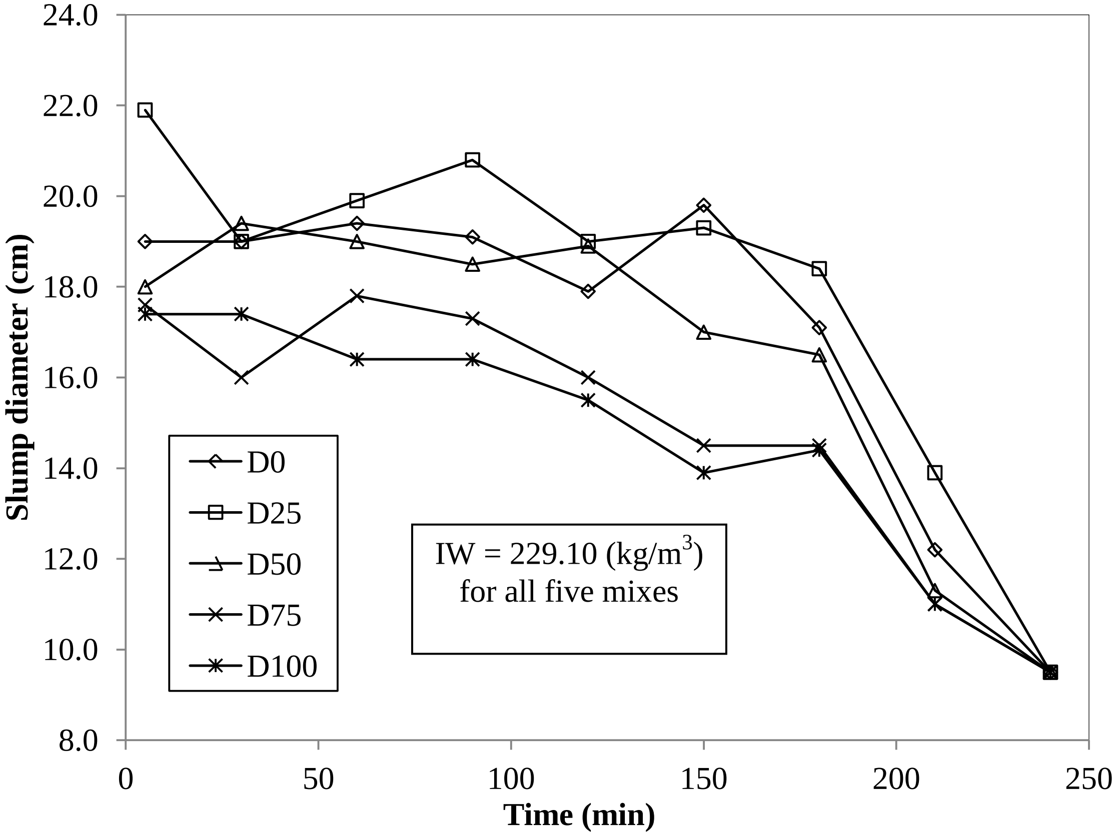


Figure 4-5 b. Change of mortar slump diameter of D series over time

The results of mortar funnel test are present in Appendix. Similar trends as in slump tests were observed. Mixtures with more water content tent to have shorter flow time. More percentage of the use of FRCA increased the absorption of the mixtures and accelerated the increase of flow time.

