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Investigating the Use of Self-Consolidating Concrete in Transportation Structures

J. Garrison Smith, Royce W. Floyd, W. Micah Hale

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16. Abstract

Self Consolidating Concrete (SCC) is a recent advancement in the concrete industry. SCC is a type of concrete that can be placed without consolidation and is beginning to be widely accepted. SCC is particularly suited for use in concrete members such as box culverts, drilled piers, and precast beams. However, current AHTD Specifications only address slump which cannot be used to specify the workability of SCC. Therefore, requirements such as slump flow test, L-box test, or J-ring test must be added to AHTD's Specifications to ensure the SCC is indeed self consolidating and is resistant to segregation.

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CHAPTER 1

INTRODUCTION

1.1 SELF-CONSOLIDATING CONCRETE

Proper concrete consolidation is essential in obtaining the desired fresh and hardened properties from any given concrete mixture. In conventional-slump concrete, appropriate consolidation is achieved through the mechanism of vibration. The ability to sufficiently vibrate concrete is a unique skill. Insufficient vibration increases the likelihood of bug holes or honeycombed areas; whereas excessive vibration can lead to bleeding and segregation. [1] In the early 1980's, the construction industry of Japan began to suffer due to the decreasing amount of skilled concrete laborers. Consequently, the structural integrity of Japan's concrete structures declined as well.[2] Self-consolidating concrete (SCC) was developed in Japan in the late 1980's as the result of a drive toward a better and more uniform quality of concrete. Its initial purpose was to solve the poor performance issues of concrete structures that existed at the time due to a lack of uniform and complete consolidation. [3] Now the popularity of SCC is expanding globally; it is revered as one of the most influential advancements in concrete technology in the past decade.[4]

1.2 BACKGROUND

Ongoing research has and will continue to be performed on SCC because of its various benefits. In the U.S., SCC has been used in many precast concrete structures including basement and foundation walls, box culverts, bridge girders, and drilled shafts. The current status of SCC is denoted as a specialty concrete, but researchers and workers in industry alike are hopeful that in the near future SCC will become a standard concrete that is routinely used for many different applications. The Arkansas State Highway and Transportation Department (AHTD) Standard Specifications for Highway Construction[5] do not address SCC. The primary goal of this research program was to develop fresh concrete guidelines for SCC.

1.3 RESEARCH OBJECTIVES

The principal goal of this project was to investigate if the binder content (611 lb/yd^3, 362.61 kg/m^3) was suitable for SCC and determine an acceptable range of fresh concrete properties for SCC. The variables examined cover cement content, water content, sand to total aggregate ratio (*S/Agg*), chemical admixtures, and supplementary cementitious materials (SCM).

CHAPTER 2

LITERATURE REVIEW

2.1 DEFINITION

SCC is proportioned to exhibit a moderate viscosity and a low yield stress value. When achieved, these parameters ensure high deformability and filling capacity of formwork while minimizing the risk of flow blockage or segregation.[6, 7] SCC is defined by ACI Committee 237[8] as “highly flowable, nonsegregating concrete that can spread into place, fill the formwork, and encapsulate the reinforcement without any mechanical consolidation.”

2.2 CONSTITUENT MATERIALS

SCC is composed of the same constituent materials as conventional-slump concrete; however, it is the different quantities of these materials that distinguish the properties of SCC. The mixture proportioning of SCC is multifaceted and involves adjusting several variables to obtain balance among the workability requirements that affect the successful casting of SCC.[9] When compared with conventional-slump concrete mixtures, it has been reported that SCC mixtures contain a lower coarse aggregate content, [10] smaller coarse aggregate, [11] similar water content, higher fine aggregate content, and higher cementitious materials (CM) content.[12] It is also necessary for SCC mixtures to include chemical admixtures such as high-range water reducing (HRWR) admixtures and/or viscosity modifying admixtures (VMA).[13] All the aforementioned trends are unique because the combination of these modified parameters results in a highly flowable yet stable concrete mixture. Figure 2.1 compares the constituent material quantities in SCC to conventional-slump concrete schematically.

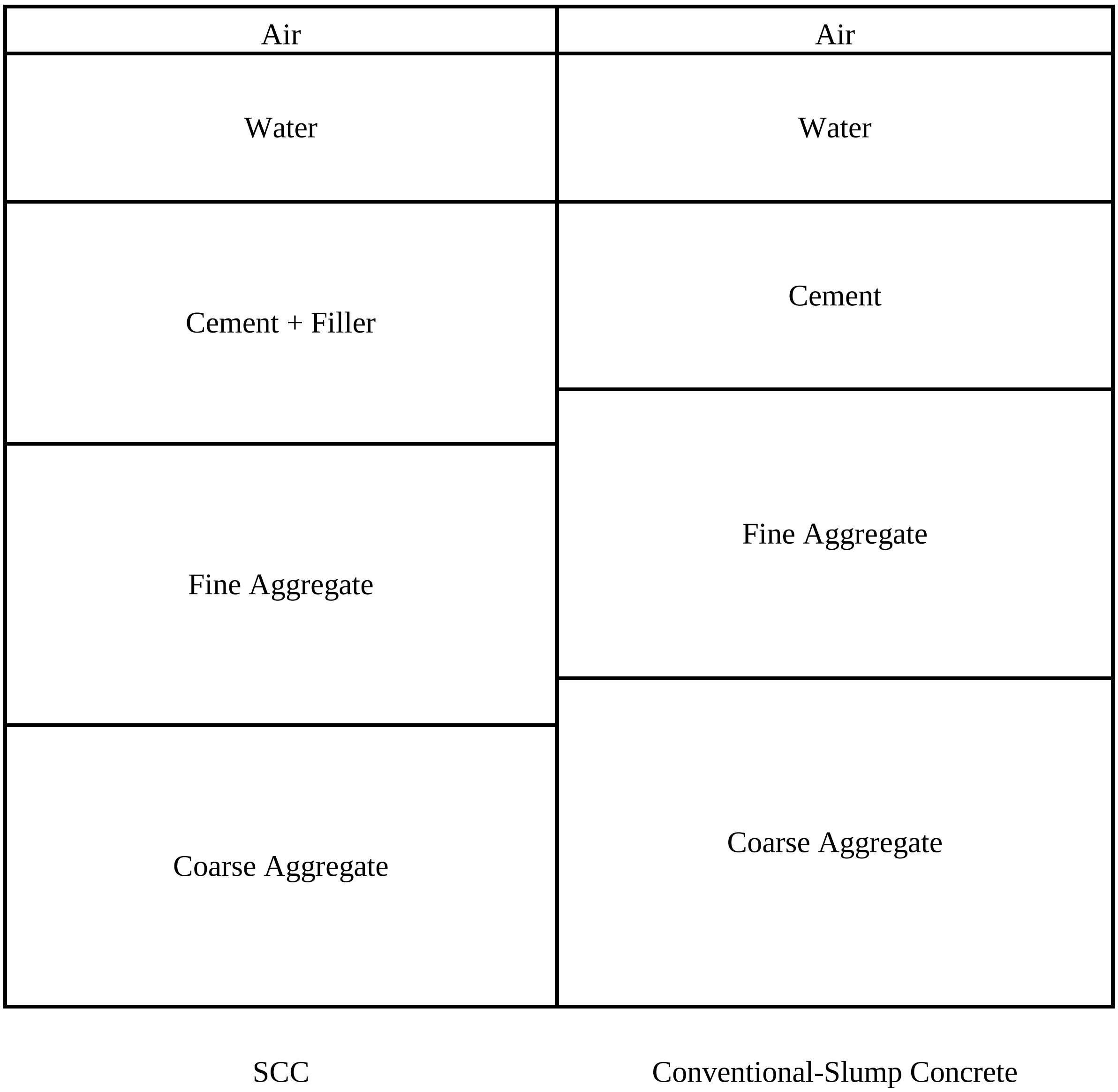

Figure 2.1: Comparison of Relative Volumes of Constituent Materials in Self-Consolidating Concrete and Conventional-Slump Concrete[12]

2.3 BENEFITS OF SCC

When compared with conventional-slump concrete mixtures, SCC can be a beneficial alternative for many reasons. Some advantages of SCC consist of, but are not limited to, the following: SCC can be used in narrow members where there is a high probability of congestion; the use of SCC can reduce construction costs by requiring fewer laborers;[14] implementing SCC can decrease construction time; SCC does not require vibration; SCC reduces noise pollution; SCC improves the interfacial transition zone (ITZ) between the cement paste and aggregate or reinforcement; SCC improves the durability and decreases the permeability of concrete; and SCC aids in constructability and promotes better structural performance.[3]

2.4 MIXTURE PROPORTIONING PROCEDURES FOR SCC

2.4.1 General Procedures

Several mixture proportioning guidelines or procedures based on experimental practices or scientific hypotheses have been developed for SCC. Generally these procedures can be categorized by either one of the following three methods. The first method requires the concrete to be fractioned into two components consisting of only coarse aggregate and mortar. The term “mortar” is defined as a mixture consisting of cement paste, filler, and fine aggregate. By incorporating chemical admixtures such as HRWR and VMA to the mixture, the flowability of the mortar is then altered to obtain SCC. The second method consists of optimizing the particle size distribution of the binder. This is achieved by increasing the amount of SCM such as fly ash (FA) or silica fume (SF) in the SCC mixture. [15] The third method is simply a combination of methods one and two. In addition to the general procedures that are previously mentioned, more specific methods are also available and discussed in detail in the following sections.

2.4.2 The Japanese Method

The 'Japanese method' was proposed by Okamura, et al.[16, 17] and is based upon research performed by Ozawa, Okamura, and Maekawa at the University of Tokyo. This method was further enhanced by Ouchi et al. The first step is to choose the air content; if no air-entrainment is specified then it is acceptable to assume an air content of about 2%. The coarse aggregate content in the concrete is then set at 50 to 60% of the volume of the concrete based on its bulk density. The fine aggregate content is also fixed at 40 to 50% of the mortar volume of the concrete. The type of filler and its ratio to cement are subsequently determined based on the designer's experience. In order to establish the apposite value of powder ratio, tests are performed on mortar for different water-powder ratios (generally 1.1, 1.2, 1.3, and 1.4) with a flow cone. The term "powder" is defined as particles that are smaller than 3.5×10^{-3} in. (90 micrometers (0.09 mm)). HRWR is then added to the mortar at different dosage rates to attain adequate flowability. Once the water-powder ratio and HRWR dosage have been selected, coarse aggregate is added to the mortar and trial batching commences.[12]

2.4.3 European Practices

In European practices[18] mixture proportioning begins by selecting a water-powder ratio by solid volume that is between 0.80 and 1.10. In this case the term “powder” is characterized by particles that are smaller than 4.9×10^{-3} in. (125 micrometers (0.125 mm)). The total powder content by solid volume is then taken to be between 674 to 1,011 lb/yd^3 (400 to 600 kg/m^3) of concrete. The coarse aggregate content is fixed to be between 28 to 35% by volume of the mixture. Next, the water-cementitious material ratio (*w/cm*) is chosen based on strength and durability constraints. For this method the sand content is a dependent variable; it balances the volume of the other constituent materials that have already been determined to account for a total volume of 27 ft^3 (0.76 m^3). VMA may be used to ensure the mixture’s stability. [19] If one elects to design a SCC mixture by this method it is imperative that the relative ratios of essential components are based upon absolute volume[20] instead of by mass. It is good practice to allow for longer mixing times when batching SCC as opposed to conventional-slump concrete mixtures to ensure the powder is dispersed homogeneously.[12]

2.4.4 The Sedran et al. [LCPC, Paris] Method

The ‘Sedran et al. [LCPC, Paris] method’ was proposed by Sedran et al. It is a method of mixture proportioning of SCC which utilizes two developments implemented at the Laboratoire Central des Ponts Chaussées (LCPC), Paris.[21, 22] The two developments are a rheometer, (BTRHEOM), which distinguishes the rheological characteristics of fresh concrete. The second is a software program, [RENE-LCPC], which optimizes the aggregate-binder granular skeleton.[12] For this method the binder quantity (cement + filler) is initially chosen based on the designer's experience. The HRWR dosage is determined from its saturation point using the Marsh cone test. To execute the test, 0.26 gallons (1 liter) of cement paste is placed into the cone and the time required for half of the paste to flow out of the cone is recorded. The plot of T versus percent of HRWR (Sp/c) in the cement paste yields the saturation point. The saturation point is the optimal amount of HRWR where any additional amount does not increase the fluidity required for all material to flow out of the cone. The Marsh cone test provides the optimum dosage of HRWR. A Marsh cone and the corresponding data are shown in Figure 2.2.

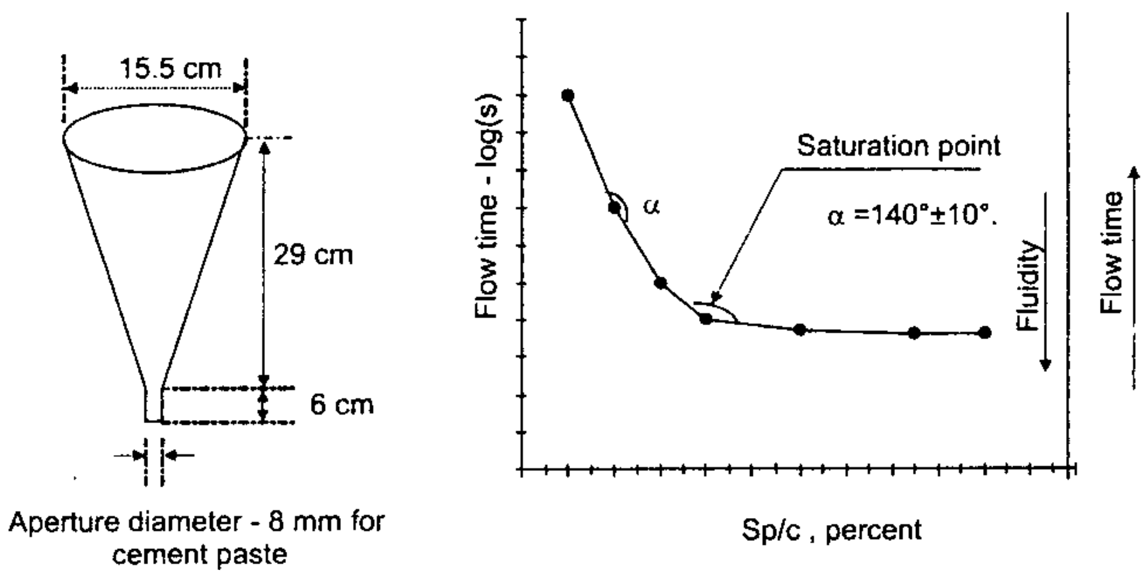

Figure 2.2: Marsh Cone Test – Determination of HRWR Dosage[12]
***NOTE: 1 in. = 2.54 cm = 25.4 mm**

The water requirement is subsequently established by utilizing the REN-LCPC software. Afterward, the mixture proportions are computed. The strength of the mixture is estimated by a theoretical formula given (developed by the authors). If the required strength is not attained or is surpassed, another trial blend of binders is selected and the mixture design process is rerun by the software. In addition to the software, trial batching can be conducted to verify the strength acquired.[12]

2.4.5 Method Proposed by Gomes, Gettu, et al.

Gomes, Gettu, et al. proposed a multi-phase optimized method for developing SCC.[23] The first phase in the process establishes the HRWR dosage based on cement content; this is determined by performing the Marsh cone test as prescribed in Section 2.4.4. In the second phase, the optimum filler dosage is determined by using a mini-slump test (Figure 2.3).

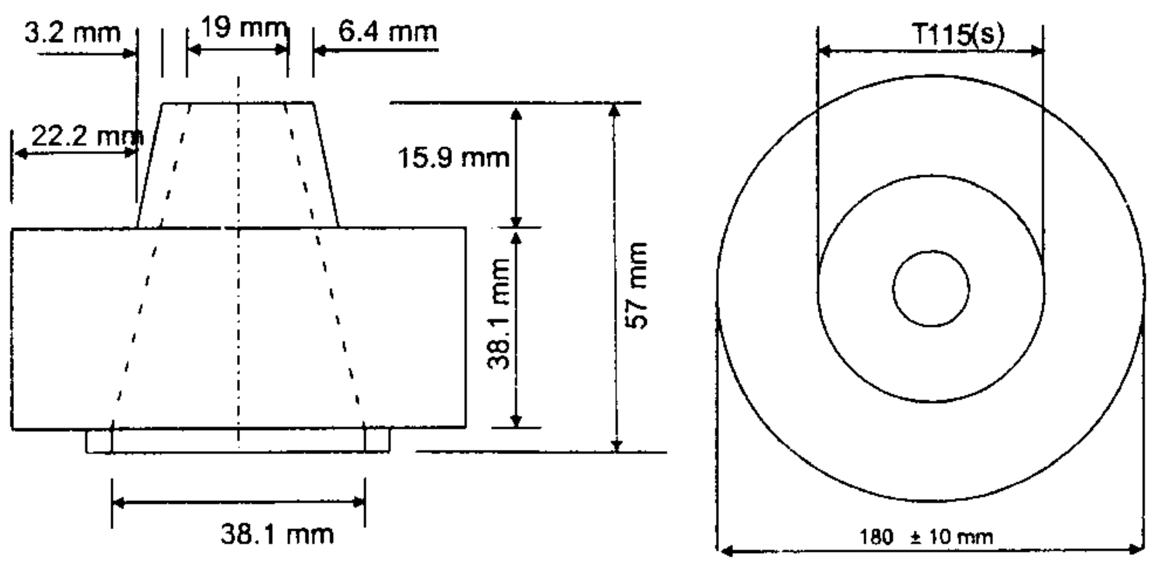

Figure 2.3: Mini-Slump Test Apparatus[12]

The time required for the pastes which are at the saturation point to reach a diameter of 4.53 in. (115 mm) is measured (T_{115}). The recommended spreads range from 6.69 to 7.48 in. (170 to 190 mm) with T_{115} values of 2 to 3.5 seconds. In the third stage, an aggregate gradation is developed that possesses the least voids. The procedure for this phase is based on ASTM C 29/C 29M[24] standard for determining the dry density of diverse aggregate mixtures without applying compaction. The fourth stage of the process is to select the paste content by volume. Tests are conducted on differing paste volumes (typically ranging from 35 to 45% of the total volume). In order to determine the fresh and hardened concrete properties that are necessary, this method mandates that the volume of paste must be the least amount necessary to facilitate fluidity and cohesion, without forfeiting the durability, resistance to shrinkage, and concrete strength. In the fifth and final phase, the original *w/cm* that was assumed is modified if the required strength is not attained during preliminary castings.[12]

2.4.6 Method Proposed by Vengala et al.

Jagadish Vengala et al. proposed a method for obtaining SCC that is similar to the mixture proportioning of conventional-slump concrete.[25] According to the authors, any of the recognized methods such as ACI[20] can be applied. For the required compressive strength (f'_c), the *w/cm* is established for the given cement content by utilizing ACI 318[26] or other analogous recommended guidelines. The desired workability is fixed between a slump of 2.95 to 3.94 in. (75 to 100 mm). The water content for this workability range is attained based upon available published guidelines and the attributes of the aggregates. No HRWR is present in the mixture at this time. Based on aggregate properties such as bulk density, fineness modulus, specific gravity, and other essential characteristics, the mixture proportion is established as indicated by the aforementioned method of choice.

The saturation point of HRWR is determined by a Marsh cone test as previously detailed in Section 2.4.4; this dosage is then added to the mixture. A trial batch is prepared, and if any bleed water is present then a small portion of the coarse aggregate (approximately 8.43 to 16.86 lb/yd^3 (5 to 10 kg/m^3)) is substituted by fine aggregate. If no visual evidence of bleeding is observed, then the mixture is deemed adequate. The process of replacing a small portion of coarse aggregate with fine aggregate, in increasing percentages is continued progressively until no bleed water is observed in the preliminary castings. This step, while possibly tedious, is crucial in guaranteeing that no excess water is present within the mixture that could lead to segregation. A portion of the coarse aggregate is subsequently replaced with a chosen filler material (such as FA) gradually in increasing quantities (such as 8.43 lb, 16.86 lb, 25.28 lb/yd^3(5 kg, 10 kg, 15 kg/m^3) of concrete). At this step of design, the concrete is evaluated as SCC. This partial replacement of coarse aggregate with the filler material ends when an acceptable SCC mixture is developed. The previous step may be omitted if the original fine aggregate content is regarded as satisfactory and does not need to be supplemented. Compressive strength data are gathered from all the preliminary castings to confirm if the assumed *w/cm* is adequate. If the assumed *w/cm* is found to be inadequate then this ratio can be increased or decreased as needed, and the final preliminary castings are completed at this time.[12]

2.5 FRESH CONCRETE PROPERTIES AND TESTS PERFORMED ON SCC

2.5.1 Introduction

High deformability, high passing ability or restricted deformability, and high resistance to segregation are the three fundamental criteria that are required to achieve self-consolidation.[27, 28] These parameters are accurately and effectively measured by performing fresh concrete tests. The tests include, but are not limited to: the slump flow test (ASTM C 1611/C 1611M) [29], the T-20 (T-50) test (ASTM C 1611/C 1611M) [29], the visual stability index (VSI) test (ASTM C 1611/C 1611M) [29], the J-Ring test (ASTM C 1621/C 1621M) [30], the L-Box test, and the surface settlement test. It has been reported that these fresh tests should be conducted as soon as mixing is finished. The time allotted to complete all tests is approximately 20 minutes. [31] These tests have been approved and utilized in practice by researchers and workers in industry alike.

2.5.2 Slump Flow Test

The slump flow test measures the filling ability of the concrete. This test can either be performed with the slump cone in the traditional orientation or inverted as per ASTM C 1611/C 1611M[29]. Slump flow is measured as the arithmetic mean of two perpendicular diameters at the base of the concrete.[32] It is desirable for the concrete spread to have no bleed water or visible segregation. Research performed by Khayat and Mitchell[33] states that low slump flow values range from 23.5 to 25.0 in. (600 to 635 mm), normal slump flow values range from 26.0 to 27.5 in. (660 to 700 mm), and high slump flow values range from 28.0 to 30.0 in. (710 to 760 mm). The Japan Society of Civil

Engineers (JSCE)[34] recommends low to normal slump flows varying from 23.5 to 27.5 in. (600 to 700 mm). A visual representation of a typical concrete spread after the slump cone has been removed from a slump flow test can be viewed in Figure 2.4.

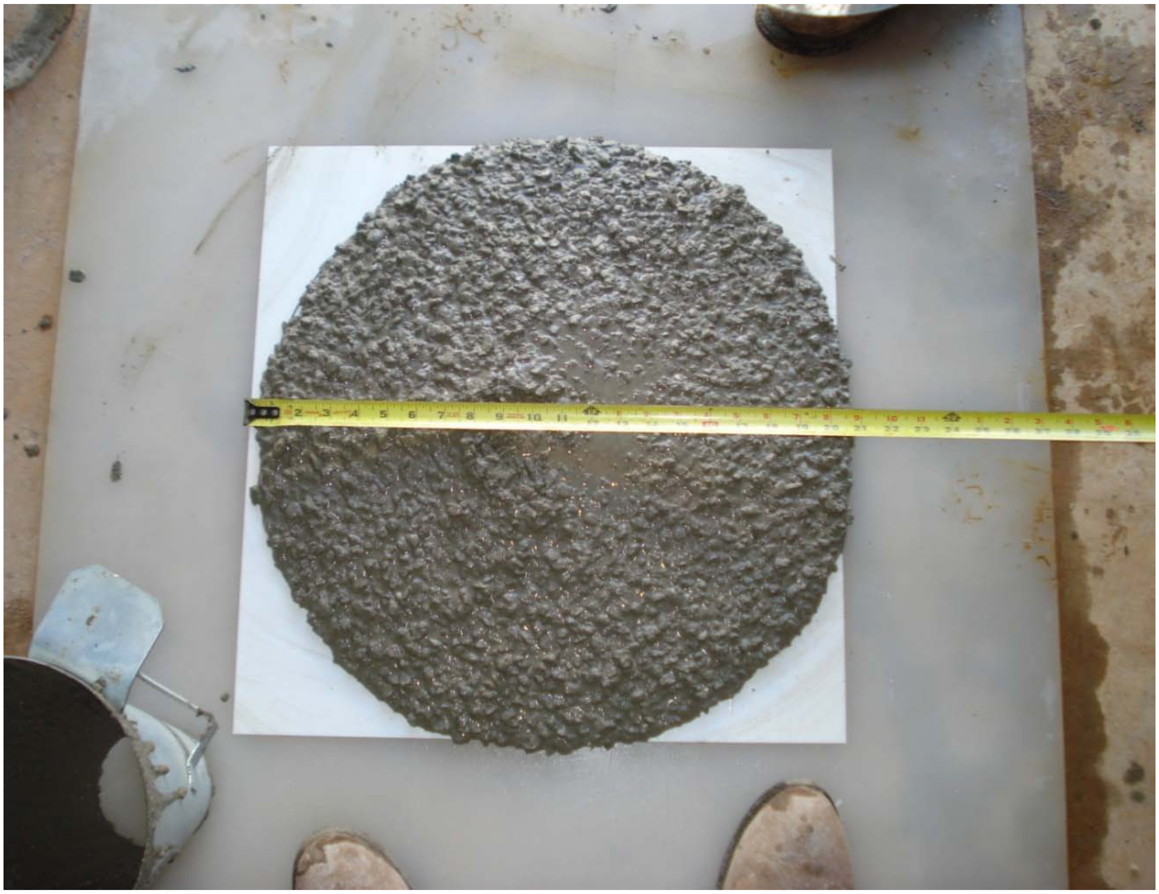

Figure 2.4: View of Slump Flow Spread

2.5.3 T-20 (T-50) Test

The T-20 (T-50) test is a measure of the time that it takes for the concrete to obtain a slump flow diameter of 20 in. (50 cm.).[31] The test, as per ASTM C 1611/C 1611M[29] (slump flow test), commences the moment the slump cone is lifted and ends as soon as the concrete spread reaches a diameter of 20 in. (50 cm). It is important to note that if the slump cone is inverted the T-20 (T-50) times will increase.[14] This test provides an indication of the mixture's viscosity. The European Federation of National Trade Associations (EFNARC)[18] recommends T-20 (T-50) values from 2 to 5 seconds. Any measured time that takes less than 2 seconds indicates that the mixture is too fluid and susceptible to segregation, whereas any time longer than 5 seconds suggests that the mixture is likely too viscous and may experience blockage. Figure 2.5 below displays a photograph of the approximate concrete spread diameter at which the T-20 (T-50) test ends.

Figure 2.5: Approximate Concrete Spread Diameter at which the T-20 (T-50) Test Ends

2.5.4 VSI Test

The VSI test is a subjective visual evaluation of the stability of the slump flow patty.[31] VSI values range from 0 to 3 in increments of 0.5 as per ASTM C 1611/C 1611M.[29] A value of 0 is warranted for SCC that is highly stable and has no evidence of segregation or bleeding, whereas a value of 3 is given for SCC that is highly unstable and has visible segregation. The Precast/Prestressed Concrete Institute (PCI) Interim Guidelines[35] proposes that VSI values ranging from 0 to 1 should ensure acceptable stability for SCC. A more thorough explanation of VSI values and their corresponding interpretations in its entirety can be observed in Table 2.1.

Table 2.1: VSI Values, Descriptions, and Criteria

VSI Value	Description	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 ≤ 0.5 in. and/or aggregate pile in the middle of the concrete mass.
3	Highly Unstable	Clearly segregating by evidence of a large mortar halo > 0.5 in. and/or large aggregate pile in the center of the concrete mass.

(Adapted from ASTM C 1611/C 1611M[29] "Slump Flow")

2.5.5 J-Ring Test

The J-Ring test assesses the passing ability (blockage) of the concrete (ASTM C 1621/C 1621M[30]). The dimensions of a standard J-Ring are 11.81 in. (300 mm) in diameter of its centerline and 3.94 in. (100 mm) in height. The clear spacing between the sixteen 0.47 in. (12 mm)-diameter rebar is 2.17 in. (55 mm).[36] The test is performed by placing the slump cone in the center of the J-Ring, filling the slump cone with SCC, and then removing the slump cone. This procedure simulates the passing ability of the concrete through narrowly spaced obstacles. [37] As with the slump flow test, it is desirable for the concrete spread to have no bleed water or visible segregation. Once the spread has settled two measurements are taken. The first measurement is the difference in the height of the SCC from the inside to the outside of the J-Ring; the PCI Interim Guidelines[35] advises that this measurement must be less than 0.59 in. (15 mm) in order to achieve sufficient passing ability. The second measurement is the J-Ring flow spread. It can be taken by the same procedure as the slump flow spread. Khayat and Mitchell[33] state that J-Ring flow spreads should range from 21.5 to 26.0 in. (545 to 660 mm) and that a difference in slump flow and J-Ring flow values should be less than 4 in. (100 mm). Conversely, The German SCC guideline proposes that the difference in slump flow and J-Ring flow measurements should not exceed 2 in. (50 mm), otherwise the concrete mixture is no longer considered adequate to permeate the reinforcement[38]; this value, however, was limited to 0.39 in. (10 mm) by the EFNARC recommendations.[18] This dissimilarity in values among the researchers suggests that the European recommendations are significantly stricter. A view of a representative J-Ring flow spread can be seen in Figure 2.6.

Figure 2.6: View of J-Ring Flow Spread

2.5.6 L-Box Test

The L-box test is an L-shaped apparatus that has a gate which separates the vertical and horizontal compartments of the apparatus. [39] The vertical component of the box is filled with concrete, and after 1 minute of rest the gate is opened. The concrete then flows down through 0.47 in. (12 mm)-diameter reinforcing bars at the base of the apparatus that are spaced at 1.38 in. (35 mm). The time elapsed for the leading edge of the concrete to reach the end of the 23.62 in. (600 mm)-long horizontal segment is then recorded. The ratio of concrete height that is present in the horizontal section h_2 to the height of the concrete still present in the vertical section h_1 is established to assess the passing and self-leveling ability of the concrete sample; this comparison is called the L-box blocking ratio.[40] The researchers are in agreement about establishing the L-box blocking ratio. Both EFNARC[18] and the Swedish Concrete Association (SCA) [41] recommend the L-box blocking ratio to be greater than 0.8, and the PCI Interim Guidelines[35] proposes that the ratio should be larger than 0.75. A schematic of the L-box test can be viewed in Figure 2.7.

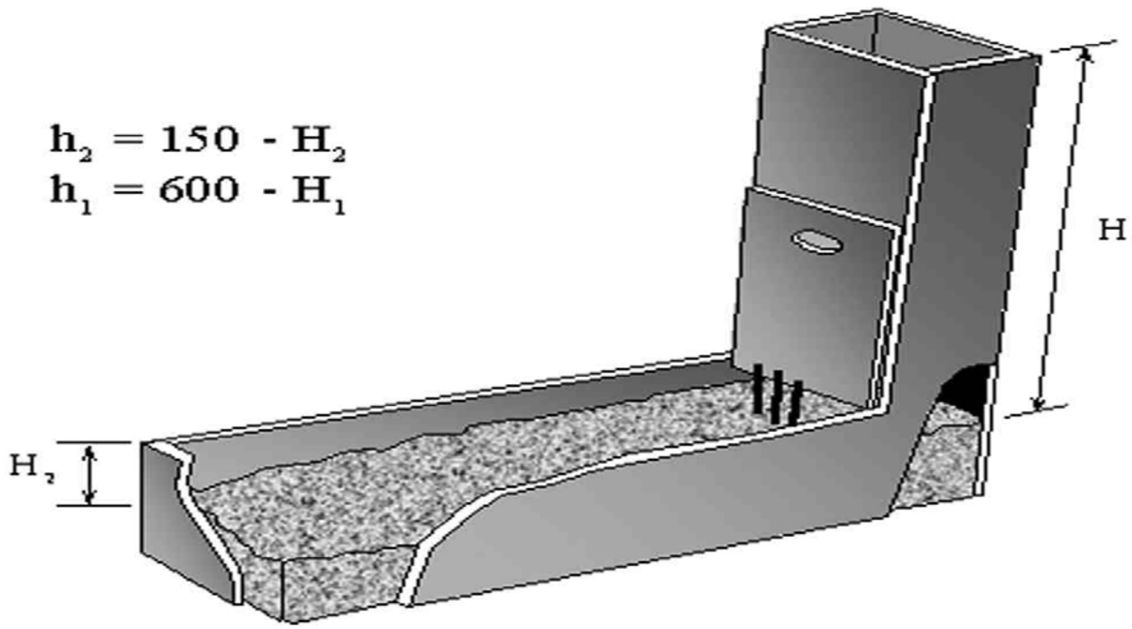

Figure 2.7: Schematic of L-Box Test[42]

2.5.7 Surface Settlement Test

The surface settlement test evaluates the static stability of SCC from the time the concrete is placed until it hardens. This is accomplished by measuring the total surface settlement while the concrete is still workable after it is cast in a cylindrical polyvinyl chloride (PVC) column 8 in. (200 mm) in diameter and 26 in. (660 mm) in height. The test begins by placing a sample of freshly mixed SCC in the PVC cylindrical column mold up to a height of approximately 19.69 in. (500 mm) without packing or vibration. A thin acrylic plate 6 in. (150 mm) in diameter and 0.15 in. (4 mm) in thickness is positioned at the upper surface of the concrete, and a linear variable differential transformer (LVDT) with a minimum travel range of 2 in. (50 mm) or a dial gage with a $4x10^{-4}$ in. (0.01 mm) precision is secured to the plate. After the monitoring system is installed the initial height of the concrete is measured. Subsequent adjustments in height are monitored at 5-minute intervals for the first 30 minutes and then every 2 hours until reaching steady state conditions, which approximately corresponds to the beginning of hardening. The difference in height designates the total settlement of the concrete specimen.[33] Hwang et al.[42] propose surface settlement values of less than or equal to 0.5% in order to ensure static stability of SCC. A detailed diagram of a typical surface settlement test can be viewed in Figure 2.8.

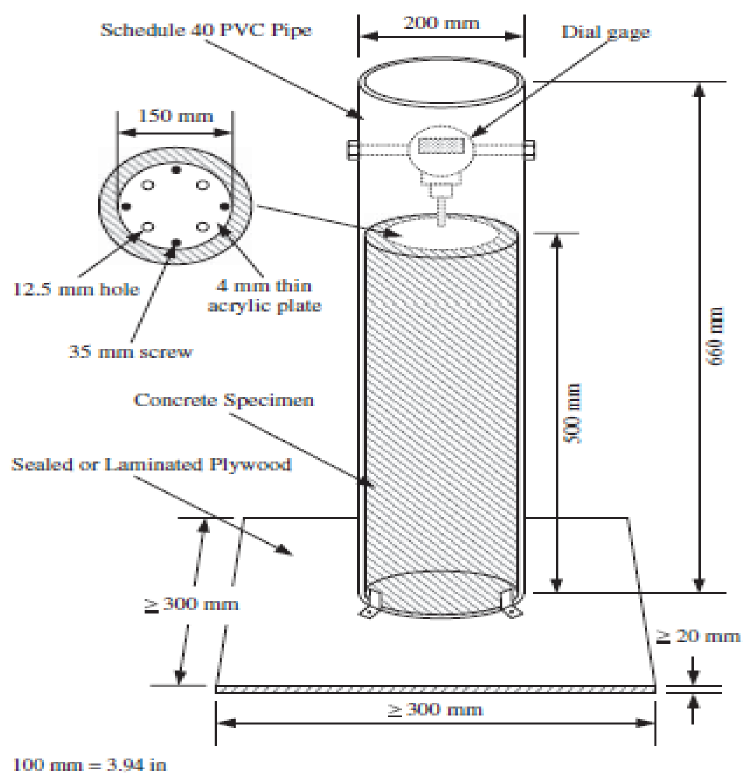

Figure 2.8: Details of Surface Settlement Test[33]

2.5.8 Conclusion

All the aforementioned test methods to evaluate the workability characteristics of SCC and several others (the V-funnel test, the U-box test, the filling vessel "caisson" test, the penetration test, and the GTM screen stability test) are summarized in Table 2.2.[42] The recommended limit values for these test methods are proposed by several different entities including Hwang et al.,[42] EFNARC,[18] JSCE,[34, 43] PCI,[35] RILEM TC 174,[27] and SCA.[41] It is essential to note that no single fresh concrete test can verify if SCC can be implemented in any given situation. Four workability categories (deformability, passing ability, filling capacity, and static stability) must be satisfied. Thus it is imperative to perform multiple fresh concrete tests on any SCC mixture to ensure adequate workability.

