FINAL REPORT

EVALUATION OF SELF-CONSOLIDATING CONCRETE

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ABSTRACT

Conventional concrete tends to present a problem with regard to adequate consolidation in thin sections or areas of congested reinforcement, which leads to a large volume of entrapped air voids and compromises the strength and durability of the concrete. Using self-consolidating concrete (SCC) can minimize the problem since it was designed to consolidate under its own mass.

This study examined several mixture designs in the laboratory with the goal of creating mixtures with desirable flow characteristics that did not require additional consolidation yet provided adequate compressive strength, low permeability, shrinkage control, and resistance to cycles of freezing and thawing. The results provided a foundation for determining if SCC could be produced on a commercial scale using locally available materials at two concrete plants. SCC from one plant was used in a field application for a small bridge in a residential area. The results showed that with adjustments to the mixture proportions, SCC can be produced successfully and provide many benefits to transportation agencies and the construction industry.

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INTRODUCTION

In response to the reduction in the skilled labor force in Japan's construction industry and the consequential reduction in the quality of construction, researchers at the University of Tokyo began developing self-consolidating concrete (SCC) in 1986.[1]

Ozawa et al.[2] authored the first paper on SCC in 1989, and Ozawa and other colleagues[3] presented a paper on the same subject at an international conference on concrete held in Istanbul in 1992. The presentation accelerated international interest in SCC. In 1998, the first international workshop on SCC was held in Kochi, Japan. Through efforts by Ozawa and his colleagues, more intensive research thrived, especially in large construction companies in Asia. Hence, SCC was used in many structures, including buildings, bridge towers, and bridge girders.[1] Positive attributes of SCC include safety, reduced labor and construction time, and improved quality of the finished product.[1,4,5]

SCC is different than conventional concrete in that it has a lower viscosity and, thus, a greater flow rate when pumped. As a consequence, the pumping pressure is lower, reducing wear and tear on pumps and the need for cranes to deliver concrete in buckets at the job site.[6]

To achieve a high workability and avoid obstruction by closely spaced reinforcing, SCC is designed with limits on the nominal maximum size (NMS) of the aggregate, the amount of aggregate, and aggregate grading. However, when the workability is high, the potential for segregation and loss of entrained air voids increases. These problems can be alleviated by designing a concrete with a high fine-to-coarse-aggregate ratio, a low water–cementitious material ratio (w/cm), good aggregate grading, and a high-range water-reducing admixture (HRWRA).[7] However, care should be exercised when a high fine-to-coarse aggregate ratio is used since shrinkage would increase. Viscosity modifying admixtures (VMA) are also used to reduce the tendency for segregation and enhance the stability of the air-void system.[8,9]

A potentially negative aspect of SCC is shrinkage. Since generally a large amount of fine material is used in the mixtures (particularly those without VMA) and the NMS is limited, the concrete typically has higher shrinkage. Increased shrinkage may result in more cracks in restrained concrete elements, which can accelerate the deterioration of both the concrete and the reinforcement.

The use of SCC has the potential to provide initial savings because of the reduction in labor required to place the concrete. The Virginia Department of Transportation (VDOT) spends approximately $13 million per year on precast/prestressed concrete bridge elements. A 5 percent reduction in cost because of labor savings could result in $650,000 annual savings for VDOT. Further savings would be obtained because the structures constructed with SCC should last longer as they will be less likely to have large voids.

PURPOSE AND SCOPE

The purpose of this project was to develop and evaluate the properties of SCC made with locally available materials, including flow, segregation, strength, permeability, resistance to cycles of freezing and thawing, and drying shrinkage. SCC was evaluated in the laboratory and the plant, followed by a formal field application.

MATERIAL, PROPORTIONING, AND TESTING

Overview

The first phase of the project involved laboratory research at the Virginia Transportation Research Council where a feasible mixture design was developed. The second phase involved determining if SCC could be manufactured in large quantities for field applications using locally available materials.

In both phases, the concrete was tested for workability in the freshly mixed state and for compressive strength, permeability, drying shrinkage, air voids, and freeze-thaw resistance in the hardened state.

