FROM THE LAB TO THE FIELD: BATCHING SCC

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ABSTRACT

Presented in the paper are results from a research program that used self-consolidating concrete (SCC) mixtures to cast a box culvert. The paper discusses the development of the mixture which included developing, batching, and testing over 40 SCC mixtures. As required by the Arkansas State Highway and Transportation Department (AHTD), the water to cementitious ratio must by equal to or less than 0.44 and have at least 611 lb/yd^3 of cement (or binder). To achieve adequate SCC, the research team determined that a minimum binder content of 775 lb/yd^3 was necessary. After the mixtures were developed, the research project then moved to the ready-mix concrete plant where trial batches (of 3 yd^3) were mixed and tested. Once the appropriate admixture dosage was determined, one 5 ft tall box culvert was cast with the mixtures. The paper concludes with recommendations for mixing SCC in a ready-mix truck regarding admixture dosage, importance of measuring initial slump, and mixing time.

Keywords: Self-Consolidating Concrete, Construction, Research

INTRODUCTION

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]

BACKGROUND

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.[5, 6] SCC is defined by ACI Committee 237[7] as "highly flowable, nonsegregating concrete that can spread into place, fill the formwork, and encapsulate the reinforcement without any mechanical consolidation."

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.[8] When compared with conventional-slump concrete mixtures, it has been reported that SCC mixtures contain a lower coarse aggregate content, [9] smaller coarse aggregate, [10] similar water content, higher fine aggregate content, and higher cementitious materials (CM) content.[11] 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).[12] All the aforementioned trends are unique because the combination of these modified parameters results in a highly flowable yet stable concrete mixture.

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;[13] 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]

MIXTURE PROPORTIONING

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. [14] 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.

FRESH CONCRETE PROPERTIES

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.[15, 16] 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) [17], the T-20 (T-50) test (ASTM C 1611/C 1611M) [17], the visual stability index (VSI) test (ASTM C 1611/C 1611M) [17], the J-Ring test (ASTM C 1621/C 1621M) [18], 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.[19] These tests have been approved and utilized in practice by researchers and workers in industry alike.

For this project, slump flow, T-20, J-Ring, and VSI were the main fresh concrete property tests performed. 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. Slump flow is measured as the arithmetic mean of two perpendicular diameters at the base of the concrete.

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.). The 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). This test provides an indication of the mixture's viscosity.

The J-Ring test assesses the passing ability (blockage) of the concrete. 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.

The VSI test is a subjective visual evaluation of the stability of the slump flow patty. VSI values range from 0 to 3 in increments of 0. 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.

HARDENED CONCRETE PROPERTIES

As with conventional-slump concrete, SCC has the greatest strength when it is in compression. 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 water to cementitious material ratio (*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*.[21]

Research performed by Schindler et al.[13] proposes that the sand to total aggregate ratio (*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.

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.[9, 22, 23]

Research conducted by Su et al.[24] 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.[13] confirms this concept.

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.[21] 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. [25] 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.[26]

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.[27] 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.[25, 27] 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.[27]

SCOPE

One of the many goals of the research project was providing the Arkansas State Highway and Transportation Department (AHTD) with guidelines regarding the minimum amount of binder needed to produce SCC. The current specifications require 6.5 bags of cement (611 lb/yd^3), a minimum w/c of 0.44, and a 28 day compressive strength of at least 4000 psi.

AHTD does not currently address SCC in their specifications; therefore the fresh SCC properties were determined based on recommendations from the literature. Based on these recommendations, the targeted slump flow was at least 23.5 in.,[28] T-20 time of 2 to 5 seconds,[29] a VSI of 0 to 1,[30] difference in height of concrete from the inside to the outside of the J-Ring to be less than 0.60 in.,[30] and for a difference in slump flow and J-Ring flow values to be less than 4 in. (100 mm).[28]

MATERIALS

All materials used in the research program were locally available. Type I portland cement from a single source was used in all mixtures. The fine aggregate 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. The nominal maximum size of the coarse aggregate was 0.5 in. To increase workability an ASTM C494 Type A and F and ASTM C1017 high range water reducer was used.