Table 2.2: Workability Characteristics, Test Methods, and Recommended Values[42]

Workability characteristic	Test methods	Recommended values suggested in 1 to 6
Deformability and flow rate (filling ability, unrestricted flow)	Slump flow	1. Authors: 620 to 720 mm 2. EFNARC: 650 to 800 mm (MSA up to 20 mm) 3. JSCE: 600 to 700 mm 4. PCI: ≥ 660 mm 5. RILEM TC 174: N/A 6. Swedish Concrete Association: 650 to 750 mm
	T-50	2. 2 to 5 seconds 4. 3 to 5 seconds 6. 3 to 7 seconds
Passing ability (narrow-opening passing ability, confined flow, restricted flow, dynamic stability)	V-funnel*	1. < 8 seconds 2. 6 to 12 seconds 4. 6 to 10 seconds
	L-box, h_2/h_1	2. > 0.8 4. > 0.75 6. > 0.8
	U-box, B_h	2. h_2/h_1: 0 to 30 mm 3. Rank 1† (35 to 60 mm reinforcing bar spacing) Rank 2‡ (60 to 200 mm reinforcing bar spacing) 4. Rank 1
	J-Ring§	2. < 10 mm 4. < 15 mm
Filling capacity (filling ability + passing ability, restricted deformability)	Filling vessel (caisson)	1. ≥ 80% 2. 90 to 100%
	L-box, h_2/h_1	Same as passing ability
	U-box, B_h	Same as passing ability
	J-Ring	Same as passing ability
Static stability (resistance to segregation, bleeding, and settlement)	Surface settlement	1. ≤ 0.5%
	Visual stability index	4. 0 or 1
	Penetration	5 and 6. ≤ 8 mm
	GTM screen stability	2. ≤ 15%

*V-funnel opening of 65 x 75 mm.
†Rank 1 refers to B_h of 305 mm through 5 to 10 mm-diameter bars with 35 mm clear spacing.
‡Rank 2 refers to B_h of 305 mm through 3 to 12 mm-diameter bars with internal and external spacing of 35 to 45 mm, respectively.
§J-Ring value is determined by difference in height of concrete between inside and outside in J-Ring.

***NOTE: 1 in. = 25.4 mm**

2.6 HARDENED CONCRETE PROPERTIES & TESTS PERFORMED ON SCC

2.6.1 Compressive Strength

As with conventional-slump concrete, SCC has the greatest strength when it is in compression. Compressive strength is one of the most important mechanical properties of concrete because it is relatively simple to test and correlate to other hardened properties such as bond strength and tensile strength. Compressive strength testing should be in accordance with ASTM C 39/C 39M[44]. When compared with conventional-slump concrete, SCC consistently exhibits compressive strength that is comparable in magnitude. Based solely on compressive strength, SCC can perform as well or even better than conventional-slump concrete.

The compressive strength of concrete is inversely related to its *w/cm*. If the *w/cm* is too low in conventional-slump concrete, the mixture will either not be workable or it will not have a sufficient amount of water present to fully hydrate the cement. However, in SCC mixtures HRWR are employed so that the concrete can develop and maintain a high degree of workability while utilizing a lower amount of water. Also, the increased amount of cement paste in SCC allows it to achieve a higher compressive strength than conventional-slump concrete with the same *w/cm*.[45]

Research performed by Schindler et al.[14] proposes that the *S/Agg* has little to no effect on the long-term compressive strength. In their study, the authors tested compressive strength on cylinders with *S/Agg* values of 0.38, 0.42, and 0.46. A possible reason why the *S/Agg* parameter was shown to have a minimal effect on compressive strength could be that the increase in binder content offset the decrease in strength that can occur with a higher coarse aggregate content.

In addition, SCC is oftentimes stronger than conventional-slump concrete because it has a demand for chemical and/or mineral admixtures. HRWR and SF assist SCC in gaining higher early-age strength, while supplementing FA allows SCC to develop superior later-age strength. Moreover, research suggests that larger quantities of SCM in SCC permit it to develop strength at a greater rate. As a result, the concrete has the ability to acquire a higher ultimate compressive strength.[46]

Although the mix design of SCC typically aids it in obtaining greater compressive strength than conventional-slump concrete, curing regimens also affect compressive strength. In tests performed at R&D Laboratories of Master Builders, Inc. in Cleveland, Ohio, when compared with conventional-slump concrete specimens designed to have the same compressive strength, the compressive strength of the steam-cured SCC specimens was slightly lower or approximately equal to that of the conventional-slump concrete specimens. However, when the samples were air-cured, the SCC surpassed the compressive strength of conventional-slump concrete with ease. These results are presented graphically in Figure 2.9.

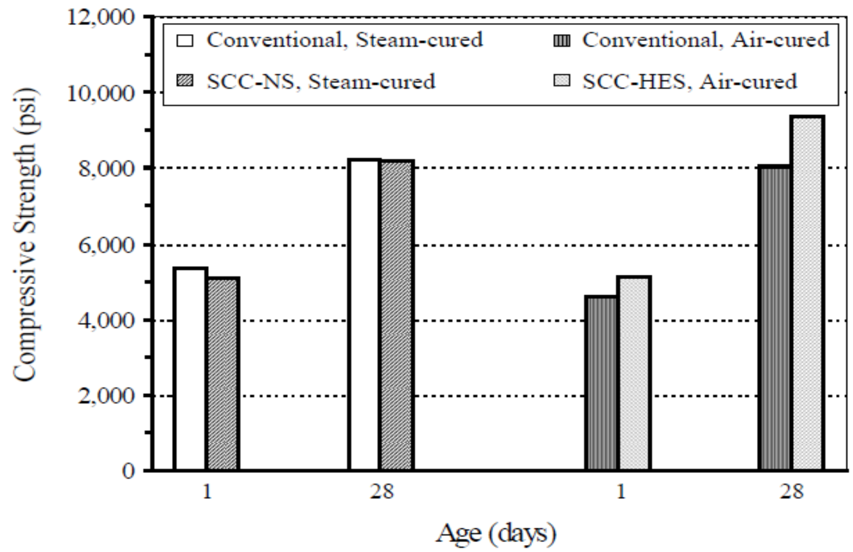

Figure 2.9: Compressive Strengths at 1 and 28 Days[47]
***NOTE: 145.04 psi = 1 MPa**

This variation in results is probably due to the fact that air-cured concrete is less prone to microcracking in the ITZ than steam-cured concrete. In addition, SCC has a stronger, more densely packed ITZ than conventional-slump concrete. Consequently, concrete's weakest link, the cement-to-aggregate bond, is stronger in SCC; this improves the compressive strength of SCC.[47] Furthermore, the findings of this research suggest that when moist-cured, SCC will perform just as well if not better than conventional-slump concrete in compression.

2.6.2 Tensile Strength

While information on SCC's tensile strength is limited, the literature indicates that SCC has comparable and, oftentimes, superior tensile performance when compared to conventional-slump concrete. SCC and conventional-slump concrete experience similar rates of tensile strength evolution over time. It has been reported that reinforced concrete members made with SCC perform well in tension because of its microstructure, mix design, and bond strength. [45, 48]

By design, SCC contains a large amount of fines and a greater quantity of smaller coarse aggregate particles. This type of particle size distribution increases the packing density, which creates a denser, less porous ITZ. As a result, the ITZ is stronger, therefore the bond between the concrete and reinforcing steel is stronger. This allows for better transfer of tensile loads from the steel to the concrete, which ultimately results in increased tensile strength in reinforced SCC members.[45]

SCC also has strong resistance to splitting tensile failure. Full scale load tests performed on SCC bridge girders at Texas A&M University confirmed that SCC girders had greater splitting tensile strength than conventional-slump concrete girders.[49] In a separate test conducted at R&D Laboratories by Attiogbe et. al, SCC specimens tested for splitting tensile resistance also exhibited equivalent or superior performance compared to conventional-slump concrete.[47] The results of Attiogbe et al.'s research are shown in Figure 2.10.

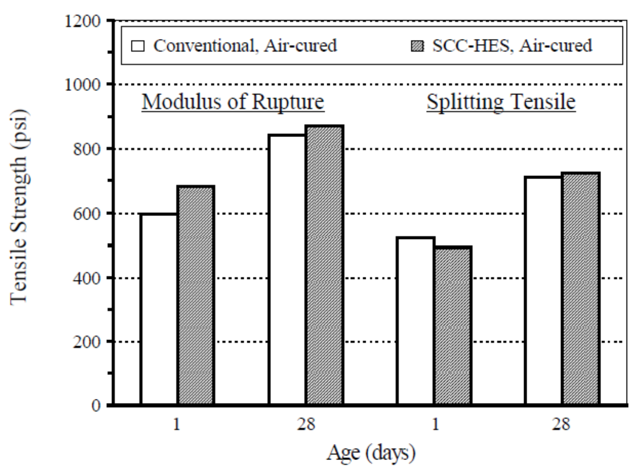

Figure 2.10: Tensile Strengths at 1 and 28 Days[47]
***NOTE: 145.04 psi = 1 MPa**

2.6.3 Bond Strength

The bond between the concrete and the reinforcing steel is a significant factor in evaluating the strength of reinforced concrete members. A weak bond can result in pull-out failures in concrete beams. This occurs when a member is subjected to flexural loading and the reinforcing bars begin to slip as a result of poor bond with the concrete, ultimately causing the member to fail. Bond behavior is affected by the properties of the cement matrix, including its compressive strength, tensile strength, and homogeneity, as well as the amount of cover around the reinforcing bars, the geometry of the deformations in the reinforcing bars, and the top-bar effect.[45, 46, 50]

The concrete's bond strength is directly proportional to the square root of its compressive strength. Most sources agree that, given a SCC and conventional-slump concrete with the same compressive strength, the SCC will exhibit a greater bond strength. This is due to the fact that SCC has a denser, more homogeneous cement matrix which corresponds to a denser and more uniform ITZ. [45, 46, 50]The weakest link in concrete typically occurs within the ITZ, so a denser ITZ results in a stronger bond between the concrete and steel. This enhanced bond strength increases the flexural resistance and capacity of the members.[46]

In addition to strengthening the bond between concrete and steel, the homogeneous nature of SCC also combats the top-bar effect, which often causes failure in reinforced concrete members. The top-bar effect is a decrease in bond strength due to bleeding, segregation, or settlement in concrete which results in an increased risk of pullout failure for bars cast in the top of a member. [47] Since SCC has the ability to fill formwork better than conventional-slump concrete without any vibration, it is less susceptible to bleeding and segregation. Hence, SCC is less prone to the top-bar effect.

Research performed by Chan et al. supports this notion. In Chan's experiment, two 47.24 X 35.43 X 169.29 in. (1200 X 900 X 4300 mm) walls were erected. Each wall contained deformed reinforcing bars at heights of 7.87, 19.69, and 31.50 in. (200, 500, and 800 mm), respectively. One wall was constructed from conventional-slump concrete, and the other wall was constructed from SCC; both walls were designed to have equivalent compressive strengths. The bond strength of the bars was tested and, while SCC and conventional-slump concrete both experienced the top-bar effect in bars cast at higher elevations, the effects were not nearly as significant in the SCC wall. This is because the conventional-slump concrete was cast in multiple lifts and each lift was vibrated, whereas the SCC was able to be cast in a single lift without the need for vibration. Consequently, the conventional-slump concrete experienced more bleeding and segregation, which ultimately resulted in pullout failure due to the top-bar effect. The bond strength of the reinforcing bars cast within both walls is illustrated in Figure 2.11.

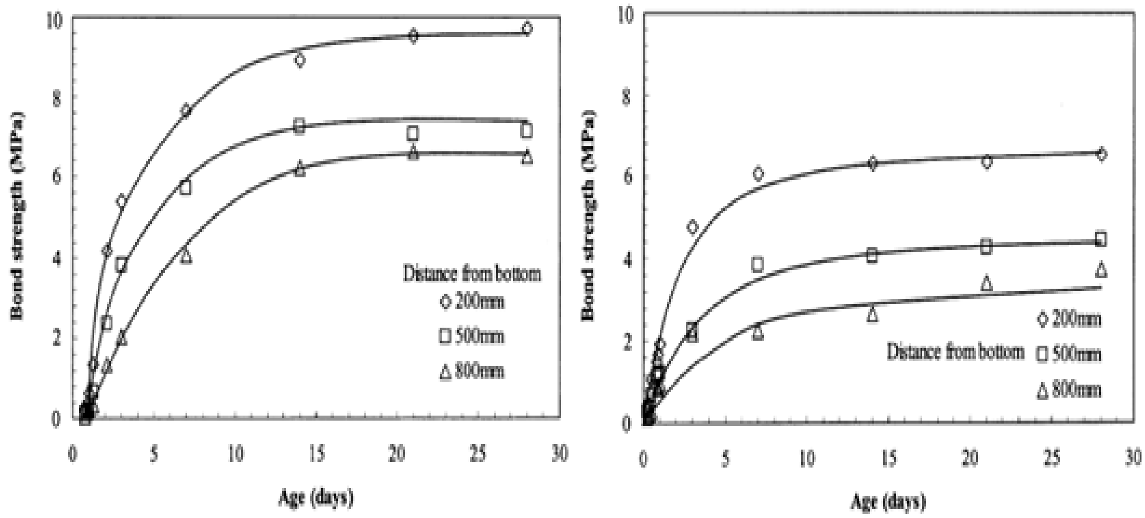

Figure 2.11: Bond Strength Development in SCC and Conventional-Slump Concrete[46]
***NOTE: 145.04 psi = 1 MPa**

Due to plastic shrinkage the top-bar effect caused some problems in the SCC wall; however, the SCC wall still outperformed the conventional-slump concrete wall. The authors state that it should be noted that plastic shrinkage is typically less of a problem in actual construction than it was in their test.[46]

An analogous test was performed by Khayat et al. at the University of Sherbrooke in Quebec, Canada. The results of this investigation were in agreement with the findings stated in Chan's conclusions. It was reported that the SCC specimens acquired pull-out and top-bar effect resistance that was equal to or greater than that of the conventional-slump concrete specimens. Under the same circumstances, the University of Sherbrooke trial also tested prestressing strands in addition to deformed reinforcing bars. Similar to the rebar, the strands cast in SCC displayed better resistance to pull-out failure than those cast in conventional-slump concrete; this was even the case for the strands cast at higher elevations in the specimen.[51] Thus, it is evident that SCC can perform well in prestressed applications.

Furthermore, the results of an investigation conducted by Sonebi et al. concur with the aforesaid trends. The authors performed bond tests (pullout tests) with 0.47 and 0.79 in. (12 and 20 mm) deformed bars cast in concrete specimens of 3.94 X 3.94 X 5.91 in. (100 X 100 X 150 mm) to study the performance of SCC compared to normal-slump concrete. The test results showed 10 to 40% higher normalized bond strength in SCC compared to normal-slump concrete.[52]

However, it should be noted that there are some conflicting results in the literature. The conclusions of research performed by Robert Peterman[53] propose that when keeping the *w/cm* of a mixture constant, an increase in concrete fluidity will result in a decrease in bond capacity. This effect becomes even more prominent near the top surface. Peterman states that the findings of this research are in agreement with previous results associated with the top-bar effect in pretensioned piles[54] and also with the present understanding of the effect of concrete's fluidity on the bond strength of deformed bars.[55]

2.6.4 Modulus of Elasticity

The modulus of elasticity of concrete (E_c) is dependent upon the modulus of elasticity of its constituents. As a result, strong, rigid aggregates will increase E_c, whereas high air content and elevated paste volume will decrease it. Since SCC has more paste and less coarse aggregate than conventional-slump concrete, it has a lower E_c.[10, 56, 57]

According to the ACI 318[58] Building Code, Section 8.5.1, E_c can be estimated implementing Eq. (1). This formulation is also utilized with the AASHTO LRFD,[59] Section 5.4.2.4 to approximate E_c.

$$E_c = 33w_c^{1.5}\sqrt{f'_c} \quad (1)$$

where E_c is the modulus of elasticity (psi, MPa), w_c is the unit weight of the concrete (lb/ft^3, kg/m^3), and f'_c is the compressive strength (psi, MPa).[14]

Research conducted by Su et al.[60] evaluated the effect of *S/Agg* values ranging from 0.30 to 0.55 on E_c. They concluded that when the fine and coarse aggregate have similar elastic moduli, and the total volume of aggregate is invariable, the *S/Agg* does not significantly affect the E_c. Further research performed by Schindler et al.[14] confirms this concept.

Due to its lower E_c, SCC requires less applied stress to deform, and it is also more ductile than conventional-slump concrete. In an experiment conducted by Lin et al., a test was established to compare the compressive strength of SCC and conventional-slump concrete in reinforced concrete columns under concentric compression. The results show that SCC was 32% more ductile than conventional-slump concrete.[56]

However, more ductility results in greater deflection. A study performed by Kim at Texas A&M University supports this statement. In the experiment, full scale reinforced SCC and conventional-slump concrete bridge girders were loaded to compare the deflections. The girders contained limestone coarse aggregate or river gravel. The results display that regardless of the type of aggregate, the SCC girders exhibited more deflection than those cast in conventional-slump concrete.[49]

As it is more densely packed and contains a greater volume of paste than conventional-slump concrete, SCC is apt to have a lower E_c than conventional-slump concrete. This dense packing of paste combined with the superior bond strength of SCC increases the tensile strength of reinforced concrete members and enables them to perform well when subjected to flexural loading. For this reason SCC can be practical in moment resisting members such as beam columns. Nevertheless, there is cause for concern since the lower E_c of SCC increases deflection. Given this undesirable effect, it may be necessary to camber SCC members in bridge and floor applications to prevent the development of uncomfortable amounts of deflection.

2.6.5 Shrinkage

2.6.5.1 Introduction

Since SCC has a higher proportion of fines and a lower quantity of coarse aggregate than conventional-slump concrete, it experiences greater amounts of shrinkage. In some cases it has been reported that SCC can experience as much as 50% more shrinkage than conventional-slump concrete.[45] Therefore, SCC is more susceptible to shrinkage cracking; shrinkage cracking occurs when a structural element resists the creep occurring within it, creating tensile stress. This stress ultimately causes concrete to crack.[48] It has been reported that some prestress losses and long-term deflection variations experienced by prestressed concrete members are the direct result of shrinkage effects.[61]

Shrinkage is a property of the paste within concrete, and the aggregates are the most significant constituents that influence the change in volume within the paste.[57, 62] When the *w/cm* is held constant, an increase in cement content will increase shrinkage because of the increased volume of hydrated cement paste.[57] Conversely, if the water content is held constant and the cement content is increased, the amount of shrinkage is less. This occurs because the higher strength paste acquires an improved resistance to shrinkage.[57] According to Neville, [57] though the size and grading of the aggregate do not have a significant impact on shrinkage, increasing the maximum size of aggregate (MSA) will create a leaner mixture, thus minimizing the shrinkage.

Several categories of shrinkage exist, all of which tend to be more detrimental to SCC than conventional-slump concrete. However, some techniques can be applied to reduce the amount of shrinkage that occurs in SCC. The different types of shrinkage include autogenous shrinkage, drying shrinkage, and plastic shrinkage and are discussed in greater detail in the following sections.

2.6.5.2 Autogenous Shrinkage

Autogenous shrinkage occurs due to the production of hydration products that form when cement reacts with water. Concrete has a tendency to shrink over time because the hydration products have smaller volumes than that of hydrated cement and water.[63] Concrete can experience autogenous shrinkage for many years after it hardens because hydration reactions continually occur long after the concrete initially sets.

Internal curing is a process that has been reported to combat autogenous shrinkage; this can be accomplished by adding presaturated lightweight aggregate or superabsorbent polymers. Supplementing a small portion of presaturated lightweight aggregate to a concrete mixture provides additional water that can restore the water lost through the formation of hydration products.[64] Research shows that adding as little presaturated lightweight aggregate as 6% of the weight of cement can produce high strength concrete without any of the effects of autogenous shrinkage.[65] Likewise, adding superabsorbent polymers to concrete has also shown to reduce autogenous shrinkage. Commercially available superabsorbent polymer products can absorb approximately 20 times their weight in water. After supplementation into a concrete mix, the polymers form macro-inclusions of water within the concrete while mixing. The macro-inclusions are utilized during the formation of cement hydration products. Hence, autogenous shrinkage effects are reduced.[64]

Barrita et al.[66] assessed high-performance concrete (HPC) mixtures that can be implemented in hot arid climates. In their research magnetic resonance imaging (MRI) was used to determine the effectiveness of lengthening the moist curing period by replacing 11% by volume of the total aggregate content with saturated lightweight aggregate in a concrete mixture that was placed in a hot arid climate. Arrays of concrete mixtures were moist-cured either for 0, 0.5, 1, or 3 days, or by applying a curing compound. This procedure was continued by air drying at 100.4°F (38°C) and 40% relative humidity.[67]

Three concrete mixtures were studied; the mixtures included low-strength concrete (*w/cm* = 0.60), SCC containing 30% FA (*w/cm* = 0.33), and high-strength concrete containing 8% SF (*w/cm* = 0.30). Samples from these mixtures were cast in triplicate. The samples were dried in an environmental chamber at 100.4°F (38°C) and 40% relative humidity after curing. MRI was used to evaluate the evaporable water supply as the samples were drying. After the drying sequence, the samples were placed inside an oven at 221°F (105°C). While in the oven, water absorption tests were conducted on the samples to ascertain their sorptivity.[66, 67]

The data acquired during the drying sequences signified a decreased moisture loss with increasing duration of moist curing. It was also reported that the addition of saturated lightweight aggregate does not abolish the requirement of providing some external moist curing for a condensed time period. The findings from the water absorption tests indicated that the incorporation of lightweight aggregate particles significantly increases the sorptivity in low strength concrete. However, when compared to the same concrete mixtures containing only normal-weight aggregate, the addition of lightweight aggregate has a subsidiary effect in both SCC and high-strength concrete.[66, 67]

2.6.5.3 Drying Shrinkage

Drying shrinkage occurs whenever concrete is mixed with more water than is necessary for cement hydration. As a result, the concrete shrinks due to the evaporation of excess water. When the concrete shrinks, the structural element resists this shrinkage and causes the concrete to crack.[47]

Although SCC does experience more shrinkage than conventional-slump concrete, research suggests that drying shrinkage is probably not the most significant portion of it. The previously mentioned tests performed by Attiogbe et al.[47] indicate that there is not a major difference in the amount of drying shrinkage that occurs among SCC and conventional-slump concrete. These results are presented in Figure 2.12.

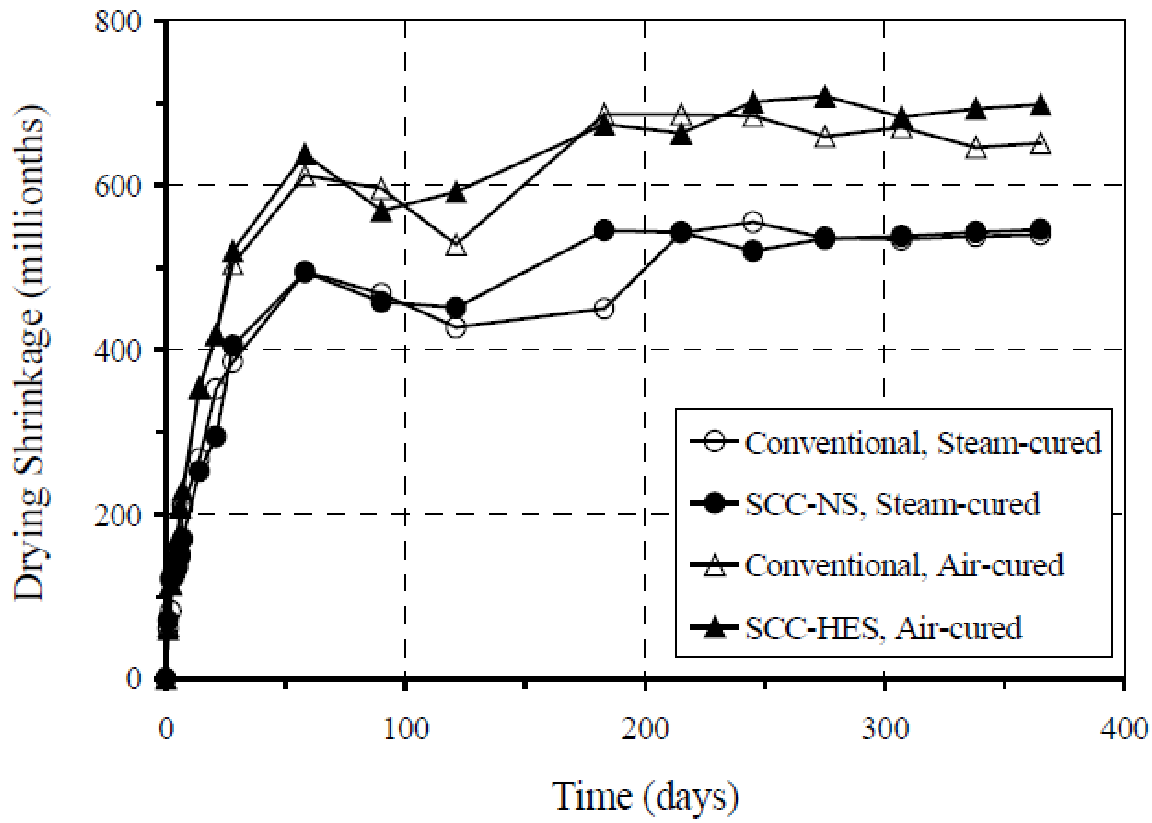

Figure 2.12: Drying Shrinkage of SCC and Conventional-Slump Concrete Mixtures[47]

The findings stated by Mazzotti et al.[68] are in agreement. In their experiment, SCC and conventional-slump concrete specimens were loaded to 35% and 50% of their equivalent compressive strengths. The results showed that the SCC specimens experienced merely a slight increase in shrinkage with respect to the conventional-slump concrete specimens.

The mix design of concrete is also a factor in mitigating the effects of drying shrinkage. SCC with a lower *S/Agg* will experience smaller amounts of drying shrinkage than SCC with a higher *S/Agg*. However, if *S/Agg* is too low the concrete will lose its flowability and cease to be self-consolidating; this side-effect can be avoided by adding VMA to the mixture. The addition of VMA enables low *S/Agg* SCC to experience less drying shrinkage while maintaining its flowability. It has been reported that implementing this method can produce SCC mixtures with slump flow values ranging from 24.02 in. to 25 in. (610 to 635 mm) with *S/Agg* of 0.48 and 0.39; these *S/Agg* values are typical for conventional-slump concrete mixtures.[47]

Further research proposed by Ozyildirim and Lane[69] recommends a large nominal maximum aggregate size (NMSA) (3/4 in. (1.905 cm)), large amount of coarse aggregate (1,550 lb/yd^3 (919.58 kg/m^3)), and low water content (270 lb/yd^3 (160.18 kg/m^3)) to diminish the effects of drying shrinkage in SCC applications. However, in congested concrete applications such as prestressed members, increasing the NMSA reduces the desired filling ability and passing ability of SCC.

In order to establish if drying shrinkage values for SCC mixtures correspond to behavior assumed during design, these values can be compared to those estimated by ACI 209R[70] and/or AASHTO LRFD.[59] The ACI 209R shrinkage prediction formulation accounts for the air content, age of the specimen, cement content, curing method and duration, fine aggregate percentage, humidity, slump, and volume-to-surface ratio. It should be noted that the AASHTO LRFD drying shrinkage formulation (Section 5.4.2.3.3) only accounts for the age of the specimen, curing method, humidity, and volume-to-surface ratio.[14]

2.6.5.4 Plastic Shrinkage

Plastic shrinkage occurs when bleed water forms menisci on the surface of freshly cast concrete during curing. Negative capillary pressure is created because the menisci evaporate faster than the concrete bleeds. This pressure causes shrinkage by pulling the solid concrete particles together. Hot or windy conditions increase the rate of drying and thus increase the risk for plastic shrinkage to occur.[71]

By subjecting samples to windless and windy conditions during setting, Turcry and Loukili[71] were able to analyze the effects of environmental conditions on plastic shrinkage in SCC and conventional-slump concrete. The results show that SCC experienced about twice the plastic shrinkage of conventional-slump concrete in the absence of wind. However, when tested in windy conditions, the rate of drying shrinkage increased; this occurred because the conventional-slump concrete samples were not protected from plastic shrinkage by a surface layer of bleed water as they were under windless conditions. Accordingly, water evaporated from the conventional-slump concrete samples faster than it could bleed, which lead to increased plastic shrinkage. These findings are exhibited in Figure 2.13.

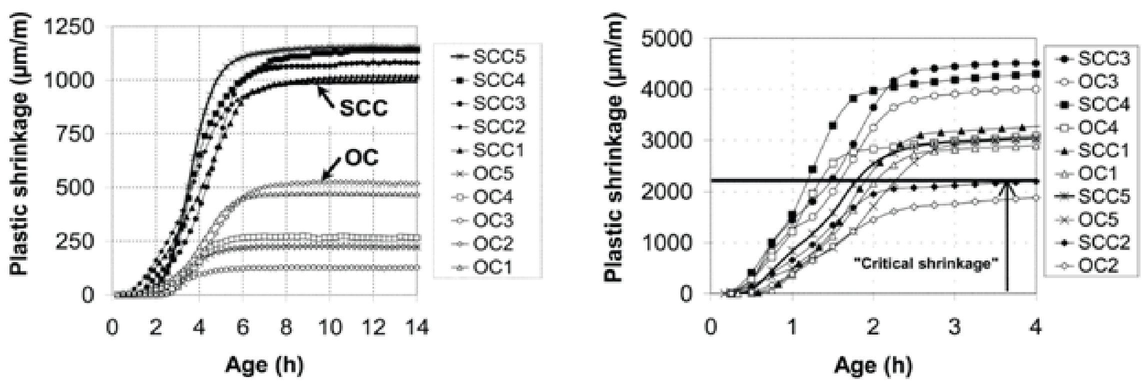

Figure 2.13: Plastic Shrinkage of SCC and Conventional-Slump Concrete Mixtures in No-Wind and Wind Conditions[71]

In the absence of wind, it was reported that SCC experienced less frequent and smaller cracks than conventional-slump concrete. These results indicate that in extreme environmental conditions the plastic shrinkage performance of SCC is comparable to or better than conventional-slump concrete.

Turcry and Loukili[71] report that plastic shrinkage can be reduced threefold by applying a curing compound to freshly cast SCC. When sprayed, curing compounds will coat the concrete's surface with a solid membrane that reduces the amount of plastic shrinkage by preventing moisture loss through evaporation.

2.6.6 Creep

Creep is an occurrence that develops after concrete expands or contracts as a result of long term loading. SCC experiences greater amounts of creep than conventional-slump concrete because the high paste content reduces its E_c.[68] However, there are conflicting results within the literature. While some research supports the claim that SCC will have greater amounts of creep than conventional-slump concrete, other research, such as that performed by Turcry et al. asserts that SCC and conventional-slump concrete of the same compressive strength will have the same specific creep.[48, 68] Also, even if creep is a larger detriment to SCC, research has shown that increased amounts of creep in SCC could counteract the negative effects of shrinkage.[48]

Mazzotti et al.[68] examined the differences in creep behavior in SCC and conventional-slump concrete. Cylinders of SCC and conventional-slump concrete measuring 3.86 X 7.87 in. (98 X 200 mm) and 4.92 X 9.84 in. (125 X 250 mm) were cast with the same compressive strength. After 6 days of curing, the cylinders were loaded longitudinally to 35% and 55% of their compressive strength for 180 days. The results of this test clearly showed that SCC experiences more creep than conventional-slump concrete. On the other hand, when Turcry et al. loaded SCC and conventional-slump concrete cylinders to 20% of their compressive strength over a period of 100 days, it was reported that both types of cylinders experienced approximately the same amount of creep.[48]

The aforementioned creep and shrinkage tests conducted by Attiogbe et al.[47] yielded results that are in agreement with Mazzotti et al. It was reported that during the first year of loading SCC specimens exhibited more creep than conventional-slump concrete specimens. Resembling the specimens tested for shrinkage, concrete displayed less creep when steam-cured than when air-cured. Also, under steam-cured conditions, SCC and conventional-slump concrete specimens demonstrated fewer discrepancies in creep values. These results are illustrated in Figure 2.14.

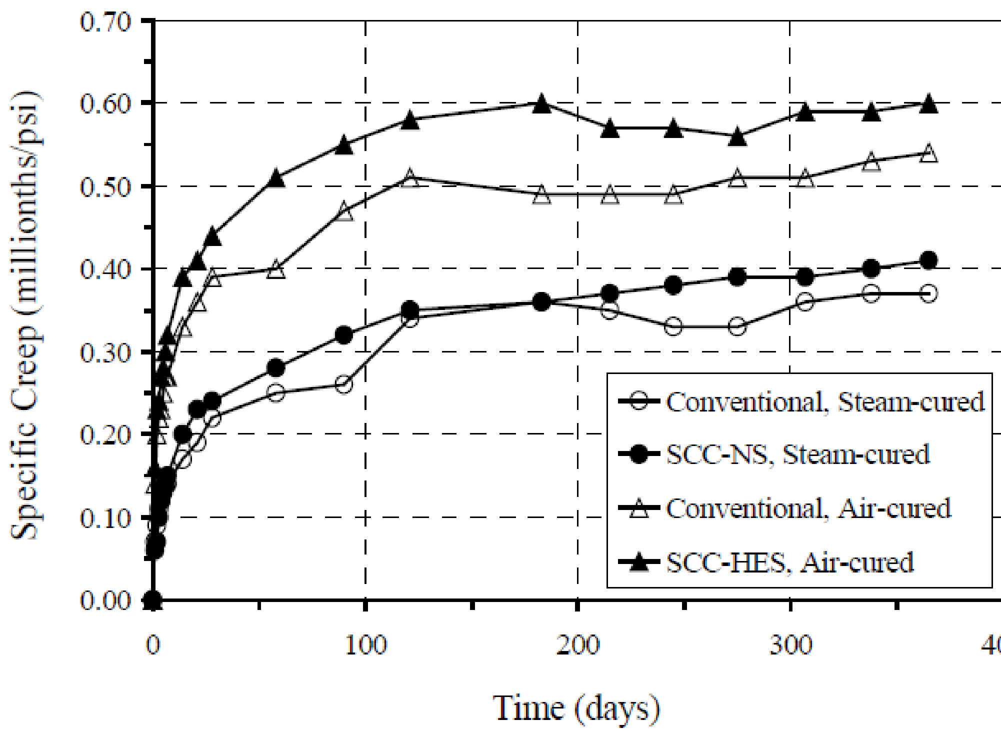

Figure 2.14: Specific Creep of SCC and Conventional-Slump Concrete Mixtures[47]
***NOTE: 145.04 psi = 1 MPa**

SCC has shown to experience more creep during the first year of loading, but mathematical models project that steam-cured SCC will begin to creep at a slower rate and experience 13.6% less creep at 10 years of age.[47]

More research concerning creep in SCC needs to be conduced to better establish the general trend of its performance compared to that of conventional-slump concrete. If SCC is proven to exhibit more creep than conventional-slump concrete, it is a possibility that this characteristic may actually be an advantage in structural applications. Turcry et al.[48] propose that creep could possibly "…compensate for the effects of shrinkage…" by expanding under applied loading when its innate propensity is to contract over time. However, further research is required to validate this assertion.

2.7 SCC APPLICATIONS

2.7.1 Deep Foundations

Many placing problems can arise with concrete when pouring in-place deep foundations. Concerning deep foundations such as drilled shafts or caissons, the majority of concrete placed can not be seen; this poses quality control concerns. Conventional-slump concrete must be vibrated as it is placed in the shaft. Since nearly all the concrete placed is not visible at ground level, under- or over-vibrating routinely occurs. If the concrete is under-vibrated, it will not fully consolidate; this can cause cavities to develop and can also lead to soil encroachment and inadequate concrete cover for the reinforcing steel. Over time this can cause corrosion in the reinforcing steel and reduce the structural properties of the element. Whereas if the concrete is over-vibrated, segregation or excessive air voids can develop; this can lead to a lack of uniformity in the member.[72] In the event that any of the aforementioned quandaries occur, the load capacity of the structure will be significantly reduced as a result.

Implementing SCC for deep foundations can resolve numerous dilemmas related to concrete homogeny and consistency. Regarding drilled shafts or caissons, the properties of SCC are especially beneficial. The flowability SCC develops enables the concrete to consolidate due to its own self weight without vibration. In addition to significantly decreasing the amount of time required to pour the in-place deep foundation, completely excluding vibration eliminates the risks associated with under- or over-vibrating the concrete. Also, SCC's deformability allows for the concrete to completely encapsulate the reinforcing steel and fill the voids of the structural member.

2.7.2 Prestressed Bridge Girders

In recent years there has been substantial interest pertaining to the use of SCC for prestressed applications. However, for use in bridge members, SCC has not yet been widely accepted by many states' departments of transportation (DOT). Research performed by Zia et al.[73] compared the performance of prestressed SCC and conventional-slump concrete bridge girders. Three AASHTO Type III girders were cast, two with SCC and one with conventional-slump concrete. All the beams had the same dimensions and equal amounts of reinforcing steel. The conventional-slump concrete girder took 30 minutes to cast, whereas the SCC girder was cast in 20 minutes without vibration.