Laboratory Phase

Materials

All mixtures contained Type II portland cement and Class F fly ash, which was added as 20 percent of the total cementitious material. The coarse aggregate was crushed granite gneiss with an NMS of 1 in (25 mm) and was prepared by blending aggregates retained on the ¾ in, ½ in, $^{3}/_{8}$ in, and No. 4 (19.0, 12.5, 9.5, and 4.75-mm) sieves, each 25 percent by weight. The fine aggregate was natural sand. The combined fine and coarse aggregate grading is shown in Figure 1. Several admixtures were included in the mixture: a saponified rosin air-entraining admixture (AEA) complying with the requirements of ASTM C 260; a lignin regular water-reducing admixture (WRA) complying with the requirements of ASTM C 494, Type A; and polycarboxylate, an HRWRA complying with the requirements of ASTM C 494, Type F.

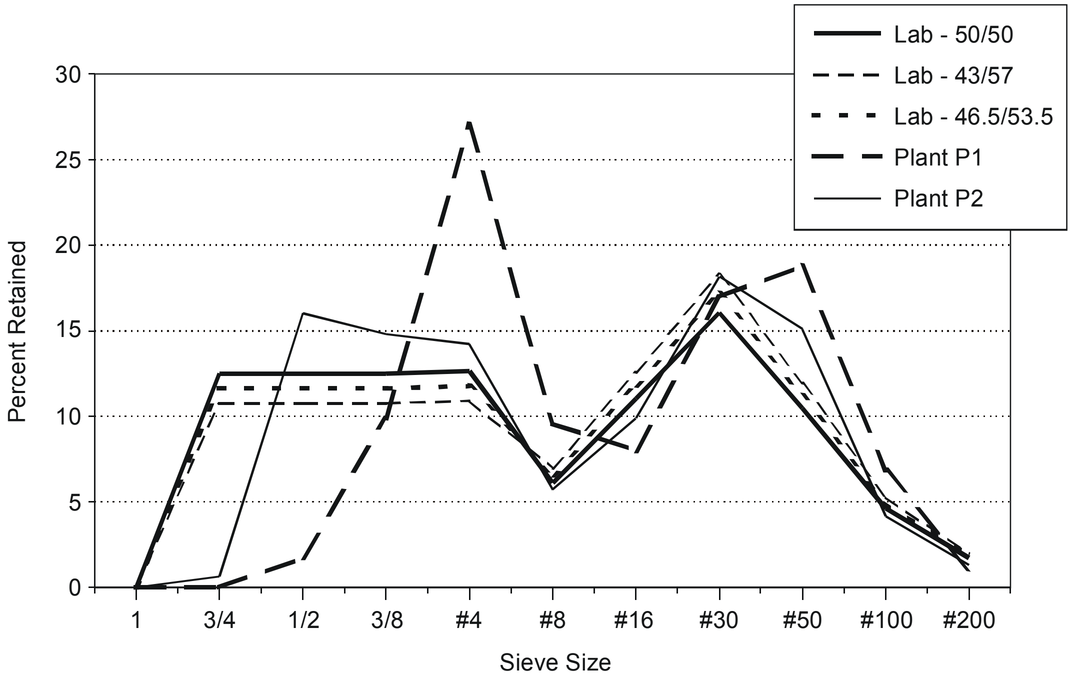

Figure 1. Aggregate Grading for Laboratory and Plant Phases (1 in = 25.4 mm)

Proportioning

Fifteen concrete mixtures were prepared in the laboratory using the three-factor central composite design method.[10] The method is basically a statistical cube design that determines the various mixture combinations where the cube has three axes for the amount of cementitious material, w/cm, and fraction of fine aggregate to total aggregate. A total of 15 points were selected on the cube, including points at the eight corners, center of the cube, and centers of the six faces. The chosen combinations of the three variables are given in Table 1. Three additional samples of Batch 7 and one extra sample of Batch 8 were made to evaluate the additional properties of drying shrinkage and the air-void system.

Freshly Mixed Concrete Testing

The air content (ASTM C 231) and unit weight (ASTM C 138) of the freshly mixed concrete were measured.

The consistency and workability were evaluated using the slump flow and the U-tube tests. Because of its ease of operation and portability, the slump flow test is the most widely used method for evaluating concrete consistency in the laboratory and at construction sites. In this test, the diameter of the concrete flowing out of the slump cone is a measure of flow, thus determining the consistency and cohesiveness of the concrete.[11,12] Typical slump flow values tend to be around 25.5 in (650 mm).[6,13] This study used a slump flow range of 23 to 29 in (585 to 735 mm) to allow for a margin of error.