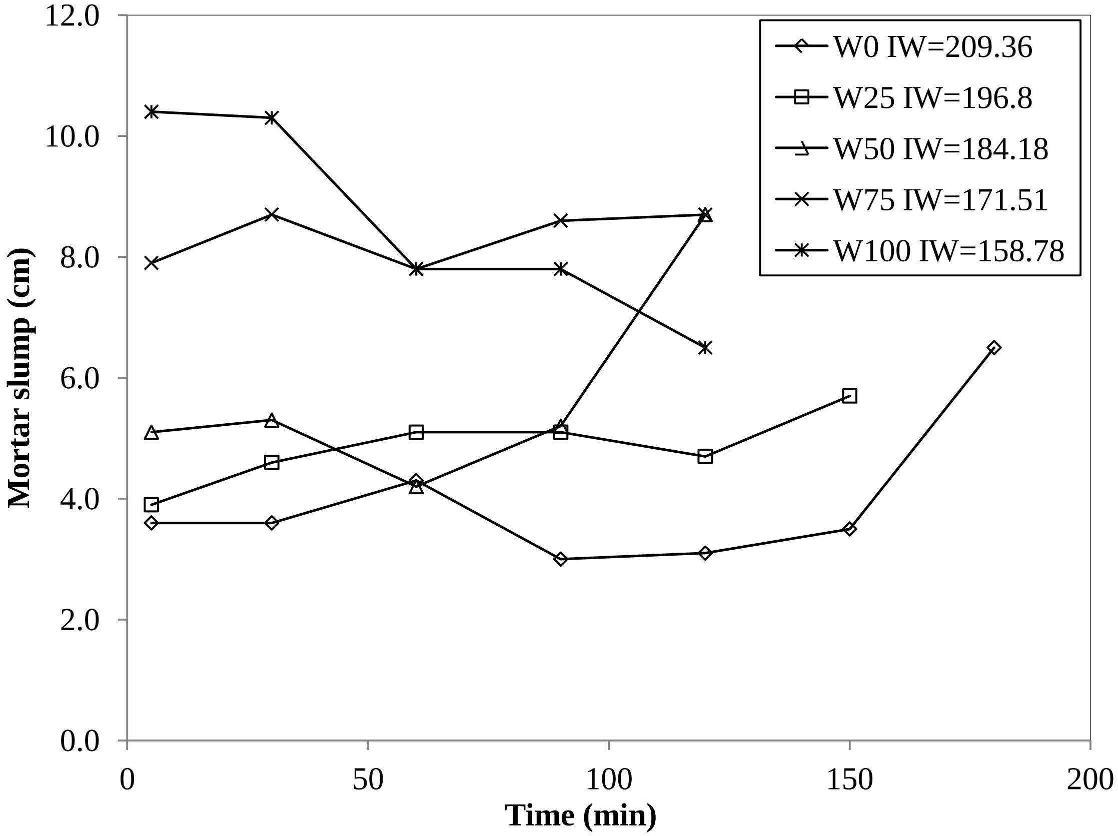


Figure 4-6 a. Change of mortar funnel flow time of W series over time

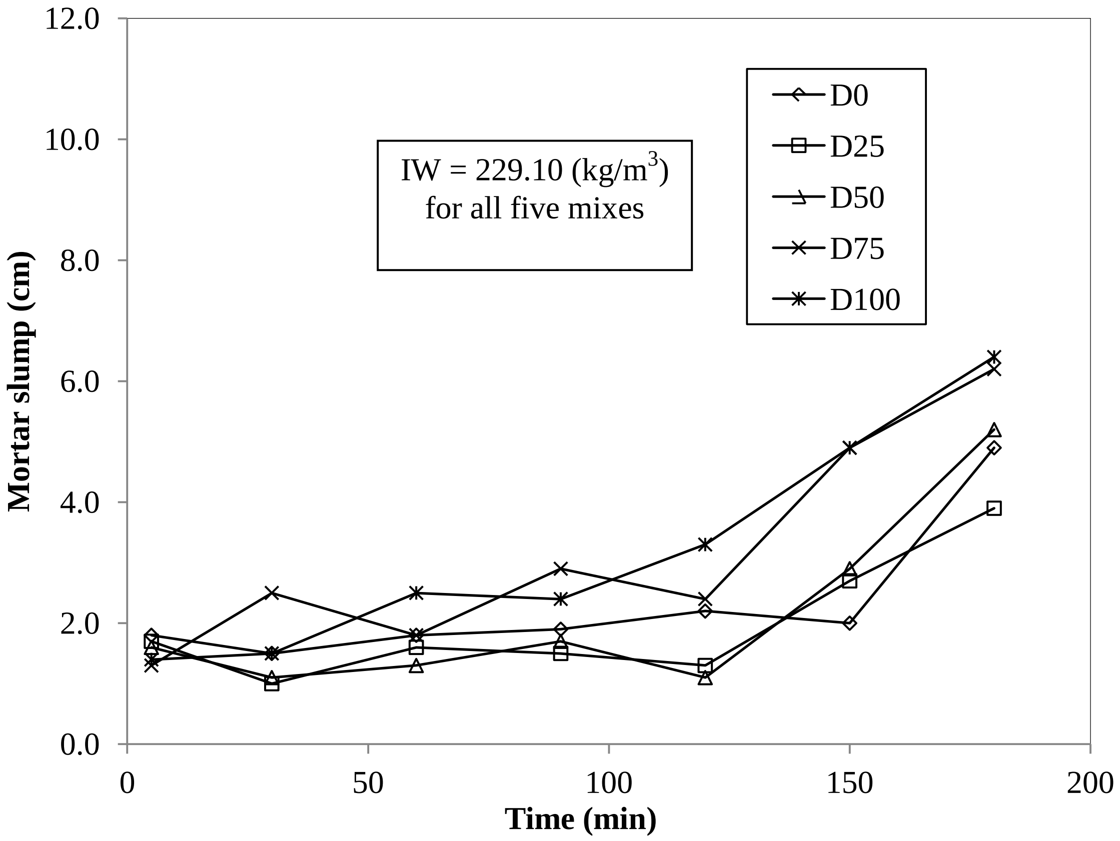


Figure 4-6 b. Change of mortar funnel flow time of D series over time

Mortar Column Segregation Test

The results of the mortar column segregation test are shown in Table 4-1. No significant segregation was observed in this study.

Table 4-1. Mortar column segregation test and ICAR rheometer test

Mix ID	Segregation rate (%)	Static yield stress		Dynamic yield stress		Plastic viscosity	
		Top	Bottom	Top	Bottom	Top	Bottom
D0	0 (-7.55)	183.0	297.9	126.3	165.8	13.4	13.4
D100	0 (-9.78)	141.3	206.3	45.1	43.4	36.5	34.7
W0	0.81	198.6	225.4	6.8	0.1	25.9	31.8
W100	0 (-3.60)	259.7	259.7	24.0	43.4	54.5	34.7

Hardened SCC Mortar Test Results and Data Analysis

The unit weight and 7-day compressive strength are shown in Figure 4-18 and 4-19. W series has higher unit weight as well as higher compressive strength than D series. This indicates that the use of saturated aggregate is able to increase the compressive strength of cement mortar. The proportion of FRCA in mixtures has an opposite relationship with compressive strength and unit weight.