RESULTS

To determine the recommended minimum cement content for SCC, over 40 different concrete mixtures with varying cement content, *S/Agg*, and HRWR dosage rates were examined. The first mixture proportions were based on AHTD's Standard Specifications. The minimum binder content for structural concrete is 6.5 bags of cement (611 lb/yd^3) per cubic yard and a minimum w/cm of 0.44. From these requirements and a *S/Agg* of 0.52 (based upon recommended *S/Agg* values from literature[31]) the first mixture proportion was developed. The mixture proportions of Mixture 1 are shown below in Table 4.1. An initial dosage rate of 3 fl. oz. /cwt for the HRWR was selected. Upon batching, this mixture did not flow and had a slump of approximately 7 inches. Fig. 1 shows the mixture after the slump flow test was performed.

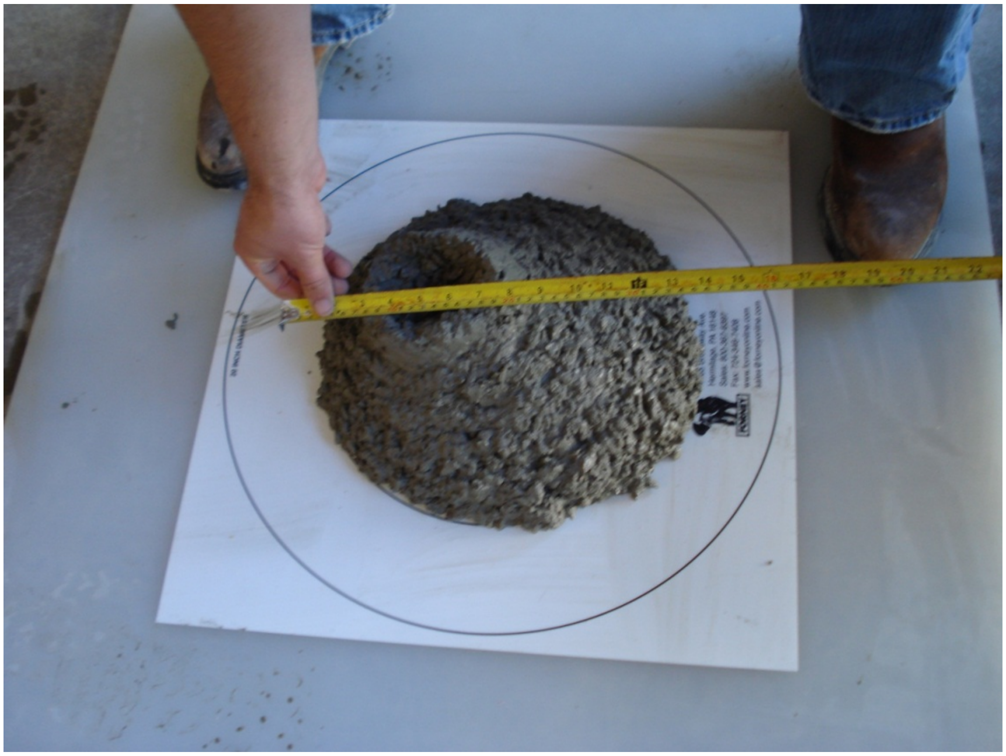

Fig. 1 Slump Flow of the First Mixture

For the next mixture, the proportions were held constant but the dosage of HRWR was increased incrementally from 3 to 5 fl oz/cwt. Even with the additional HRWR, the mixture did not flow, but had a slump. The next step in the program was increasing the cement content from 611 lb/yd^3 to 711 lb/yd^3 but maintaining the same w/c of 0.44 and S/agg of 0.52 (Mixture 4). Mixture 4 was the first mixture that had a slump flow, but it was only 14 in. Even with increases in HRWR, SCC could not be developed at a binder content of 711 lb/yd^3.