Table 1. Mixture Designs of Laboratory Concrete

Batch No.	Cementitious Material (lb)	w/cm	FA/TA
1	800	0.33	0.57
2	800	0.33	0.50
3	700	0.33	0.57
4	700	0.33	0.50
5	750	0.33	0.54
6	800	0.40	0.54
7	700	0.40	0.54
8	750	0.40	0.54
9	750	0.40	0.57
10	750	0.40	0.50
11	800	0.47	0.57
12	800	0.47	0.50
13	750	0.47	0.54
14	700	0.47	0.57
15	700	0.47	0.50

Note: Cementitious material contained 80% portland cement and 20% fly ash by weight. FA = fine aggregate, TA = total aggregate.

In the U-tube test, the testing apparatus is a U-shaped container where a vertical wall separates the two legs of the "U." This wall extends for most of the height of the container, except for the bottom, where three vertical reinforcing bars replace the wall. After SCC is poured up to the full height of one side of the tube, a vertical gate is raised such that the material flows past the reinforcing bars and rises in the other side of the container. The equilibrium height of the U-tube is about 14 in (350 mm); SCC is expected to rise over 12 in (300 mm).[1]

Rheological properties, i.e., yield stress and viscosity, were determined. Rheology is the science that deals with the flow of materials.[14] If a shear force is applied, a velocity gradient is induced in a liquid. The velocity gradient is equal to the shear rate. The proportionality between the force and shear rate is the viscosity. The stress needed to initiate flow is known as the yield stress. Concrete typically behaves like a liquid modeled by the Bingham equation:

$$\tau = \tau_0 + \mu\dot{\gamma}$$

which describes flow as a linear relationship between the shear rate ($\dot{\gamma}$) and the shear stress (τ), The viscosity (μ) is the slope in this relationship, and the intercept marks the yield stress (τ_0). Rheometers measure the yield stress and the viscosity, such as the BTRHEOM rheometer used in this study. The BTRHEOM rheometer is a parallel plate rheometer where the concrete is sheared between two plates. In this study, the two rheological parameters were calculated using the Bingham equation. Yield stress should be less than 0.058 psi (400 Pa) for good flow, and the viscosity should be below 0.0290 psi·sec (200 Pa·s) for satisfactory pumping or high flowability.[15] All the concretes were highly flowable, leading to low yield stress values. The Bingham model is used to estimate yield stress from a linear extrapolation of the shear rate versus shear stress curve to zero shear rate. However, a more appropriate model would have been the Herschel-Buckley, which assumes a curvilinear relationship. Negative values for yield stress are attributed to the error in the extrapolation process and have no real physical meaning.

The samples were also checked for concrete segregation during testing of the fresh SCC. The aggregate distribution and mortar halo around the spread in the slump flow test, as well as the lack of coarse aggregate in the top of the U-tube, indicated the extent of segregation within the concrete.

Hardened Concrete Testing

Most of the laboratory specimens for the hardened state tests were cast in molds without being mechanically consolidated; a few were vibrated for 5 seconds to determine if vibration improved the compressive strength. All of the samples were moist cured and then air dried. The samples were tested for compressive strength, permeability, shrinkage, freeze-thaw resistance, and air voids, as summarized in Table 2.

For the air-void analysis, two samples were subjected to a linear traverse analysis (ASTM C 457). In this analysis, air bubbles less than 0.04 in (1 mm) in diameter define spherical air-entrained bubbles and air bubbles greater than 0.04 in (1 mm) in diameter are considered to be entrapped because of lack of consolidation and extra water. Properly consolidated concrete should contain less than 2 percent of these larger bubbles.[16]

Table 2. Hardened Concrete Tests and Specifications

Tests	Specification	Age (days)	Size (in)
Compressive Strength	AASHTO T 22	[a]	4 x 8
Permeability	AASHTO T 277	28[b]	2 x 4
Drying Shrinkage	ASTM C 157	28	3 x 3 x 11¼
Freeze-Thaw Analysis	ASTM C 666	[c]	3 x 4 x 16
Air Void Analysis	ASTM C 457	28	4 x 8

[a]At 28 days for lab specimens and 1, 7, and 28 days for plant specimens.
[b]Cured 1 week at 73°F (23°C) and 3 weeks at 100°F (38°C).
[c]These specimens are cured 2 weeks moist and then air dried at least 1 week before testing. Test water contained 2% NaCl.