At 28 days of age, the conventional-slump concrete cylinders obtained average compressive strength values that surpassed 7,000 psi (48.3 MPa) and the SCC cylinders exceeded 10,000 psi (69 MPa). When tested, bond strength and transfer length were comparable between the conventional-slump concrete and SCC. The flexural modulus (*MOR*) for the conventional-slump concrete and SCC were also comparable, yet lower than expected given the compressive strength. It was reported that this likely occurred due to the fact that weak fine aggregate was used in the mixture, and the samples were not moist-cured. As was predicted, the E_c for the SCC cylinders showed lower values than those recorded from the conventional-slump concrete cylinders. It should be noted that since the cylinders tested were not nearly as massive as the girders, they were not subjected to the curing benefits associated with a high heat of hydration like the girders were. It is also important to note that the E_cs recorded 98 days after load testing were comparable to the E_cs acquired from the initial camber measurements. While the compressive strength of the girders increased with age, this finding indicates that as the girders aged (without moist curing) the E_c was not improved.[73]

Subsequent load testing indicated elastic behavior in all girders. The initial camber of all three girders was equivalent. During the first 98 days after casting, all three girders experienced growth; this occurred during the summer season. As temperatures fell and the fall season arrived, the camber of the three girders was reduced; the most significant decrease in camber occurred in the SCC girders. This suggests that the stiffness diminishes most prevalently in SCC girders subjected to sustained loading.[73]

In the future, long term hardened properties of SCC should be tested in order to completely assess its performance in prestressed bridge girder applications.

2.7.3 Basement and Foundation Walls

For residential and small building construction it is customary to utilize concrete in basement and foundation wall applications. However, oftentimes poor quality, extremely fluid concrete is used in an attempt to decrease the need for vibration and also to decrease casting times. This type of mixture is produced by increasing the *w/cm*. Although this can improve workability, the lasting effects of a poor quality concrete can lead to various problems for future owners, such as high permeability and excessive cracking due to bleed water and segregation.

Khayat et al.[74] examined the effects of implementing SCC in basement and foundation walls. In the experiment, two trial walls and a foundation wall of a three townhouse complex were cast. If SCC is to be used in residential and small building construction, it is imperative that the mixture design is economical. A portion of the cement was replaced with SF and either FA or blast-furnace slag (BFS) in order to reduce the cost and also to enhance the fresh and hardened properties of the SCC mixtures. The mixtures were designed to readily deform through narrow formwork containing no steel reinforcement.

The two trial walls were cast at a single location. After approximately 20 hours the formwork was removed, and the walls were draped with wet burlap for 4 days and allowed to moist-cure. The SCC readily flowed throughout every section of the formwork, and no surface defects as a result of bleeding, honey combing, or segregation were observed. The plywood formwork was the only source of any surface blemishes (which consisted solely of air bubbles) that were detected. Coring was also performed on the walls. The examination of core samples taken from areas where surface air bubbles were prevalent did not reveal any large concentration of air voids. This finding suggests that the high air void concentration in some locations is purely a surface phenomenon. Upon inspection, there was no shrinkage cracking examined in the trial walls three months after casting.[74]

The townhouse complex was cast simultaneously in two locations to ensure that the spreading concrete would not exceed 82.02 ft. (25 m). The formwork varied from 7.55 to 8.53 ft. (2.3 to 2.6 m) in height, and additional steel reinforcement was included at the bottom of the formwork due to the enlarged hydrostatic pressure of SCC. The SCC flowed well all through the formwork, filling in the entire space, and totally encapsulating the reinforcement. The width of the foundation wall was not consistent as the slopes at the end of the pour were 1.5 to 2.5%. In order to level the surface of the wall, a garden rake was dragged across the concrete at the end of casting.[74]

After two days had passed, the formwork was removed. The concrete proved to be soundly compacted and showed no substantial evidence of segregation. The surface finish contained a large amount of air bubbles where the form releasing agent had not been applied. However, the authors affirm that those surface flaws would lessen by employing well-oiled high quality plywood. After one year had elapsed, only three shrinkage cracks were present along the 262.47 ft. (80 m) length of wall.[74]

Pertaining to the application of basement and foundation walls, SCC acquires all of the essential fresh and hardened properties to be an effective alternative to conventional-slump concrete. In residential locations, the capability of SCC to totally consolidate due to its own self weight without vibration while retaining the stability to resist segregation makes it a particularly reliable option. The utilization of SCC can greatly increase durability, impermeability, and resistance to shrinkage. These characteristics are immensely beneficial for any would-be owner of a structure that has a SCC basement or foundation wall. In addition, implementing SCC enables construction crews to pour basement and foundation walls swiftly, thus decreasing labor costs. Seeing that long-term testing on SCC structures is limited, research should be ongoing in the future to make certain that SCC can perform adequately throughout its intended useful life.

2.8 CONCLUSION

When compared with conventional-slump concrete, SCC can be an advantageous alternative. Fresh concrete properties, hardened concrete properties, the tests associated with each, and common applications for SCC were discussed in the preceding sections. It is necessary to reiterate the following; multiple fresh concrete tests should be conducted on SCC mixtures to ensure that the four workability categories (deformability, passing ability, filling capacity, and static stability) are satisfied. In many cases the hardened properties of SCC are comparable or superior to that of conventional-slump concrete. Furthermore, deep foundations, prestressed bridge girders, basement and foundation walls, and other precast elements are ideal applications for SCC.

The scope of the research program included trial batching SCC and FA SCC mixtures to establish fresh concrete specifications. The SCC and FA SCC mixtures that possessed the most desirable fresh concrete properties were employed in casting two reinforced box culverts.

The advantages presented in previous research efforts substantiate re-evaluation of the current Standard Specifications in Arkansas based on research specifically proposed to test materials that are readily available in this state. If the same advantages are established from the current research program as from prior research efforts, the state of Arkansas would benefit from an amendment to the Standard Specifications[5] that includes fresh concrete provisions for SCC mixtures.

CHAPTER 3

EXPERIMENTAL PROCEDURE

3.1 INTRODUCTION

The goal of this research program was to develop fresh concrete specifications for SCC mixtures. In the "Arkansas 2003 Standard Specification for Highway Construction"[5] (Table 802-1), AHTD lists a minimum binder content and slump range for a Class S "structural" concrete as 6.5 bags (611 lb/yd^3,362.61 kg/m^3) and 1 – 4 in. (25.4 – 101.6 mm), respectively. These specifications can be seen below in Table 3.1.

Table 3.1: Minimum Binder Content and Slump Range Specified for Structural Concrete[5]

802

TABLE 802-1

Characteristic	Class of Concrete: A	B	S	S(AE)	Seal
Minimum Compressive Strength (psi [MPa] at 28 days)	2100 [15.0]	3000 [21.0]	3500 [24.0]**	4000 [28.0]**	2100 [15.0]
Minimum Cement Factor (bags per cubic yard) [kg/cu m]	5.5 [307]	*	6.5 [362]	6.5 [362]	6.0 [335]
Maximum Water/Cement Ratio (gal. per bag) [kg/kg]	6.5 [0.58]	*	5.5 [0.49]	5.0 [0.44]	6.5 [0.58]
Slump Range (inches) [mm]	1"-4" [25-100]	1"-4" [25-100]	1"-4" [25-100]	1"-4" [25-100]	4"-8" [100-200]
Air Content Range (%)	--	--	--	6 ± 2	--

* As determined by trial batch. Maximum water-cement ratio is 0.49. In addition, Class B shall obtain 3500 psi (24.0 MPa) compressive strength in the trial batch at 90 days.

** Class S or S(AE) concrete for use in prestressed concrete members shall have a minimum compressive strength of 5000 psi (35.0 MPa) at 28 days unless otherwise shown on the plans. The maximum size of coarse aggregate shall be 1" (25 mm).

***NOTE: 1 lb/yd^3 = 0.59 kg/m^3, 1 in. = 25.4 mm, 145.04 psi = 1 MPa**

Although SCC is a structural concrete, its properties, particularly fresh concrete properties such as deformability, passing ability, filling capacity, and static stability, differ significantly from those of conventional-slump concrete. Therefore, it is relevant for SCC to have its own set of standard specifications. The distinctive fresh properties of SCC were determined by performing the slump flow test (ASTM C 1611/C 1611M), the T-20 (T-50) test (ASTM C 1611/C 1611M), the VSI test (ASTM C 1611/C 1611M), and the J-Ring test (ASTM C 1621/C 1621M). The ranges of the values acquired from these tests were based upon recommendations listed in the literature. A slump flow or spread of at least 23.5 in. (600 mm), [33] T-20 (T-50) time within the range of 2 to 5 seconds, [18] VSI of 0 to 1, [35] for the difference in height of concrete from the inside to the outside of the J-Ring to be less than 0.59 in. (15 mm), [35] and for a difference in slump flow and J-Ring flow values to be less than 4 in. (100 mm).[33] Also, as prescribed in Figure 3.1, the mixtures were designed to obtain a minimum compressive strength of 3500 psi (24 MPa) at 28 days.[5]

3.2 MATERIALS

3.2.1 Materials

All materials used in the research program were locally available. As stipulated by AHTD Standard Specifications for Highway Construction[5], Division 800, Section 802.02 Materials, Type I portland cement conforming to the requirements of AASHTO M 85 was used. Multiple adequate SCC mixtures were developed by only utilizing cement as the binder component. However, in an attempt to make the mixtures more economical, Class C FA was also included in the scope of the research program. The FA used was in compliance with AASHTO M 295. SCC was successfully batched with FA replacement rates of 5, 10, 15, 20, and 25%.

The fine aggregate used in the mixtures was washed river sand which consisted of clean, hard, durable particles. The coarse aggregate was crushed limestone which consisted of clean and durable fragments of rock of uniform quality. *S/Agg* values varying from 0.44 to 0.56 were used in all mixtures. The sieve requirements listed in AHTD's Standard Specifications[5] were followed for both the fine and coarse aggregates.

Table 3.2 lists the tests performed on the fine and coarse aggregate. The fine aggregate gradation and physical properties are shown in Table 3.3 and Table 3.4, respectively. The coarse aggregate gradation and physical properties are shown correspondingly in Table 3.5 and 3.6.

Table 3.2: Aggregates, Tests, and Standards

Material	Test Name	Standards
Fine Aggregate	Sieve Analysis	ASTM C 136
	Specific Gravity and Absorption	ASTM C 128
	Dry Rodded Unit Weight	ASTM C 29
Coarse Aggregate	Sieve Analysis	ASTM C 136
	Specific Gravity and Absorption	ASTM C 127
	Dry Rodded Unit Weight	ASTM C 29

Table 3.3: Fine Aggregate Gradation

Sieve Size (mm)	Fine Aggregate	AHTD Specifications
	% Passing	% Passing
3/8 in. (9.5)	100	100
No. 4 (4.75)	96.89	95 – 100
No. 8 (2.36)	89.72	70 – 95
No. 16 (1.18)	73.99	45 – 85
No. 30 (0.600)	52.53	20 – 65
No. 50 (0.300)	13.53	5 – 30
No. 100 (0.150)	1.81	0 – 5

Table 3.4: Fine Aggregate Physical Properties

Fine Aggregate	
Specific Gravity	2.604
Absorption (SSD)	0.48
Dry Rodded Unit Weight (lb/ft^3)	112.1

***NOTE: 1 lb/ft^3 = 16.02 kg/m^3**

Table 3.5: Coarse Aggregate Gradation

Sieve Size (mm)	Coarse Aggregate
	% Passing
1-1/2 in. (37.5)	100
1-1/4 in. (31.5)	100
1 in. (25.0)	100
3/4 in. (19.0)	100
1/2 in. (12.5)	99.89
3/8 in. (9.5)	88.56
No. 4 (4.75)	9.5
No. 8 (2.36)	0.92

Table 3.6: Coarse Aggregate Physical Properties

Coarse Aggregate	
Specific Gravity	2.678
Absorption (SSD)	0.38
Dry Rodded Unit Weight (lb/ft^3)	89.5

***NOTE: 1 lb/ft^3 = 16.02 kg/m^3**

The water used in the mixtures was in agreement with AHTD's Standard Specifications.[5] It was clean and free from harmful amounts of oil, salts, and other deleterious substances, and it did not contain more than 1000 ppm of chlorides. Also, as recommended by AHTD, the *w/b* was set at 0.44 for all trial mixtures.

3.2.2 Chemical Admixtures

HRWRs provided by Grace Construction were implemented in the concrete mixtures to promote flowability. It is important to note that every mixture contained at least one HRWR. The first chemical admixture used was ADVA Cast 530. ADVA Cast 530 is a polycarboxylate-based HRWR that is designed to conform to ASTM C 494/C 494M as a Type A and F admixture and ASTM C 1017/C 1017M as a Type I admixture. It is manufactured to substantially enhance the flowability of SCC without causing segregation. Also, it aids concrete in acquiring high early-age compressive strength. Consequently, it is especially appropriate for the production of SCC in precast/prestressed applications. Although dosage rates can fluctuate with the type of application, addition rates will typically be within the range of 3 to 10 fl. oz. /cwt (195 to 650 mL/100 kg).[75]

The second chemical admixture implemented was ADVA 170. It is a HRWR developed for the ready-mix concrete industry. It complies with ASTM C 494/C 494M as a Type A and F admixture and ASTM C 1017/C 1017M as a Type I admixture. ADVA 170 produces concrete mixtures that are exceptionally workable, but it also allows concrete to be batched with low *w/b* for high strength. In addition, ADVA 170 improves the slump life of concrete without lengthening the setting time. While addition rates can be different depending on the type of application, dosage rates will normally be within the range of 3 to 9 fl. oz. /cwt (195 to 590 mL/100 kg). ADVA 170 should be added to the mixing water to yield optimal results.[75]

The final chemical admixture employed in the research program was ADVA Cast 575. ADVA Cast 575 is a polycarboxylate-based HRWR that is intended for the production of an extensive variety of concrete mixtures, from conventional-slump concrete to SCC. Its high efficiency, low dosage rate design allows for concrete mixtures to be extremely workable without segregating. ADVA Cast 575 meets the requirements of ASTM C 494/C 494M as a Type A and F admixture and ASTM C 1017/C 1017M as a Type I admixture. It is formulated to obtain high early-age compressive strength, and is particularly suitable for the production of SCC in precast/prestressed applications. ADVA Cast 575 can be used to produce concrete mixtures with low *w/b* while preserving desirable workability characteristics. Addition rates can be altered to meet a broad range of performance standards. Dosage rates can vary from 2 to 10 fl. oz. /cwt (130 to 650 mL/100 kg) depending on the kind of application. However, the usual rate range is from 3 to 6 fl. oz. /cwt (195 to 390 mL/100 kg).[75]

3.3 MIXING PROCEDURE

One day prior to batching, both coarse and fine aggregates were weighed in 5-gallon (18.93-liter) buckets and stored indoors within the concrete laboratory to ensure that the moisture contents were consistent. Aggregate samples were weighed in steel pans and oven-dried over night to evaluate the moisture contents of the aggregates. On the day of batching, the mixture proportions were adjusted based on the moisture contents of the aggregates. The mixture proportions were scaled to volumes ranging from 1.5 to 2 ft^3 ($4.25x10^{-2}$ to $5.66x10^{-2}$ m^3) for all the trial SCC batches. All SCC mixtures were batched in a 12.5 ft^3 (0.35 m^3) rotating drum mixer. The mixer is displayed in Figure 3.1.

Figure 3.1: Rotating Drum Mixer

The mixing procedure was followed in accordance with an adapted edition of ASTM C 192/C 192M; the only adjustment made to the standard was to utilize a longer time frame allotted for initial mixing. By design, SCC mixtures typically contain more paste volume than conventional concrete mixtures. According to research performed by Chopin et al.[76], when compared with coarse aggregate, it was reported that sand and fine particles take a longer amount of time to disperse homogeneously in SCC mixtures. Hence, the initial mixing time was lengthened with the purpose of ensuring that all the constituent materials could diffuse uniformly. In addition, prolonging the initial mixing time supplies extra time for the chemical admixtures to achieve their desired effectiveness.

For every batching sequence, all the coarse aggregate and half of the mixing water were added to the mixer as per ASTM C 192/ C 192M. At this time, the HRWR was combined with the residual mixing water, and the mixer was activated. The measured quantities of fine aggregate, binder, and remaining mixing water were subsequently incorporated into the mixer. Batching commenced for a period of 5 minutes once all the constituent materials had been integrated. The mixer was then switched off, and a 2 to 3 minute break from mixing ensued. Once the concrete had settled inside the mixer, the mixture was assessed to determine if any additional HRWR needed to be added. After evaluating the mixture, one of three scenarios occurred. If the concrete had segregated, then the mixture was rejected and discarded. If the concrete was fluid and stable, then a concluding mixing segment of 2 to 3 minutes followed. If the concrete was thick and viscous, then additional HRWR was incorporated, and the intermediate mixing segment proceeded for approximately 3 more minutes to enable the chemical admixtures to react with and further disperse the binder particles. After the intermediate mixing period, the mixer was turned off, and the concrete was reevaluated by repeating the previously mentioned steps. In some trial mixtures, HRWR was incrementally added up to three times in order to obtain adequate SCC or to cause the concrete to segregate.

It is important to note that all of the chemical admixtures were introduced separately into the mixtures based on the type of chemical admixture. If only one HRWR was utilized, it was combined with the residual mixing water. In certain mixtures, both ADVA 170 and ADVA Cast 530 were implemented. The primary goal for these mixtures was to produce a concrete sample that was extremely flowable and stable. Also, the secondary objective was to enhance the slump life without lengthening the setting time of the concrete. For these mixtures, the ADVA 170 was combined with the residual mixing water and the ADVA Cast 530 was added during the break period. This procedure is validated with research performed by Grace Construction[75] on these chemical admixtures. The findings affirm that for ADVA 170 to yield optimal results, it should be dissolved in the residual mixing water. To promote flowability and reduce the segregation potential of the mixture, ADVA Cast 530 would then be added during the break period.

3.4 TESTS PERFORMED ON SCC

Immediately after mixing, the concrete was poured into a wheelbarrow and the mixer was switched off. The wheelbarrow was then moved to a level surface where testing would occur. Using a concrete scoop, the SCC was stirred for approximately 1 minute to ensure a uniform consistency; this was done because the last bit of concrete to leave the mixture was usually paste. Fresh concrete tests were conducted promptly thereafter. The stirring process is displayed below in Figure 3.2.

Figure 3.2: Stirring Process

3.4.1 Slump Flow

The slump flow test is simple in nature and easy to conduct. This test is most widely used to establish the flowability properties of SCC. The only materials required to perform the test are a concrete scoop, a traditional slump cone, a tape measure, and a flat, level, nonabsorbent surface. The test can be executed with the slump cone in the conventional orientation or inverted. The slump cone is first filled in one lift with concrete. The slump cone is then lifted and the concrete spreads out. The slump flow is measured by computing the arithmetic mean of two perpendicular diameters at the base of the concrete. When compared with established values in the literature, the slump flow measurement is an adequate indication of the flowability of the SCC mixture. Khayat and Mitchell[33] have established three defined ranges of slump flow measurements. Specifically, low slump flow values vary from 23.5 to 25.0 in. (600 to 635 mm), normal slump flow values vary from 26.0 to 27.5 in. (660 to 700 mm), and high slump flow values vary from 28.0 to 30.0 in. (710 to 760 mm). Depending on the type of application, numerous researchers specify different ranges of slump flow values. However, regarding SCC intended for various structural applications, JSCE[34] recommends low to normal slump flows varying from 23.5 to 27.5 in. (600 to 700 mm) to ensure that the mixture acquires sufficient self-consolidation.

3.4.1.1 Slump Flow Procedure

Prior to testing, the board (Figure 3.3) was wiped down (Figure 3.4) with a damp sponge; this ensured saturated conditions that would promote the slump flow. In this research program, the slump cone was inverted during testing. This approach was implemented as a convenience to the operative; being that the cone was inverted, it was not required for the operative to stand on the base and hold on to the handles as is the case when the cone is set up conventionally. Immediately before testing, the slump cone was wiped down with a damp sponge (Figure 3.5); this prevented the SCC from sticking to the inside of the cone and allowed for a smooth transition through the outlet.

Figure 3.3: Slump Flow Board

Figure 3.4: Dampening the Slump Flow Board

Figure 3.5: Wetting the Slump Cone

A visual depiction of the inverted slump flow test procedure is shown in Figures 3.6, 3.7, and 3.8.

Figure 3.6: Filling the Slump Cone

Figure 3.7: Lifting the Slump Cone

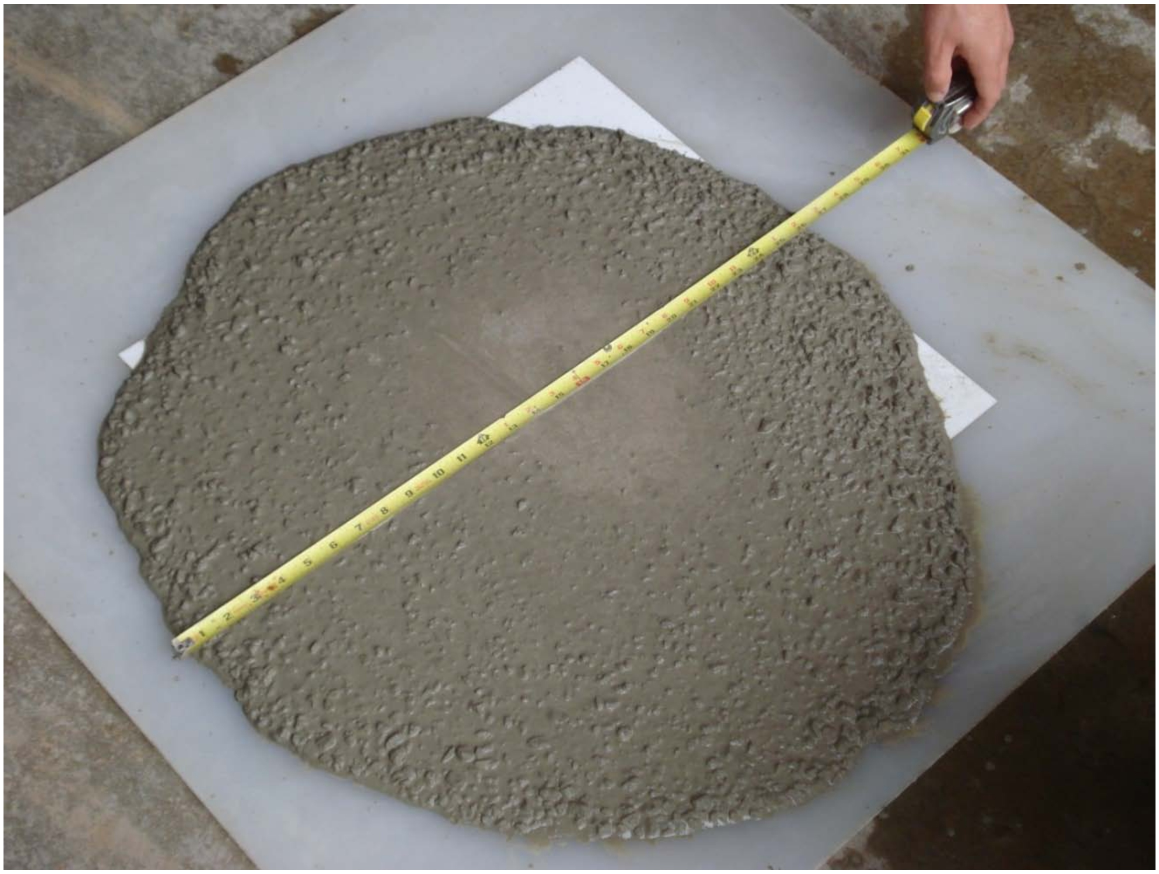

Figure 3.8: Measuring the Slump Flow Spread

3.4.2 T-20 (T-50)

The T-20 (T-50) test measures the time that it takes for the concrete to reach a slump flow diameter of 20 in. (50 cm). This measurement provides an indication of the relative viscosity of the mixture, and it is performed in conjunction with the slump flow test as per ASTM C 1611/C 1611M. EFNARC[18] recommends T-20 (T-50) values that range from 2 to 5 seconds. Any measured time that takes less than 2 seconds indicates that the mixture is likely too fluid and susceptible to segregation, whereas any measured time that takes longer than 5 seconds suggests that the mixture is likely too viscous and have severe blockage potential. In this research program, a stopwatch was used to obtain all T-20 (T-50) measurements.

3.4.3 VSI

The VSI test is a subjective visual assessment of the stability of the slump flow spread. It was utilized in the research program to establish the quality of SCC. By evaluating the VSI, it could be determined if the particular mixture was adequate or if modifications were needed. As stated in ASTM C 1611/C 1611M, VSI values vary from 0 to 3 in increments of 0.5. The PCI Interim Guidelines[35] states that VSI values of 0 to 1 should guarantee sufficient stability. A value of 0 is assigned to a slump flow spread that is highly stable, has a uniform distribution of coarse aggregate, has no mortar halo around the perimeter of the spread, and has no visual indication of segregation or bleeding. The mixture displayed below in Figure 3.9 has a VSI value of 0 and is highly recommended for use.

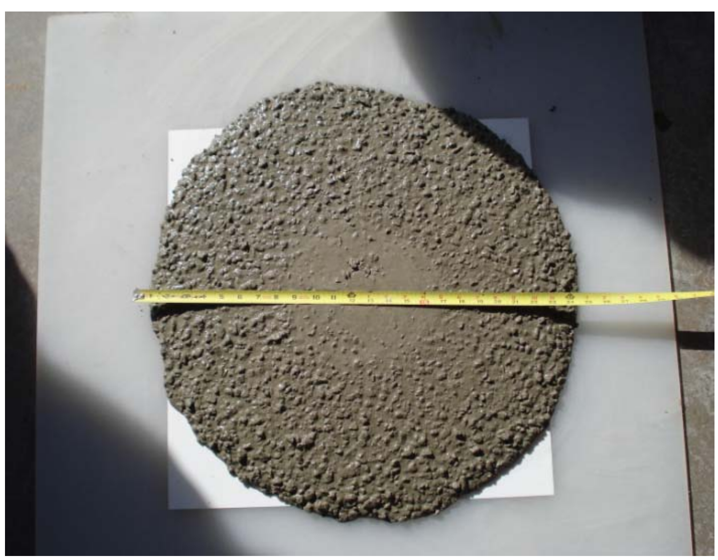

Figure 3.9: Mixture with VSI equal to 0

A value of 1 is designated to a slump flow spread that is stable, has a uniform distribution of coarse aggregate, has no mortar halo around the perimeter of the spread, and has no visual indication of segregation. However, such a mixture will exhibit slight bleeding, which is observed as a sheen on the concrete mass. The mixture shown below in Figure 3.10 has a VSI value of 1 and is recommended for use.

Figure 3.10: Mixture with VSI equal to 1

A value of 2 is given to a slump flow spread that is unstable, has an irregular distribution of coarse aggregate, has a slight mortar halo (less than or equal to 0.5 in. (12.7 mm)) and/or an aggregate pile in the center of the concrete mass, and has a visual indication of segregation or bleeding. The mixture presented in Figure 3.11 has a VSI value of 2 due to the visible mortar halo and bleed water. This mixture is not recommended for use until modifications are made to improve the stability.


Figure 3.11: Mixture with VSI equal to 2

A value of 3 is specified to a slump flow spread that is highly unstable, has an irregular distribution of coarse aggregate, and has clearly segregated by evidence of a large mortar halo (greater than 0.5 in. (12.7 mm)) and/or a large aggregate pile in the center of the concrete mass. The mixture displayed in Figure 3.12 has a VSI value of 3 due to the irregular distribution of coarse aggregate, the large mortar halo, and the indication of severe segregation. Obviously, this mixture is not recommended for use, and adjustments should be made in subsequent trial batches.


Figure 3.12: Mixture with VSI equal to 3

3.4.4 J-Ring

As prescribed in ASTM C 1621/C 1621M, the J-Ring test is utilized for evaluating the passing ability (blockage) of SCC. The J-Ring test is performed in conjunction with the slump flow test. The test is conducted by positioning the slump cone in the middle of the J-Ring, completely filling the slump cone with SCC, and then lifting the slump cone. Figure 3.13 shows the setup for the J-Ring test apparatus that was used in the research program.

Figure 3.13: J-Ring Setup

This procedure simulates the passing ability of concrete through closely spaced impediments. Once the concrete spread has come to rest, two measurements are recorded. The first measurement is the difference in the height of the SCC from the inside to the outside of the J-Ring. The PCI Interim Guidelines[35] recommends that this measurement must be less than 0.59 in. (15 mm) in order to acquire adequate passing ability. Figure 3.14 demonstrates how this measurement was obtained.

Figure 3.14: Measuring SCC Height Difference

The second measurement is of the J-Ring flow spread, and it is evaluated by the same process as the slump flow spread. Research performed by Khayat and Mitchell[33] states that the difference in slump flow and J-Ring flow measurements should be less than or equal to 4 in. (100 mm) to ensure that the SCC can readily encapsulate the reinforcement. The measurement process is shown below in Figure 3.15.

Figure 3.15: Measuring the J-Ring Flow Spread

3.4.5 Supplementary Concrete Tests

Additional concrete tests, such as temperature, unit weight, compressive strength, and modulus of elasticity were also measured for some of the trial SCC mixtures. Fresh concrete temperature was assessed as stated in ASTM C 1604/C 1604M. Fresh concrete unit weight was calculated as indicated in ASTM C 138/ C 138M. Hardened concrete compressive strength was computed at 1, 7, and 28 days of age following the guidelines of ASTM C 39/ C 39M. Hardened concrete modulus of elasticity was determined at 28 days of age as per ASTM C 469. Figure 3.16 shows a photograph of three SCC cylinders that were tested to failure in compression at 28 days of age. Also, the data acquisition system (DAQ) and the apparatus that was used to test for concrete modulus of elasticity are presented in Figure 3.17.

Figure 3.16: SCC Cylinders Tested in Compression

Figure 3.17: DAQ and Apparatus used for Modulus of Elasticity Testing

3.5 CURING

For compressive strength testing, nine cylinders were cast from each batch and placed inside an environmental chamber. As outlined in ASTM C 192/C 192M, the temperature inside the environmental chamber was held constant at 73°F (23°C) with a relative humidity of approximately 50%. Testing occurred for an array of three cylinders at 1, 7, and 28 days of age. After 24 hours had elapsed from the time of casting, all nine cylinders were de-molded and visually evaluated for surface deficiencies. The three cylinders that exhibited the most severe defects were tested that same day. The three cylinders that showed moderate surface flaws were labeled to be tested at 7 days of age.

The last three cylinders that displayed the least amount of blemishes were labeled to be tested at 28 days of age. The six cylinders that were not tested after the de-molding procedure were submerged in a lime saturated water bath located in the environmental chamber. These specimens remained in the lime saturated water until testing. Figure 3.18 displays a selection of labeled cylinders that were placed inside the tub filled with lime saturated water to cure.

Figure 3.18: Labeled Cylinders Curing in Lime Saturated Water

For modulus of elasticity testing, three cylinders were cast from each batch and placed inside the environmental chamber. After 24 hours had passed from the time of casting, the cylinders were de-molded and submerged in the lime saturated water bath.

All three specimens were left in the lime saturated water until testing was to occur at 28 days of age.

CHAPTER 4

DEVELOPING SCC SPECIFICATIONS

4.1 EXPERIMENTAL PROGRAM

This portion of the research program developed fresh concrete specifications for structures cast with self-consolidating concrete (SCC), specifically for box culverts. However, results from this research easily apply to precast wall panels of similar size and configuration. The experimental program consisted of selecting an SCC mix design and then using this mix proportion to cast 11 mock box culvert wall sections. Cores were taken throughout the depth of the wall sections and tested in compression. The compressive strength of the concrete was examined throughout the depth of the section as well as to cylinders cast at the same time as the wall section. The cores were also examined for aggregate segregation as well.

4.2 MIXTURE PROPORTIONS

The research began with mixing several test batches. The test batches were used to ensure that the fresh concrete properties of the chosen mix design were within the desired ranges. Some adjustment of high range water reducer (HRWR) dosage was required to get a feasible SCC mixture. The ability to vary the flow characteristics and other fresh properties was essential to getting a good range of results. The desired range of slump flow and T_{20} were between 25 and 29 in. and 2 and 5 seconds respectively. The SCC mix proportion chosen for use in this experimental program was the result of previous research at the University of Arkansas.[2] This mixture was developed for use in prestressed concrete bridge girders. Since this research only focused on the effects of fresh concrete properties on concrete performance, the exact mix proportion was not critical, only the fresh properties. The mix proportion used in this research is shown in Table 4.1.

Table 4.1: SCC Mix Proportion

Material	Quantity
Cement (lb/yd^3)	950
Fly Ash (lb/yd^3)	0
Coarse Aggregate (lb/yd^3)	1350
Fine Aggregate (lb/yd^3)	1474
Water (lb/yd^3)	285
w/b	0.3
ADVA 170 (fl oz/cwt)	9-13[a]
ADVA 555 (fl oz/cwt)	0-2.0[a]

Note: 1 lb = 0.454 kg; 1 oz = 29.57 mL

[a]Admixture dosage varied due to temperature and desired flow

The fresh concrete properties that were examined in this research include: Slump Flow, T_{20} time, Visual Stability Index (VSI) and, J-Ring. Slump flow and T_{20} were used as a measure of filling ability, J-Ring as a measure of passing ability and VSI as a measure of segregation resistance.

4.3 PROCEDURE

4.3.1 Wall Selection and Construction

The criteria used to select the test specimen size were based upon ease of construction and available mixer capacity. The wall sections employed were constructed by mimicking current AHTD box culvert plans. It was determined that a 4-foot by 4-foot barrel should be adequate for both of the previously mentioned criteria. Specifically, a single barrel edge wall was chosen and three sets of mobile wooden forms were created. When cast, the resulting wall sections measured 4 feet high by four feet wide, with a thickness of 6 inches, and a required volume of concrete of 8 ft^3. Also included in the plan set were the reinforcing bar size and spacing requirements. The typically used steel reinforcing bars were replaced with wooden dowel rods of equal diameter. Since the wooden dowels had the same cross-section as the required reinforcing bars they created an equivalent blocking effect. The wooden dowel rods proved quite rigid when tied and placed in the arrangement required in the plans. No failure of dowel rods was observed during concrete placement. Once again, the goal of this project is not to determine any flexural or compressive strengths of the entire composite wall section, rather the strength of the wall cores versus their molded counterparts.

4.3.2 Mixing and Pouring

In order to have an adequate amount of concrete to fill the form and perform tests, two mixers of differing capacities were used. The first and primary mixer, a Stone, capable of handling 12.5 ft^3, contained batch sizes of 9.5 ft^3. The second and alternate mixer was also of the Stone brand; with a capacity of 4 ft^3, this mixer was used to batch an additional 2 ft^3. The second mixer was used strictly for contingency purposes. The required material quantities were carefully weighed in advance of each batch and the required quantity of HRWR was added to the mixing water.

For each pour, the wall form was placed on level ground and the mix was introduced via a wheelbarrow at one end only. A small trough was created to help channel and minimize loss of material during placement into the wall form. When poured into the trough, the concrete was allowed to flow on its own and fill the form without any method of vibration being utilized. Shovels were used to help regulate the flow for both fast and slow moving mixes. Once the forms were filled, hooks were placed in top of the walls to allow for transport once the concrete had sufficiently set. The forms were not removed for a minimum of 20 hours after the final placement.

4.3.3 Testing

Slump flow tests were performed in accordance with ASTM C 1611. The research team preferred the inverted cone method based on previous experience and its ease of use. The cone was filled in one lift; afterwards, the cone was raised and the concrete was allowed to flow until it ceased. Next, the maximum diameter of the displaced concrete was measured, and another measurement was taken perpendicular to the first measurement. Measurements were made to the nearest ¼ in. The two resulting values were then averaged and recorded to the nearest ½ in. Two slump flow tests were performed for each batch since some previous research has indicated increasing slump flows over the short term.

When the slump flow test is performed, the time in which it takes for the sample to reach a 20 inch diameter is known as the T_{20} time. The test method is also from ASTM C 1611. The researchers utilized a board specific for testing SCC. The board essentially provides a template for placement of the inverted slump cone and a clearly marked 20 inch diameter ring. Since two slump flow tests were conducted for each batch, two T_{20} values were also recorded.