Table 1 Phase 1 Mix Designs and Slump Flow Data

Materials	Mixtures			
	1	3	4	5
Cement (lb/yd^3)	611	611	711	711
Coarse Aggregate (lb/yd^3)	1527	1527	1429	1429
Fine Aggregate (lb/yd^3)	1606	1606	1506	1506
Water (lb/yd^3)	269	269	313	313
Water/Binder	0.44	0.44	0.44	0.44
Sand/Aggregate	0.52	0.52	0.52	0.52
HRWR (fl oz./cwt)	3	5	5	7.5
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 series of mixtures (Mixtures 6 through 14), the binder content was increased from 711 lb/yd^3 to 811 lb/yd^3. The slump flow was 25 in. and showed no evidence of segregation or bleed water. The VSI was 0, and a T-20 of 5.37 seconds was measured. The slump flow of Mixture 6 is presented in Fig. 2. The mixture achieved a 28 day compressive strength of 9490 psi. For Mixtures 7 through 14, the cement content and w/c remained constant but the *S/Agg* ranged from 0.52 to 0.44. SCC with adequate flows and T-20 were produced (Table 2).

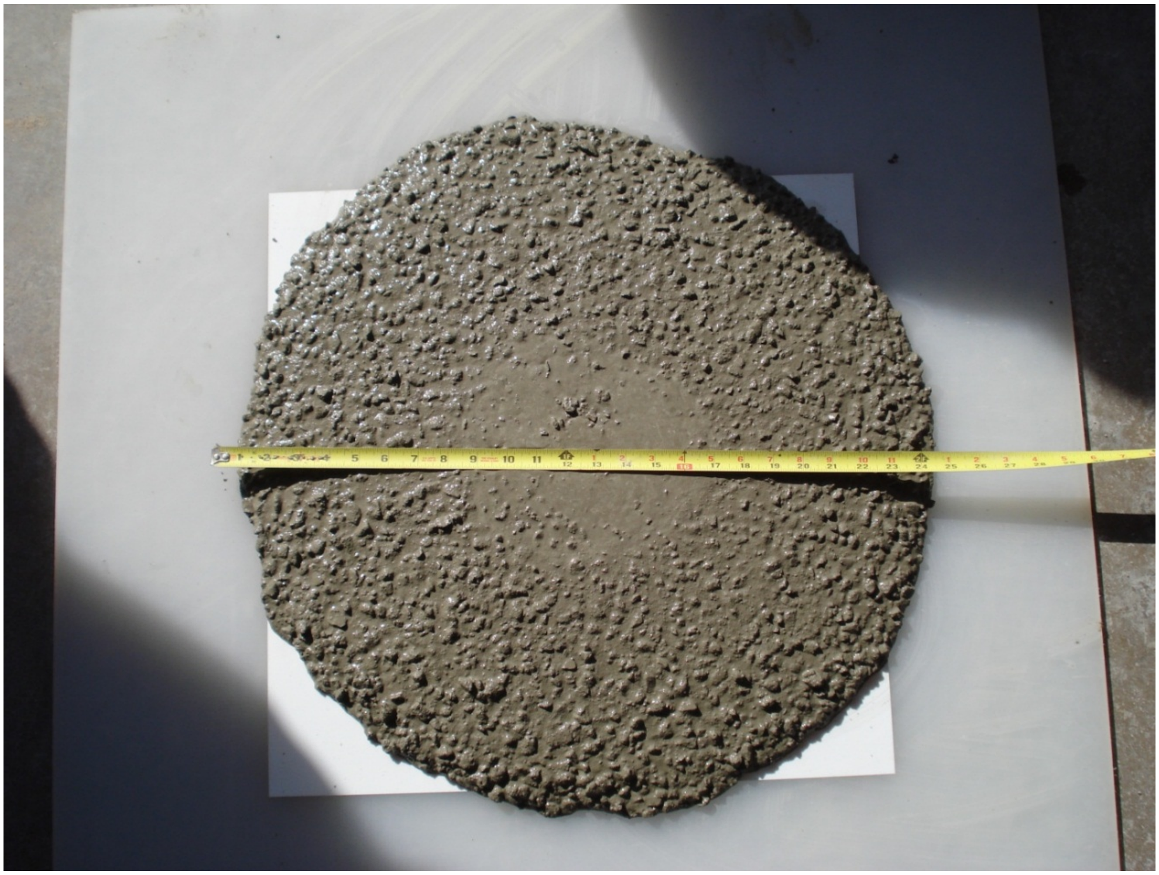

Fig. 2 Slump Flow of Mixture 6

Table 2 Phase 2 Mix Designs and Test Results

Materials	Mixtures								
	6	7	8	9	10	11	12	13	14
Cement (lb/yd^3)	811	811	811	811	811	811	811	811	811
Fly Ash (%)	---	---	---	---	---	---	---	---	---
Coarse Agg. (lb/yd^3)	1332	1277	1222	1388	1443	1499	1499	1554	1554
Fine Agg. (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	0.50	0.48	0.46	0.46	0.44	0.44
HRWR (fl oz./cwt)	5	5	5	5	5	5	6	6	7
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

In next phase of trial batching, the cement content was reduced to 761 lb/yd^3 in order to determine the minimum amount of binder necessary to produce SSC. The mixture proportions (Mixtures 15 through 21) are shown below in Table 3. Overall, there were three mixtures which had slump flows greater than 24 inches, but each mixture also segregated when in the mixer and in the wheelbarrow.

Table 3 Phase 3 Mix Designs and Test Results

Materials	Mixtures						
	15	16	17	18	19	20	21
Cement (lb/yd^3)	761	761	761	761	761	761	761
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	0.50	0.52	0.52	0.54
HRWR (fl oz./cwt)	5	6	7	7	5	7	7
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

For the next round of batching, the binder content was reduced to 750 lb/yd^3. The mixtures proportions are shown in Table 4. As expected, the overall water content decreased since the w/c was held constant which decreased the slump flows. To offset the reduction in overall water content, the HRWR dosage rate was increased. Even with the higher dosages of HRWR, only two of the mixtures had a slump flows greater than 24 in. and they both experienced segregation.

Table 4. Phase 4 Mix Designs and Test Results