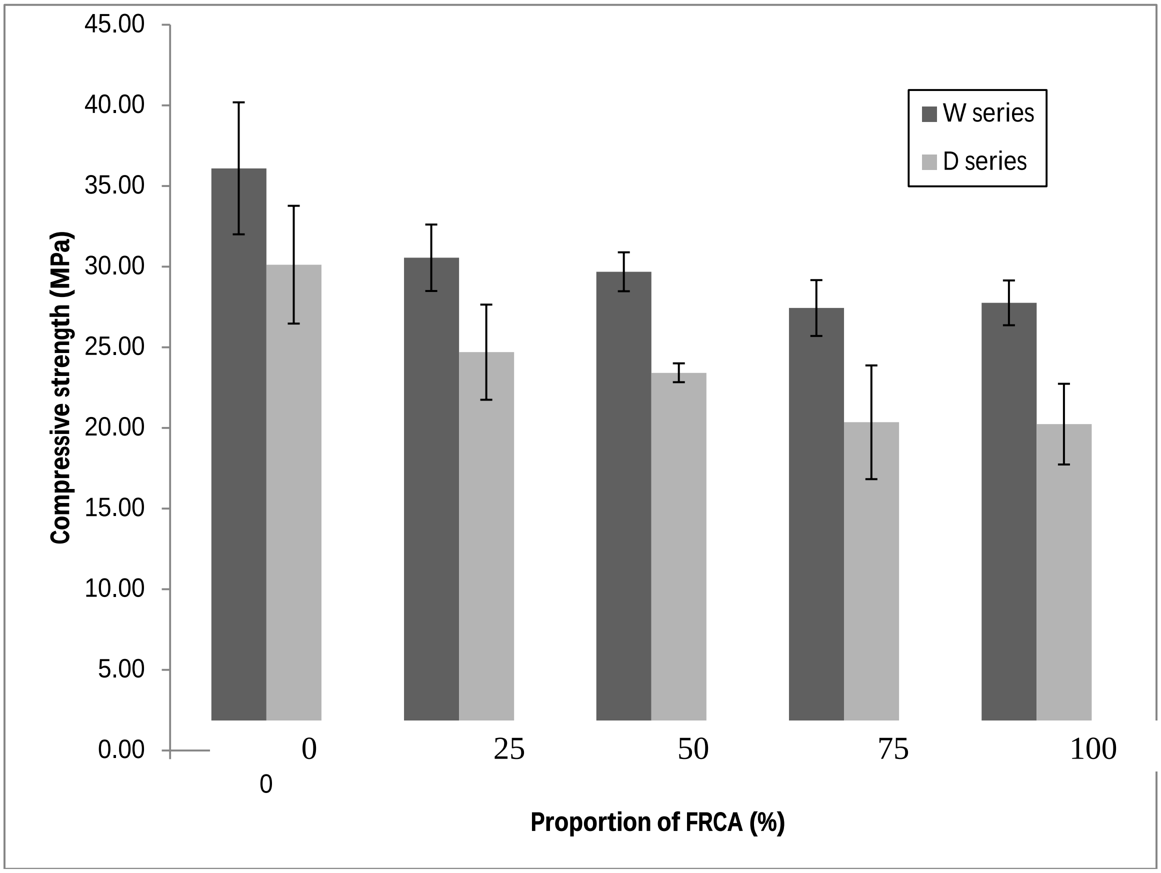


Figure 4-7. 7-day compressive strength

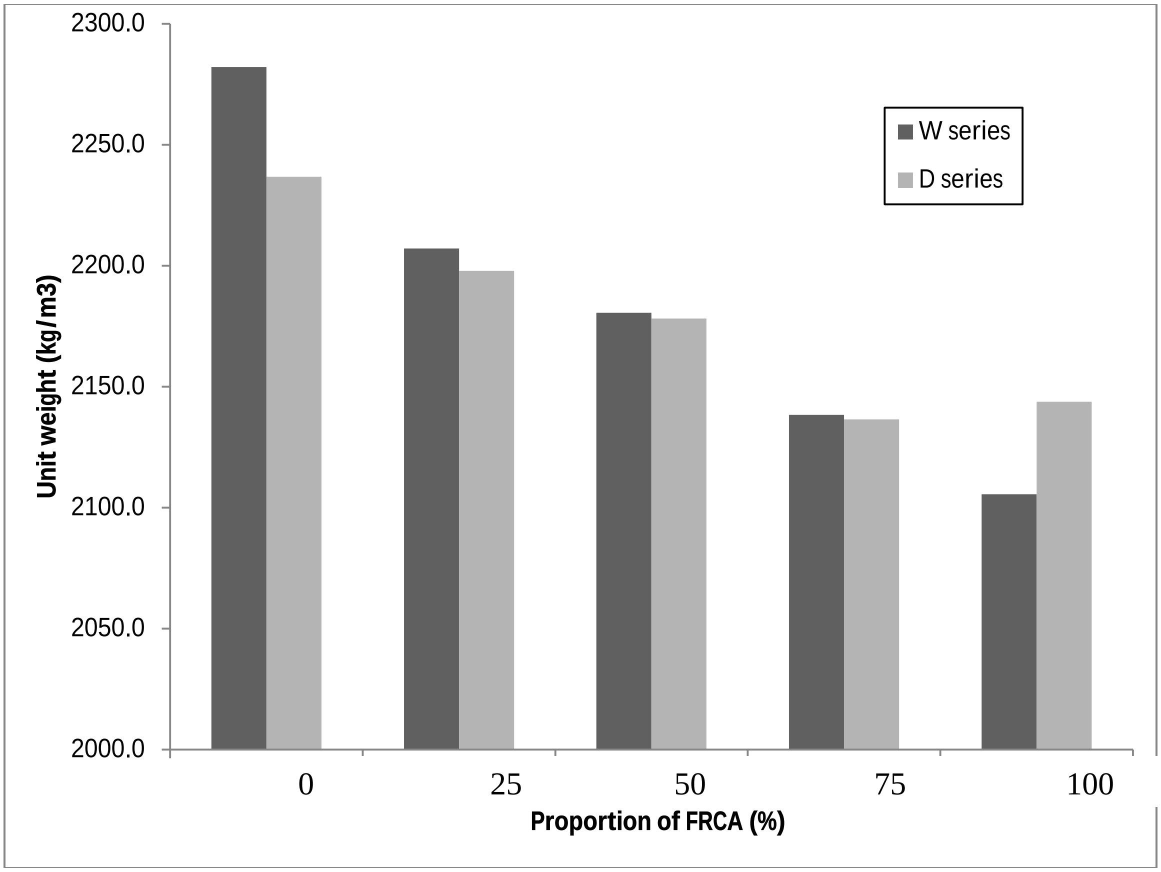


Figure 4-8. Unit weight

CHAPTER V. CONCLUSIONS AND RECOMMENDAIONS

Conclusions

The effects of aggregate moisture conditions on rheological behaviors of SCC mortar prepared with FRCA were investigated in this study. FRCA was used to replace natural aggregate in mortar mixes with different proportions. Wet aggregate and dry aggregate were separately used in ten different mortar mixtures. The rheological parameters including static yield stress, dynamic yield stress, and plastic viscosity were measured by a rheometer. A mortar slump test and a mortar funnel test were used to evaluate the workability of SCC mortar, and the results were compared to the rheology of mortar mixtures.

Findings

- With proper mix proportion, FRCA in both wet condition and wet condition can be used to substitute natural fine aggregate up to 100% in producing SCC mortar with high flowability and good stability.
- The initial free water content in the mixtures affects the rheological properties of fresh SCC mortar. In W series, where five mixes prepared with different portions of FRCA and different initial water content, when the initial free water content in the mix was higher, the yield stress and plastic viscosity of SCC mortar tended to increase faster. In mortar slump

test, this phenomenon showed as faster slump loss of SCC mortar. While in D series, although the five mixes had different FRCA content, due to the initial water content in each mix was same, there was no significant difference of yield stress and plastic viscosity growth was observed within different mixes.

§ Rheological parameters can be used to describe the workability of SCC mortar. The yield stress and plastic viscosity are coincident with the results of mortar slump and mortar funnel test.

§ The more FRCA used in the mixtures, the lower unit weight and lower compressive strength the mixtures have. The unit weight can be reduced up to 4.16% in D series and 7.74% in W series when used FRCA to substitute 100% natural aggregate. The 7 day compressive strength was reduced up to 46.88% in D series and 37.75 % in W series with using 100% of FRCA in the mixtures.

Research Limitations and Recommendations

The water absorption rate of FRCA is hard to be measured. The change of dry FRCA moisture condition in the first 10 to 20 minutes should be directly related to the rheological behavior changes, which is not measured in this study. Method should be developed to continually measure the moisture of FRCA.