The Visual Stability Index or VSI, has its basis in ASTM C 1611 as well. The purpose of this test is to categorize the stability of a mix by observing the concrete once it has been displaced from the slump cone. The sample is indexed from 0 to 3 in increments of 0.5. For the scale, 0 indicates the best possible mix, one that includes no segregation, mortar halo, or bleed water. A value of 3 indicates the worst possible case: a heavily segregated mix which includes a pile of aggregate surrounded by a thin, wide spread of paste with very little aggregate interspersed. The outer edges of this sample will have a ring of paste, known as mortar halo, as well as bleed water which may be seen as a discoloration on or around the edges of the sample and a sheen on the surface.

The J-Ring test is also used in conjunction with the slump flow test. The J-Ring test was performed in accordance with ASTM C 1621. The J-ring contains 16 vertical bars of ⅝ in. diameter and 4 in. height evenly spaced around a 12 in. diameter ring. The ring serves to simulate the ability of the mix to pass through rebar similar to field conditions. For the test to be performed, the ring is placed on the testing surface and the inverted slump cone is placed inside of the ring. The slump cone is filled and lifted in accordance with ASTM C 1621. Once the concrete has stopped flowing, a diameter is measured across the largest part of the displaced concrete mass and a second diameter is measured perpendicular to the first. These measurements are made to the nearest ¼ in. and then the average of the two is taken to the nearest ½ in. In addition to the J-ring flow, the height difference between the inside and outside the ring was measured to the nearest ¼ in.

4.4 RESULTS

The fresh concrete properties of each batch along with one day compressive strengths are shown in Table 4.2. Slump flow tests were performed before and after the J-Ring test for each batch and the first slump flow was recorded as the official value. The overall values of fresh concrete properties gave a good representation of the target range as well as covering values just outside of that range. VSI values were consistently between 0 and 1 with only two of the batches showing significant segregation. One day compressive strengths met the desired value for all batches except for Batch 11, where segregation was readily noticeable.

4.4.1 Slump Flow

Slump flows varied between 15 in. and 37.5 in. This range easily covered the desired range of 25.5 to 29.0 in. as well as values on both the high and low side of the desired range. These limits show that both the extremes of basically high slump concrete (non SCC) and segregated mixtures were examined as well as everything in between. All batches except Batch 11 met the target values for strength at one day. Wall sections cast with Batches 5, 6, 7, and 9 (having slump flows in the desired range) had a good surface finish without significant bugholes. An example can be seen in Figure 4.1. Walls cast with batches having a slump flow larger than the desired range also showed a good finish. Low slump flows led to significant bug holes and a poor finish as can be seen in Figure 4.2.

Table 4.2: Summary of Concrete Properties

Batch	Slump Flow (in.)	T_{20} (sec)	VSI	J-Ring Flow (in.)	J-Ring ΔH (in.)	1 Day f_c
1*	NA	NA	NA	NA	NA	NA
2*	18.5	NA	NA	NA	NA	NA
3*	26.0	NA	0	27.5	NA	NA
4*	27.5	NA	1	27.5	0.50	7670
5	27.0	NA	1	27.5	0.75	6880
6	26.5	10.4	1	27.5	0.50	7500
7	26.5	8.4	1	27.0	0.25	NA
8	22.5	9.8	0	22.0	1.00	6720
9	27.5	6.4	0	30.0	0.25	7420
10	21.0	15.6	0	19.0	1.75	7600
11	37.5	1.6	2.5	41.0	0.00	2330
12	31.0	3.8	2	29.5	0.75	6290
13	24.0	5.0	0	22.5	1.00	6510
14	29.5	4.0	1	27.0	0.50	6230
15*	15.0	NA	NA	NA	NA	NA
16	16.0	NA	NA	NA	NA	6190

*Indicates test batch only.

Figure 4.1: Wall 7 Showing Good Slump Flow

Figure 4.2: Wall 16 Showing Poor Slump Flow

Since previous research at the University of Arkansas had indicated[5] that slump flows tended to increase over the short term, a second slump flow test was performed after each J-Ring test. These tests yielded some interesting results. A comparison of the first set of slump flow tests to the second set are shown in Table 4.3. Batches 4, 5, 6, 7, 8, 9, and 11 showed an increase in slump flow in the approximately 10 minutes between tests. This increase ranged from 0.5 in to 4 in. The source of the increase in slump flow is unclear, but may be caused by water exiting the aggregate as the concrete sits, or by continued action of the HRWR. Batches 10, 12, 13, 14, and 16 showed a decrease in slump flow, as would typically be expected. T_{20} times followed the same pattern as slump flows, with lower T_{20} when slump flow increased and higher T_{20} when slump flow decreased.

Table 4.3: Comparison of Slump Flow Tests

	First Trial			Second Trial		
Batch	Slump Flow (in.)	T_{20} (sec)	VSI	Slump Flow (in.)	T_{20} (sec)	VSI
1	NA	NA	NA	NA	NA	NA
2	18.5	NA	NA	NA	NA	NA
3	26.0	NA	0	NA	NA	NA
4	27.5	NA	1	31.5	NA	NA
5	27.0	NA	1	29.0	NA	1
6	26.5	10.4	1	28.5	NA	1
7	26.5	8.4	1	30.0	6.4	1
8	22.5	9.8	0	25.0	7.6	1
9	27.5	6.4	0	30.5	4.0	1
10	21.0	15.6	0	19.5	20.0	0
11	37.5	1.6	2.5	38.0	4.4	2.5
12	31.0	3.8	2	31.0	4.0	2
13	24.0	5.0	0	22.0	7.2	0
14	29.5	4.0	1	27.5	4.2	1
15	15.0	NA	NA	NA	NA	NA
16	16.0	NA	NA	15.0	NA	NA

4.4.2 T_{20} Time

T_{20} times covered a broad range with a minimum of 1.6 seconds and a maximum of 15.6 seconds. Wall sections cast with Batches 12, 13, and 14, exhibiting T_{20} times in the desired range of 2 to 5 seconds, had a good finish with a minimum amount of bugholes. Figure 4.3 shows the surface finish of the wall cast with Batch 12. Wall 11 had a very low T_{20} but showed some poor surface finish due to segregation. Batches with a high T_{20} but good slump flow yielded a good surface finish as well. However, since T_{20} is a measure of filling ability, consequences of high T_{20} times may not be discovered until cores are examined. The mixture used in this research program tended to have a high viscosity and more batches are necessary to obtain additional data points for low T_{20} times.

Figure 4.3: Wall 12 Showing Good T_{20}

4.4.3 VSI

All batches had a VSI in the target range of 0 to 1 except for Batches 11 and 12. Batch 11 showed significant segregation (VSI of 2.5) and the wall cast with this batch had a substantial amount of bugholes. Batch 12 showed moderate segregation (VSI of 2), but the wall had a good surface finish. As mentioned previously, the cores will give a much better indication of how this segregation affected concrete performance. The low VSI values for all other batches indicate adequate segregation resistance.

4.4.4 J-Ring

Differences between slump flow and J-Ring flows were typically less than 2 in. However, in some cases the J-Ring flow was higher than the slump flow. The increase could also be attributed to the water in the aggregate or HRWR action mentioned in the slump flow section. This result was true for Batches 3, 5, 6, 7, 9, and 11. The difference in height inside and outside the J-Ring was seemingly more consistent in showing the true value of blockage. Height differences varied from 0.25 in. to 1.75 in. From previous research, a height difference of 0.5 in. or less indicated minimal blockage. Batches 4, 6, 7, 9, 11, and 14 exhibited this characteristic. This implies that all other batches had some measure of blockage. Only Batches 10, 15, and 16 had a value higher than 1 in. All three of these batches had low slump flows and batch 15 was not used to cast a wall section. The J-Ring values will be useful when examining the cores from the wall sections to determine how the reinforcement affected consolidation of the concrete.

4.4.5 Compressive Strength

All batches for which cylinders were cast met the target one day compressive strength of 6000 psi except for Batch 11, which had significant segregation. Since the target compressive strength was met at one day, core strengths should meet the target compressive strength at time of testing. The variation of compressive strength with slump flow and T_{20} is shown in Figures 4.4 and 4.5 with the target range of fresh properties indicated.

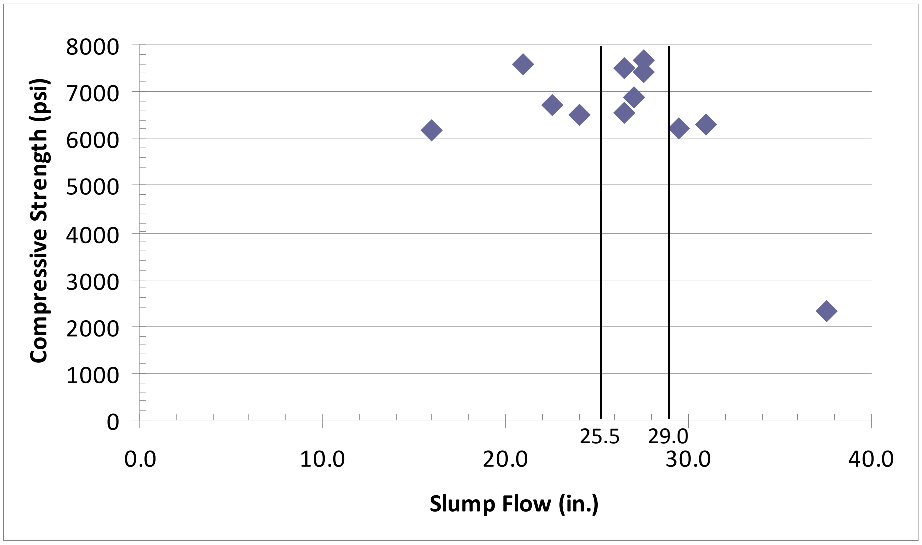

Figure 4.4: Variation of One Day Strength with Slump Flow

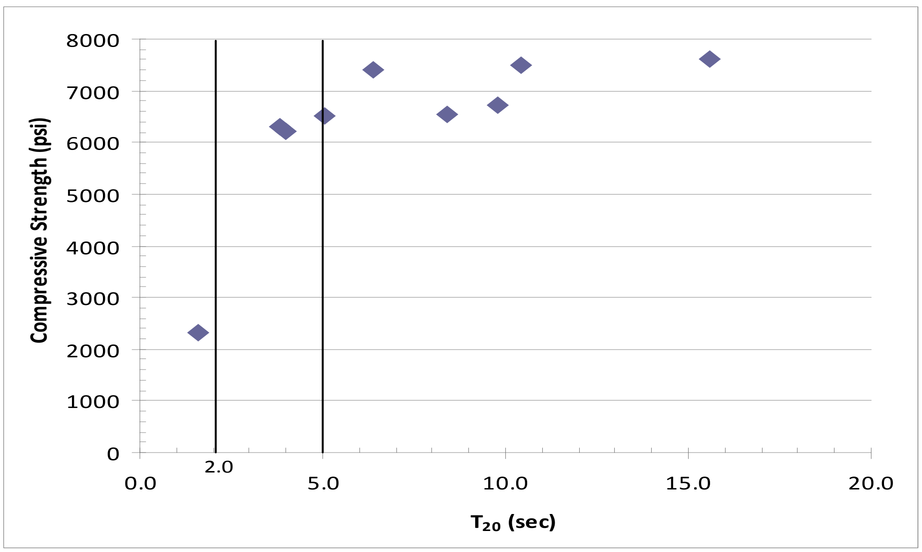

Figure 4.5: Variation of Compressive Strength with T_{20}

4.4.6 Aggregate Distribution

Each wall slab was cored in nine locations which are identified in Figure 4.6. The approximate locations of the cores are identified by Row and Column number. Also shown in Figure 4.6 are the corresponding compressive strengths and aggregate distributions for the cores of Wall 5. The compressive strength or aggregate distribution for each core location and wall section is given in Table 4.4.

Each wall specimen was cored in new locations. Three cores equally spaced along the top of the wall, three cores equally specimen in the center of the specimen, and three along the bottom of the specimen. For each row, two of the three cores were tested in compression and the third core was used to measure aggregate distribution. To measure aggregate distribution, the core was cut lengthwise and the number of coarse aggregate particles was counted. This number was then divided by the area of the core. For Wall 5 (Figure 4.6), the aggregate distribution was 7.53 aggregate particles per square inch (agg./in.^{2}) in Row 1, 7.88 agg./in.^{2} in Row 2, and 5.81 agg./in.^{2} in Row 3. Likewise, the compressive strength ranged from a low of 13,170 psi to a high of 15,000 psi. Data from all wall sections along with the fresh concrete properties are shown in Table 4.4.

For all samples, the average number of coarse aggregate particles per square inch of concrete was 7.02. The lowest aggregate count per square inch was 5.51 and the greatest was 8.74. All mixtures no matter the fluidity had aggregate distribution near the average. For example, Wall 10 which was a very viscous mixture had a slump flow of 21 in. and a T_{20} of 15.6 seconds, but the aggregate was evenly dispersed through the wall section. This mixture was an extremely stable mixture with little to no potential of segregation. However, Wall 11 had a slump flow of 37.5 in. and a T_{20} of 1.6 seconds. This mixture had a very low viscosity and therefore a high potential for segregation, but the aggregate distribution ranged from 6.91 to 8.74 agg./in^2. For all wall sections, the greatest disparity amongst samples from the same wall was approximately 2 agg./in.^{2}.

The compressive strength results also followed a familiar trend. For eight of the nine wall panel in which strength was measured, the was little variability amongst the compressive strength results of the same wall section. This was not the case for Wall 11. As previously mentioned the mixture used to cast Wall 11 was highly unstable (VSI = 2.5, T_{20} = 1.6, and slump flow = 37.5 in.) and resulting strengths varied by more than 50 percent throughout the wall.

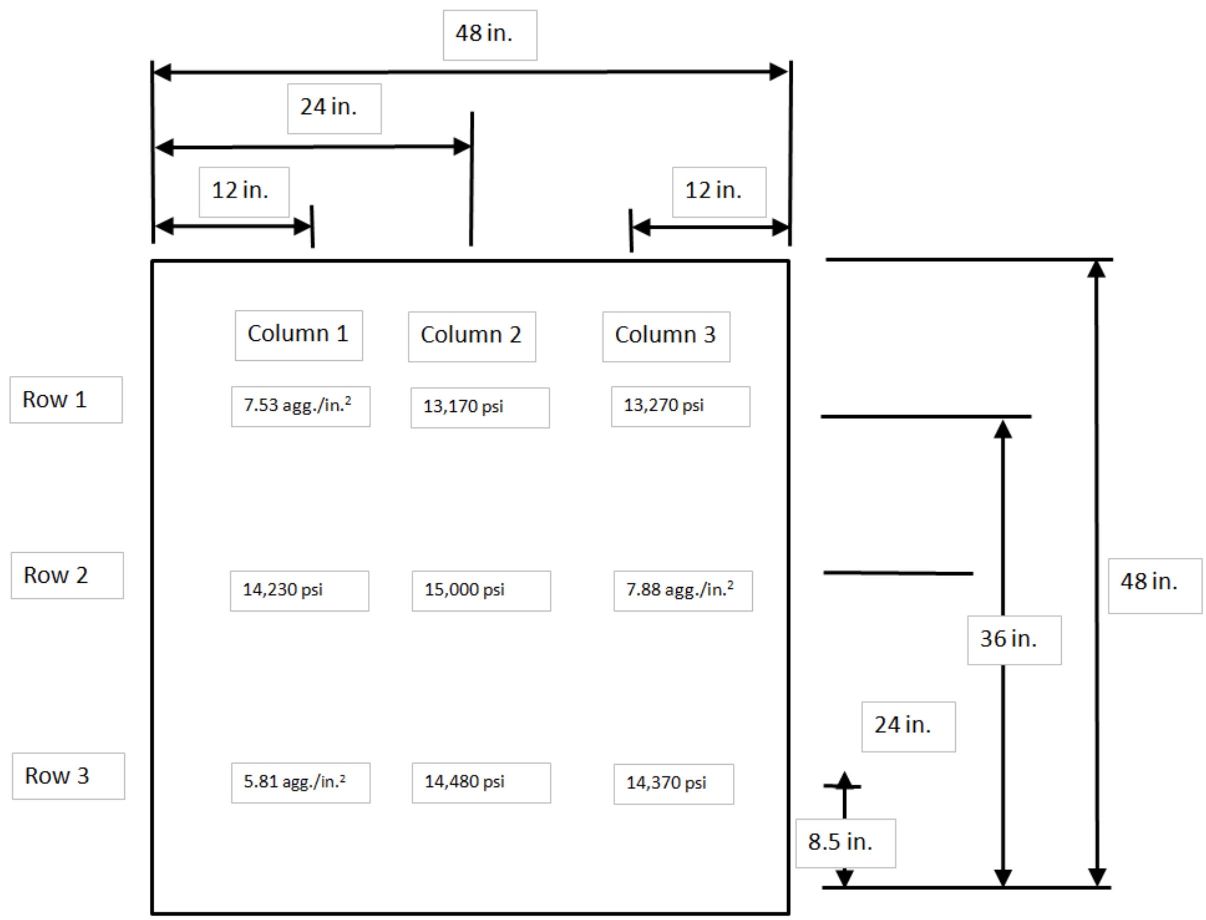

Figure 4.6: Core Locations for Wall 5.

Table 4.4: Aggregate Distribution and Core Strength.

Wall ID	Fresh Concrete Properties					Row	Column		
	Flow (in.)	T_{20} (sec)	VSI	J-Ring (in.)	J-Ring ΔH (in.)		1	2	3
5	27.0	-	1.0	27.5	0.50	1	***7.53***[A]	13,710	13,270
						2	14,230	15,000	***7.88***
						3	***5.81***	14,440	14,370
6	26.5	10.4	1	27.5	0.50	1	14,730	12,960	***7.44***
						2	13,970	13,260	***7.01***
						3	11,970	***8.47***	12,840
7	26.5	8.4	1	27.0	0.25	1	***6.41***	14,280	14,530
						2	12,010	***6.82***	-
						3	14,840	12,990	***6.61***
8	22.5	9.8	0	22.0	1.00	1	12,630	13,930	***7.22***
						2	12,580	13,130	***7.04***
						3	14,170	14,200	***7.34***
9	27.5	6.4	0	30.0	0.25	1	12,990	13,810	***7.22***
						2	13,260	***6.77***	13,000
						3	***6.57***	13,820	13,090
10	21.0	15.6	0	19.0	1.75	1	13,090	***7.27***	14,420
						2	13,450	***7.00***	12,330
						3	14,360	13,600	***6.03***
11	37.5	1.6	2.5	41.0	37.5	1	8,820	***8.39***	***8.54***
						2	5,920	8,590	***8.74***
						3	***6.91***	5,590	7,582
12	31.0	3.8	2	29.5	0.75	1	***6.42***	11,590	12,990
						2	13,090	11,480	***7.15***
						3	***8.08***	12,220	***8.10***
13	24.0	5.0	0	22.5	1.00	1	12,800	***7.17***	14,590
						2	12,400	***6.13***	13,220
						3	13,670	***6.80***	12,790
14	29.5	4.0	1	27.0	0.50	1	***6.88***	***7.74***	***6.11***
						2	***6.95***	***6.93***	***5.95***
						3	***5.92***	***7.02***	***5.86***
16	16.0	NA	NA	NA	NA	1	***6.43***	***5.81***	***5.51***
						2	***6.27***	***6.00***	***7.59***
						3	***6.37***	***7.35***	***7.69***

A = Bold and italicized numbers represent coarse aggregate distribution per square inch of the core. The remaining numbers represent concrete compressive strength in psi.

4.5 CONCLUSIONS

Conclusions from this portion of the research project are summarized below.

- Mixtures with slump flows within the target range of 25 in. to 29.0 in. yielded wall sections with a good surface finish.
- Mixtures with T_{20} times within the target range of 2-5 seconds yielded wall sections with a good surface finish.
- Mixtures with low slump flows and high T_{20} times resulted in wall sections with a very poor surface finish.
- Surface finish of the wall sections was affected by a combination of slump flow and T_{20}.
- All mixtures except one with very significant segregation reached the target compressive strength of 6000 psi at one day.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 INTRODUCTION

Chapter 5 is separated into two sections. The opening section explains the development process of a SCC mixture using only Type I portland cement as the binder constituent. The next section investigates the use of Class C FA in SCC mixtures; replacement rates of cement with FA were utilized in increments of 5, 10, 15, 20, and 25%. There are forty batches separated into seven phases that present the experimental procedure of developing a SCC mixture with Type I portland cement. An additional twelve batches (two phases) were examined to develop SCC mixtures with different replacement rates of FA. This chapter also presents quandaries that the author experienced throughout the development process coupled with an explanation of how the dilemmas were overcome. Finally, a methodology for developing SCC mixtures based upon the findings of this research program will be presented.

5.2 SELECTION/DETERMINATION OF CONSTITUENT MATERIALS

Initially, the mixture proportions were chosen based on AHTD's Standard Specifications[5]. The minimum binder content for structural concrete is 6.5 bags (611 lb/yd^3, 362.49 kg/m^3) per cubic yard. Binder is one of if not the most expensive component in any given concrete mixture. Hence, contractors will typically utilize the minimum specified binder content for concrete mixtures in an attempt to reduce costs. For this reason, 611 lb/yd^3 (362.49 kg/m^3) was the preliminary quantity of binder that was used. Also, the Standard Specifications[5] state that the water-to-binder ratio (*w/b*) should not exceed a value of 0.49 (a value of 0.44 was recommended). Accordingly, this value (*w/b* = 0.44) was implemented in every trial mixture with the exception of the first. The water content was established by multiplying the binder content by the *w/b*. All the SCC mixtures were designed to be non-air-entrained; this corresponds to an assumed air content of 2%. The total volume of aggregate was calculated by applying the ACI Absolute Volume Method[20]. The proportion of fine aggregate was determined via multiplying a selected *S/Agg* value "0.52" (based upon recommended *S/Agg* values from literature[77]) by the total volume of aggregate. Subsequently, the amount of coarse aggregate was computed by subtracting the volume of fine aggregate from the total aggregate volume. An example mixture design analysis that was performed for the first mixture is shown in Appendix A.

5.3 DEVELOPING SCC USING TYPE I PORTLAND CEMENT

5.3.1 Phase 1 – Binder Content

As previously discussed in the literature review (Section 2.4.1), there are essentially three mixture proportioning procedures that can be followed to obtain SCC. The first method was primarily followed in this research program because multiple SCMs were not utilized in any of the trial mixtures. However, it should be noted that the third "combination" method was used in the trial mixtures containing FA.

The mixture proportions of the first trial batch are shown below in Table 4.1. In addition to those constituents, ADVA Cast 530 was incorporated to promote the flowability. An initial dosage rate of 3 fl. oz. /cwt (195 mL/100 kg) was selected. This addition rate is listed on the low end of the manufacturer's "Grace Construction[75]" recommended range.

The mixture was batched as previously discussed in the experimental procedure (Section 3.3). During the break period, the concrete was evaluated for flowability and stability. For the purpose of this research program, stability is defined as the resistance of SCC mixtures to the onset of segregation. Upon assessment, the mixture seemed dry and still appeared to have a slump. This mixture failed because it did not flow. The target slump flow for the mixture was anywhere within the range of 23.5 to 30.0 in. (600 to 760 mm). Figure 4.1 shows the mixture after the slump flow test was performed.

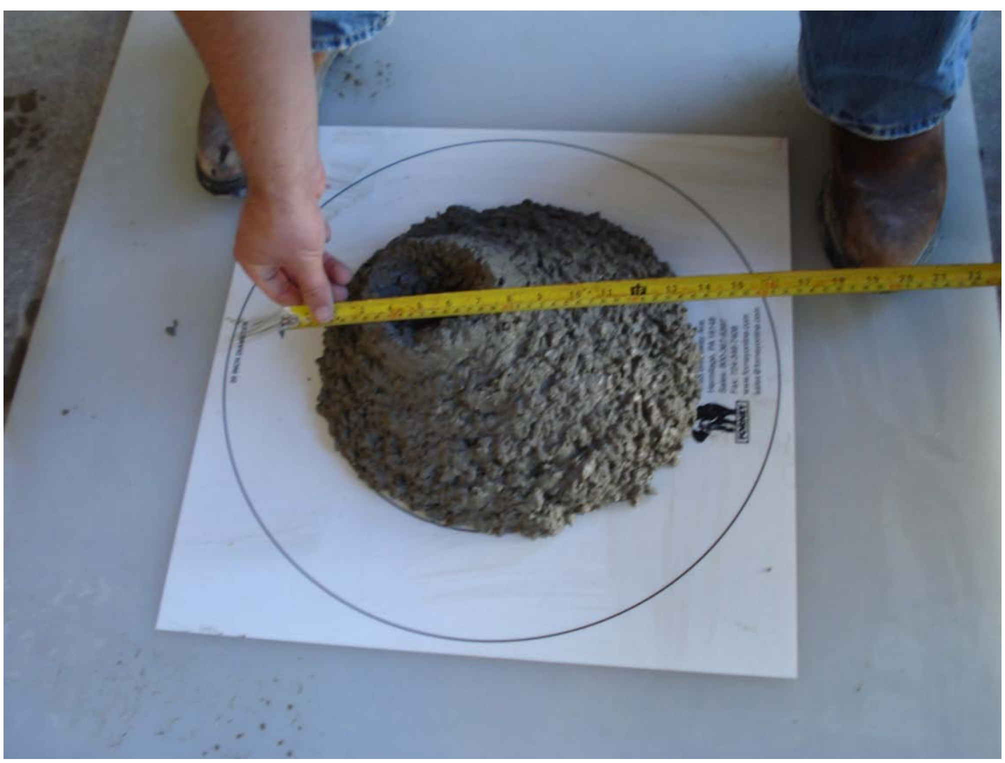

Figure 5.1: Slump Flow of the First Mixture

As can be seen in the figure, the concrete still had a slump. Consequently, the mixture was discarded.

For the second batch, the *w/b* was increased to the recommended value of 0.44. In order to account for this increase in water volume, the proportions of fine and coarse aggregate were reduced slightly. Also, to enhance the flowability, a total of 5 fl. oz. HRWR/cwt (326 mL/100 kg) was implemented. This sum consisted of 2.5 fl. oz. ADVA Cast 530/cwt (163 mL/100 kg) and 2.5 fl. oz. ADVA 170/cwt (163 mL/100 kg). All other mixture parameters were held constant. When tested, there was only a slight improvement in workability when the results were compared with those of the first mixture. This mixture also had a slump, so it was rejected.

In the next mixture, only ADVA 170 was added. A dosage rate of 5 fl. oz. /cwt (326 mL/100 kg) was incorporated in an attempt to further increase the workability of the concrete. The proportions of all additional constituents remained unchanged.

The mixture was evaluated during the break period, and upon assessment the concrete appeared thick and viscous. The slump flow test was conducted on the batch; however, it was determined that this mixture still had a slump as well. This mixture failed because the concrete did not flow.

After three SCC mixtures had been batched with unsatisfactory results, a new strategy was developed. The previous mixtures were unable to flow and self-consolidate due to an insufficient amount of water that was made available in the mix design. The *w/b* was recommended to be 0.44, so this parameter was held constant. The only other way to allow for more water during mixing was to increase the binder content.

In the fourth trial mixture, the binder content was increased from 611 lb/yd^3 (362.49 kg/m^3) to 711 lb/yd^3 (421.82 kg/m^3). To account for this increase in binder volume, the fine and coarse aggregate volumes were reduced significantly. When compared with the previous mix design it was evident that the 100 lb/yd^3 (59.33 kg/m^3) increase in binder content resulted in an increase in water content from 269 lb/yd^3 (159.59 kg/m^3) to 313 lb/yd3 (185.70 kg/m^3). This adjustment allotted for 16.36% more water to be utilized during mixing. All other design constraints were held constant.

When the mixture was evaluated during the break period it appeared workable and stable. The slump flow test was subsequently performed. The results of the test yielded a 14 in. (355.6 mm) slump flow. In addition, a VSI value equal to 1 was warranted. The concrete proved to be workable and stable, and it did not exhibit any indication of segregation or bleed water. However, because the mixture failed to acquire a slump flow that was greater than or equal to 23.5 in. (600mm), it was discarded.

For the fifth mixture, all the mixture proportions remained constant (when compared with the fourth mixture). However, the ADVA 170 dosage was increased to 7.5 fl. oz. /cwt (489 mL/100 kg); this was done to increase the mixture's flowability. When the slump flow test was conducted, segregation and bleed water were not observed. A slump flow of 18.5 in. (469.9 mm) and a VSI value of 1 were recorded. Although the additional ADVA 170 did increase the flowability of the mixture, the desired slump flow was still not acquired. Thus, this mixture also failed.

The first five mixtures complete Phase 1 of the trial batching process. The mix designs for these mixtures along with the corresponding slump flow test data are presented in Table 5.1. It is important to note that since all of these mixtures proved to be inadequate to classify as SCC, no further fresh or hardened concrete tests were performed.

Table 5.1: Phase 1 Mix Designs and Slump Flow Data

Materials	Mixtures				
	1	2	3	4	5
Total Cementitious Materials (lb/yd^3)	611	611	611	711	711
Fly Ash (%)	---	---	---	---	---
Coarse Aggregate (lb/yd^3)	1550	1527	1527	1429	1429
Fine Aggregate (lb/yd^3)	1631	1606	1606	1506	1506
Water (lb/yd^3)	251	269	269	313	313
Water/Binder	0.41	0.44	0.44	0.44	0.44
Sand/Aggregate	0.52	0.52	0.52	0.52	0.52
ADVA CAST 530 (fl oz./cwt)	3	2.5	---	---	---
ADVA 170 (fl oz./cwt)	---	2.5	5	5	7.5
ADVA CAST 575 (fl oz./cwt)	---	---	---	---	---
Fresh Concrete Properties					
Slump Flow (in.)	---	---	---	14	18.5
Segregation Observed	---	---	---	no	no
VSI	---	---	---	1	1
Bleed Water	---	---	---	no	no
T-20 (sec)	---	---	---	---	---

For the next phase of mixtures, the objective was to further improve the rheological properties. To accomplish this, the binder content was increased to 811 lb/yd^3 (481.15 kg/m^3). The methodology behind this adjustment is more thoroughly explained in the following section.

5.3.2 Phase 2 – Increasing Binder Content to 811 lb/yd^3

Since the specified binder content and ADVA 170 dosage rate for the fifth mixture (Table 4.1) were unsatisfactory, the author elected to further increase the binder content. This step was taken because the mixture's flowability needed to increase without exceeding the manufacturer's maximum recommended dosage rate of ADVA 170. Therefore, for the sixth mixture, the binder content was increased from 711 lb/yd^3 (421.82 kg/m^3) to 811 lb/yd^3 (481.15 kg/m^3). This increase in binder content decreased the fine and coarse aggregate proportions. Also, when compared with the previous mix design (mixture # 5), it was apparent that the 100 lb/yd^3 (59.33 kg/m^3) increase in binder content increased the water content from 313 lb/yd^3 (185.70 kg/m^3) to 357 lb/yd3 (211.80 kg/m^3). This adjustment allowed for 14.06% more water to be utilized during mixing. The ADVA 170 dosage rate was reduced to 5 fl. oz. /cwt (326 mL/100 kg) to diminish the likelihood of segregation occurring.

The mixture was assessed during the break period. For the first time, the concrete appeared to be fluid. The results of the slump flow test displayed a concrete spread that had no evidence of segregation or bleed water. Additionally, a slump flow of 25 in. (635 mm), a VSI value of 0, and a T-20 (T-50) of 5.37 seconds were recorded. The slump flow of mixture # 6 is presented in Figure 5.2.

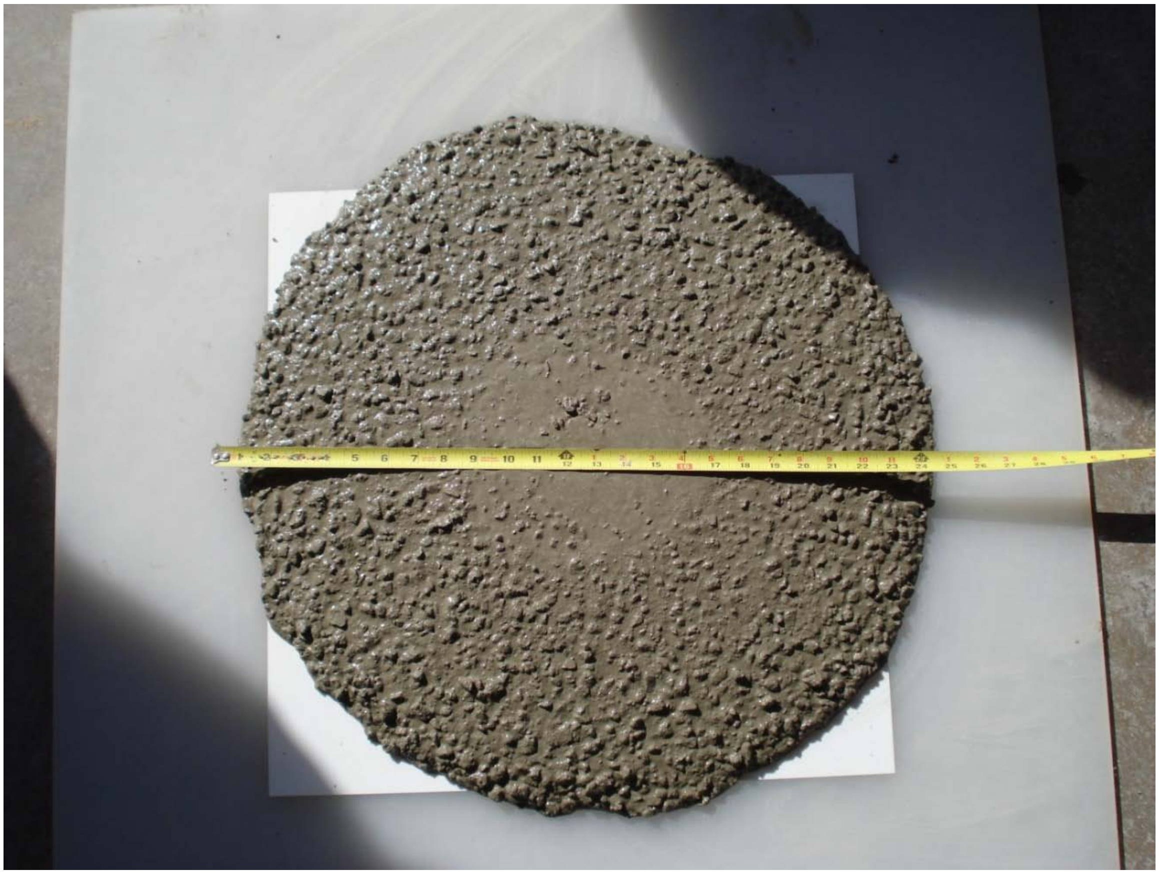

Figure 5.2: Slump Flow of Mixture # 6

Upon performing the J-Ring test, the height difference between concrete inside and outside the J-Ring was recorded to be 0 in. (0 mm), and the difference between the slump flow spread and the J-Ring spread was documented to be 1 in. (25.4 mm). Consequently, this mixture proved to be an adequate SCC mixture because all of the fresh concrete properties were consistent with those found in the literature to classify acceptable SCC mixtures.

Since the results of the fresh concrete tests indicated that this mixture was an acceptable SCC mixture, compressive strength testing was also performed to determine if the hardened properties would satisfy requirements (3500 psi, (24.0 MPa) at 28 days) present in the Standard Specifications[5]. The 1, 7, and 28-day breaks had averages of

2940, 7310, and 9490 psi (20.25, 50.37, 65.41 MPa), respectively. The 28-day strength exceeded the minimum specified compressive strength by more than 271%. Thus, it was confirmed that mixture # 6 would also develop adequate compressive strength as well.

5.3.2.1 *S/Agg*

A broad range of *S/Agg* values was recommended in the literature.[77] Therefore, the author chose to examine each one and determine the effect that it had on the properties of SCC. Seeing as the sixth mixture performed so well, the only adjustment that was made for the seventh mixture was to increase the *S/Agg* from 0.52 to 0.54. All other mixture proportions were held constant. A slump flow of 26 in. (660.4 mm) was reported. The spread did not segregate, but some bleed water was present; this justified a VSI designation equal to 1. The slump flow for this mixture is shown below in Figure 5.3.

Figure 5.3: Slump Flow of Mixture # 7

When compared with mixture # 6, the T-20 (T-50) decreased; a time of 5.16 seconds was recorded. The author attributes this to the increase in fine aggregate content which elevated the concentration of fine particles and resulted in a more fluid transition through the outlet of the inverted slump cone. The results of the J-Ring test showed the height difference between concrete inside and outside the J-Ring to be 0.5 in. (12.7 mm), and the difference between the slump flow spread and the J-Ring spread was reported to be 2.5 in. (63.5 mm). Finally, mixture # 7 developed strength in compression that was similar to mixture # 6. The average 28-day compressive strength was 9680 psi (66.73 MPa). Accordingly, mixture # 7 was also established to be an acceptable SCC mixture.