Materials	Mixtures						
	22	23	24	25	26	27	28
Cement (lb/yd^3)	750	750	750	750	750	750	750
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
HRWR (fl oz./cwt)	5	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 the final phase of mixing, the binder content was increased to 775 lb/yd^3 with hopes of maintaining slump flows of 24 in. or greater without segregating. Several mixtures were batched, and the only variance between them was that they were batched with different dosage rates of HRWR and *S/Agg*. The mixtures proportions are shown below in Tables 5, 6, and 7. With a binder content of 775 lb/yd^3, SCC was produced at *S/Agg* of 0.52, 0.50, and 0.48 and within the manufacturer's recommended dosage rates for the HRWR.

Table 5 Phase 5 Mix Designs and Test Results

Materials	Mixtures			
	29	30	31	32
Cement (lb/yd^3)	775	775	775	775
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
HRWR (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

Table 6 Phase 6 Mix Designs and Test Results

Materials	Mixtures			
	33	34	35	36
Cement (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	0.50	0.50	0.50	0.50
HRWR (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

Table 7: Phase 7 Mix Designs and Test Results

Materials	Mixtures			
	37	38	39	40
Cement (lb/yd^3)	775	775	775	775
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
HRWR (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

BOX CULVERT

The next phase of the research project involved casting a box culvert with Mixture 29. Mixture 29 was one of the better performing mixtures developed in the study and was therefore chosen to cast the culvert.

The culvert had a clear height of 4 ft. and an overall width of 5 ft. The thickness of the top slab was 7 in., the thickness of each sidewall was 6 in., and the thickness of the bottom slab was 6.5 in. The overall height was 5 ft. 1.5 in. The culvert was cast vertically to a depth of 5 ft. This resulted in a total required concrete volume of approximately 1.78 yd^3. The culvert and rebar mat is shown in Fig 3.

Fig. 3 Box culvert and reinforcing steel.

TRIAL BATCHING

Trial batching was conducted at a local ready mix company using Mixture 29. 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 slump test. Based on the slump, the HRWR dosage would be determined. To simulate the time it would take for the concrete to be delivered to the Engineering Research Center (ERC) at the University of Arkansas (UA), the concrete was mixed for 20 minutes. After this time had elapsed, a sample of concrete was placed into a wheel barrow, and the slump test was measured.