APPENDIX. DATA TABLE AND FIGURES

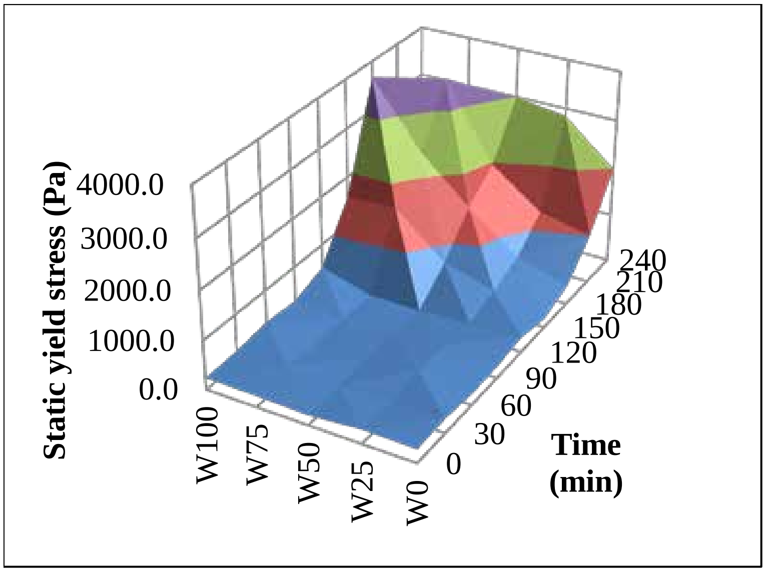


Figure A-1 a. Statistic yield stress of W series

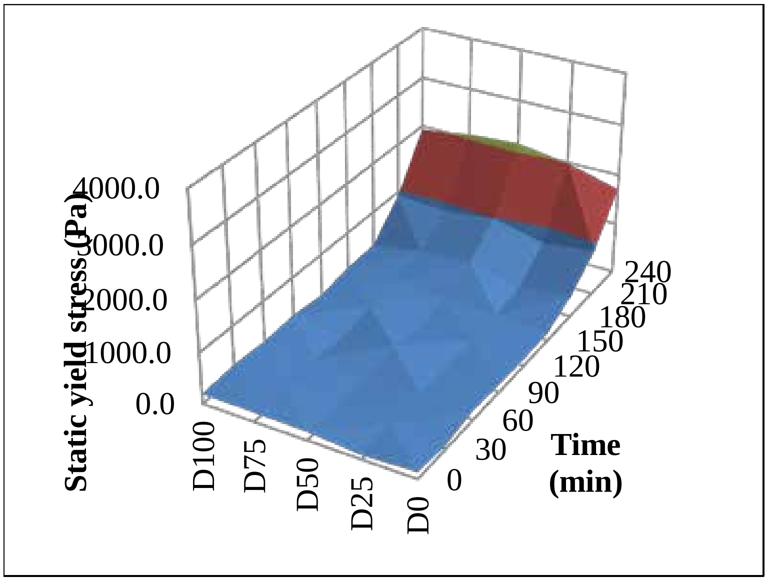


Figure A-1 b. Statistic yield stress of D series

Table A-1 a. Static yield stress of W series (Pa)

Mix ID	Free water	Time (min)								
	(kg/m^3)	0	30	60	90	120	150	180	210	240
W0	209.36	278.8	301.8	221.5	240.6	305.6	183.3	382.0	996.9	1993.9
W25	196.80	294.1	225.4	374.3	343.8	271.2	462.2	702.8	1214.7	2845.7
W50	184.18	206.3	244.5	252.1	255.9	213.9	756.3	1482.1	1967.2	2990.8
W75	171.51	229.2	301.8	202.4	225.4	225.4	1623.4	2379.7	3514.1	NA
W100	158.78	244.5	255.9	340.0	282.7	519.5	1577.5	3674.6	NA	NA

Table A-1 b. Static yield stress of D series (Pa)

Mix ID	Free water	Time (min)								
	(kg/m^3)	0	30	60	90	120	150	180	210	240
D0	231.33	129.9	76.4	183.3	152.8	137.5	160.4	424.0	882.4	1711.2
D25	230.21	84.0	145.1	183.3	129.9	179.5	206.3	305.6	756.3	1986.3
D50	229.10	168.1	129.9	129.9	263.6	141.3	236.8	527.1	985.5	2135.2
D75	228.00	183.3	202.4	156.6	122.2	240.6	301.8	450.7	878.5	2070.3
D100	226.92	191.0	248.3	206.3	240.6	175.7	286.5	301.8	924.4	1929.0

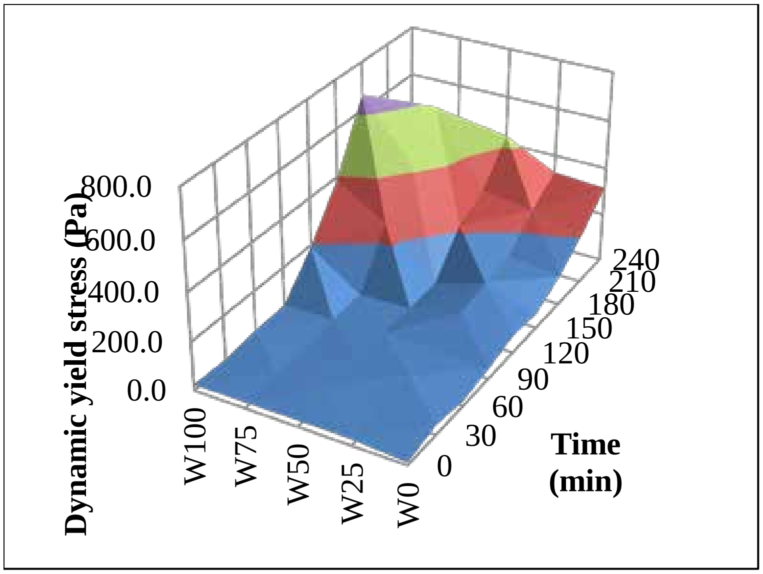


Figure A-2 a. Dynamic yield stress of W series

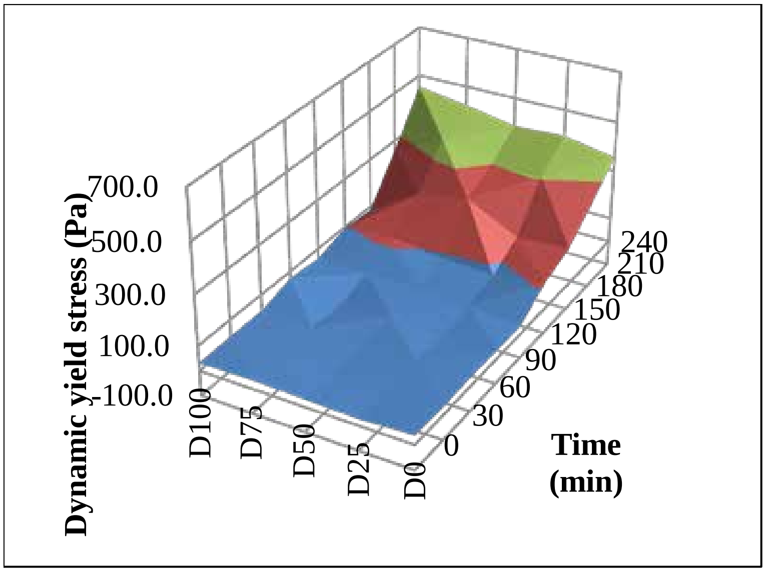


Figure A-2 b. Dynamic yield stress of D series

Table A-2 a. Dynamic yield stress of W series (Pa)