For mixture # 8, the *S/Agg* was further increased to 0.56. All the other mixture design parameters remained the same. This mixture had a slump flow equal to 27.5 in. (698.5 mm), which was an increase compared with that of mixture # 7. However, the slump flow patty had visibly segregated; a small aggregate pile was present in the center of the spread and a small mortar halo was displayed around the perimeter of the spread. Hence, a VSI value of 2 was given for the mixture. The T-20 (T-50) value decreased to 4.53 seconds; the author attributes this to the same phenomenon described in the previous paragraph. The J-Ring test confirmed that segregation had occurred as well. The height difference between concrete inside and outside the J-Ring increased to 1 in. (25.4 mm), and the difference between the slump flow spread and the J-Ring spread increased to 4 in. (101.6 mm). The recorded 28-day compressive strength was 7880 psi (54.30 MPa). When compared with the 28-day compressive strength of mixture # 7 that is a reduction of 18.63%. The author believes that the reduction in strength is directly related to the segregation that occurred. As a result of the segregation, this mixture was proven to be inadequate.

In the ninth mixture, the *S/Agg* was decreased from the initial starting point of 0.52 to 0.50. The other mixture proportions remained unchanged. The slump flow for this mixture was 25.5 in. (647.7 mm), and the T-20 (T-50) time was 6.03 seconds. No visible segregation or bleed water was present, so a VSI of 0 was issued. The results of the J-Ring test indicated that the blockage potential of the mixture was not significant. Also, the 28-day compressive strength for this mixture was 9380 psi (64.65 MPa). Therefore, this mixture was validated as a suitable SCC mixture.

For mixture # 10, the *S/Agg* was further decreased to a value of 0.48. All the other mixture constituents were held constant. A slump flow of 23.5 in. (596.9 mm) was documented, and the measured T-20 (T-50) time was 4.89 seconds. The mixture did not segregate, but a small amount of bleed water was present across the slump flow spread; this rationalized a VSI value of 1. The height difference between concrete inside and outside the J-Ring was 0.75 in. (19.05 mm), and the difference between the slump flow spread and the J-Ring spread was 2.5 in. (63.5 mm); these results signified that this mixture had slight to moderate blockage potential. In addition, the average 28-day compressive strength was 9610 psi (66.23 MPa). Mixture # 10 was classified as a passable SCC mixture. However, the blockage potential of the mixture was a cause for concern.

The trend of decreasing the *S/Agg* continued in mixture # 11. For this mixture, the S/Agg that was utilized was 0.46. The other mixture proportions did not change. The measured slump flow was 22 in. (558.8 mm). While the spread did not segregate, it did have more bleed water than was present in mixture # 10. Therefore, the spread was designated a VSI equal to 1.5. The T-20 (T-50) time measured was 7.64 seconds; this was a significant increase in time from the T-20 (T-50) of mixture # 10 considering that the slump flow for mixture # 11 was smaller in diameter. The author believes that the increase in coarse aggregate content (which occurred by decreasing the *S/Agg*) is the reason why it took longer for the slump flow to reach a diameter of 20 in. (50 cm). The quantity of larger particles present decreased the amount of fines within the mixture, which caused more congestion at the outlet of the inverted slump cone during the slump flow test. While the concrete mixture was flowable, it did not acquire the flowability necessary to classify it as SCC. Therefore, the J-Ring test and compressive strength testing were not conducted for mixture # 11.

5.3.2.2 Flowability

In the twelfth mixture, the *S/Agg* and all the other mixture components with the exception of the ADVA 170 dosage were held constant. For this mixture, the objective was to enhance the flowability. Therefore, the ADVA 170 dosage rate was increased to 6 fl. oz. /cwt (391.19 mL/100 kg).

The results of the slump flow test were surprising. The slump flow did increase to 26.5 in. (673.1 mm). However, the spread had clearly segregated. A large aggregate pile was located in the center of the concrete mass, and a considerable mortar halo had developed around the entire perimeter of the spread. Hence, a VSI value of 3 was given to the mixture. The recorded T-20 (T-50) time was 9.07 seconds. The author attributes this lengthy T-20 (T-50) measurement to the severe segregation that occurred between the aggregates and the cement paste. Within the inverted slump cone, the concrete diffused into two sections; the aggregates sank to the bottom while the cement paste rested above it. When the slump cone was initially lifted, blockage had occurred at the outlet. It took a few seconds for the weight of the cement paste to take effect and unclog the outlet, but once the outlet had been cleared the cement paste was able to flow out with ease.

The height difference between concrete inside and outside the J-Ring was 1.25 in. (31.75 mm), and the difference between the slump flow spread and the J-Ring spread was 1 in. (25.4 mm); these results indicated that this mixture had severe blockage potential. The majority of aggregate particles were stacked up inside the J-Ring, while most of the cement paste was able to flow around the deformed bars.

Mixture # 12 acquired an average 28-day compressive strength of 7490 psi (51.63 MPa). The results of the compressive strength testing regimen were significantly lower than previous mixtures' that were batched with the same *w/b* and binder content. This is likely due to the occurrence of segregation, which ultimately led to this mixture failing to qualify as an acceptable SCC mixture. The cylinders that were broken at twenty-eight days of age are displayed in Figure 5.4 below. As can be seen in the photograph, numerous bug holes are present on each of the three cylinders. The author also attributes this occurrence to segregation.

Figure 5.4: Compressive Strength Cylinders for Mixture # 12 at 28 Days

The author decided that for mixture # 13 the *S/Agg* would be decreased to 0.44. The other mixture design constraints did not change from those used in mixture # 12. The results of the slump flow test yielded a spread of 23 in. (584.2 mm). The spread had no evidence of segregation or bleed water, so a VSI value of 0 was granted. The T-20 (T-50) measurement was 6.57 seconds. This mixture was flowable; however, since the spread failed to reach the desired diameter of at least 23.5 in. (596.9 mm), the mixture failed. For that reason, the mixture was discarded and no further tests were performed.

The only modification that was made in mixture # 14 was that 7 fl. oz. ADVA 170/cwt (456.39 mL/100 kg) was incorporated. This increase in HRWR increased the slump flow spread to 28.5 in. (723.9 mm). However, upon viewing the spread, it was apparent that the mixture had segregated; an aggregate pile was present in the center of the spread and a large mortar halo had formed around the perimeter. Therefore, a VSI value of 3 was issued. The recorded T-20 (T-50) time was 11.44 seconds. The author expects that the extended spread time occurred due to the same incident (segregation) that transpired in mixture # 12.

The height difference between concrete inside and outside the J-Ring was 1.5 in. (38.1 mm), and the difference between the slump flow spread and the J-Ring spread was 3.5 in. (88.9 mm). Due to severe segregation, it was clear that this mixture was susceptible to blockage problems.

The average 28-day compressive strength for mixture # 14 was 7130 psi (49.18 MPa). Although segregation had reduced the strength of the concrete, the cylinders were still able to acquire strengths that exceeded the minimum by more than 203%. Nevertheless, due to the blockage concerns associated with the fresh concrete properties, this mixture failed to classify as an acceptable SCC.

The nine aforementioned mixtures complete Phase 2 of the trial batching process. The mix designs for these mixtures along with the subsequent slump flow, J-Ring, and compressive strength data are displayed in Table 5.2.

Table 5.2: Phase 2 Mix Designs and Test Results

Materials	Mixtures								
	6	7	8	9	10	11	12	13	14
Total Cementitious Materials (lb/yd^3)	811	811	811	811	811	811	811	811	811
Fly Ash (%)	---	---	---	---	---	---	---	---	---
Coarse Aggregate (lb/yd^3)	1332	1277	1222	1388	1443	1499	1499	1554	1554
Fine Aggregate (lb/yd^3)	1402	1455	1509	1347	1294	1240	1240	1186	1186
Water (lb/yd^3)	357	357	357	357	357	357	357	357	357
Water/Binder	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
Sand/Aggregate	0.52	0.54	0.56	0.5	0.48	0.46	0.46	0.44	0.44
ADVA CAST 530 (fl oz./cwt)	---	---	---	---	---	---	---	---	---
ADVA 170 (fl oz./cwt)	5	5	5	5	5	5	6	6	7
ADVA CAST 575 (fl oz./cwt)	---	---	---	---	---	---	---	---	---
Fresh Concrete Properties									
Slump Flow (in.)	25	26	27.5	25.5	23.5	22	26.5	23	28.5
Segregation Observed	no	no	yes	no	no	no	yes	no	yes
VSI	0	1	2	0	1	1.5	3	0	3
Bleed Water	no	yes	yes	no	yes	yes	yes	no	yes
T-20 (sec)	5.37	5.16	4.53	6.03	4.89	7.64	9.07	6.57	11.44
Δh^* (in.)	0	0.5	1	0.5	0.75	---	1.25	---	1.5
Slump Flow Spread - J-Ring Spread (in.)	1	2.5	4	2	2.5	---	1	---	3.5
Compressive Strength									
1-day strength (psi)	2940	3020	2190	2660	2720	---	2010	---	1860
7-day strength (psi)	7310	7360	5910	6940	7010	---	5920	---	5350
28-day strength (psi)	9490	9680	7880	9380	9610	---	7490	---	7130

Δh*: height difference between concrete inside and outside the J-Ring

Several acceptable SCC mixtures were developed in Phase 2. However, it is important to note that mixtures having *S/Agg* of 0.44, 0.46, and 0.56 were not able to classify as SCC. Therefore, these *S/Agg* values were no longer utilized during trial batching. For the next phase of mixtures, the objective was to successfully develop SCC mixtures with lower binder contents. This process is explained more clearly in the following section.

5.3.3 Phase 3 – Reducing Binder Content to 761 lb/yd^3

In Phase 3 of the trial batching process the author began to narrow the search for the minimum binder content at which SCC can be developed. Specifically, the binder content was reduced to 761 lb/yd^3 (451.48 kg/m^3). This value was selected because it was midway between the two binder contents that were previously implemented (711 lb/yd^3 (421.82kg/m^3) and 811 lb/yd^3 (481.15 kg/m^3)).

In mixture # 15, an *S/Agg* value equal to 0.48 was used. Additionally, 5 fl. oz. ADVA 170 /cwt (326 mL/100 kg) was added during batching. When tested the concrete attained a slump flow of 19.5 in. (495.3 mm). The spread was uniform and stable. However, since the concrete did not acquire sufficient flowability, the mixture was proven to be inadequate. No further tests were performed on this mixture. The slump flow spread for this mixture can be viewed in Figure 5.5.

Figure 5.5: Slump Flow of Mixture # 15

For the next mixture it was desired for the concrete to have more flowability. To accomplish this, the ADVA 170 dosage rate was increased to 6 fl. oz. /cwt (391.19 mL/100 kg). The other mixture constituents were held constant. This mixture developed a slump flow of 22 in. (558.8 mm). A slight amount of bleed water was observed as sheen on the concrete spread, so a VSI value of 1 was issued. The measured T-20 (T-50) time was 5.49 seconds. When compared with the previous mixture it was evident that the concrete was more flowable, but it still did not reach the minimum specified slump flow spread diameter of 23.5 in. (596.9 mm). Hence, this mixture failed to qualify as an adequate SCC mixture and no additional tests were conducted.

It was apparent that the concrete needed to be more flowable, so in mixture # 17 the addition rate of ADVA 170 was further increased to 7 fl. oz. /cwt (456.39 mL/100 kg). After batching, fresh concrete tests were performed. The slump flow was 27.5 in. (698.5 mm), but the spread was elliptical in shape rather than circular. The two perpendicular measurements recorded were 25.5 in. (647.7 mm) and 29.5 in. (749.3 mm).Upon assessing the spread for uniformity and stability, segregation was observed. A small aggregate mound was present in the center of the concrete mass, and bleed water surrounded the entire circumference of the spread. Therefore, the mixture was assigned a VSI value equal to 2. The T-20 (T-50) time was 4.68 seconds.

Unlike the irregular elliptical shape of the slump flow spread, the J-Ring flow spread was circular as expected. After comparing the two spreads, the author attributes the asymmetry of the slump flow spread to operator error. It is expected that the slump cone was lifted at a slight angle, which caused the concrete to flow through the outlet at an uneven rate. The height difference between concrete inside and outside the J-Ring was 1.25 in. (31.75 mm), and the difference between the slump flow spread and the J-Ring spread was 2.5 in. (63.5 mm). These results indicated that the mixture had moderate blockage potential.

The average 28-day compressive strength was 7010 psi (48.34 MPa). However, as a result of the segregation that occurred, this mixture did not qualify as an acceptable SCC mixture.

In mixture # 18, the only alteration made to the mix design was to increase the *S/Agg* to 0.50. After mixing, fresh concrete tests were performed on the concrete. This mixture acquired an acceptable slump flow of 24.5 in. (622.3 mm), but severe segregation was observed. As a result, a VSI value of 3 was assigned to the mixture. The author found it perplexing that a concrete mixture with such a low slump flow could experience such excessive segregation. The concrete appeared dry, so a possible reason as to why this incident occurred was that the mixture was not given enough time to mix properly. An extended mixing time would have diminished the amount of flocculated cement particles by enabling the HRWR to be dispersed in a more uniform manner. Additionally, a T-20 (T-50) time of 3.58 seconds was recorded for the mixture.

The height difference between concrete inside and outside the J-Ring was 1.50 in. (38.1 mm), and the difference between the slump flow spread and the J-Ring spread was 4.5 in. (114.3 mm). These measurements indicate that blockage is likely to occur for this mix design.

The average 28-day compressive strength yielded a satisfactory value of 7830 psi (54 MPa). Yet since the mixture had segregated, it did not qualify as an SCC mixture.

For the 19th mixture, the author elected to make the following changes to the previous mix design: increase the *S/Agg* to 0.52 and decrease the ADVA 170 dosage rate to 5 fl. oz. /cwt (326 mL/100 kg). These changes resulted in a reduced slump flow of 19 in. (482.6 mm), but the slump flow patty showed no evidence of segregation. Nevertheless, the concrete could not be classified as an SCC mixture due to its limited flowability, and no supplementary concrete tests were conducted on this mixture.

An increase in flowability was desired for the next mixture. To accomplish this, the addition rate of ADVA 170 was increased to 7 fl. oz. /cwt (456.39 mL/100 kg). This adjustment in the amount of HRWR present in the mixture increased the slump flow to 29 in. (736.6 mm). Segregation was not a concern in this mixture, but a small amount of bleed water was present across the spread. A VSI value equal to 1 was given to this mixture, and the recorded T-20 (T-50) time was 4.13 seconds.

There was not a measurable height difference between concrete inside and outside the J-Ring, and there was also no disparity between the slump flow spread and the J-Ring spread. These results confirm that the segregation potential for this mixture is incredibly low. The J-Ring flow spread is exhibited below in Figure 5.6.

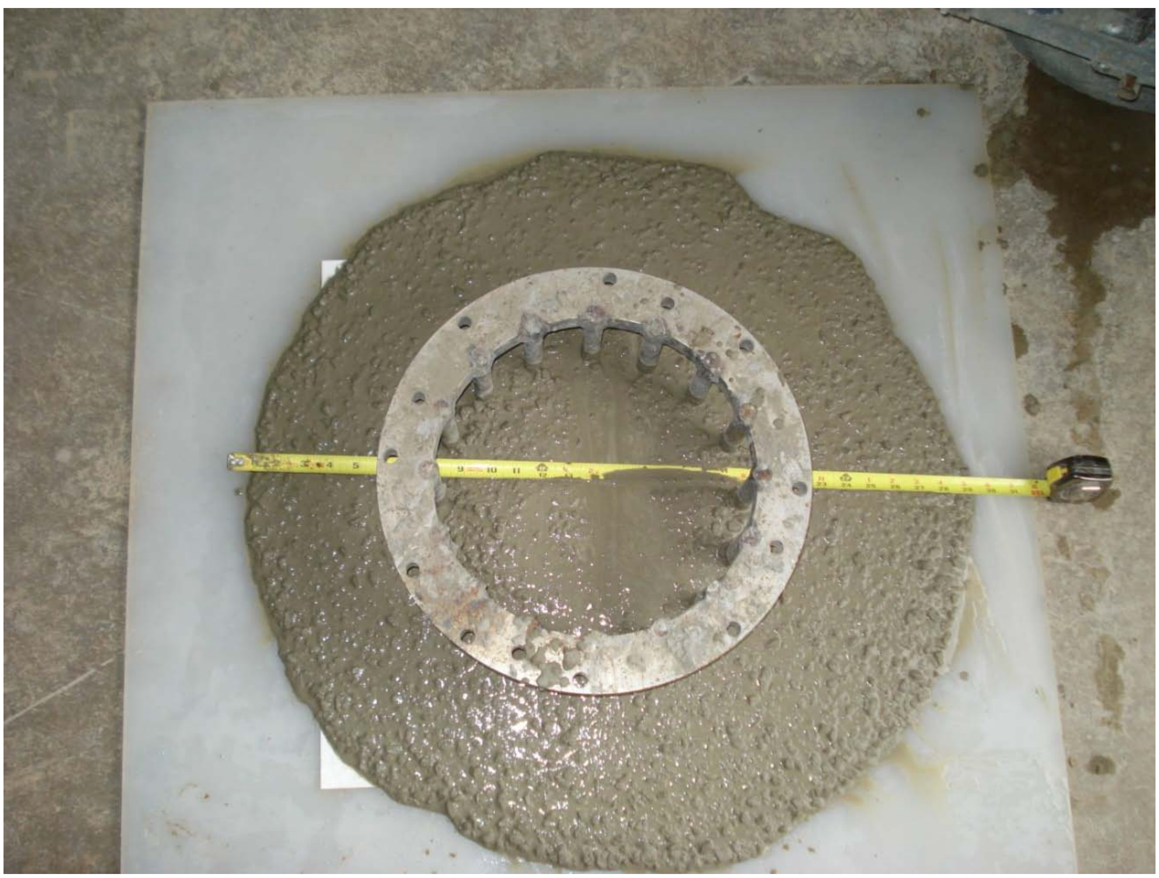

Figure 5.6: J-Ring Flow Spread of Mixture # 20

An average 28-day compressive strength of 8330 psi (57.43 MPa) verified that the hardened properties of this mixture were adequate. As a result, mixture # 20 qualified as an acceptable SCC mixture.

One final mixture was batched in Phase 3. For this mixture, the *S/Agg* was further increased to 0.54. All the other mixture components remained unchanged. Increasing the *S/Agg* value yielded a slump flow of 29 in. (736.6 mm), although segregation did occur. An aggregate pile was present in the center of the spread, and a considerable mortar halo had developed around the perimeter. Seeing this justified a VSI designation equal to 2. Also, the measured T-20 (T-50) time was 4.04 seconds.

After the slump flow test was completed, the J-Ring test was performed. The height difference between concrete inside and outside the J-Ring was 0.25 in. (6.35 mm), and the difference between the slump flow spread and the J-Ring spread was 1.75 in. (44.45 mm). These results suggest that even though segregation had occurred, blockage problems would likely not be a concern due to the excessive fluidity of the mixture.

Mixture # 21 acquired an average 28-day compressive strength of 7190 psi (49.59 MPa). Despite the fact that this value exceeded the minimum specified compressive strength with ease, the unsatisfactory fresh concrete properties (segregation) kept this mixture from being classified as a sufficient SCC mixture.

The seven abovementioned mixtures complete Phase 3 of trial batching. The detailed mix designs along with the corresponding slump flow, J-Ring, and compressive strength test results are presented in tabular form in Table 5.3.

Table 5.3: Phase 3 Mix Designs and Test Results

Materials	Mixtures						
	15	16	17	18	19	20	21
Total Cementitious Materials (lb/yd^3)	761	761	761	761	761	761	761
Fly Ash (%)	---	---	---	---	---	---	---
Coarse Aggregate (lb/yd^3)	1496	1496	1496	1439	1380	1380	1324
Fine Aggregate (lb/yd^3)	1341	1341	1341	1397	1454	1454	1509
Water (lb/yd^3)	335	335	335	335	335	335	335
Water/Binder	0.44	0.44	0.44	0.44	0.44	0.44	0.44
Sand/Aggregate	0.48	0.48	0.48	0.5	0.52	0.52	0.54
ADVA CAST 530 (fl oz./cwt)	---	---	---	---	---	---	---
ADVA 170 (fl oz./cwt)	5	6	7	7	5	7	7
ADVA CAST 575 (fl oz./cwt)	---	---	---	---	---	---	---
Fresh Concrete Properties							
Slump Flow (in.)	19.5	22	27.5	24.5	19	29	29
Segregation Observed	no	no	yes	yes	no	no	yes
VSI	0	1	2	3	1	1	2
Bleed Water	no	yes	yes	yes	no	yes	yes
T-20 (sec)	---	5.49	4.68	3.58	---	4.13	4.04
Δh^* (in.)	---	---	1.25	1.5	---	0	0.25
Slump Flow Spread - J-Ring Spread (in.)	---	---	2.5	4.5	---	0	1.75
Compressive Strength							
1-day strength (psi)	---	---	1870	1900	---	2510	1800
7-day strength (psi)	---	---	5260	5780	---	6160	5470
28-day strength (psi)	---	---	7010	7830	---	8330	7190

Δh^*: height difference between concrete inside and outside the J-Ring

In Phase 3 of trial batching only one mixture was established as a suitable SCC mixture. Mixture # 21 contained an S/Agg equal to 0.54, but it did not have desirable fresh concrete properties. Consequently, the author elected to not implement this ratio in future mixtures. Previous research conducted at the University of Arkansas[77] concluded that SCC mixtures were able to be batched with *S/Agg* values varying from 0.44 to 0.56. However, due to unsatisfactory fresh concrete properties, only the central portion of this range was implemented for the remaining mixtures (0.48 – 0.52).

With the exception of one mixture, Phase 4 of trial batching focused on developing SCC mixtures at even lower binder contents. A new type of HRWR was also introduced during this phase. The reasoning for this is explained in greater detail in the following section.

5.3.4 Phase 4 – Further Reducing Binder Content to 750 lb/yd^3

The first mixture batched in Phase 4 was the outlier of the group. A binder content of 786 lb/yd^3 (466.32 kg/m^3) was utilized. This value was chosen because Phase 3 proved to be futile as a whole, and the binder content was halfway between the previous binder content (761 lb/yd^3 (451.48 kg/m^3)) and the highest overall binder content that was used (811 lb/yd^3 (481.15 kg/m^3)). When compared with mixture # 20, the coarse and fine aggregate proportions were decreased and the water content was increased to account for the increase in binder content. This mixture was batched with an *S/Agg* equal to 0.52 and 5 fl. oz. ADVA 170 /cwt (326 mL/100 kg) was incorporated to promote flowability.

The mixture was observed during the break period. It flowed well, but it appeared and felt viscous. The author elected not to add any additional ADVA 170 at this time because it was believed that the concrete would become susceptible to segregation.

Batching continued for a few more minutes and then the fresh concrete properties were evaluated.

A slump flow of 22 in. (558.8 mm) was measured. The mixture did not segregate, and only negligible bleed water was present so a VSI value of 0.5 was issued. The recorded T-20 (T-50) time was an acceptable 4.37 seconds; however, mixture # 22 was rejected because it did not acquire the desired flowability.

For mixture # 23 and all of the remaining mixtures in Phase 4, a binder content of 750 lb/yd^3 (444.96 kg/m^3) was used, an *S/Agg* equal to 0.52 was utilized, and ADVA Cast 575 was introduced as the HRWR source. ADVA Cast 575 replaced ADVA 170 because it can be used to produce concrete mixtures with low *w/cm* while preserving desirable workability characteristics. Also, ADVA Cast 575 is better formulated to combat segregation.

Mixture # 23 was batched with an ADVA Cast 575 dosage rate of 7 fl. oz. /cwt (456.39 mL/100 kg) as a starting point. This resulted in a measured slump flow of 23 in. (584.2 mm). Since the mixture did not achieve the required flowability, it was rejected. However, the concrete appeared stable; it did not segregate and minimal bleed water was present. It was apparent that in order to enhance the flowability of the next mixture, more HRWR would need to be added.

For the next mixture, the addition rate of ADVA Cast 575 was increased to 9 fl. oz. /cwt (586.79 mL/100 kg). All the other mixture proportions were held constant. The extra HRWR did not, however, result in an increase in slump flow. A value of 23 in. (584.2 mm) was recorded. As was the case in the previous mixture, no segregation was observed and only a small amount of bleed water was present. Nevertheless, since the mixture failed to attain the desired flow, it was unable to qualify as SCC.

In mixture # 25, the author decided to decrease the ADVA Cast 575 dosage rate to 3 fl. oz. /cwt (195.60 mL/100 kg). This change was made to assess how sensitive the concrete would be to this polycarboxylate-based HRWR. A smaller amount of HRWR was expected to make the concrete more viscous; however, severe segregation was observed when the slump flow test was performed. The recorded slump flow measurement was 25 in. (635 mm), but the T-20 (T-50) test took 12.50 seconds to complete. The author attributes such a lengthy T-20 (T-50) time to the blockage that occurred at the outlet of the inverted slump cone.

In addition to the segregation that was observed while performing the slump flow test, the J-Ring test also displayed segregation. The two recorded J-Ring measurements indicated that the blockage potential for this mixture was extremely high as well. Figure 5.7 illustrates the blockage that occurred.

Figure 5.7: J-Ring Flow Spread of Mixture # 25

The cylinders acquired an average 28-day compressive strength of 6840 psi (47.19 MPa). This was the lowest value computed for any of the trial batches so far in this research program. The author believes that this occurred for two reasons. First, compressive strength data had not been determined for concrete mixtures containing lower binder contents than 750 lb/yd^3 (444.96 kg/m^3). Also, the segregation experienced by the concrete reduced the compressive strength. As a result of the segregation and blockage that occurred, the mixture did not meet the criteria to qualify as an SCC mixture.

The results of the fresh concrete tests performed on the previous mixture did not make sense to the author given the amount of HRWR that was present in the mixture. So for the next mixture, the opposite end of the HRWR dosage range was selected to analyze the effect on the concrete. In this mixture, 12 fl. oz. /cwt (782.38 mL/100 kg) was utilized during batching. It was anticipated that adding such a large quantity of HRWR would cause segregation. Segregation did occur, but the slump flow spread only reached an average diameter of 23 in. (584.2 mm). The author predicted that the slump flow measurement would exceed 30 in. (762 mm) due to such a high dosage rate of ADVA Cast 575. When compared with the previous mixture, it was evident that mixture # 26 was more viscous even though 9 more fl. oz. /cwt (586.79 mL/100 kg) was added. There were no logical explanations. Regardless, the fresh concrete properties did not meet the essential requirements so the mixture was eliminated from consideration. Compressive strength testing was not conducted on this mixture because of the limited flowability.

At this point, the author began to suspect that the binder content might be the problem. A mixture that contains a binder content that is too low will not flow well without segregating. For mixture # 27, the ADVA Cast 575 dosage rate was reduced to 10.5 fl. oz. /cwt (684.58 mL/100 kg) to see what the effect would be. After mixing had concluded, the slump flow test was performed. A T-20 (T-50) time of 11.25 seconds was recorded along with a maximum spread of 28.5 in. (723.9 mm). As was the case with the previous two mixtures, this mixture also experienced segregation. Therefore, a VSI value of 3 was assigned.

After the slump flow test was concluded, the J-Ring test was executed. The height difference between concrete inside and outside the J-Ring was 1.0 in. (25.4 mm), and the difference between the slump flow spread and the J-Ring spread was 2.50 in. (63.5 mm). These measurements suggested that the mixture had moderate blockage potential.

Even though the fresh concrete properties of this mixture were already proven to be inadequate, compressive strength testing was still performed to assess if the hardened properties were sufficient. The average 28-day compressive strength of 8170 psi (56.32 MPa) was acceptable.

The author chose to batch one more mixture in this phase. For this final mixture, the addition rate of HRWR was slightly reduced to 10 fl. oz. /cwt (651.98 mL/100 kg). The other mixture proportions did not change. Once mixing was finished, the concrete was poured into a wheelbarrow and the fresh concrete properties were evaluated.

The slump flow test yielded a T-20 (T-50) of 8.18 seconds, a maximum spread of 23 in. (584.2 mm), and a VSI designation equal to 2. Segregation did occur, but it was not as severe a case as had been viewed in the previous three mixtures. At any rate, the mixture was still rejected from consideration because the concrete did not acquire adequate flowability, and the mixture experienced segregation. In addition, compressive strength testing was not performed due to the inability of the concrete to flow effectively.

The seven mixtures that were previously described complete Phase 4 of trial batching. The mix designs for these mixtures are exhibited along with the related slump flow, J-Ring, and compressive strength data in Table 5.4 below.

Table 5.4: Phase 4 Mix Designs and Test Results

Materials	Mixtures						
	22	23	24	25	26	27	28
Total Cementitious Materials (lb/yd^3)	786	750	750	750	750	750	750
Fly Ash (%)	---	---	---	---	---	---	---
Coarse Aggregate (lb/yd^3)	1357	1392	1392	1392	1392	1392	1392
Fine Aggregate (lb/yd^3)	1428	1465	1465	1465	1465	1465	1465
Water (lb/yd^3)	346	330	330	330	330	330	330
Water/Binder	0.44	0.44	0.44	0.44	0.44	0.44	0.44
Sand/Aggregate	0.52	0.52	0.52	0.52	0.52	0.52	0.52
ADVA CAST 530 (fl oz./cwt)	---	---	---	---	---	---	---
ADVA 170 (fl oz./cwt)	5	---	---	---	---	---	---
ADVA CAST 575 (fl oz./cwt)	---	7	9	3	12	10.5	10
Fresh Concrete Properties							
Slump Flow (in.)	22	23	23	25	23	28.5	23
Segregation Observed	no	no	no	yes	yes	yes	no
VSI	0.5	0.5	0.5	3	3	3	2
Bleed Water	no	no	no	yes	yes	yes	no
T-20 (sec)	4.37	3.1	3.89	12.5	15.23	11.25	8.18
Δh^* (in.)	---	0.5	1.5	1.5	1.25	1	1.25
Slump Flow Spread - J-Ring Spread (in.)	---	---	---	3.5	---	2.5	---
Compressive Strength							
1-day strength (psi)	---	---	---	1710	---	1960	---
7-day strength (psi)	---	---	---	5270	---	5960	---
28-day strength (psi)	---	---	---	6840	---	8170	---

Δh^*: height difference between concrete inside and outside the J-Ring

In Phase 4 of trial batching, none of the mixtures satisfied the necessary criteria to qualify for an SCC mixture. The author believes that this trend transpired because the binder content was too low. Regardless of the HRWR dosage rate, every mixture was either too viscous and did not acquire enough flowability, or it experienced segregation. For the next set of mixtures, the binder content was increased. This adjustment was made for two reasons. An increase in binder content would promote flowability by elevating the amount of fine particles within each mixture. Also, an increase in binder content would allow for more water to be utilized during mixing; this in turn, would also encourage the concrete to flow. A thorough discussion of each mixture is presented in the following section.

5.3.5 Phase 5 – Increasing Binder Content to 775 lb/yd^3 and Setting *S/Agg* Equal to 0.52

In this phase of mixing, the binder content was increased to 775 lb/yd^3 (459.79 kg/m^3), and the *S/Agg* was set at a value of 0.52. Four mixtures were batched, and the only variance between them is that they were batched with different dosage rates of ADVA Cast 575.

For mixture # 29, 7 fl. oz. HRWR /cwt (456.39 mL/100 kg) was added during mixing. The concrete appeared uniform and it possessed a high degree of fluidity when it was evaluated during the break period. After mixing was concluded, the slump flow test was performed.

A T-20 (T-50) time of 5.07 seconds was measured along with a maximum slump flow spread of 28.5 in. (723.9 mm). The spread did not show any signs of segregation, and only a slight amount of bleed water was present. Hence, a VSI value of 1 was given for this mixture.

The measurements related to the J-Ring test were desirable as well; a height difference between concrete inside and outside the J-Ring was recorded to be 0.25 in. (6.35 mm), and the difference between the slump flow spread and the J-Ring spread was 2.0 in. (50.8 mm). These results signified that the concrete could flow through and around obstructions with ease.

Since the fresh concrete properties were satisfactory, the hardened concrete properties were also tested for adequacy. The average 1, 7, and 28-day compressive strengths were reported to be 2590, 6470, and 8620 psi (17.84, 44.60, 59.45 MPa), respectively. As the 28-day compressive strength exceeded the value stipulated in the Standard Specifications[5] (3500 psi, 24.13 MPa) by more than 246%, mixture # 29 was recommended for use as an SCC mixture. Figure 5.8 shows a cylinder that was cast from this mixture and tested in compression at twenty-eight days of age.

Figure 5.8: 28-Day Compressive Strength Testing on Cylinder Cast from Mixture # 29

In mixture # 30, the ADVA Cast 575 addition rate was reduced to 6 fl. oz. /cwt (391.19 mL/100 kg). The author decided to decrease the amount of HRWR incrementally so that the fresh concrete results obtained could be compared with those of the previous mixture. When the mixture was assessed during the break period, evidence of segregation was present. The final mixing segment was extended in an attempt to make the concrete more homogeneous. However, once the slump flow test was operated, it was obvious that segregation was still present.

A T-20 (T-50) time of 1.37 seconds was measured. By looking at the concrete, it was evident that the cement paste had almost completely separated from the aggregates. The aggregates created a pile in the center of the spread, and the excess paste took shape as a disproportionate mortar halo. The maximum slump flow spread was 32.5 in. (825.5 mm); this was the largest value measured thus far in this research program.

The results of the J-Ring test suggested that the probability that blockage would occur for the mixture was low. However, these findings were deceiving. The cement paste was able to flow around the simulated rebar effortlessly because it was extremely fluid, but the aggregates created a massive mound that did not spread out so far as to reach the inside circumference of the J-Ring. This is why the height difference between concrete inside and outside the J-Ring was recorded to be 0 in. (0 mm).

Mixture # 30 failed to qualify as an SCC mixture due to its undesirable fresh concrete properties. Regardless, the author decided to conduct compressive strength testing. Twenty-eight days after batching, the compressive strength was 7210 psi (49.73 MPa).

When the fresh concrete properties of this mixture were compared with those of the previous mixture, the findings did not follow a logical trend. A decrease in the quantity of HRWR was expected to lower the slump flow spread, not enlarge it by 4 in. (101.6 mm). Also, if segregation were to occur, the mixture was anticipated to be exceptionally viscous rather than remarkably fluid. The author considers that this disparity among the results is due to an extreme difference in aggregate moisture. Prior to batching mixture # 29, the weather was clear for the previous two days and no precipitation had accumulated. On the other hand, the day before mixture # 30 was batched, it had rained heavily. Therefore, when the aggregates were shoveled into buckets and placed inside overnight, excess water had coated the aggregates. This type of occurrence is routinely accounted for by decreasing the amount of water added during mixing. However, it is possible that a significant portion of the excess water that encompassed the aggregates could have collected at the bottom of the bucket and was included during mixing.

For the next mixture, the dosage rate of ADVA Cast 575 was further reduced to 5 fl. oz. /cwt (326 mL/100 kg). It was expected that this mixture would produce desirable or at least analogous results to those of mixture # 29. When the concrete was viewed during the break period, it flowed well but felt slightly viscous to the touch.

After the slump flow test was performed, a T-20 (T-50) time of 6.19 seconds was recorded along with an average maximum spread of 21.5 in. (546.1 mm). The concrete was fluid, but it did not acquire the necessary flowability to be classified as SCC. The consistency of the spread was uniform though; it showed no signs of segregation or bleed water, so a VSI value of 0 was granted. The slump flow for this mixture is presented in Figure 5.9.

Figure 5.9: Slump Flow of Mixture # 31

Although the results of the slump flow test were adverse, they did make sense. A reduction in the amount of HRWR increased the T-20 (T-50) time and decreased the average slump flow spread by making the mixture more viscous.

Given the previous trend that was established, it was palpable that the addition rate of HRWR needed to increase. In mixture # 32, the ADVA Cast 575 dosage rate was increased to 5.5 fl. oz. /cwt (358.59 mL/100 kg). When the mixture was evaluated inside the mixer, the concrete appeared to be fluid but it felt thick. The decision was made to not add any more HRWR to the mixture at this time, because it was believed that doing so would cause the concrete to segregate.

When the slump flow test was run, a T-20 (T-50) time of 5.71 seconds was measured. Also, the maximum spread was 21 in. (533.4 mm). Since the slump flow diameter did not reach the minimum established value of 23.5 in. (596.9 mm), mixture # 32 did not meet the criteria to qualify for SCC. Due to such a low recorded slump flow measurement, compressive strength testing was not performed.

The four preceding mixtures conclude Phase 5 of trial batching. The mix designs for these mixtures combined with the appropriate slump flow, J-Ring, and compressive strength information are presented in Table 5.5.