The first trial mixture had an initial slump of 2.75 in. Based on trial batching in the laboratory, Mixture 29 had a HRWR dosage rate of 7 fl oz/cwt. This dosage rate was reduced to 6 fl. oz/cwt for the ready mix truck. It was assumed that the ready mix truck would provide better agitation and mixing than the rotating drum mixer and therefore require less HRWR. Once the HRWR was added, the concrete was mixed for 5 minutes. After 5 minutes, 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 (Fig. 4). Severe segregation was observed (VSI = 3), and the mixture was discarded. Aggregate samples were obtained from the stockpiles at the plant, and it was determined that the actual moisture contents in both fine and coarse aggregates were much more than what used in the batch weights.

Fig. 4 Segregation Observed in Trial Batch

Since the first trial batch was unsuccessful, 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 the first trial batch. After the initial batching sequence was completed, the concrete sample had a slump of 3.25 in. This value was larger than the slump of first batch which experienced segregation. For this reasons, the initial HRWR dosage rate was reduced to 3 fl. oz. /cwt. After 5 minutes of batching, the slump flow was 14.5 in. Since the concrete had limited flowability, an additional 1 fl. oz. /cwt was added at this time. Once this 5 minute batching sequence was complete, the slump flow was 20 in. 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. The decrease in the mixture's flowability is a result of 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.

Six cylinders were cast from the trial batch 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 average 1 and 28-day compressive strengths were 3810 and 7930 psi (26.29, 54.67 MPa), respectively.

BOX CULVERT CASTING – PART 1

For the culvert, 3 yd^3 of concrete was batched in a ready-mix truck. 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. To improve workability, 5 fl. oz. /cwt of HRWR was added to the truck. After the 5 minute batching sequence, the slump flow was 18 in. At this time, an additional 0.5 fl. oz. of HRWR /cwt was added to improve the flowability. Following another 5 minutes of mixing, the slump flow increased to 19 in. 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. As soon as the slump flow test was performed, the mixture had a 5 in. 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.

BOX CULVERT CASTING – PART 2

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. At 10:00 A.M., 4 fl. oz./cwt of HRWR were added. When tested at 10:10 A.M., the concrete had a slump of 3 in. Two minutes later at 10:12 A.M., an additional 2 fl. oz./cwt of HRWR was added. This increased the flowability; the slump flow spread was 19.5 in. at 10:19 A.M. To further improve flowability, 1 more fl. oz./cwt was added at 10:20 A.M. The final series of fresh concrete tests was conducted at 10:25 A.M. The T-20 was 2.25 seconds, and the spread was 25.5 in. The VSI was 0.5 due to the slight amount of bleed water that was present. The height difference between concrete inside and outside the J-Ring was 0.25 in. Once all of the fresh concrete properties were established as sufficient, the culvert was cast.

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. of the total 5 ft. depth, the formwork failed (Fig.5). 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.

Fig. 5 Formwork Failure 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. The interior and exterior corners finished smoothly as well. In fact, the only visible defect was some localized surface blemishes that had occurred due to the entrapment of air voids.

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. The 28-day modulus of elasticity was 6300 ksi.

CONCLUSION

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. After conducting an array of fresh and hardened concrete tests, performing trial batching inside of a ready-mix truck, and casting a full-size reinforced box culvert the following conclusions were made.

- The *w/c* 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). The lowest binder content at which SCC was consistently batched was 775 lb/yd^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) content must be increased if the w/c is to remain constant (which will increase total water content).
- The *S/Agg* value can be incrementally increased to improve flowability (if necessary).
- The T-20 test was important in evaluating the blockage and segregation potential of all the trial mixtures. In this study, mixtures that had T-20 times varying from 2 to 6 seconds performed well in the J-ring test. Many of the mixtures that had T-20 times that surpassed 6 seconds were viscous and experienced blockage. Conversely, the mixtures with T-20 times of less than 2 seconds were extremely flowable and experienced segregation.
- 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. and a difference between the slump flow spread and the J-Ring spread that was less than 4.0 in. 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.
- 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. During this project, the HRWR began to lose its effectiveness after 45 minutes of mixing.
- 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.

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