Plant Phase

Materials and Proportions

During the plant phase of this project, SCC mixtures were produced at a precast plant and a prestressing plant, designated as P1 and P2, respectively. The mixture proportions used at the two plants are provided in Tables 3 and 4. The acceptable range for the air content was 5.5 ± 1.5 percent. The various admixtures used complied with the appropriate specifications. Both AEAs

Table 3. Mixture Proportions for P1 Concrete (lb/yd^3)

Material	Description	Amount
Cement	Type III	476
Pozzolans	Natural, ASTM C 618, Class N	204
Fine aggregate	Natural sand	1391
Coarse aggregate	Granite, $^3/_4$ in NMS	1550
Water	——	279
w/cm	——	0.41
AEA	Sodium-salt type soap	0.3 oz/cwt
HRWRA	Polycarboxlyate	8.0 oz/cwt

Table 4. Mixture Proportions for P2 For (lb/yd^3)

Material	Description	Amount
Cement	Type III	451
Slag	40%, ASTM C 989, Grade 120	301
Fine aggregate	Natural sand	1552
Coarse aggregate	Granite, $^1/_2$ in NMS	1345
Water	——	270
w/cm	——	0.36
Test 1 Admixtures		
AEA	Neutralized Vinsol rosin	0.13 oz/cwt
HRWRA	Polycarboxylate	12.0 oz/cwt
Test 2 Admixtures		
AEA	Neutralized Vinsol rosin	0.13 oz/cwt
WRA	Sugar and lignin solution	14.0 oz/cwt
HRWRA	Polycarboxylate	5.0 oz/cwt

complied with the requirements of ASTM C 260; the WRA complied with the requirements of ASTM C 494, Type A; and the HRWRA complied with the requirements of ASTM C 494, Type F.

Testing

Batches from both plants were prepared and tested in the same manner as the laboratory batches without any consolidation, except rodding in some of the compressive strength and permeability specimens. The strength and permeability tests of the consolidated samples provided a baseline for evaluating the need for consolidation. The P2 samples also underwent a different curing regime. They were divided into three groups. The first group was rodded and moist cured, the second group was not rodded but was moist cured, and the third group was not rodded but was steam cured.

Freeze-thaw resistance and drying shrinkage were also determined in the plant mixtures. Moist-cured beams were tested. One P1 specimen was subjected to linear traverse analysis. The samples were also checked for concrete segregation during testing of the fresh SCC.

RESULTS AND DISCUSSION

Laboratory Phase

Freshly Mixed Concrete

The combined fine and coarse aggregate grading is given in Figure 1. Satisfactory SCC mixtures were accomplished with the laboratory gradings. The properties of the freshly mixed concrete and the observations of the behavior of the concrete are given in Table 5 for each batch. The slump flows ranged from 23 in (585 mm) to 29 in (735 mm) as planned. Except for Batch 15, the batches reached an equilibrium height of 13 in (325 mm) or more in the U-tube test. In addition, all batches had viscosity values below 0.029 psi·sec (200 Pa·s), and all batches except Batch 8 had yield stresses below 0.058 psi (400 Pa), thus indicating that most mixtures could be pumped easily and had high workability.[15] However, there was variability in viscosity numbers and there was no correlation between the viscosity number and segregation or equilibrium height or spread in this limited study. Further work is recommended. There were difficulties in entraining the desired amount of air, some air contents were outside the specified range of 6 ± 2 percent. The wide range of air content was attributed to the large amount of HRWRA used in the mixtures. Large dosages of HRWRA can induce excessive paste fluidity and segregation

Table 5. Fresh Concrete Properties of Laboratory Mixes

Batch No.	Spread (in)	U-Tube (in)	Air (%)	Yield Stress (Pa)	Viscosity (Pa-s)	Observations
1	29	14.3	6.5	—	—	Sticky, segregation
2	29	14.0	—	—	—	Some segregation
3	26	13.8	11.7	21	151	Sticky, some segregation
4	28	14.8	—	—	—	Sticky, segregation
5	27	13.5	8.5	-64	64	Some segregation
6	28	13.8	2.7	-230	46	Good Mix
7	26	13.5	7.6	276	52	Very good mix
8	26	13.5	7.8	470	53	OK
9	25	13.5	7.5	354	49	OK
10	27	13.5	5.6	189	38	OK
11	28	14.0	5.5	233	5	Good mix
12	23	14.0	0.5	—	—	Wet, some segregation
13	27	13.5	3.8	173	35	Segregation
14	28	13.0	2.0	—	—	Segregation
15	29	10.3	3.7	117	52	Segregation

resulting in loss of air. This negative aspect can be controlled by the use of VMA.[9] Despite the difficulty in achieving all of the desired qualities, a number of mixtures from the laboratory phase had sufficient air content while maintaining the desired flow characteristics for SCC.