Mix ID	Free water	Time (min)								
	(kg/m^3)	0	30	60	90	120	150	180	210	240
W0	209.36	10.5	40.3	19.9	41.3	72.3	60.9	121.4	208.2	315.0
W25	196.80	26.1	38.6	57.9	45.9	102.9	128.6	147.1	249.5	326.9
W50	184.18	26.4	46.7	42.7	52.7	53.3	60.8	214.9	280.3	432.8
W75	171.51	25.1	34.1	22.8	45.0	47.4	257.2	430.5	585.0	NA
W100	158.78	24.1	18.8	34.9	38.6	192	387.6	665.0	NA	NA

Table A-2 b. Dynamic yield stress of D series (Pa)

Mix ID	Free water	Time (min)								
	(kg/m^3)	0	30	60	90	120	150	180	210	240
D0	231.33	36.6	31.4	35.4	33.6	33.0	112.7	153.8	251.7	356.1
D25	230.21	25.6	22.2	36.2	22.2	46.6	77.6	141.4	306.9	394.1
D50	229.10	30.1	19.8	25.2	44.8	53.0	88.3	246.4	298.1	385.6
D75	228.00	35.0	30.6	31.1	20.7	59.9	113.5	210.5	355.0	423.7
D100	226.92	31.6	35.2	34.5	72.9	59.5	95.6	85.9	258.4	452.9

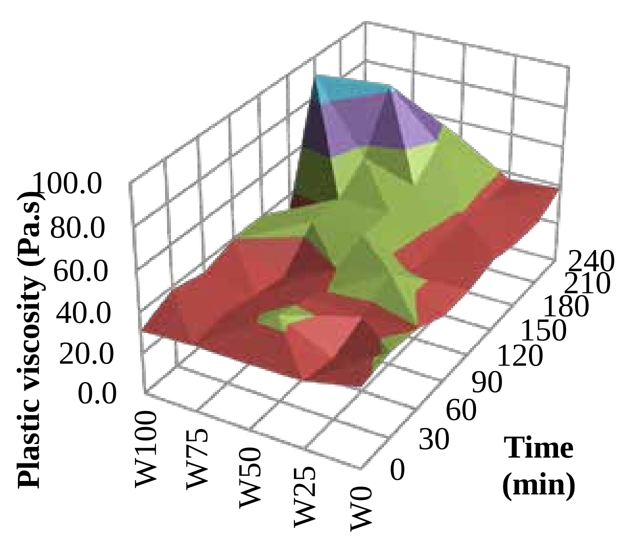


Figure A-3 a. Plastic viscosity of W series

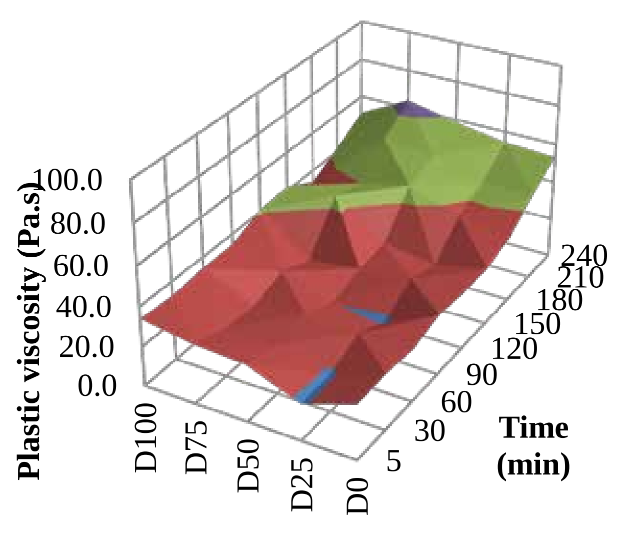


Figure A-3 b. Plastic viscosity of D series

Table A-3 a. Plastic viscosity of W series (Pa s)

Mix ID	Free water (kg/m^3)	Time (min)																	
		0	R^2	30	R^2	60	R^2	90	R^2	120	R^2	150	R^2	180	R^2	210	R^2	240	R^2
W0	209.36	39.0	0.81	41.8	0.88	39.9	0.88	32.9	0.93	33.2	0.94	36.1	0.97	32.7	0.99	32.2	0.97	38.8	0.97
W25	196.80	32.9	0.77	30.1	0.85	36.9	0.88	46.0	0.75	36.0	0.88	37.4	0.95	38.6	0.88	36.8	0.98	36.6	0.95
W50	184.18	32.3	0.74	42.5	0.87	38.2	0.95	39.9	0.92	45.0	0.95	45.1	0.90	47.6	0.97	59.1	0.96	52.0	0.94
W75	171.51	32.5	0.78	35.1	0.88	31.3	0.93	29.0	0.81	44.2	0.99	45.0	0.92	55.5	0.97	82.6	0.97	NA	0.98
W100	158.78	31.2	0.80	38.7	0.83	34.9	0.89	40.0	0.91	40.6	0.94	32.2	0.99	91.4	0.96	NA	0.96	NA	0.95