Table 5.5: Phase 5 Mix Designs and Test Results

Materials	Mixtures			
	29	30	31	32
Total Cementitious Materials (lb/yd^3)	775	775	775	775
Fly Ash (%)	---	---	---	---
Coarse Aggregate (lb/yd^3)	1367	1367	1367	1367
Fine Aggregate (lb/yd^3)	1439	1439	1439	1439
Water (lb/yd^3)	341	341	341	341
Water/Binder	0.44	0.44	0.44	0.44
Sand/Aggregate	0.52	0.52	0.52	0.52
ADVA CAST 530 (fl oz./cwt)	---	---	---	---
ADVA 170 (fl oz./cwt)	---	---	---	---
ADVA CAST 575 (fl oz./cwt)	7	6	5	5.5
Fresh Concrete Properties				
Slump Flow (in.)	28.5	32.5	21.5	21
Segregation Observed	no	yes	no	no
VSI	1	3	0	0
Bleed Water	no	yes	no	no
T-20 (sec)	5.07	1.37	6.19	5.71
Δh^* (in.)	0.25	0	0.75	1.25
Slump Flow Spread - J-Ring Spread (in.)	2	1.5	---	---
Compressive Strength				
1-day strength (psi)	2590	1840	---	---
7-day strength (psi)	6470	5520	---	---
28-day strength (psi)	8620	7210	---	---

Δh^*: height difference between concrete inside and outside the J-Ring

One SCC mixture was successfully batched in Phase 5. The author believes that more mixtures would have passed if the HRWR dosage rate was higher. In Phase 6, the minimum addition rate of ADVA Cast 575 that was to be utilized was set at 7 fl. oz. /cwt (456.39 mL/100 kg). The mixtures entailed in Phase 6 are covered more scrupulously in the next section.

5.3.6 Phase 6 – Reducing *S/Agg* to 0.50

In this phase of mixing, the *S/Agg* was 0.50 for all mixtures. To account for this, the coarse aggregate proportion was increased to 1425 lb/yd^3 (845.42 kg/m^3), and the quantity of fine aggregate was decreased to 1384 lb/yd^3 (821.09 kg/m^3). The other mixture design parameters were held constant. When compared with the other mixtures in the phase, the only variation (if any) was the quantity of HRWR that was added.

For mixture # 33, 7 fl. oz. ADVA Cast 575 /cwt (456.39 mL/100 kg) was used. When the mixture was observed in the mixer, the concrete flowed well and it did not feel viscous. The results of the slump flow test presented a T-20 (T-50) time of 7.49 seconds and a maximum spread equal to 25 in. (635 mm). Also, a VSI designation of 0 was given because the spread was almost perfectly round, and it was free of segregation and bleed water.

The findings related to the J-Ring test indicated that the mixture had moderate blockage potential; a height difference between concrete inside and outside the J-Ring was 1.25 in. (31.75 mm), and the difference between the slump flow spread and the J-Ring spread was 3.0 in. (76.2 mm).

Compressive strength testing was performed at 1, 7, and 28 days after batching. The final three-cylinder average at 28 days of age was 9120 psi (62.87 MPa). Overall, this mixture was confirmed to be an adequate SCC mixture. However, there were some issues that needed to be addressed. The T-20 (T-50) time of 7.49 seconds was longer than desired. Also, the height difference between concrete inside and outside the J-Ring (1.25 in., 31.75 mm) would have been more advantageous had it been less than or equal to 0.7

in. (17.78 mm). For this trial batch, these concerns were not extreme and were acceptable. Nonetheless, if this mixture were to be employed in the field, those involved in batching and testing the concrete should be aware of the risks.

In the next mixture, the ADVA Cast 575 dosage rate was increased to 8 fl. oz. /cwt (521.59 mL/100 kg). This was done to improve the flowability concerns that were witnessed while performing fresh concrete tests on mixture # 33. A more flowable mixture would not only acquire a shorter T-20 (T-50) measurement, but it would also reduce the blockage potential of the mixture. When the concrete was evaluated during the break period, it appeared extremely fluid and more importantly, stable.

The slump flow test demonstrated an improved T-20 (T-50) time of 3.88 seconds. Also, the slump flow spread was 29 in. (736.6 mm). As was expected, the concrete was able to remain stable throughout the final mixing segment. Segregation and bleed water were not observed, thus a VSI value of 0 was specified.

The J-Ring test results were slightly better when compared with the previous mixture. The height difference between concrete inside and outside the J-Ring did not change, but the difference between the slump flow spread and the J-Ring spread was reduced by 0.5 in. (12.7 mm). These findings showed that the flowability of the mixture was enhanced; consequently, the blockage potential was not as significant.

The fresh concrete test results met the criteria for mixture # 34 to be recommended as a satisfactory SCC mixture. Compressive strength testing was performed to ensure that the hardened properties were adequate as well. An average 28-day compressive strength of 8590 psi (59.20 MPa) corroborated that the mixture was indeed sufficient. The cylinders that were tested at twenty-eight days of age are displayed below in Figure 5.10. Upon viewing the photograph it can be seen that the cylinders had minimal bug holes. The author attributes the lack of surface blemishes to the stability of the mixture.

Figure 5.10: Compressive Strength Cylinders for Mixture # 34 at 28 Days

Since mixture # 34 had performed so well, none of the design constraints were adjusted for the next mixture. The author decided to do this in an attempt to duplicate the previous results. When the slump flow test was operated, the T-20 (T-50) measurement took considerably longer to complete; a time of 6.53 seconds was recorded. The slump flow spread was smaller in diameter, but it was still comparable; an average length of 27 in. (685.8 mm) was computed. Also, the spread was of a similar consistency. It was stable, but a small amount of bleed water was present. This justified a VSI value of 1.

When compared with the preceding mixture, the J-Ring test results were less desirable. The height difference between concrete inside and outside the J-Ring was invariable; however, the difference between the slump flow spread and the J-Ring spread was 3.5 in. (88.9 mm). These results were in agreement with those of the slump flow test; the flowability of the mixture was worse. Therefore, the blockage potential was more considerable.

As a whole, the fresh concrete properties were poorer for mixture # 35. However, the results obtained still met the necessary requirements for the mixture to be classified as an acceptable SCC mixture. Additionally, the average compressive strength was 9010 psi (62.11 MPa) at 28 days of age.

For mixture # 36, the addition rate of ADVA Cast 575 was increased to 9 fl. oz. /cwt (586.79 mL/100 kg). It was anticipated that the additional quantity of HRWR would either improve the fresh concrete properties by making the mixture more flowable, or the mixture would become excessively fluid and experience segregation. Once the concrete was poured into the wheel barrow, it became obvious that the latter event had occurred. Figure 5.11 shows the segregation that was observed before fresh concrete testing was performed.

Figure 5.11: Evidence of Segregation in Mixture # 36

The T-20 (T-50) measurement was completed in 1.92 seconds. Such a short time span proposed that the aggregates had separated from the cement paste. When the spread was observed, it was unmistakable that this incident had indeed occurred. A VSI description of 2 was given, and the average slump flow was measured to be 32 in. (812.8 mm).

The results of the J-Ring test were similar to those recorded in mixture # 30. On paper, the findings appear to be desirable. Yet, this was not the case. Due to the excessive fluidity of the cement paste, it flowed readily around the metal pegs. However, the aggregates created a substantial pile that barely spread out far enough to reach the inside circumference of the J-Ring apparatus. This is why the height difference between concrete inside and outside the J-Ring was measured as only 0.25 in. (6.35 mm).

As a result of the segregation that transpired, mixture # 36 was rejected. Nevertheless, even though the mixture had failed, a valuable piece of information was learned. It was validated that 9 fl. oz. ADVA Cast 575 /cwt (586.79 mL/100 kg) was too high of a dosage rate for a binder content of 775 lb/yd^3 (459.79 kg/m^3). Therefore, said dosage rate was not employed nor exceeded in the future mixtures that contained a binder content of 775 lb/yd^3 (459.79 kg/m^3).

The four mixtures discussed above complete Phase 6 of trial batching. The proper mix designs coupled with the supplementary slump flow, J-Ring, and compressive strength data are displayed in Table 5.6.

Table 5.6: Phase 6 Mix Designs and Test Results

Materials	Mixtures			
	33	34	35	36
Total Cementitious Materials (lb/yd^3)	775	775	775	775
Fly Ash (%)	---	---	---	---
Coarse Aggregate (lb/yd^3)	1425	1425	1425	1425
Fine Aggregate (lb/yd^3)	1384	1384	1384	1384
Water (lb/yd^3)	341	341	341	341
Water/Binder	0.44	0.44	0.44	0.44
Sand/Aggregate	0.5	0.5	0.5	0.5
ADVA CAST 530 (fl oz./cwt)	---	---	---	---
ADVA 170 (fl oz./cwt)	---	---	---	---
ADVA CAST 575 (fl oz./cwt)	7	8	8	9
Fresh Concrete Properties				
Slump Flow (in.)	25	29	27	32
Segregation Observed	no	no	no	yes
VSI	0	0	1	2
Bleed Water	no	no	no	yes
T-20 (sec)	7.49	3.88	6.53	1.92
Δh^* (in.)	1.25	1.25	1.25	0.25
Slump Flow Spread - J-Ring Spread (in.)	3	2.5	3.5	2
Compressive Strength				
1-day strength (psi)	2750	2540	2700	2210
7-day strength (psi)	6840	6360	6740	5750
28-day strength (psi)	9120	8590	9010	7780

Δh^*: height difference between concrete inside and outside the J-Ring

In general, Phase 6 was a success because three out of the four mixtures that were batched were classified as adequate SCC mixtures. For phase 7 of trial batching, the *S/Agg* was further decreased to see what effect this would have on the fresh concrete properties. An in-depth discussion of the findings of this research is exhibited in the subsequent section.

5.3.7 Phase 7 - Further Reducing *S/Agg* to 0.48

In this phase of the study, the only noteworthy alteration that took place was decreasing the *S/Agg* to 0.48. The author elected to do this so that the low end of the *S/Agg* range (0.48 – 0.52) could be evaluated. As a result, the volume of coarse aggregate increased to 1482 lb/yd^3 (879.24 kg/m^3) and the volume of fine aggregate decreased to 1327 lb/yd^3 (787.28 kg/m^3) for all the mixtures.

In mixture # 37, 7 fl. oz. ADVA Cast 575 /cwt (456.39 mL/100 kg) was added during mixing. After batching had concluded, the slump flow test was performed. A T-20 (T-50) time of 5.69 seconds was measured along with a slump flow of 27 in. (685.8 mm). Segregation was not observed, but a small aggregate pile was situated in the center of the spread; therefore, a VSI value of 1 was specified.

The results of the J-Ring test were also favorable. A height difference between concrete inside and outside the J-Ring was 1.0 in. (25.4 mm), and the difference between the slump flow spread and the J-Ring spread was 2.5 in. (63.5 mm). These findings signified that the blockage potential for the mixture was low.

All of the fresh concrete test results were adequate. An average 28-day compressive strength of 9510 psi (65.57 MPa) confirmed that mixture # 37 could be categorized as a sufficient SCC mixture.

For the next mixture, all of the mixture design constraints were held constant to see if similar results could be achieved. When the mixture was observed during the break period, the concrete appeared to be more viscous than the previous mixture (# 37). However, additional HRWR was not added at this time because segregation was likely to occur.

When the slump flow test was performed, a T-20 (T-50) time of 5.97 seconds was recorded. After the concrete stopped flowing it was evident that segregation had not occurred, yet a larger aggregate pile was located in the middle of the spread. Consequently, the concrete was labeled with a VSI designation equal to 1.5. Additionally, since this concrete sample was more viscous, it acquired a lower slump flow of 24 in. (609.6 mm). In general, the slump flow test results were not as good as those recorded for mixture # 37.

The findings of the J-Ring test were also worse. While there was not a measurable difference between the slump flow spread and the J-Ring spread, the height difference between concrete inside and outside the J-Ring increased to 1.5 in. (38.1 mm). It was clearly identifiable that the concrete had difficulty flowing around the metal pegs of the J-Ring apparatus. The blockage experienced by this mixture can be seen in Figure 5.12.

Figure 5.12: J-Ring Flow Spread of Mixture # 38

An average 28-day compressive strength of 8850 psi (61.0 MPa) proved that the hardened properties of the mixture were satisfactory. However, in the end, mixture # 38 was rejected due to the inadequacy of the fresh concrete properties.

Since mixture # 38 was quite viscous and failed to qualify as an SCC mixture, for the next mixture the ADVA Cast 575 dosage rate was increased to 8 fl. oz. /cwt (521.59 mL/100 kg). This adjustment was made to promote the flowability of the concrete. When the mixture was evaluated inside the mixer, the concrete appeared to be particularly fluid and on the verge of segregating. Therefore, the final mixing segment was lengthened to allow more time for the concrete to homogenize.

Promptly after mixing, the concrete was poured into a wheelbarrow and the slump flow test was conducted. When compared to mixture # 38, an improved T-20 (T-50) measurement of 5.14 seconds was recorded, and the average slump flow diameter was 29 in. (736.6 mm). The VSI value remained the same, although a considerable aggregate pile was not the problem. Instead, the designation of 1.5 was given due to excessive bleed water that had formed a large mortar halo around the entire circumference of the spread. The mixture was rejected because of its instability. However, more tests were operated to assess the blockage potential and strength of the mixture. The abovementioned mortar halo is illustrated in Figure 5.13.

Figure 5.13: Slump Flow of Mixture # 39

As was expected, the results of the J-Ring test turned out to be better than the previous mixture. The difference between the slump flow spread and the J-Ring spread did increase to 3.0 in. (76.2 mm), but more importantly, the height difference between concrete inside and outside the J-Ring was decreased to 1.25 in. (31.75 mm). The author attributes the latter decrease in measurable height to an improvement in the fluidity of the mixture. The average 28-day compressive strength was 8320 psi (57.37 MPa).

Mixture # 40 was the final trial batch that was mixed during Phase 7. In this mixture, the author elected to incrementally decrease the addition rate of ADVA Cast 575 to 7.5 fl. oz. /cwt (489.0 mL/100 kg). This decrease in HRWR was intended to improve the stability of the concrete and promote more desirable fresh concrete properties.

When the slump flow test was operated, the T-20 (T-50) assessment took 6.83 seconds to complete. Once the concrete came to rest, it was noticeable that a large amount of bleed water had collected on the spread. The central portion of the slump flow patty appeared to be stable, but the same statement did not hold true for the outer segment. Hence, a VSI value of 2 was specified. The average slump flow diameter was 27 in. (685.8 mm); however, since the stability of the concrete was questionable, the mixture could not be classified as SCC.

The two measurements taken during the J-Ring test matched the findings of mixture # 39. Also, the average 28-day compressive strength was 8760 psi (60.40 MPa). It is important to note that through mixture # 40 in this research program, all of the mixtures acquired adequate strength in compression.

This concludes Phase 7 of trial batching. The mix designs that were discussed above are tabularized along with the pertinent slump flow, J-Ring, and compressive strength data in Table 5.7.

Table 5.7: Phase 7 Mix Designs and Test Results

Materials	Mixtures			
	37	38	39	40
Total Cementitious Materials (lb/yd^3)	775	775	775	775
Fly Ash (%)	---	---	---	---
Coarse Aggregate (lb/yd^3)	1482	1482	1482	1482
Fine Aggregate (lb/yd^3)	1327	1327	1327	1327
Water (lb/yd^3)	341	341	341	341
Water/Binder	0.44	0.44	0.44	0.44
Sand/Aggregate	0.48	0.48	0.48	0.48
ADVA CAST 530 (fl oz./cwt)	---	---	---	---
ADVA 170 (fl oz./cwt)	---	---	---	---
ADVA CAST 575 (fl oz./cwt)	7	7	8	7.5
Fresh Concrete Properties				
Slump Flow (in.)	27	24	29	27
Segregation Observed	no	no	no	no
VSI	1	1.5	1.5	2
Bleed Water	no	no	yes	yes
T-20 (sec)	5.69	5.97	5.14	6.83
Δh^* (in.)	1	1.5	1.25	1.25
Slump Flow Spread - J-Ring Spread (in.)	2.5	2.5	3	3
Compressive Strength				
1-day strength (psi)	2820	2690	2480	2640
7-day strength (psi)	7020	6720	6490	6570
28-day strength (psi)	9510	8850	8320	8760

Δh^*: height difference between concrete inside and outside the J-Ring

As a whole, Phase 7 was unsuccessful since only one of the four mixtures was SCC. Mixture # 40 was the last mixture that was batched that contained only portland Type I cement as the binder constituent. All of the future mixtures also contained varying replacement rates of Class C FA. A comprehensive discussion of these mixtures and the accompanying results are presented in Phase 8 of the following section.

5.4 DEVELOPING SCC USING TYPE I PORTLAND CEMENT AND CLASS C FA

5.4.1 Phase 8 – FA Replacement Rates of 5, 10, and 15%

This phase consists of trial mixtures that contained FA replacement rates of 5, 10, and 15% of the total cementitious material. It is important to note that the FA substitution rate was incrementally increased by a value of 5% to develop a consistent trend. As was stated earlier, the third “combination” method of mixture proportioning was employed to batch every FA mixture. The particle size distribution of the binder was improved by adding FA to the mixtures because FA particles contain finer constituents than cement. Subsequently, the flowability of each mixture was then modified by using HRWR to obtain SCC. The mixture design analysis for the FA SCC mixtures was similar to the procedure demonstrated in Appendix A; however, these mixtures required additional steps because the binder content now included a specific replacement rate of FA. For this reason, it was relevant to illustrate another example so the reader would have a better understanding of how the mixture proportions were calculated. An example mixture design analysis that was performed for mixture # 41 is shown in Appendix B.

For this mixture, an ADVA Cast 575 dosage rate of 7 fl. oz. /cwt (456.39 mL/100 kg) was chosen. The mixture was assessed during the break period, and at that time the concrete was fluid and stable. When the slump flow test was conducted, a T-20 (T-50) measurement of 4.37 seconds was recorded. The concrete was free of segregation, but bleed water was observed as a sheen over the spread. This authenticated a VSI designation equal to 1. Also, the average slump flow was 26 in. (660.4 mm).

The results of the J-Ring test suggested that the blockage potential for the mixture was moderate. A height difference between concrete inside and outside the J-Ring was 1.25 in. (31.75 mm), and the difference between the slump flow spread and the J-Ring spread was 3.5 in. (88.9 mm).

The average 28-day compressive strength was 9980 psi (68.81 MPa); this was the strongest mixture developed so far in the research program. The author attributes the superior later-age strength to the addition of FA. When FA is added to a concrete mixture, its size and shape improves the particle size distribution of the entire quantity of binder. Furthermore, since FA is also pozzolanic, more Calcium Silicate Hydrate (C-S-H) is produced. As a result, there is a better bond between the aggregates and the cement paste within the ITZ. This, in turn, enables the concrete mixture to acquire enhanced strength in compression. Since the fresh and hardened concrete properties were suitable, mixture # 41 was accepted as an adequate SCC mixture. Figure 5.14 shows a shear-type failure in one of the cylinders that was tested in compression at twenty-eight days of age.

Figure 5.14: Shear-Type Compression Failure

In mixture # 42, the FA replacement rate was increased to 10%. The author decided to do this because of its inexpensive nature when compared to cement. To account for the extra FA, the quantities of coarse and fine aggregate were reduced. However, the other mixture proportions did not change.

When the slump flow test was performed, a suitable T-20 (T-50) time of 4.64 seconds was measured. The spread did not show any evidence of segregation or bleed water, so a VSI value equal to 0.5 was given. Furthermore, the concrete flowed well; a slump flow of 27 in. (685.8 mm) was recorded.

The results of the J-Ring test were not advantageous. When compared with the preceding mixture, the height difference between concrete inside and outside the J-Ring was constant. However, the difference between the slump flow spread and the J-Ring spread increased to 5 in. (127 mm). This disparity in flow measurements suggested that the mixture was subject to blockage problems.

The average 28-day compressive strength was 10780 psi (74.32 MPa). This value exceeded the required minimum compressive strength by approximately 308%. Nonetheless, even though the slump flow and compressive strength test results were desirable, the blockage issues associated with the mixture prevented it from qualifying as SCC.

For the next mixture, the *S/Agg* was increased to 0.50. All the other mixture design parameters were held constant. When tested, the T-20 (T-50) time was 5.93 seconds; this measurement took roughly one second longer than the author would have liked, but it was still satisfactory. The slump flow spread was stable and uniform, so a VSI depiction equal to 0 was specified. Also, the average slump flow diameter was 27.5 in. (698.5 mm).

Concerning the J-Ring test, the relevant findings signified that the concrete had only slight to temperate blockage concerns. When compared with the foregoing mixture (# 42), the height difference between concrete inside and outside the J-Ring did not show a measurable change. On the other hand, the difference between the slump flow spread and the J-Ring spread was 1.5 in. (38.1 mm).

After 28 days of age, the concrete had a compressive strength of 10140 psi (69.93 MPa). This end result combined with the sufficient fresh concrete properties permitted mixture # 43 to be categorized as an SCC mixture.

In mixture # 44, the *S/Agg* was further increased to a value of 0.52. When the concrete was examined during the break period, it appeared that the mixture was beginning to segregate. In an attempt to counteract this, the final mixing segment was extended five additional minutes so that the concrete would have more time to become uniform.

After mixing had concluded, the slump flow test was operated. A T-20 (T-50) time of 3.89 seconds was measured. It seemed that the extended mixing time had little effect on homogenizing the concrete because the slump flow spread was unstable and on the verge of segregating. Bleed water was present and took shape as a large mortar halo around the entire perimeter of the spread; therefore, a VSI value of 1.5 was issued. In addition, the average slump flow diameter was 28.5 in. (723.9 mm). At this point, the mixture had already failed to qualify as SCC due to its instability. However, J-Ring and compressive strength testing were still performed to evaluate the blockage potential and hardened properties of the mixture. Figure 5.15 shows the mixture on the brink of segregation before the J-Ring test was initiated.

Figure 5.15: Instability Observed in Mixture # 44

The height difference between concrete inside and outside the J-Ring was 0.5 in. (12.7 mm), and the difference between the slump flow spread and the J-Ring spread was 1.0 in. (25.4 mm). These results implied that the mixture was not at risk to experience blockage problems. The author believes that the excessive fluidity of the mixture aided in obtaining this desirable result. When compressive strength testing was performed at 28 days of age, mixture # 44 had a strength of 9720 psi (67.0 MPa).

Having batched three mixtures with a FA replacement rate of 10%, in mixture # 45 the substitution rate was incrementally increased to 15%. Additionally, the *S/Agg* was lowered to 0.48, but all the other mixture quantities did not vary. When the concrete was inspected inside the mixer, it looked and felt viscous. However, additional HRWR was not added because it was believed that segregation would likely occur.

Once batching was complete, the slump flow test was conducted. The recorded T-20 (T-50) time was sufficient at 4.86 seconds. Segregation and bleed water did not occur, so a satisfactory VSI designation of 0.5 was granted. However, the slump flow measurement was 22 in. (558.8 mm) which was too low.

When the J-Ring test was performed, the findings proposed that the blockage potential for the mixture was high. The height difference between concrete inside and outside the J-Ring was 1.25 in. (31.75 mm). However, the author measured a difference in diameter between the slump flow spread and the J-Ring spread of 5.0 in. (127 mm). Lastly, the average 28-day compressive strength for mixture # 45 was 10270 psi (70.79 MPa).

Since the previous batch had limited flowability, in mixture # 46 the *S/Agg* was increased to 0.50 and the ADVA Cast 575 dosage rate was 8 fl. oz. /cwt (521.59 mL/100 kg). The concrete did not appear to be uniform when it was evaluated during the break period; bleed water was seen seeping out of the concrete whenever the mixer came to rest. For this reason, the concluding mixing segment was lengthened so the concrete would have more time to become homogeneous.

After mixing was complete, the concrete was poured into a wheel barrow and the slump flow test was conducted without delay. The T-20 (T-50) time was 4.22 seconds. Next, the spread was assessed for stability. Segregation did not occur, but the presence of bleed water formed a large mortar halo around the circumference of the spread. Therefore, the VSI was 1.5. To finish, the average slump flow diameter was 26 in. (660.4 mm).

Subsequently, the J-Ring test was performed. There was a measurable height difference between concrete inside and outside the J-Ring of 1.25 in. (31.75 mm), and the variation between the slump flow spread and the J-Ring spread was 2.5 in. (63.5 mm). These results suggest that the mixture had moderate blockage potential. Also, the cylinders that were cast from the mixture showed desirable gains in compressive strength through 28 days after batching. An average 28-day compressive strength of 9910 psi (68.34 MPa) verified that the hardened properties of the mixture were sufficient. However, due to the blockage concerns associated with the fresh properties, mixture # 46 was rejected from consideration as an SCC mixture.

For mixture # 47, the S/Agg was increased to 0.52. When the concrete was observed in the mixer, it was evident that segregation had occurred. The author attributes this incident to the increased quantity of fine aggregate coupled with the already high HRWR dosage rate. It was anticipated that the fresh concrete properties would be inadequate, but testing was still performed to verify this.

Upon operating the slump flow test, a T-20 (T-50) measurement of 1.88 seconds was recorded. As was predicted, segregation had transpired; the aggregates were separated from the cement paste, so a VSI value of 3 was specified. Also, the average slump flow was 29.5 in. (749.3 mm).

The findings of the J-Ring test implied that the mixture would not be subject to blockage problems. However, the results were analogous to those recorded in mixture # 30 and mixture # 36. Indeed, the mixture was prone to experience blockage because the cement paste had disbanded from the aggregates. If this mixture were utilized in the field, the cement paste would readily flow around any confined rebar with ease, but the aggregates would pile up and need to be vibrated. Additionally, due to the severe segregation, the recorded compressive strengths were smaller in magnitude than was expected. The 28-day compressive strength was 8810 psi (60.76 MPa). Since the effects of segregation were detrimental to the fresh concrete properties, mixture # 47 did not qualify as an acceptable SCC mixture.

The seven aforementioned mixtures complete Phase 8 of trial batching. The mix designs, fresh concrete properties, and compressive strength data are shown in Table 5.8.

Table 5.8: Phase 8 Mix Designs and Test Results

Materials	Mixtures						
	41	42	43	44	45	46	47
Total Cementitious Materials (lb/yd^3)	775	775	775	775	775	775	775
Fly Ash (%)	5	10	10	10	15	15	15
Coarse Aggregate (lb/yd^3)	1475	1468	1411	1355	1460	1404	1348
Fine Aggregate (lb/yd^3)	1322	1315	1370	1425	1308	1363	1417
Water (lb/yd^3)	341	341	341	341	341	341	341
Water/Binder	0.44	0.44	0.44	0.44	0.44	0.44	0.44
Sand/Aggregate	0.48	0.48	0.5	0.52	0.48	0.5	0.52
ADVA CAST 530 (fl oz./cwt)	---	---	---	---	---	---	---
ADVA 170 (fl oz./cwt)	---	---	---	---	---	---	---
ADVA CAST 575 (fl oz./cwt)	7	7	7	7	7	8	8
Fresh Concrete Properties							
Slump Flow (in.)	26	27	27.5	28.5	22	26	29.5
Segregation Observed	no	no	no	no	no	no	yes
VSI	1	0.5	0	1.5	0.5	1.5	3
Bleed Water	yes	no	no	yes	no	yes	yes
T-20 (sec)	4.37	4.64	5.93	3.89	4.86	4.22	1.88
Δh^* (in.)	1.25	1.25	1.25	0.5	1.25	1.25	0
Slump Flow Spread - J-Ring Spread (in.)	3.5	5	1.5	1	5	2.5	1
Compressive Strength							
1-day strength (psi)	2400	2440	2220	2160	2050	2350	1960
7-day strength (psi)	7690	8270	7610	7480	8040	7240	5860
28-day strength (psi)	9980	10780	10140	9720	10270	9910	8810

Δh^*: height difference between concrete inside and outside the J-Ring

As a group, Phase 8 was unproductive in developing SCC mixtures; only two out of the seven mixtures exhibited acceptable fresh concrete properties. In Phase 9 of the experimental program, mixtures with higher replacement rates of FA were batched. Specifically, these mixtures contained 20 and 25% FA by volume of the total quantity of binder. A complete investigation of these mixtures is presented along with the associated results in the subsequent section.

5.4.2 Phase 9 – FA Replacement Rates of 20 and 25%

Mixture # 48 contained a FA replacement rate of 20% and an *S/Agg* equal to 0.48. Also, since segregation had occurred in the previous mixture, the addition rate of ADVA Cast 575 was reduced to 7 fl. oz. /cwt (456.39 mL/100 kg). When the concrete was viewed during the break period, segregation was observed. For that reason, the final mixing segment was lengthened by five minutes or until the mixture appeared stable. After mixing was complete, the concrete was poured into a wheel barrow. Upon assessing the mixture in the wheel barrow, there was still evidence of segregation. The author predicted that the mixture would fail because of this, but to make certain, fresh and hardened concrete testing was performed on the mixture.

When the slump flow test was conducted, a surprisingly lengthy T-20 (T-50) time of 7.30 seconds was measured. The author believes that this arose due to the same blockage issues that had occurred at the outlet of the slump cone in mixtures #12, 14, 25, 26, and 27. The VSI was 2.5 because of the segregation, and the average slump flow was 28 in. (711.2 mm).

The results of the J-Ring test indicated that the mixture had moderate blockage potential. A height difference between concrete inside and outside the J-Ring was 1.25 in. (31.75 mm), but there was no difference between the slump flow spread and the J-Ring spread. The findings of the compressive strength testing regimen were desirable; the 28-day compressive strength was 8730 psi (60.16 MPa). However, mixture # 48 was unable to qualify as an SCC mixture.

In the next mixture, the dosage rate of ADVA Cast 575 was reduced to 3 fl. oz. /cwt (195.60 mL/100 kg). This was done to decrease the probability of segregation. The other mixture proportions were held constant. Upon evaluating the concrete inside the mixer, it appeared to be and felt quite viscous. However, no further HRWR was added at this time. If the results of the fresh concrete tests validated that the mixture acquired limited flowability, then the dosage rate of HRWR would be elevated in the next trial mixture.

When the slump flow test was operated, the mixture was confirmed to have inadequate flowability. The slump flow had a diameter of only 19 in. (482.6 mm). Since the concrete failed to acquire a slump flow of at least 20 in. (508 mm), a T-20 (T-50) measurement could not be recorded. Also, due to a considerable aggregate pile that was positioned in the center of the spread, the VSI value was 2.5. Hence, the mixture failed to qualify as SCC. Figure 5.16 shows the spread of this mixture immediately after the slump flow test had been conducted.

Figure 5.16: Slump Flow of Mixture # 49

The J-Ring test was not conducted on this concrete sample because it was simply too viscous. However, the compressive strength was 7380 psi (50.87 MPa) at 28 days. While this value met the criterion listed in the Standard Specifications[5], it was the lowest average of any of the preceding mixtures that contained a quantity of FA. The author believes that this occurred for one particular reason. The cement that was used in this mixture was produced by a different manufacturer. It is likely that this cement had a different fineness, which affected viscosity and compressive strength.

Due to the undesirable fresh and hardened concrete properties of the prior mixture, for mixture # 50 (and all of the remaining mixtures) the author switched back to the original cement brand. Additionally, the S/Agg was increased to 0.50, and the dosage rate of ADVA Cast 575 was increased to 6 fl. oz. /cwt (391.19 mL/100 kg) so as to increase the mixture's flowability. These adjustments resulted in satisfactory slump flow measurements. A T-20 (T-50) time of 3.71 seconds was recorded. Since the concrete did not segregate and bleed water was not present, the VSI designation was 0. Also, the average slump flow was 24.5 in. (622.3 mm).

The results of the J-Ring test were adequate as well. The height difference between concrete inside and outside the J-Ring was 0.5 in. (12.7 mm), and the deviation between the slump flow spread and the J-Ring spread was only 1.5 in. (38.1 mm). The mixture developed an average 28-day compressive strength of 11240 psi (77.46 MPa).

For mixture # 51, the *S/Agg* was further increased to a value of 0.52. This resulted in more fine aggregate by volume than coarse aggregate. The other mixture design parameters were held constant. When the concrete was assessed inside the mixer, it appeared to be flowable and stable. Since additional HRWR was not needed, the concluding mixing segment was run and fresh concrete testing followed.

Upon operating the slump flow test, the T-20 (T-50) was 2.98 seconds. The concrete did not exhibit any segregation, but some bleed water was present as a sheen over the spread. Therefore, the VSI was 1. The slump flow was sufficient as well; a measurement of 26 in. (660.4 mm) was recorded. The results of the J-Ring test were desirable also because the spread did not display a differentiation in height between concrete inside and outside the J-Ring. Furthermore, when the second measurement was taken, the difference between the slump flow spread and the J-Ring spread was only 1.0 in. (25.4 mm). The fresh concrete properties were proven to be adequate, and the average 28-day compressive strength was 10730 psi (74.0 MPa).

In the final mixture, the replacement rate of FA was increased to 25% and the *S/Agg* was lowered to 0.48. These amendments to the mix design resulted in a coarse and fine aggregate content of 1445 lb/yd^3 (857.28 kg/m^3) and 1295 lb/yd^3 (768.29 kg/m^3), respectively. The other design constraints did not change. The T-20 (T-50) was 4.56 seconds. The concrete did not segregate, though a small aggregate pile was observed in the center of the spread. The VSI was 0.5. Lastly, the average slump flow diameter was 24 in. (609.6 mm). These results proved that the mixture had satisfactory flowability and stability. A view of this slump flow spread can be seen in Figure 5.17.

Figure 5.17: Slump Flow of the Final Mixture

Next, the J-Ring test was performed to evaluate the blockage potential of the mixture. A height difference between concrete inside and outside the J-Ring was 0.25 in. (6.35 mm), and the variation between the slump flow spread and the J-Ring spread was 0.75 in. (19.05 mm). These findings indicated that blockage would not be a concern.

Finally, the hardened properties of the mixture were evaluated at 1, 7, and 28 days after batching. The compressive strength results at these days were 2730 psi (18.84 MPa), 8250 psi (56.91 MPa), and 11010 psi (75.88 MPa), correspondingly. These results combined with the suitable findings from fresh concrete testing validated that mixture # 52 was acceptable. Also, it is important to note that throughout the duration of this research program, every mixture that was tested for compressive strength was adequate

($f'_c \geq 3500$ psi (24.13 MPa) at 28 days) in that regard. All of the mixtures that did not meet the requirements to qualify as SCC did so due to unsatisfactory fresh concrete properties.

Overall, Phase 9 was a success. Three out of the five mixtures had satisfactory fresh concrete properties. Thus, it was established that SCC could be developed with replacement rates of FA of 5 to 25%. The completion of Phase 9 concluded trial batching in this research program. The five mix designs entailed in this phase are presented along with the pertinent slump flow, J-Ring, and compressive strength results in Table 5.9.

Table 5.9: Phase 9 Mix Designs and Test Results

Materials	Mixtures				
	48	49	50	51	52
Total Cementitious Materials (lb/yd^3)	775	775	775	775	775
Fly Ash (%)	20	20	20	20	25
Coarse Aggregate (lb/yd^3)	1453	1453	1397	1341	1445
Fine Aggregate (lb/yd^3)	1302	1302	1356	1411	1295
Water (lb/yd^3)	341	341	341	341	341
Water/Binder	0.44	0.44	0.44	0.44	0.44
Sand/Aggregate	0.48	0.48	0.5	0.52	0.48
ADVA CAST 530 (fl oz./cwt)	---	---	---	---	---
ADVA 170 (fl oz./cwt)	---	---	---	---	---
ADVA CAST 575 (fl oz./cwt)	7	3	6	6	6
Fresh Concrete Properties					
Slump Flow (in.)	28	19	24.5	28	24
Segregation Observed	yes	no	no	no	no
VSI	2.5	2.5	0	1	0.5
Bleed Water	yes	no	no	yes	no
T-20 (sec)	7.3	---	3.71	2.98	4.56
Δh^* (in.)	1.25	---	0.5	0	0.25
Slump Flow Spread - J-Ring Spread (in.)	0	---	1.5	1	0.75
Compressive Strength					
1-day strength (psi)	2090	1850	2850	2560	2730
7-day strength (psi)	6720	5160	8540	7940	8250
28-day strength (psi)	8730	7380	11240	10730	11010

Δh^*: height difference between concrete inside and outside the J-Ring

5.5 METHODOLOGY FOR DEVELOPING SCC MIXTURES

In order for an SCC mixture to be deemed satisfactory, four workability categories (deformability, passing ability, filling capacity, and static stability) must be satisfied. The major difficulty is being able to develop a mixture that possesses a high degree of flowability but does not segregate. For example, in conventional-slump concrete mixtures, incrementally increasing the *w/b* will improve the workability characteristics. Be that as it may, a certain limit is present where an increase in *w/b* will no longer improve workability without causing instability within the mixture. The same trend is true with respect to SCC mixtures. However, in SCC, this effect is amplified because flowability (not workability) is being modified, and mixtures that have high flowability are extremely sensitive to changes in the mix design. This is why the methodology utilized in selecting SCC mixture proportions is critical and can require numerous considerations.