Table A-3 b. Plastic viscosity of D series (Pa s)

Mix ID	Free water (kg/m^3)									Time (min)									
		0	R^2	30	R^2	60	R^2	90	R^2	120	R^2	150	R^2	180	R^2	210	R^2	240
D0	231.33	27.6	0.89	28.1	0.82	26.4	0.93	30.4	0.91	28.7	0.96	29.1	0.98	33.8	0.99	44.3	0.99	53.2
D25	230.21	18.4	0.72	18.9	0.78	26.2	0.92	18.4	0.95	28.3	0.98	23.0	0.92	37.1	0.98	43.4	0.98	54.5
D50	229.10	28.7	0.81	24.9	0.88	27.8	0.92	20.2	0.88	25.5	0.91	26.9	0.98	45.9	0.98	51.0	0.99	58.8
D75	228.00	30.1	0.89	24.3	0.76	23.2	0.97	28.3	0.87	22.3	0.97	44.5	0.98	40.1	0.99	53.4	0.96	64.1
D100	226.92	34.2	0.72	32.9	0.75	34.7	0.80	34.8	0.90	41.1	0.92	42.3	0.92	33.7	0.99	42.1	0.98	51.0

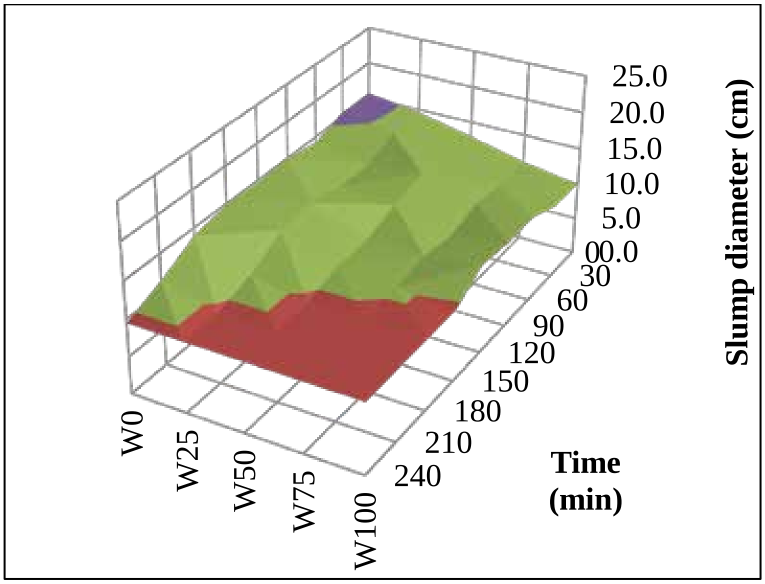


Figure A-4 a. Mortar slump diameter of W series

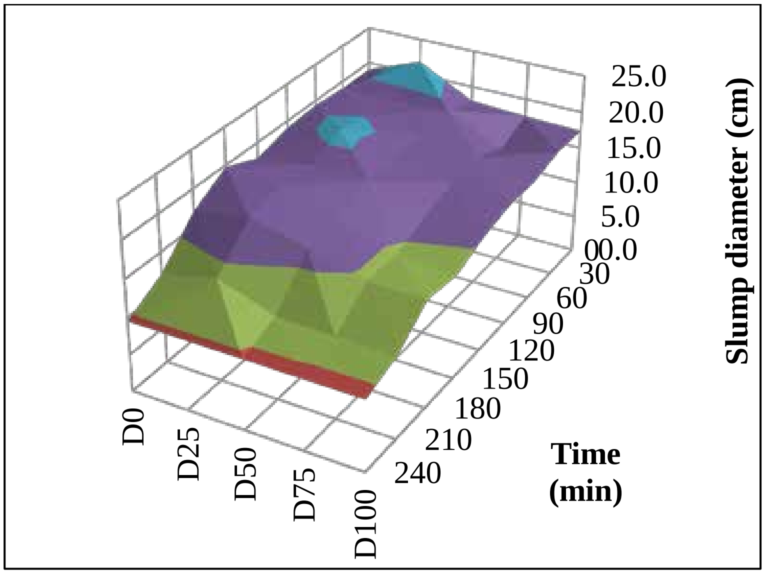


Figure A-4 b. Mortar slump diameter of D series

Table A-4 a. Mortar slump diameter of W series (cm)

Mix ID	Time (min)								
	0	30	60	90	120	150	180	210	240
W0	15.6	15.6	14.3	15.0	14.8	14.9	14.0	11.5	9.5
W25	14.6	14.4	13.0	13.0	14.0	13.5	11.0	9.5	9.5
W50	13.0	12.8	13.8	12.5	11.0	10.9	9.5	9.5	9.5
W75	11.3	11.0	11.5	10.3	11.0	10.3	9.5	9.5	9.5
W100	10.0	10.0	11.6	11.5	12.1	9.5	9.5	9.5	9.5