Through trial batching in this research program, steps were developed to successfully achieve SCC. The elements associated with each step are discussed by degree of importance in the subsequent section. It is important to note that for this investigation, AHTD recommended that the *w/b* should be held constant at a value of 0.44 since the concrete was classified as Class S (structural) and did not have any substantial compressive strength requirements. Therefore, from the beginning the most significant element (selecting a *w/b*) had already been established.

5.5.1 Binder Content

5.5.1.1 Binder Content and Flowability

When compared with conventional-slump concrete, SCC mixtures will typically have higher binder contents. The reason for this is that SCC mixtures are highly flowable. The addition of water is the mechanism that promotes flowability, and in some instances the *w/b* may be increased to account for this. However, in this research program the *w/b* was set at 0.44. Therefore, the author determined that the only way to acquire more water in any given mixture was to increase the binder content. The effect an increase in binder content had on the slump flows of specific trial mixtures is presented below in Table 5.10.

Table 5.10: Effect of Increasing Binder Content on Slump Flow

Materials	Mixtures						
	3	4	6	19	22	23	29
Total Cementitious Materials (lb/yd^3)	611	711	811	761	786	750	775
Coarse Aggregate (lb/yd^3)	1527	1429	1332	1380	1357	1392	1367
Fine Aggregate (lb/yd^3)	1606	1506	1402	1454	1428	1465	1439
Water (lb/yd^3)	269	313	357	335	346	330	341
Water/Binder	0.44	0.44	0.44	0.44	0.44	0.44	0.44
Sand/Aggregate	0.52	0.52	0.52	0.52	0.52	0.52	0.52
ADVA CAST 530 (fl oz./cwt)	---	---	---	---	---	---	---
ADVA 170 (fl oz./cwt)	5	5	5	5	5	---	---
ADVA CAST 575 (fl oz./cwt)	---	---	---	---	---	7	7
Fresh Concrete Properties							
Slump Flow (in.)	---	14	25	19	22	23	28.5

In mixture # 3, a binder content of 611 lb/yd^3 (362.49 kg/m^3) was employed. At this binder content, the concrete did not acquire any flowability; in fact, it still had a slump. So for mixture # 4, the binder content was increased to 711 lb/yd^3 (421.82 kg/m^3). When the slump flow test was performed, the concrete did spread out. However, it had attained limited flowability; a slump flow of 14 in. (355.6 mm) was recorded. To allow for more water to be utilized during mixing, in mixture # 6 the binder content was further increased to 811 lb/yd^3 (481.15 kg/m^3). This resulted in an adequate slump flow of 25 in. (635 mm). This progression in mixing shows that slump flows will improve as binder contents are elevated and the *w/b* held constant.

For the next two mixtures displayed in Table 5.10, the goal was to optimize the binder content. Mixture # 19 was batched at a binder content of 761 lb/yd^3 (451.48 kg/m^3). When tested, an insufficient slump flow of 19 in. (482.6 mm) was measured. In mixture # 22, the binder content was increased to 786 lb/yd^3 (466.32 kg/m^3). This resulted in a recorded slump flow of 22 in. (558.8 mm). It is important to note that neither of these mixtures qualified as SCC due to limited flowability. However, the trend is still evident that an increase in binder content will improve concrete flowability for a constant *w/b*.

In the last two mixtures exhibited in Table 4.10, the HRWR source and dosage rate incorporated during mixing were different than in previous mixtures. However, these parameters were invariable in mixtures # 23 and # 29. In mixture # 23, the binder content was 750 lb/yd^3 (444.96 kg/m^3). When fresh concrete testing was conducted, an average slump flow of 23 in. (584.2 mm) was measured. For mixture # 29, a binder content of 775 lb/yd^3 (459.79 kg/m^3) resulted in a slump flow of 28.5 in. (723.9 mm). These findings verify that an increase in binder content will improve slump flow regardless of the HRWR source or dosage rate.

5.5.1.2 Binder Content and Stability

An adequate binder content is essential in producing SCC. The higher the binder content, the more water that is allotted for mixing, which results in enhanced flowability. This tendency has already been established. However, as binder content increases the potential for segregation increases as well. This occurs because the density of the mixture is decreased; water is accounting for volume that was previously occupied by coarse and fine aggregate particles. As a result, this increased water content can lead to segregation. The effect an increase in binder content had on the density and segregation potential of certain mixtures is shown in Table 5.11.

Table 5.11: Effect of Increasing Binder Content on Concrete Density and Segregation Potential

Materials	Mixtures		
	23	21	30
Total Cementitious Materials (lb/yd^3)	750	761	775
Coarse Aggregate (lb/yd^3)	1392	1324	1367
Fine Aggregate (lb/yd^3)	1465	1509	1439
Water (lb/yd^3)	330	335	341
Water/Binder	0.44	0.44	0.44
Sand/Aggregate	0.52	0.54	0.52
Concrete Density (lb/ft^3)	145.8	145.5	145.1
ADVA CAST 530 (fl oz./cwt)	---	---	---
ADVA 170 (fl oz./cwt)	---	7	---
ADVA CAST 575 (fl oz./cwt)	7	---	6
Fresh Concrete Properties			
Slump Flow (in.)	23	29	32.5
Segregation Observed	no	yes	yes
VSI	0.5	2	3
Bleed Water	no	yes	yes

For the three mixtures listed above in Table 5.11, as binder content increased the concrete densities decreased. Subsequently, these mixtures progressively became more unstable. Mixture # 23 was batched with a binder content equal to 750 lb/yd^3 (445 kg/m^3). The density was calculated to be 145.8 lb/ft^3 (2335 kg/m^3), and the concrete did not show any signs of segregation or bleed water. Conversely, the slump flow for mixture # 21 showed evidence of bleed water as well as segregation. In this mixture, the only significant change made to the mix design was that the binder content was increased to 761 lb/yd^3 (451.48 kg/m^3). This caused the density to decrease to a value of 145.5 lb/ft^3 (2330.69 kg/m^3) as well. Moreover, in mixture # 30 the binder content was further increased to 775 lb/yd^3 (459.79 kg/m^3). The slump flow of this mixture was highly unstable; severe segregation and a large quantity of bleed water justified a VSI designation equal to 3. Also, the density was reduced even more; a value of 145.1 lb/ft^3 (2324.28 kg/m^3) was computed. These results prove two effects. First of all, as binder content is elevated, the density will decrease. Secondly, a decrease in density will ultimately increase the segregation potential for SCC mixtures. This does not necessarily mean that segregation will occur, but the concrete is definitely put at a greater risk.

5.5.1.3 High Binder Content (with Class C FA Replacement) and Stability

It is imperative for SCC mixtures to have high binder contents. High binder contents have the capacity to improve flowability, but they can also lead to instability. The latter case is intensified more whenever Class C FA is utilized as cement replacement. The basis for this is that FA has a lower specific gravity than portland Type I cement (2.20 vs. 3.15). Therefore, whenever a percentage of cement is replaced by FA, the FA takes up more volume than that same equivalent amount of cement. As a result, the volumes of coarse and fine aggregates are further reduced to account for the increase in binder volume. Ultimately, this decreases the density of SCC. With such a high volume of binder utilized during mixing, excess cement paste can occur and lead to segregation. The effect an increase in FA replacement had on the density and segregation potential of particular mixtures is exhibited in Table 5.12.

Table 5.12: Effect of an Increase in FA Replacement on Concrete Density and Segregation Potential

Materials	Mixtures				
	37	41	44	47	48
Total Cementitious Materials (lb/yd^3)	775	775	775	775	775
Fly Ash (%)	---	5	10	15	20
Coarse Aggregate (lb/yd^3)	1482	1475	1355	1348	1453
Fine Aggregate (lb/yd^3)	1327	1322	1425	1417	1302
Water (lb/yd^3)	341	341	341	341	341
Water/Binder	0.44	0.44	0.44	0.44	0.44
Sand/Aggregate	0.48	0.48	0.52	0.52	0.48
Concrete Density (lb/ft^3)	145.4	144.9	144.3	143.7	143.4
ADVA CAST 530 (fl oz./cwt)	---	---	---	---	---
ADVA 170 (fl oz./cwt)	---	---	---	---	---
ADVA CAST 575 (fl oz./cwt)	7	7	7	8	7
Fresh Concrete Properties					
Slump Flow (in.)	27	26	28.5	29.5	28
Segregation Observed	no	no	no	yes	yes
VSI	1	1	1.5	3	2.5
Bleed Water	no	yes	yes	yes	yes

The five mixtures included above contained a binder content of 775 lb/yd^3 (459.79 kg/m^3). As FA was added and the replacement rate was incrementally increased, the concrete densities decreased accordingly. As a result, the stability of the mixtures declined as well. For mixture # 37, a density of 145.4 lb/ft^3 (2329.08 kg/m^3) was measured. Also, the slump flow spread did not show any indication of bleed water or segregation. In mixture # 41, a FA replacement rate of 5% was employed. The density decreased to a value of 144.9 lb/ft^3 (2321.08 kg/m^3), and bleed water was present after the slump flow test was operated. However, segregation did not occur. A FA substitution rate of 10% was used in mixture # 44. This decreased the density to 144.3 lb/ft^3 (2311.46 kg/m^3). Additionally, when fresh concrete testing was conducted, the concrete was on the verge of segregating. For mixture # 47, the FA replacement rate was set at 15%. This reduced the density further; a value of 143.7 lb/ft^3 (2301.85 kg/m^3) was calculated. Moreover, severe segregation occurred during fresh concrete testing. In mixture # 48, the substitution rate of FA was further increased to 20%. This modification reduced the density to 143.4 lb/ft^3 (2297.05 kg/m^3). In addition, the concrete segregated even though it was batched with less HRWR than the previous mixture. These findings confirm that as FA is added and incrementally increased in SCC mixtures, the concrete density will decrease. Furthermore, this decrease in density will increase the segregation potential of each mixture. As stated earlier, this does not automatically denote that segregation will indeed occur. However, the concrete will be more susceptible to the effects of segregation.

5.5.1.4 Conclusion

It has been demonstrated that increasing binder content will enhance the flowability of SCC. However, as binder content is increased, the density of the mixture will decrease. This decrease in density can lead to instability. Also, at already high binder contents, replacing a portion of the cement with FA results in SCC mixtures having lower densities. Therefore, SCC mixtures containing high percentages of FA are at an even greater risk for developing segregation. An agenda to combat the effects of segregation is presented in the following section.

5.5.2 HRWRs

HRWRs are an essential element in developing SCC mixtures. When utilized, these admixtures significantly impact the rheological properties of SCC. Many different kinds of HRWRs are available for use in various applications. However, any single HRWR will not be compatible in every circumstance. Most HRWRs are formulated to enhance flowability while also combating the onset of segregation. For this reason, it would be difficult to produce flowable yet stable SCC mixtures without implementing at least one HRWR in the mixing regimen. In this research program, three different types of HRWRs were employed during trial batching. Table 5.13 shows the effects of HRWR type and dosage rate on the rheological properties of selected trial mixtures.

Table 5.13: Effects of HRWR Type and Dosage Rate on Rheological Properties

Materials	Mixtures					
	1	2	19	20	33	34
Total Cementitious Materials (lb/yd^3)	611	611	761	761	775	775
Coarse Aggregate (lb/yd^3)	1550	1527	1380	1380	1425	1425
Fine Aggregate (lb/yd^3)	1631	1606	1454	1454	1384	1384
Water (lb/yd^3)	251	269	335	335	341	341
Water/Binder	0.41	0.44	0.44	0.44	0.44	0.44
Sand/Aggregate	0.52	0.52	0.52	0.52	0.5	0.5
ADVA CAST 530 (fl oz./cwt)	3	2.5	---	---	---	---
ADVA 170 (fl oz./cwt)	---	2.5	5	7	---	---
ADVA CAST 575 (fl oz./cwt)	---	---	---	---	7	8
Fresh Concrete Properties						
Slump Flow (in.)	---	---	19	28	25	29
Segregation Observed	---	---	no	no	no	no
VSI	---	---	1	1	0	0
Bleed Water	---	---	no	no	no	no
T-20 (sec)	---	---	---	4.13	7.49	3.88

Initially, ADVA Cast 530 was used because this type of HRWR improves concrete flowability without causing segregation. ADVA Cast 530 was only utilized in the first two trial mixtures, and neither of these mixtures was able to acquire any degree of flowability. However, the author attributes this occurrence to the low binder content (611 lb/yd^3, 362.49 kg/m^3).

The next HRWR that was used in trial batching was ADVA 170. ADVA 170 was selected because it has the ability to produce concrete mixtures that are extremely workable, and it also improves the slump life of concrete without lengthening the setting time. Twenty-one trial mixtures were batched with this HRWR. In Table 4.13 above, when mixtures # 19 and 20 are compared it is evident that an increase in the ADVA 170 dosage rate reduced the yield stress of the concrete. The slump flow measurement improved (28 in. (711.2 mm) vs. 19 in. (482.6 mm)), but perhaps more importantly, the stability did not change.

The final HRWR that was utilized was ADVA Cast 575. This HRWR was used throughout the remainder of trial batching because it is designed to produce concrete mixtures that are particularly workable without segregating. ADVA Cast 575 was employed in thirty trial mixtures. If mixtures # 33 and 34 are compared (Table 5.13), it can be seen that an increase in the addition rate of ADVA Cast 575 decreased the yield stress of the concrete. The results show that the average slump flow diameter was increased (29 in. (736.6 mm) vs. 25 in. (635 mm)), and the T-20 (T-50) time decreased significantly (3.88 seconds vs. 7.49 seconds). Also, the stability of the mixture was constant.

From these results, the mixtures that were batched with ADVA 170 and ADVA Cast 575 demonstrated an improvement in flowability while preserving the stability of the mixtures. Therefore, both of these HRWRs are recommended for use in producing SCC.

5.5.3 *S/Agg*

The *S/Agg* is another element that affects the flowability of SCC. In general, as the *S/Agg* increases so does flowability. The reason for this is that an increase in the *S/Agg* reduces the coarse aggregate content. This, in turn, reduces the overall viscosity of the mixture. For instance, consider the slump flow test. When the *S/Agg* is increased, the decreased quantity of coarse aggregate particles does not collide at the outlet of the slump cone as frequently whenever the test is being performed. This results in improved slump flows and decreased T-20 (T-50) times. This effect is displayed in Table 5.14.

Table 5.14: Effect of Increasing *S/Agg* on Slump Flow and T-20 (T-50)

Materials	Mixtures								
	6	7	8	20	21	33	29	50	51
Total Cementitious Materials (lb/yd^3)	811	811	811	761	761	775	775	775	775
Fly Ash (%)	---	---	---	---	---	---	---	20	20
Coarse Aggregate (lb/yd^3)	1332	1277	1222	1380	1324	1425	1367	1397	1341
Fine Aggregate (lb/yd^3)	1402	1455	1509	1454	1509	1384	1439	1356	1411
Water (lb/yd^3)	357	357	357	335	335	341	341	341	341
Water/Binder	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
Sand/Aggregate	0.52	0.54	0.56	0.52	0.54	0.5	0.52	0.5	0.52
ADVA CAST 530 (fl oz./cwt)	---	---	---	---	---	---	---	---	---
ADVA 170 (fl oz./cwt)	5	5	5	7	7	---	---	---	---
ADVA CAST 575 (fl oz./cwt)	---	---	---	---	---	7	7	6	6
Fresh Concrete Properties									
Slump Flow (in.)	25	26	27.5	28	29	25	28.5	24.5	28
T-20 (sec)	5.37	5.16	4.53	4.13	4.04	7.49	5.07	3.71	2.98

The first set of mixtures detailed in Table 5.14 consists of mixtures # 6, 7, and 8. These mixtures were batched with a binder content of 811 lb/yd^3 (481.15 kg/m^3). As the *S/Agg* was increased (0.52, 0.54, 0.56), the slump flows increased (25, 26, 27.5 in. (635, 660.4, 698.5 mm)). This also decreased the T-20 (T-50) times (5.37, 5.16, 4.53 seconds). The second array included mixtures # 20 and 21. For these mixtures, the binder content was 761 lb/yd^3 (451.48 kg/m^3). When the *S/Agg* increased from 0.52 to 0.54, the average slump flow diameters also increased (29 in. vs. 28 in. (736.6 mm vs. 711.2 mm)). In addition, the T-20 (T-50) measurements decreased from 4.13 to 4.04 seconds. The third selection was comprised of mixtures # 33 and 39. These mixtures had a binder content equal to 775 lb/yd^3 (459.79 kg/m^3). The results show that whenever the *S/Agg* increased from 0.50 to 0.52, the slump flows also increased from 25 in. (635 mm) to 28.5 in. (723.9 mm). This modification to the mix design produced a less viscous mixture, thus the T-20 (T-50) time decreased from 7.49 to 5.07 seconds. The final assortment contained mixtures # 50 and 51. These mixtures were batched with the same binder content as the previous range. However, a cement replacement of 20% FA was utilized. The findings display that when the *S/Agg* increased from 0.50 to 0.52, the corresponding slump flows expanded from 24.5 in. (622.3 mm) to 28 in. (711.2 mm). Furthermore, the T-20 (T-50) times were faster (2.98 vs. 3.71 seconds).

Overall, these results verify that (regardless of binder content) an increase in *S/Agg* will improve the flowability and decrease the viscosity of SCC.

5.5.4 Steps to Develop SCC

Through trial batching in this research program, a methodology was followed to develop SCC mixtures. The steps associated with this methodology are presented below.

Step 1: Achieve adequate flowability

I. Select a *w/b* based on literature. *NOTE: For this research program, the *w/b* was recommended to be a constant value of 0.44. The concrete was classified as Class S “structural”, and it did not have any significant compressive strength requirements. In this study, fifteen SCC mixtures were developed with a *w/b* equal to 0.44. For that reason, (*w/b* = 0.44) is recommended for use in the field.

II. Select an initial binder (water) content based on literature. *NOTE: For this research program, the Standard Specifications[5] mandated that the minimum allowable binder content was 611 lb/yd^3 (362.49 kg/m^3). Therefore, this was the initial binder content that was used. However, SCC was unable to be batched at this binder content because an insufficient amount of water was provided. In this study, the lowest binder content at which SCC was able to be batched consistently was 775 lb/yd^3 (459.79 kg/m^3). As a result, 775 lb/yd^3 (459.79 kg/m^3) is the minimum binder content that is recommended for use when batching SCC.

III. Select an initial *S/Agg* value based on literature. Previous research conducted at the University of Arkansas[77] recommends *S/Agg* values ranging from 0.44 to 0.56 for batching SCC. However, in this research program, only the central portion of the specified range (0.48 – 0.52) produced SCC mixtures consistently. Thus, *S/Agg* values of 0.48, 0.50, and 0.52 are recommended for use.

IV. Batch trial mixtures to establish an adequate HRWR dosage rate. *NOTE: If the HRWR dosage rate exceeds the maximum value listed by the manufacturer and the mixture still does not classify as SCC, the binder content should be increased.

V. The *S/Agg* value can be incrementally increased to enhance flowability (if needed).

VI. Slump flow spreads ranging from 23.5 to 30.0 in. (596.9 – 762 mm) are an indication of adequate flowability. Any measurement that falls within this specified range is recommended. Slump flows that are less than 23.5 in. (596.9 mm) in diameter are susceptible to blockage problems, and slump flows that exceed 30.0 in. (762 mm) have high segregation potential

Step 2: Achieve adequate blockage resistance

I. T-20 (T-50) measurements that take longer than 6 seconds indicate that the mixture is viscous. As a result, blockage may occur.

II. Reducing the size of coarse aggregate can improve T-20 (T-50) measurements and decrease blockage potential.

III. Increasing the *S/Agg* can improve T-20 (T-50) measurements and decrease blockage potential.

IV. The height difference between SCC inside and outside the J-Ring is recommended to be less than or equal to 0.5 in. (12.7 mm); a measurement that exceeds this stipulation is an indication that the concrete does not have sufficient passing ability.

V. The difference between the slump flow spread and the J-Ring spread is recommended to be less than 4.0 in. (101.6 mm); a measurement that exceeds this specification suggests that the SCC is not adequate to permeate the reinforcement.

Step 3: Achieve adequate segregation resistance

I. T-20 (T-50) times less than 2 seconds indicate that the mixture is extremely flowable. As a result, segregation may occur.

II. Do not exceed the manufacturer's maximum recommended dosage rate of HRWR. This can lead to segregation because the HRWR may surpass its saturation point.

III. VSI designations that are less than or equal to 1.5 are recommended.

IV. Decreasing binder (water) content can improve concrete stability by increasing the density.

V. In this research program, SCC was developed with FA replacement rates that varied from 5 to 25%. Thus, this provision (5 – 25%) is recommended for use.

VI. If FA is included as a percentage replacement of cement and the mixture experiences segregation, the FA replacement rate can be reduced. This will improve concrete stability by increasing the density.

Step 4: Batch additional trial mixtures to ensure consistent results

CHAPTER 6

CASTING REINFORCED BOX CULVERTS USING THE DEVELOPED SCC MIXTURES

6.1 INTRODUCTION

This chapter reviews the casting of two reinforced box culverts using the developed SCC mixtures. The first box culvert was cast with mixture #29 (5.3.5), and the second box culvert was cast with mixture # 52 (5.4.2). The corresponding mixture designs are displayed below in Table 6.1. This chapter also presents difficulties that the author experienced during this procedure combined with an explanation of how the problems were resolved.

Table 6.1: Mixture Designs used in Culvert Casting

Materials	Mixtures	
	29	52
Total Cementitious Materials (lb/yd^3)	775	775
Fly Ash (%)	---	25
Coarse Aggregate (lb/yd^3)	1367	1445
Fine Aggregate (lb/yd^3)	1439	1295
Water (lb/yd^3)	341	341
Water/Binder	0.44	0.44
Sand/Aggregate	0.52	0.48
ADVA CAST 530 (fl oz./cwt)	---	---
ADVA 170 (fl oz./cwt)	---	---
ADVA CAST 575 (fl oz./cwt)	7	6

6.2 REINFORCED BOX CULVERT DESIGN

The culverts were designed using two of the Arkansas State Highway Commission's standard drawings[78, 79] as a reference. Preliminary dimensions were chosen. The author selected a clear span of 4 ft. (1.22 m), a clear height of 4 ft. (1.22 m), and an overall width of 5 ft. (1.52 m) for each culvert. For these dimensions, the thickness of the top slab was set at 7 in. (177.8 mm), the thickness of each sidewall was 6 in. (152.4 mm), and the thickness of the bottom slab was 6.5 in. (165.1 mm).This resulted in an overall height of 5 ft. 1.5 in. (1.56 m). Also, the culverts were cast vertically to a depth of 5 ft. (1.52 m). This resulted in a total required concrete volume of approximately 1.78 yd^3 (1.36 m^3) for each culvert.

After the clear span, clear height, and depth of the culverts were chosen, the reinforcing steel was designed. In the top and bottom slabs of each barrel, five # 5 rebar that were 57 in. (1.45 m) in length were spaced at 12 in. (304.8 mm). In addition, five # 6 bent rebar that were 70 in. (1.78 m) in length (7 in. (177.8 mm) per 180 degree hook) were alternated every 12 in. (304.8 mm). The longitudinal steel located in the top slab of each barrel consisted of six # 5 rebar that were 57.5 in. (1.46 m) in length and spaced at 10.5 in. (266.7 mm). Eight # 4 rebar were included longitudinally in the sidewalls of both culverts. These rebar were 57.5 in. (1.46 m) long and spaced at 8 in. (203.2 mm). The longitudinal steel positioned in the bottom slab of the barrels was comprised of five # 4 rebar that were 57.5 in. (1.46 m) in length and spaced at 12 in. (304.8 mm). Lastly, six # 4 rebar that were 59 in. (1.50 m) long and spaced at 11.5 in. (292.1 mm) were incorporated vertically in the sidewalls of each culvert. This resulted in 59 total rebar that was required for each culvert. The cross-section of each culvert including rebar placement is presented in Figure 6.1. Additionally, Figure 6.2 shows the steel-ply formwork and bundles of rebar before the culverts were assembled.

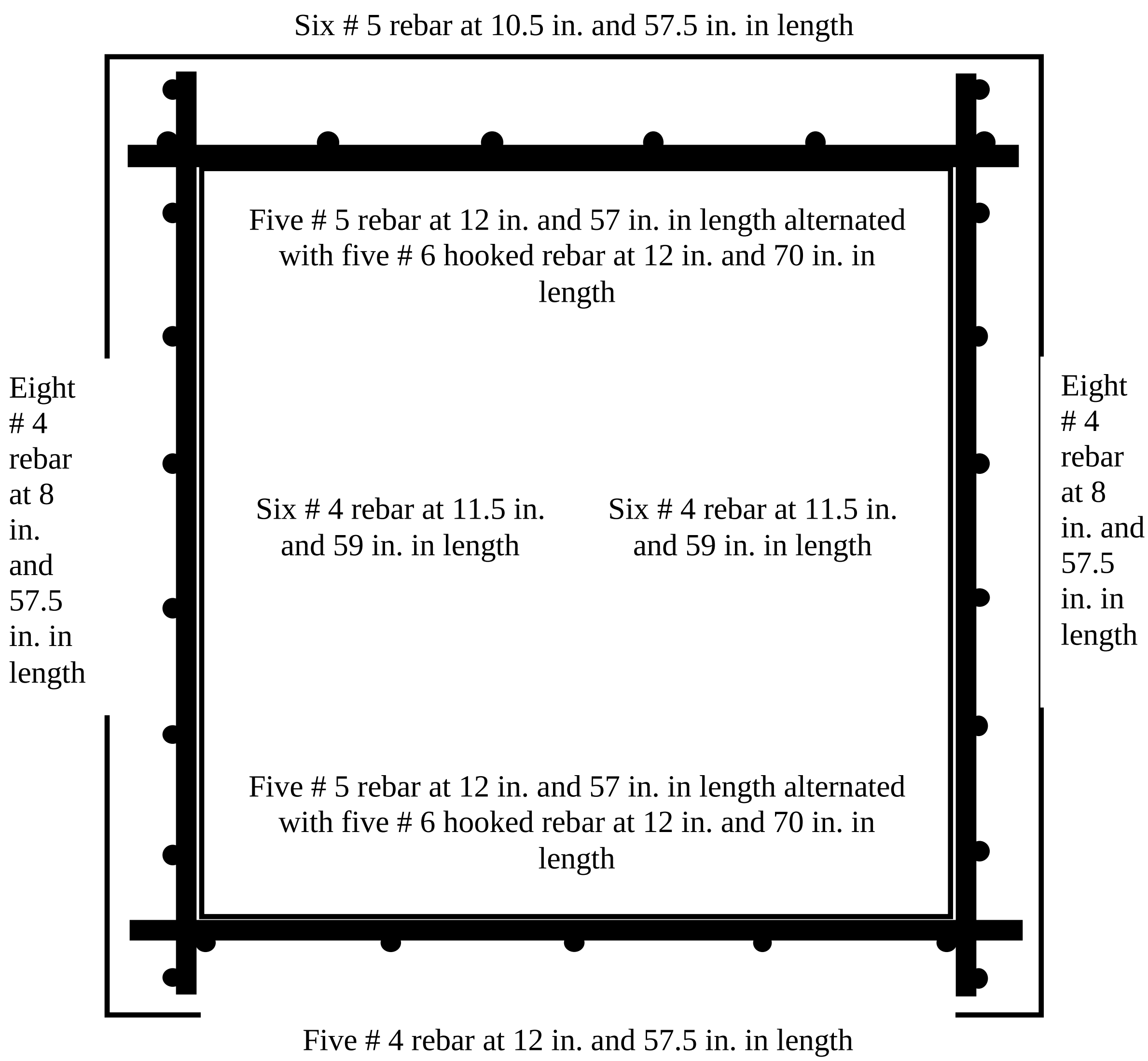

Figure 6.1: Culvert Cross-Section Including Rebar Placement

Figure 6.2: Steel-ply Formwork and Rebar

6.3 ASSEMBLY

The culverts were cast on a concrete pad behind the ERC. The culverts were spaced several feet apart and free from obstructions so that a ready-mix truck could back up and dispense the concrete without any interference. To make the base of each culvert, the author cut multiple sheets of 5/8 in. (15.88 mm) plywood to size and stapled them together. The formwork used for the culverts consisted of a set of steel-ply pieces that were rented from Darragh Company in Lowell, Arkansas.

6.3.1 Erection

6.3.1.1 Inner Wall

The first goal was to construct the inner wall of each culvert. To accomplish this, the steel-ply pieces were put together by pushing steel keys through adjoining members which created a tight lock. Each side of the wall consisted of one 1 ft. (304.8 mm) wide steel-ply section, one 2 ft. (609.6 mm) wide steel-ply section, and two 6 in. (152.4 mm) wide corner pieces. For the middle section of each wall, steel wall ties were inserted between the neighboring steel-ply sections before they were locked; the steel wall ties provided lateral reinforcement and spanned from the inner wall to the outer wall of each culvert. When one side of the wall was completed, it was picked up and situated on top of the plywood base. The next step was to combine the other three wall sections in the same manner. Once this was done, the inner wall was completely assembled. Lastly, the author secured the formwork to the base with wood screws. The steel key locking system can be seen in Figure 6.3, and the completed inner wall of the first culvert is displayed in Figure 6.4.

Figure 6.3: Steel Key Locking System

Figure 6.4: Inner Wall of the First Culvert

6.3.1.2 Rebar, Spacing, and PVC Pipe

Rebar cages were constructed by spacing out the necessary bars as indicated by the culvert design. The rebar was then tied accordingly. Once tied, each cage was erected on the appropriate side of the culvert. This process was then repeated three more times per culvert so that a rebar cage could be placed at the top, bottom, and sidewalls. When all four cages had been raised, a rebar matrix was built by tying each cage to the adjacent cage. Figure 6.5 presents both the four finished rebar cages and the corresponding rebar matrix for the first culvert.

Figure 6.5: Rebar Cages and the Corresponding Rebar Matrix

Each rebar matrix was tied with 40 ought wire and was then suspended from a series of crossing rebar that was laid across the top of the formwork; this guaranteed that the vertical spacing requirements were satisfied. To ensure that the horizontal spacing requirements were met, rebar chairs were placed between the inner wall and the sides of the rebar matrix. After that, the rebar chairs were tied to the matrix so that the spacing would remain constant whenever the SCC was poured.

Subsequently, PVC pipe that had an outside diameter of 1.5 in. (38.1 mm) was cut to size and positioned around the steel wall ties. In the field, this would simulate drainage. However, it also served an additional purpose. The PVC pipe along with the rebar chairs and the congested rebar matrix would test the flowability of the SCC. A view of the first culvert at this stage of erection is exhibited in Figure 6.6.

Figure 6.6: Completed Inner Structure of the First Box Culvert

6.3.1.3 Outer Wall

Once the inner structure of each box culvert was finished, the outer wall was connected by the same method as the inner wall. The top and bottom sides of each wall consisted of three 1 ft. (304.8 mm) wide steel-ply sections, and one 2 ft. (609.6 mm) wide steel-ply section. To account for the additional 1.5 in. (38.1 mm) that was necessary on each sidewall, a 1 in. (25.4 mm) steel spacer was inserted at the top of each wall. At the bottom of the wall, a 0.5 in. (12.7 mm) spacer was needed on either side. The spacer was made by cutting a sheet of ½ in. (12.7 mm) plywood to size. To secure the spacer to the formwork, several holes were bored along the length of the plywood so the steel keys could fit through it and be locked.

The aforementioned steel wall ties were provided by Darragh Company and came in two sizes. The ties in the sidewalls of each culvert had a clear span of 6 in. (152.4 mm). These ties fit securely without being altered. However, the steel ties used in the top and bottom slabs of the culverts were required to be unusual sizes (7 and 6.5 in. (177.8, 165.1 mm)). Therefore, these ties were made by using # 2 straight rebar. The rebar was cut in 24 in. (609.6 mm) sections to make certain that adequate length would be provided to properly secure it. To lock the rebar tightly in place between the inner and outer formwork, a series of clamps were placed around the rebar and firmly fastened. Once this task was completed, the outer formwork was secured to the plywood base with wood screws. Figure 6.7 shows the two culverts near completion.

Figure 6.7: Reinforced Box Culverts near Completion

6.4 TRIAL BATCHING

Even though a rotating drum mixer was located on site at the ERC, the research team elected to have a ready-mix company mix, deliver, and pour the concrete for the culverts. For this research program, Arkhola Sand & Gravel Company was used. The culverts required a much larger volume of concrete than was utilized whenever the SCC mixtures were being developed (1.78 yd^3 vs. 2 ft^3, (1.36 m^3 vs. 0.06 m^3)). Also, it was expected that the friction and shearing rates were different from a rotating drum mixer to a ready-mix concrete truck. For these two reasons, trial batching was conducted at Arkhola Sand & Gravel Company's plant in Johnson, Arkansas so the mixtures could be modified (if necessary) prior to the culverts being cast.

6.4.1 SCC Mixture # 1

6.4.1.1 Trial Batch # 1a

The first culvert was cast using mixture # 29, which was developed during the laboratory phase of the study. For the first batch, all of the constituent materials except the HRWR were added to the ready-mix truck. The HRWR was not included at this time so the workability of the concrete could be assessed by performing a traditional slump test. The slump would give the research team a better understanding of how workable the concrete actually was. From this measurement, a HRWR dosage could be determined. To simulate the time it would take for the concrete to be delivered to the ERC, the initial mixing time was 20 minutes. After this time had elapsed, a sample of concrete was poured into a wheel barrow (Figure 6.8) and the slump test was conducted. The mixture had an initial slump of 2.75 in. (69.85 mm) (Figure 6.9). The HRWR dosage rate was decreased from 7 to 6 fl. oz. /cwt (391.19 mL/100 kg). Once the HRWR was added (Figure 6.10), the concrete was mixed for 5 minutes. When that time had passed, a sample of concrete was placed into the wheel barrow and the slump flow test was performed. Before the test was initiated, it was apparent that segregation had already occurred (Figure 6.11). The test was still performed regardless (Figure 6.12). Severe segregation was observed (VSI = 3), so the mixture was discarded.

Figure 6.8: Sample of Trial Batch # 1a Before HRWR was Added

Figure 6.9: Conducting Slump Test on Sample of Trial Batch # 1a

Figure 6.10: Adding HRWR to Trial Batch # 1a

Figure 6.11: Segregation Observed in Trial Batch # 1a

Figure 6.12: View of Slump Flow Spread for Trial Batch # 1a

6.4.1.2 Trial Batch # 1b

Since trial batch # 1a had undesirable fresh concrete properties, a second trial batch was mixed. Batching for this mixture began approximately 40 minutes after the first. The volume of concrete, mixture proportions, and batching sequences were identical to trial batch # 1a. After the initial batching sequence was completed, the concrete sample had a slump of 3.25 in. (82.55 mm). This value was larger than the slump of trial batch # 1a which experienced segregation. For these reasons, the initial HRWR dosage rate was reduced to 3 fl. oz. /cwt (195.60 mL/100 kg). After 5 minutes of batching, the slump flow was 14.5 in. (368.3 mm). Since the concrete had limited flowability, an additional 1 fl. oz. /cwt (65.20 mL/100 kg) was added at this time. Once this 5 minute batching sequence was complete, the slump flow was 20 in. (508 mm). A small aggregate pile was present in the center of the concrete spread, so a VSI designation of 1 was given. Given that the concrete did not achieve sufficient flowability, another 0.5 fl. oz. /cwt (32.60 mL/100 kg) was incorporated. Following one more 5 minute batching sequence, the slump flow was 18 in. (457.2 mm). The author attributes the decrease in the mixture's flowability to the HRWR losing its effectivenesss; the mixture had been mixing for approximately 50 minutes. Even though the mixture did not develop adequate flowability, the research team felt confident that the HRWR dosage rate could be modified to acquire SCC. On the day the first culvert was to be cast, if the initial HRWR dosage rate was increased to 5 fl. oz. /cwt (326 mL/100 kg) then the mixture could achieve the required flowability.

Six cylinders were cast from trial batch # 1b for compressive strength testing. Three cylinders were tested at 1 day of age, and the other three cylinders were tested at 28 days of age. The results proved that the mixture had adequate hardened properties; average 1 and 28-day compressive strengths were reported to be 3810 and 7930 psi (26.29, 54.67 MPa), respectively

6.4.1.3 Conclusion

The research team considered why such severe segregation had occurred in trial batch # 1a when a smaller addition rate of HRWR was utilized. It is important to note that it had rained earlier in the day and also during trial batching. Therefore, the aggregates were exposed to the elements because they were not covered. When measuring out the required quantities of coarse and fine aggregate, moisture contents of approximately 3% were assumed. However, when aggregate samples were taken and tested at the ERC, the actual moisture contents of the coarse and fine aggregates were reported to be 4.39 and 12.03%, respectively. These results showed that a larger quantity of water was included during mixing than was required by the mix design. This explains why the initial slump measurements were so high. The batch time, batch size, HRWR dosage rate, and fresh and hardened concrete properties for the two trial batches conducted on the first SCC mixture are located below in Table 6.2.

Table 6.2: Trial Batch # 1a and Trial Batch # 1b Details

Culvert	SCC Mixture # 1	
	Trial Batch # 1a	Trial Batch # 1b
Batch Time	1:00 P.M.	1:40 P.M.
Batch Size (yd^3)	2.0	2.0
Initial Slump (in.)	2.75	3.25
ADVA CAST 575 (fl oz./cwt)	6	4
Slump Flow (in.)	---	20
Segregation Observed	yes	no
VSI	3	1
Bleed Water	yes	no
T-20 (sec)	---	---
1-day Compressive Strength (psi)	---	3810
7-day Compressive Strength (psi)	---	---
28-day Compressive Strength (psi)	---	7930

6.4.2 SCC Mixture # 2

For the second trial mixture, 25% of the cement was replaced with FA (mixture # 52). This mix design was sent to Arkhola Sand & Gravel Company and a batching date was set. The batching sequence and progression of tests did not change from those utilized in the first SCC mixture (trial batch # 1a and # 1b). The initial slump was 0.5 in. (12.7 mm). The preliminary HRWR dosage rate was 4 fl. oz. /cwt (260.79 mL/100 kg); the research team decided to employ a lower dosage of HRWR in an attempt to promote concrete flowability without causing segregation such that occurred in trial batch # 1a. Following the 5 minute mixing sequence, the slump was 1.5 in. (38.1 mm). To advance the flowability, an additional 2 fl. oz. HRWR /cwt (130.40 mL/100 kg) was added. After another 5 minute mixing sequence, the slump flow was 18 in. (457.2 mm). The concrete was flowable, but it was too viscous. For this reason, a supplementary 1 fl. oz. HRWR /cwt (65.20 mL/100 kg) was incorporated to increase flowability. At this point a total of 118.35 fl. oz. (3500 mL) HRWR had been used. Following one more 5 minute mixing sequence, the slump flow increased to 21 in. (533.4 mm). Also, a small aggregate pile had settled in the middle of the spread; consequently, a VSI value of 1 was issued. Although the concrete did not acquire the necessary flowability, no further HRWR was added to the mixer. The research team elected to conclude batching because it was believed that the HRWR was beginning to lose its effectiveness. SCC was not obtained, but the concrete was still quite flowable. This result was promising. On the day of batching, if the initial HRWR dosage rate was increased to 5 fl. oz. /cwt (326 mL/100 kg) then the flowability would likely improve as well.

Nine cylinders were cast from this mixture for compressive strength testing. A set of three cylinders were tested at 1, 7, and 28 days of age. The average 28-day compressive strength was 11720 psi (80.83 MPa). The moisture contents of the coarse and fine aggregates were also tested. The moisture contents of the coarse and fine aggregates were 1.72 and 3.23%, respectively. These percentages were far less extreme than those that were previously computed for trial batch # 1a. This explains why the initial slump was so small. Furthermore, this reveals why the segregation resistance for the mixture was much higher. Less water was utilized during mixing, which increased the stability of the mixture. The batch time, batch size, HRWR dosage rate, and fresh and hardened concrete properties for the second SCC mixture are presented below in Table 6.3.

Table 6.3: SCC Mixture # 2 Details

Culvert	SCC Mixture # 2
Batch Time	1:00 P.M.
Batch Size (yd^3)	2.0
Initial Slump (in.)	0.5
ADVA CAST 575 (fl oz./cwt)	7
Slump Flow (in.)	21
Segregation Observed	no
VSI	1
Bleed Water	no
T-20 (sec)	---
1-day Compressive Strength (psi)	5040
7-day Compressive Strength (psi)	9750
28-day Compressive Strength (psi)	11720

6.5 CASTING PROCEDURE

For both culverts, on the day prior to casting, a form-releasing agent was applied to the forms to ensure easy formwork removal 24 hours after casting. The casting procedure of both culverts is discussed in detail below.

6.5.1 Box Culvert # 1a

The first box culvert was cast with the original SCC mixture (mixture # 29) containing only portland Type I cement as the binder constituent. For this culvert, 3 yd^3 (2.29 m^3) of concrete was batched. On the day of casting, the ready-mix truck arrived at the ERC at 1:38 P.M. The batching sequence and series of tests were identical to those performed during trial batching. The mixture had an initial slump of 1 in. (25.4 mm). To improve workability, 5 fl. oz. /cwt (326 mL/100 kg) was used as the preliminary dosage rate. After the 5 minute batching sequence, the slump flow was 18 in. (457.2 mm). At this time, an additional 0.5 fl. oz. of HRWR /cwt (32.60 mL/100 kg) was added to improve the flowability. Following another 5 minutes of mixing, the slump flow increased to 19 in. (482.6 mm). The mixture was stable, but a small aggregate pile was located in the central portion of the spread. As a result, the VSI was 0.5. To further increase the flowability, an additional 1 fl. oz. /cwt (65.20 mL/100 kg) was incorporated. Once the next concrete sample was dispensed into the wheel barrow for testing, it was apparent that the HRWR had lost its effectiveness (Figure 6.13). As soon as the slump flow test was performed, the mixture was only able to develop a 5 in. (127 mm) slump. Consequently, the mixture was rejected because the concrete did not acquire adequate flowability. Mixing was concluded and testing stopped at 2:16 P.M. The batch time, batch size, HRWR dosage rate, and fresh concrete properties for the mixture attempted in casting the first box culvert are presented in Table 6.4.

Figure 6.13: Evidence of the Declining Effectiveness of HRWR at an Extended Batching Time

Table 6.4: Box Culvert # 1a Details

Culvert	SCC Mixture # 1
	Box Culvert # 1a
Batch Time	1:38 P.M.
Batch Size (yd^3)	3.0
Initial Slump (in.)	1
ADVA CAST 575 (fl oz./cwt)	5.5
Slump Flow (in.)	19
Segregation Observed	no
VSI	0.5
Bleed Water	no
T-20 (sec)	---

6.5.2 Box Culvert # 1b

Since the preceding attempt at casting the first box culvert was unsuccessful, a second batch was scheduled for the following day. The concrete arrived at 9:58 A.M, and it had an initial slump of 1.5 in. (38.1 mm). At 10:00 A.M., 4 fl. oz. HRWR /cwt (260.79 mL/100 kg) was added. When tested at 10:10 A.M., the concrete had a slump of 3 in. (76.2 mm). Two minutes later at 10:12 A.M., an additional 2 fl. oz. HRWR /cwt (130.40 mL/100 kg) was added. This increased the flowability; the slump flow spread was 19.5 in. (495.3 mm) at 10:19 A.M. To further improve flowability, 1 more fl. oz. HRWR /cwt (65.20 mL/100 kg) was added at 10:20 A.M. The final series of fresh concrete tests was conducted at 10:25 A.M. The T-20 (T-50) was 2.25 seconds, and the spread was 25.5 in. (647.7 mm). The VSI was 0.5 due to the slight amount of bleed water that was present. Upon operating the J-Ring test, a height difference between concrete inside and outside the J-Ring was 0.25 in. (6.35 mm). Moreover, the J-Ring flow spread was larger in diameter when compared with the slump flow spread; an average measurement of 27.25 in. (692.15 mm) was documented. This yielded a variation between the slump flow spread and the J-Ring spread that was 1.75 in. (44.45 mm) in magnitude. Once all of the fresh concrete properties were established as sufficient, the culvert was cast.

Once fresh concrete testing was complete, the ready-mix truck was able to back up to the culvert. The author stood inside the formwork and held a section of 5/8 in. (15.88 mm) plywood to guide the SCC into the culvert. This was done to prevent any concrete from spilling over the edges of the culvert. The culvert was filled in one lift from a single location. The SCC remained homogenous and stable and flowed around the congested rebar and other obstructions with ease. However, when the concrete was at approximately 4 ft. (1.22 m) of the total 5 ft. (1.52 m) depth, the formwork failed (Figure 6.14). After 24 hours had passed, the formwork was removed. Upon removing the formwork, it was apparent the failure occurred because one of the steel wall ties had straightened out due to the excessive hydrostatic pressure of the SCC. Consequently, the formwork became weak at this location and was forced outward causing failure. Figure 6.15 shows the location where failure occurred.

Figure 6.14: Formwork Failure in Box Culvert # 1

Figure 6.15: Critical Location Where Failure Occurred in Box Culvert # 1

Approximately one-third of the total quantity of SCC remained within the formwork. There was no evidence of segregation as aggregates were seen at the top of what was left of the culvert. Also, the culvert had a smooth finish (Figure 6.16). The interior and exterior corners finished smoothly as well (Figure 6.17). In fact, the only visible defect was some localized surface blemishes that had occurred due to the entrapment of air voids (Figure 6.18).

Figure 6.16: Smooth Finish of Box Culvert # 1

Figure 6.17: Smooth Finish of Interior and Exterior Corners of Box Culvert # 1

Figure 6.18: Localized Surface Blemishes Present on Box Culvert # 1

Nine cylinders were cast from this mixture to evaluate the hardened concrete properties. Six cylinders were cast for compressive strength testing and three cylinders were cast for modulus of elasticity testing. Compressive strength was 4740 psi at one day of age and 9500 psi at 28 days of age (32.67, 65.53 MPa). The 28-day modulus of elasticity was 6300 ksi (43495 MPa). The predicted value for the mixture that was calculated using Equation 1 (Section 2.6.4) was 5650 ksi (38849 MPa) based on the measured unit weight (145.3 lb/ft^3, 2327.48 kg/m^3) and 28-day compressive strength. When compared with the predicted elastic modulus, the measured value was approximately 12% greater. A graphical comparison between the predicted and measured 28-day elastic modulii is presented below in Figure 6.19. Also, the batch time, batch size, HRWR dosage rate, and fresh and hardened concrete properties for the mixture used in casting the first box culvert are displayed in Table 6.5.

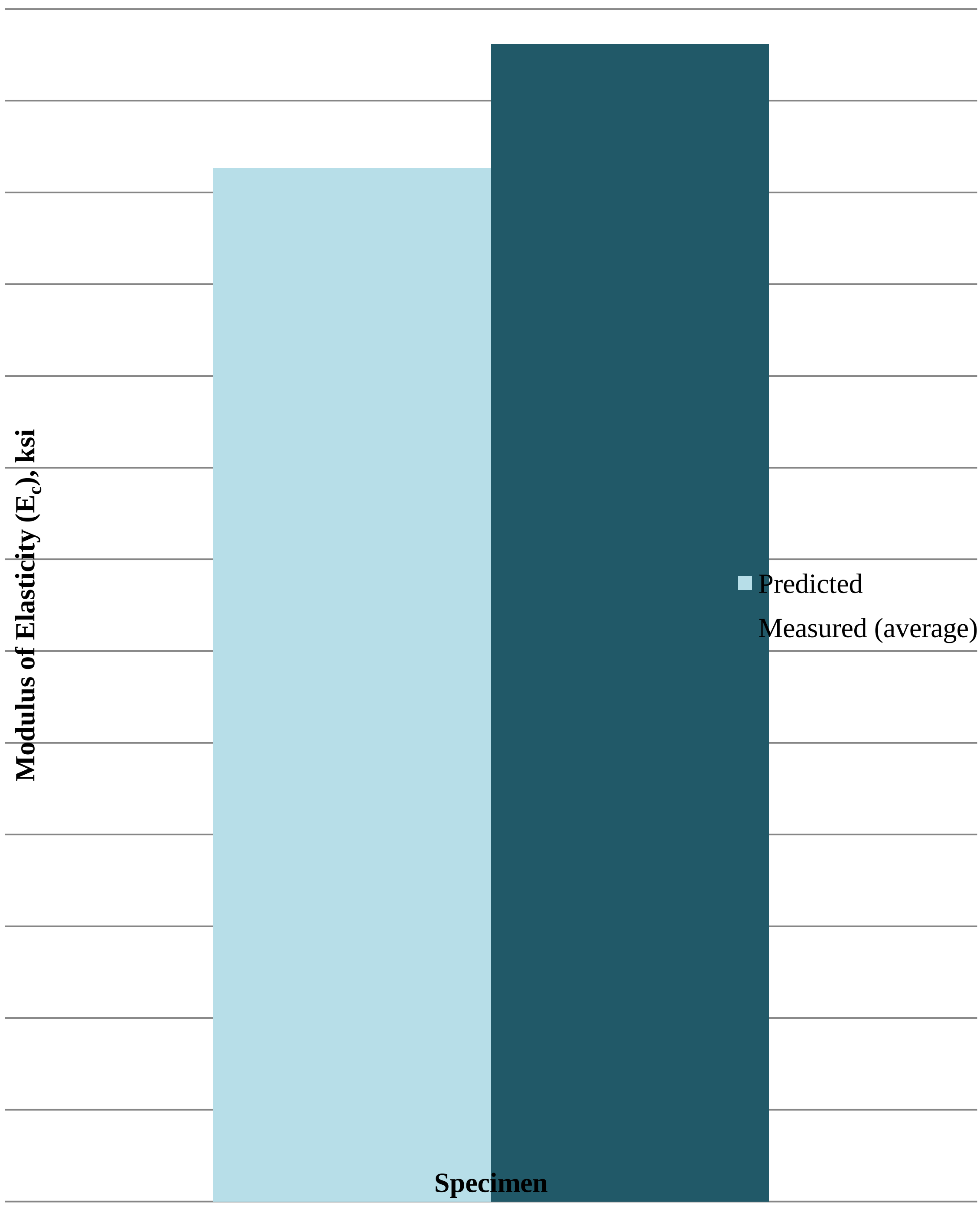

Figure 6.19: Comparison between Predicted and Measured Elastic Modulii for Box Culvert # 1b

Table 6.5: Box Culvert # 1b Details

Culvert	SCC Mixture # 1
	Box Culvert # 1b
Batch Time	9:58 A.M.
Batch Size (yd^3)	3.0
Initial Slump (in.)	1.5
ADVA CAST 575 (fl oz./cwt)	7
Slump Flow (in.)	25.5
Segregation Observed	no
VSI	0.5
Bleed Water	yes
T-20 (sec)	2.25
Δh^* (in.)	0.25
Slump Flow Spread - J-Ring Spread (in.)	1.75
Unit Weight (lb/ft^3)	145.3
1-day Compressive Strength (psi)	4740
7-day Compressive Strength (psi)	---
28-day Compressive Strength (psi)	9500
28-day Modulus of Elasticity (ksi)	6300

Δh^*: height difference between concrete inside and outside the J-Ring

6.5.3 Box Culvert # 2

Since the SCC exerted substantial hydrostatic pressure on the first box culvert (ultimately causing failure), additional lateral reinforcement was provided for the second box culvert. The formwork was braced with 2 in. (50.8 mm) by 8 in. (203.2 mm) lumber along its base. Figure 6.20 shows the external lateral reinforcement that was furnished.

Figure 6.20: External Lateral Reinforcement that was provided for Box Culvert # 2

The second box culvert was cast with mixture # 52 which included a FA content of 25%. On the day of casting, the ready-mix truck arrived at the ERC at 1:35 P.M with 3 yd^3 (2.29 m^3) of concrete. The initial slump was 2.5 in. (63.5 mm) at 1:43 P.M. At 1:44 P.M., 5 fl. oz. /cwt (326 mL/100 kg) of HRWR was added to the mixture to increase flowability. The concrete was mixed for 5 minutes before testing. When the concrete was poured into the wheel barrow at 1:49 P.M., it was evident that the mixture was not homogeneous; the concrete was too wet and too dry in sections. So the concrete was allowed to mix for 12 more minutes. At 2:01 P.M., the T-20 (T-50) was 2.1 seconds, and the slump flow was 30 in. (762 mm). Upon viewing the spread it was apparent that segregation had occurred (VSI = 2). The concrete was mixed for another 8 minutes in an attempt for the excess bleed water to be absorbed. Following this mixing sequence, a second slump flow test was conducted at 2:09 P.M. The T-20 (T-50) was 1.41 seconds, and the slump flow was 27 in. (685.8 mm). When the concrete was evaluated for stability, moderate bleed water was present but the sample showed no evidence of segregation (VSI = 1). As a result, the mixture was deemed acceptable. The SCC was placed inside the culvert at 2:10 P.M by implementing the same procedure that was utilized in casting the first box culvert (Section 5.5.2) (Figure 5.21). Two minutes later, the culvert had been filled to the full depth of 5 ft. (1.52 m) and the top surface was finished (Figure 5.22). At 2:12 P.M., the J-Ring test was performed. There was not a measurable height difference between concrete inside and outside the J-Ring. Additionally, the J-Ring flow spread of 30.25 in. (768.35 mm) was larger in diameter when compared with the slump flow spread. One final slump flow test was performed at 2:15 P.M. The ensuing T-20 (T-50) measurement was 1.78 seconds, and the slump flow spread had an average diameter of 29 in. (736.6 mm). A VSI designation of 1 was issued because a slight mortar halo was present around the perimeter of the spread (Figure 6.23).

Figure 6.21: Ready-Mix Truck Casting Box Culvert # 2

Figure 6.22: Top Surface of Box Culvert # 2 after Finishing


Figure 6.23: Bleed Water Observed in Mixture Used for Casting Box Culvert # 2

Twenty-four hours after casting, the formwork was removed. Upon viewing the box culvert, it was apparent that the mixture had performed well. Segregation had not occurred because aggregates were visible at the top surface of the culvert. Also, the culvert had a smooth finish along each wall and at each interior and exterior corner. Furthermore, the author only observed a few surface defects that were caused by air voids. Figure 6.24 displays the second box culvert after the formwork had been removed.

Figure 6.24: Completed Box Culvert # 2 after Removal of Formwork

Twelve cylinders were cast from this mixture to assess the hardened concrete properties. Nine cylinders were cast for compressive strength testing at 1, 7, and 28 days and three cylinders were cast for modulus of elasticity testing at 28 days. Compressive strength and modulus of elasticity values are shown in Table 5.6. When compared to the predicted value, the measured elastic modulus was approximately 12 % greater in magnitude than the predicted elastic modulus. Figure 6.25 exhibits a comparison between the predicted and measured 28-day elastic modulii. Furthermore, the batch time, batch size, HRWR dosage rate, and fresh and hardened concrete properties for the mixture utilized in casting the second box culvert are shown in Table 6.6.

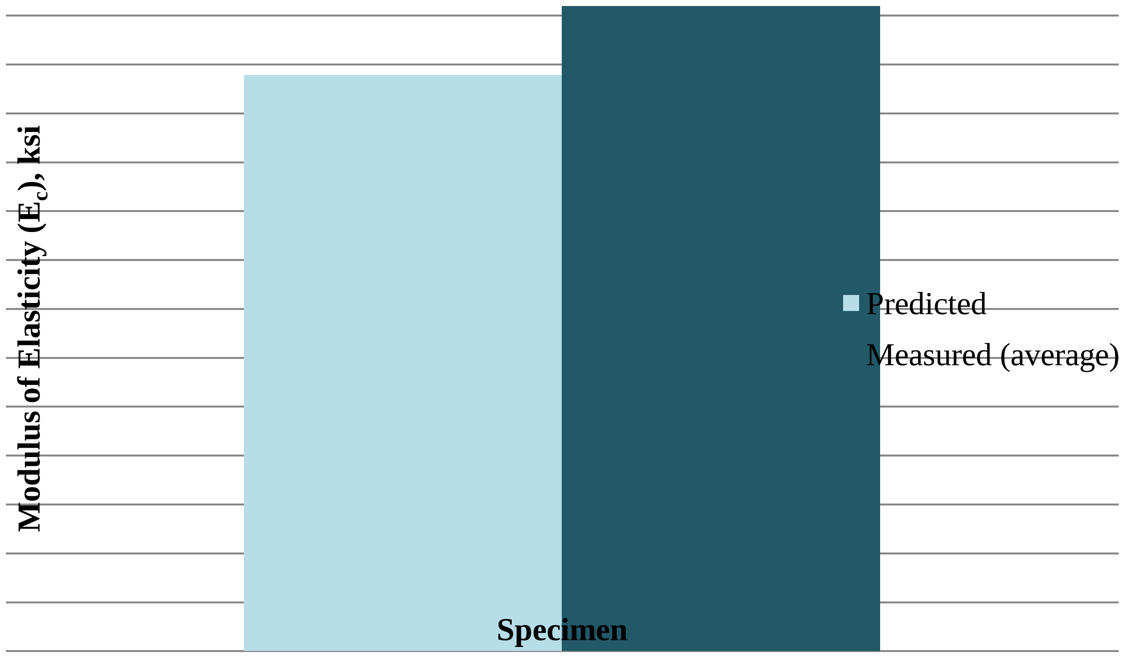

Figure 6.25: Comparison between Predicted and Measured Elastic Modulii for Box Culvert # 2

Table 6.6: Box Culvert # 2 Details

Culvert	SCC Mixture # 2
	Box Culvert # 2
Batch Time	1:35 P.M.
Batch Size (yd^3)	3.0
Initial Slump (in.)	2.5
ADVA CAST 575 (fl oz./cwt)	5
Slump Flow (in.)	29
Segregation Observed	no
VSI	1
Bleed Water	yes
T-20 (sec)	1.78
Δh^* (in.)	0
Slump Flow Spread - J-Ring Spread (in.)	1.25
Unit Weight (lb/ft^3)	148.24
1-day Compressive Strength (psi)	3280
7-day Compressive Strength (psi)	7670
28-day Compressive Strength (psi)	9780
28-day Modulus of Elasticity (ksi)	6600

Δh^*: height difference between concrete inside and outside the J-Ring

6.6 CONCLUSIONS

After the trial batching and casting of the two aforementioned reinforced box culverts, several conclusions can be made and are listed below.

- SCC can be successfully batched with a ready-mix truck.
- Trial batching is essential to ensure that SCC mixtures will perform as expected once applied.
- The original HRWR dosage rate should be based upon the initial slump of the concrete.
- The moisture contents of the aggregates can significantly influence the flowability of SCC. If aggregate moisture is not accurately accounted for, excess mixing water can be incorporated during mixing; this can lead to segregation.
- The author recommends that the total mixing time should not exceed 30 minutes. With extended mixing times, the HRWR can lose its desired effectiveness. An indicator of this effect can be observed whenever an SCC mixture exhibits a decrease in flowability after additional HRWR has been added. If this occurs, then the mixture should be discarded.
- The formwork associated with any SCC application must provide sufficient reinforcement to withstand the additional lateral hydrostatic forces that the concrete exerts.
- SCC does not require any internal or external vibration and less time is needed to finish the concrete. For these reasons, construction times can be reduced whenever SCC is implemented. In this research program, the second box culvert was cast and finished in two minutes.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

When compared with conventional-slump concrete, SCC can be a beneficial alternative because of its enhanced rheological properties. However, developing SCC can be a complex and lengthy process due to the sensitivity of these properties to changes with the mix design. In this research program, 52 trial mixtures were batched. After conducting an array of fresh and hardened concrete tests, performing trial batching inside of a ready-mix truck, and casting two full-size reinforced box culverts the following conclusions were made.

- The *w/b* is the most significant parameter that affects the flowability of SCC. Therefore, it should be the first factor that is selected when developing SCC.
- In this study, SCC was unable to be batched at the minimum binder content of 6.5 bags per cubic yard (611 lb/yd^3, 362.49 kg/m^3) that was stated in Table 802-1 of the Standard Specifications[5]. The lowest binder content at which SCC was consistently batched was 775 lb/yd^3 (459.79 kg/m^3).
- Trial mixtures that were batched with *S/Agg* values of 0.48, 0.50, or 0.52 frequently acquired desirable fresh concrete properties.
- An adequate HRWR dosage rate was established through trial batching. If the HRWR dosage rate exceeds the maximum value listed by the manufacturer and

the mixture still does not acquire sufficient flowability, the binder (water) content must be increased.

- The *S/Agg* value can be incrementally increased to improve flowability (if necessary).
- Slump flow spreads that range from 24 to 30.0 in. (596.9 – 762 mm) indicate that an SCC mixture has adequate flowability. Slump flows that are less than 24 in. (610 mm) in diameter are prone to experience blockage problems, and slump flows that surpass 30.0 in. (762 mm) are at a high risk for segregation.
- The T-20 (T-50) test was important in evaluating the blockage and segregation potential of all the trial mixtures. In this study, mixtures that had T-20 (T-50) times varying from 2 to 6 seconds performed well. Many of the mixtures that had T-20 (T-50) times that surpassed 6 seconds were viscous and experienced blockage. Conversely, the mixtures with T-20 (T-50) times of less than 2 seconds were extremely flowable and experienced segregation.
- Reducing the size of coarse aggregate (NMSA ≤ 3/8 in., 9.53 mm) can improve T-20 (T-50) times and decrease blockage potential. Additionally, a smaller coarse aggregate can decrease the segregation potential because the sedimentation rate of coarse aggregate particles will be reduced.
- Increasing the *S/Agg* can improve T-20 (T-50) times and decrease blockage potential.
- In this study, mixtures that had a height difference between SCC inside and outside the J-Ring that was less than or equal to 0.5 in. (12.7 mm) and a difference between the slump flow spread and the J-Ring spread that was less than

4.0 in. (101.6 mm) performed well. In certain mixtures where these conditions were not met, oftentimes blockage occurred.

- If at all possible, do not exceed the manufacturer's maximum recommended dosage rate of HRWR. This can lead to segregation because the HRWR may exceed its saturation point. Additionally, an overdose of HRWR can increase the setting time.
- Trial mixtures that had VSI designations that were less than or equal to 1.5 had sufficient stability. Any mixture that had a VSI which surpassed this limitation was either too viscous or was unstable due to excessive bleed water or segregation.
- Decreasing binder (water) content can improve concrete stability by increasing the density.
- In this study, SCC was developed with FA replacement rates that varied from 5 to 25%.
- If FA is included as a percentage replacement of cement and the mixture experiences segregation, the FA replacement rate can be reduced. This will improve concrete stability by increasing the density.
- Additional trial mixtures should be batched to ensure consistent results.
- SCC can be successfully batched inside a ready-mix truck. If this method of mixing is selected then driving time must be accounted for during trial batching. Also, since the concrete cannot be seen while it is mixing, the preliminary HRWR dosage rate must be based upon the initial slump of the concrete.

- The moisture contents of the aggregates can significantly influence the flowability of SCC. If aggregate moisture is not accurately accounted for, excess mixing water can be incorporated during mixing; this can lead to segregation.
- With extended batching times, the HRWR can lose its desired effectiveness. An indicator of this effect can be observed whenever an SCC mixture exhibits a decrease in flowability after additional HRWR has been added. If this occurs, then the mixture should be discarded.
- The formwork associated with SCC applications must provide adequate reinforcement to resist the additional lateral hydrostatic pressure that the concrete exerts.
- SCC does not require any internal or external vibration and less time is needed to finish the concrete. For these reasons, construction times can be reduced whenever SCC is implemented. In this study, the second box culvert was cast and completely finished in two minutes.

7.2 RECOMMENDATIONS

The results of this research program confirm that AHTD would benefit from an amendment to the Standard Specifications[5]. Since the fresh concrete properties and tests associated with SCC are different than those related to conventional-slump concrete, the author proposes that the following table (Table 7.1) should be included as an addition to Table 802-1. The criteria and fresh concrete specifications that were developed in this study are highlighted in yellow.

Table 7.1: Proposed Addition to Table 802-1 of the Standard Specifications[5]

Table 802-1a

Characteristic	**Class of Concrete** **S(SCC)**
Minimum Compressive Strength (psi [Mpa] at 28 days)	3500 [24.0]*
Minimum Cement Factor (bags per cubic yard) [kg/cu m]	8.25 [460]
Maximum Water/Cement Ratio (gal. per bag) [kg/kg]	5.0 [0.44]
Sand/Total Aggregate Ratio (lb/lb) [kg/kg]	0.48 - 0.52
T-20 [T-50] (seconds)	2 - 6
Slump Flow Range (inches) [mm]	24" - 30.0" [597 - 762]
Visual Stability Index	≤ 1.5
Δh (inches) [mm]	≤ 0.5" [13]**
Slump Flow Spread - J-Ring Spread (inches) [mm]	< 4.0" [100]
Range of Cement Replacement by Fly Ash (%)	5 - 25
High Range Water-Reducer Dosage Rate (fl oz./cwt)	***
Air Content Range (%)	--

* Class S(SCC) for use in prestressed concrete members shall have a minimum compressive strength of 5000 psi (35.0 Mpa) at 28 days unless otherwise shown on the plans. The maximum size of coarse aggregate shall be 1" (25 mm).

** Δh: height difference between concrete inside and outside the J-Ring

*** As determined by trial batch. High Range Water-Reducer dosage rates should not exceed those specified by the manufacturer.

The primary focus of this research program was to develop fresh concrete specifications for SCC. However, the author proposes that additional research should be conducted to evaluate the fresh and hardened concrete properties of SCC and also to assess how SCC performs in various applications. These recommendations include, but are not limited to, the following:

- Evaluating the fresh and hardened concrete properties of SCC whenever entrained air is added at different percentages.
- Evaluating the fresh and hardened concrete properties of SCC whenever different types of cement are used.
- Evaluating the fresh and hardened concrete properties of SCC whenever different types and sizes of aggregates are used.
- Evaluating the fresh and hardened concrete properties of SCC whenever different types and quantities of chemical and mineral admixtures are used.
- Assessing the hardened concrete creep, durability, freeze – thaw resistance, rapid chloride permeability, and shrinkage of SCC mixtures.
- Predicting the modulus of elasticity of SCC mixtures.
- Casting SCC in vertical PVC pipes and measuring the variations of strength and modulus of elasticity with depth.
- Casting a full-scale SCC bridge girder.
- Field casting a reinforced SCC culvert.
- Assessing the flowability, blockage potential, and segregation resistance of SCC mixtures cast at different temperatures and with varying aggregate moisture contents.

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APPENDIX A

MIXTURE DESIGN ANALYSIS FOR MIXTURE # 1

Step 1: Binder Content = **611 lb/yd^3**

Specific Gravity $_{Binder}$ = 3.15

Step 2: Volume $_{Binder}$ = (Binder Content)/(Specific Gravity $_{Binder}$ x 62.4 lb/ft^3)

Volume $_{Binder}$ = (611 lb)/(3.15 x 62.4 lb/ft^3) = 3.108 ft^3

Step 3: ***w/b* = 0.41**

Step 4: Water Content = (*w/b*) x (Binder Content) = (0.41) x (611 lb/yd^3)

= **250.51 lb/yd^3**

Specific Gravity $_{Water}$ = 1.00

Step 5: Volume $_{Water}$ = (Water Content)/(Specific Gravity $_{Water}$ x 62.4 lb/ft^3)

Volume $_{Water}$ = (250.51 lb)/(1.00 x 62.4 lb/ft^3) = 4.015 ft^3

Step 6: Air = 2%

Step 7: Volume $_{Air}$ = (% Air) x (27 ft^3) = (0.02) x (27 ft^3) = 0.54 ft^3

Step 8: Volume $_{Total\ Aggregate}$ = (27 ft^3) - (Volume $_{Binder}$) – (Volume $_{Water}$) –

(Volume $_{Air}$)

$Volume_{Total\ Aggregate} = (27\ ft^3) - (3.108\ ft^3) - (4.015\ ft^3) - (0.54\ ft^3)$

$= 19.337\ ft^3$

Step 9: ***S/Agg*** **= 0.52**

Step 10: $Volume_{Fine\ Aggregate} = (S/Agg) \times (Volume_{Total\ Aggregate})$

$Volume_{Fine\ Aggregate} = (0.52) \times (19.337\ ft^3) = 10.055\ ft^3$

$Specific\ Gravity_{Fine\ Aggregate} = 2.60$

Step 11: Fine Aggregate Content = $(Volume_{Fine\ Aggregate}) \times$

$(Specific\ Gravity_{Fine\ Aggregate}) \times (62.4\ lb/ft^3) = (10.055\ ft^3) \times (2.60) \times$

$(62.4\ lb/ft^3) =$ **1631 lb/yd^3**

Step 12: $Volume_{Coarse\ Aggregate} = (Volume_{Total\ Aggregate}) - (Volume_{Fine\ Aggregate})$

$Volume_{Coarse\ Aggregate} = (19.337\ ft^3) - (10.055\ ft^3) = 9.282\ ft^3$

$Specific\ Gravity_{Coarse\ Aggregate} = 2.68$

Step 13: Coarse Aggregate Content = $(Volume_{Coarse\ Aggregate}) \times$

$(Specific\ Gravity_{Coarse\ Aggregate}) \times (62.4\ lb/ft^3) = (9.282\ ft^3) \times (2.68) \times$

$(62.4\ lb/ft^3) =$ **1550 lb/yd^3**

APPENDIX B

MIXTURE DESIGN ANALYSIS FOR MIXTURE # 41

Step 1: Binder Content = **775 lb/yd^3**

Step 2: % FA = **5%**

Step 3: FA Content = (% FA) x (Binder Content) = (5%) x (775lb/yd^3)

= 38.75 lb/yd^3

Step 4: Cement Content = (Binder Content) – (FA Content) = 775lb/yd^3 –

38.75 lb/yd^3 = 736.25 lb/yd^3

Specific Gravity $_{FA}$ = 2.20

Specific Gravity $_{Cement}$ = 3.15

Step 5: Volume $_{FA}$ = (FA Content)/(Specific Gravity $_{FA}$ x 62.4 lb/ft^3)

Volume $_{FA}$ = (38.75 lb)/(2.20 x 62.4 lb/ft^3) = 0.282 ft^3

Step 6: Volume $_{Cement}$ = (Cement Content)/(Specific Gravity $_{Cement}$ x 62.4 lb/ft^3)

Volume $_{Cement}$ = (736.25 lb)/(3.15 x 62.4 lb/ft^3) = 3.746 ft^3

Step 7: ***w/b* = 0.44**

Step 8: Water Content = (*w/b*) x (Binder Content) = (0.44) x (775 lb/yd^3)

= **<u>341 lb/yd³</u>**

Specific Gravity $_{Water}$ = 1.00

Step 9: Volume $_{Water}$ = (Water Content)/(Specific Gravity $_{Water}$ x 62.4 lb/ft^3)

Volume $_{Water}$ = (341 lb)/(1.00 x 62.4 lb/ft^3) = 5.465 ft^3

Step 10: Air = 2%

Step 11: Volume $_{Air}$ = (% Air) x (27 ft^3) = (0.02) x (27 ft^3) = 0.54 ft^3

Step 12: Volume $_{Total\ Aggregate}$ = (27 ft^3) - (Volume $_{FA}$) – (Volume $_{Cement}$) – (Volume $_{Water}$) – (Volume $_{Air}$)

Volume $_{Total\ Aggregate}$ = (27 ft^3) – (0.282 ft^3) - (3.746 ft^3) – (5.465 ft^3) – (0.54 ft^3) = 16.967 ft^3

Step 13: ***<u>S/Agg</u>* <u>= 0.48</u>**

Step 14: Volume $_{Fine\ Aggregate}$ = (*S/Agg*) x (Volume $_{Total\ Aggregate}$)

Volume $_{Fine\ Aggregate}$ = (0.48) x (16.967 ft^3) = 8.144 ft^3

Specific Gravity $_{Fine\ Aggregate}$ = 2.60

Step 15: Fine Aggregate Content = (Volume $_{Fine\ Aggregate}$) x (Specific Gravity $_{Fine\ Aggregate}$) x (62.4 lb/ft^3) = (8.144 ft^3) x (2.60) x (62.4 lb/ft^3) = **<u>1322 lb/yd³</u>**

Step 16: $\text{Volume}_{\text{Coarse Aggregate}} = (\text{Volume}_{\text{Total Aggregate}}) - (\text{Volume}_{\text{Fine Aggregate}})$

$\text{Volume}_{\text{Coarse Aggregate}} = (16.967\ \text{ft}^3) - (8.144\ \text{ft}^3) = 8.823\ \text{ft}^3$

$\text{Specific Gravity}_{\text{Coarse Aggregate}} = 2.68$

Step 17: Coarse Aggregate Content = $(\text{Volume}_{\text{Coarse Aggregate}})$ x

$(\text{Specific Gravity}_{\text{Coarse Aggregate}})$ x $(62.4\ \text{lb/ft}^3) = (8.823\ \text{ft}^3)$ x (2.68) x

$(62.4\ \text{lb/ft}^3) =$ **1475 lb/yd^3**