Table A-4 b. Mortar slump diameter of D series (cm)

Mix ID	Time (min)								
	0	30	60	90	120	150	180	210	240
D0	19.0	19.0	19.4	19.1	17.9	19.8	17.1	12.2	9.5
D25	21.9	19.0	19.9	20.8	19.0	19.3	18.4	13.9	9.5
D50	18.0	19.4	19.0	18.5	18.9	17.0	16.5	11.3	9.5
D75	17.6	16.0	17.8	17.3	16.0	14.5	14.5	11.0	9.5
D100	17.4	17.4	16.4	16.4	15.5	13.9	14.4	11.0	9.5

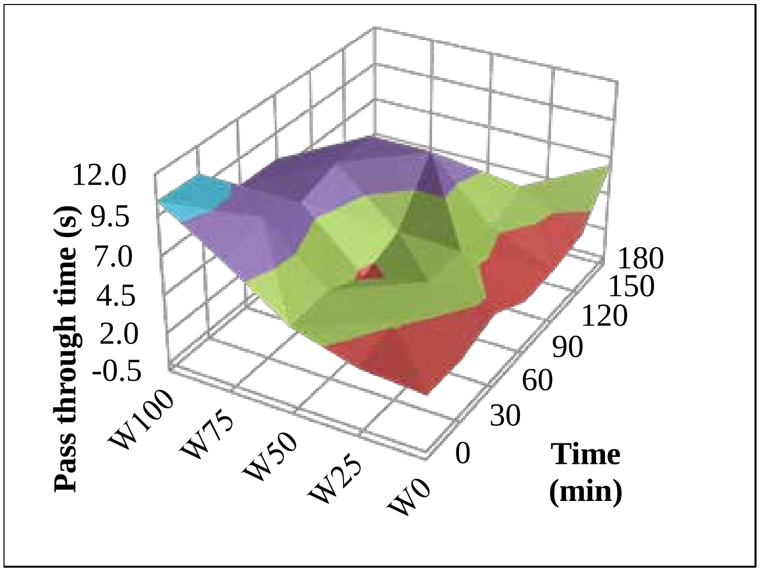


Figure A-5 a. Mortar funnel flow time of W series

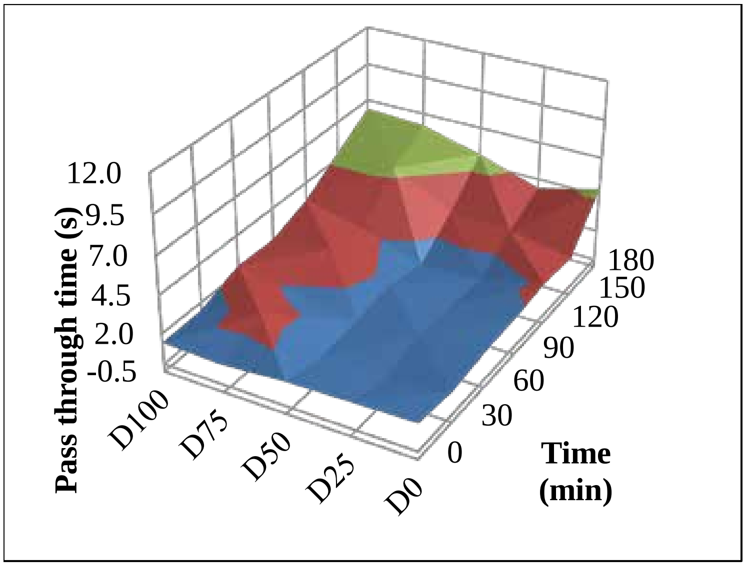


Figure A-5 b. Mortar funnel flow time of D series

Table A-5 a. Mortar funnel flow time of W series (s)

Mix ID	Time (min)								
	0	30	60	90	120	150	180	210	240
W0	1.8	1.5	1.8	1.9	2.2	2.0	4.9	NA	NA
W25	1.7	1.0	1.6	1.5	1.3	2.7	3.9	NA	NA
W50	1.6	1.1	1.3	1.7	1.1	2.9	5.2	NA	NA
W75	1.3	2.5	1.8	2.9	2.4	4.9	6.2	NA	NA
W100	1.4	1.5	2.5	2.4	3.3	4.9	6.4	NA	NA

Table A-5 b. Mortar funnel flow time of D series (s)

Mix ID	Time (min)								
	0	30	60	90	120	150	180	210	240
D0	3.6	3.6	4.3	3.0	3.1	3.5	6.5	NA	NA
D25	3.9	4.6	5.1	5.1	4.7	5.7	NA	NA	NA
D50	5.1	5.3	4.2	5.2	8.7	NA	NA	NA	NA
D75	7.9	8.7	7.8	8.6	8.7	NA	NA	NA	NA
D100	10.4	10.3	7.8	7.8	6.5	NA	NA	NA	NA

Table A-6. Unit weight and 7-Day Compressive Strength

Mix ID	Unit weight (kg/m^3)	Compressive strength (MPa)
W0	2282.1	36.09
W25	2207.2	30.55
W50	2180.5	29.68
W75	2138.4	27.43
W100	2105.6	27.75
D0	2236.8	30.12
D25	2197.9	24.69
D50	2178.1	23.42
D75	2136.5	20.35
D100	2143.7	20.23

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