Many of the laboratory batches had segregation problems. The aggregate distribution in the slump test, the mortar halo around the spread, and the lack of aggregates at the top of the U-tube clearly showed that segregation was an issue that must be watched closely. The 1-in (25-mm) NMS coarse aggregate, low amount of material retained on the No. 8 (2.36 mm) sieve, and high amount of HRWRA may have made these concretes prone to segregation and bleeding. Despite the number of designs that failed to comply with the specifications or did not have satisfactory flow characteristics, a number of mixtures proved to be viable candidates for SCC (Mixtures 6, 7, and 11 were good mixtures as shown in Table 5.)

Hardened Concrete

Although the 15 specimens had variable 28-day compressive strengths, all samples exceeded the minimum specified strength of 4,000 psi (27.6 MPa), as shown in Table 6. The strengths of specimens were similar, irrespective of the consolidation effort. No samples were made from Batch 14 because of extensive segregation in the mixture.

Table 6. Hardened Concrete Properties of Laboratory Batches at 28 Days

Batch No.	Strength (psi)		Permeability (coulombs)		Shrinkage (microstrain)		
	No Vibration	Vibration (5 sec)	No Vibration	Vibration (5 sec)	28 day	4 mo	8 mo
1	5260	5360	—	—	—	—	—
2	5790	—	—	—	—	—	—
3	5950	—	1223	—	—	—	—
4	4270	4400	—	—	—	—	—
5	7250	—	1295	—	—	—	—
6	6680	—	992	—	—	—	—
7	5380	5180	—	—	—	—	—
7A	4540	5290	1015	1196	—	—	—
7B	6350	6090	1134	1325	—	—	—
7D	5040	—	545	—	365	490	560
8	5240	—	1726	2112	—	—	—
8A	6090	—	429	—	380	520	590
9	5400	—	—	—	—	—	—
10	5850	—	—	—	—	—	—
11	4770	—	—	—	—	—	—
12	5500	—	1909	—	—	—	—
13	4720	—	—	—	—	—	—
15	4840	—	—	—	—	—	—

Table 6 also displays the results of permeability tests conducted in accordance with AASHTO T 277 with accelerated curing that involved 1 week of moist curing at 73°F (23°C) and 3 weeks at 100°F (38°C). The values were much lower than the specified maximum value of 2500 coulombs. Although the vibrated samples had slightly higher values than the non-vibrated samples, the differences were within the expected variability.

Batches 7 and 8 were tested for shrinkage, with the results shown in Table 6. The values for both batches were below 400 microstrain at 28 days and 700 microstrain at 4 months, which are the maximum limits for satisfactory performance in bridge deck concretes.[18]

Batches 7 and 8 were also subjected to linear traverse analysis. Large air voids (those with a diameter larger than 0.04 in [1 mm]) made up less than 2 percent of the air in both batches, indicating adequate consolidation (see Table 7). Batch 7 had a spacing factor slightly above and Batch 8 below the maximum of 0.008 in (0.20-mm) required for satisfactory freeze-thaw resistance in a severe environment.[17] Both batches had high air contents exceeding 8 percent; the one with the higher air content had a lower spacing factor. Specific surface values less than the recommended minimum of 600 in^{-1} (24 mm^{-1}) indicate slightly large bubbles. If low spacing factor were desired, a higher air content than conventional concrete may be needed.

Table 8 summarizes the resistance to freezing and thawing for Batches 3, 5, and 6. The acceptance criteria at 300 cycles were a weight loss of 7.0 percent or less, a durability factor of 60 or greater, and a surface rating less than or equal to 3. All three laboratory batches met the criteria.

Table 7. Linear Traverse Analyses

Location	Batch No.	Air Content (%)			Specific Surface (in^{-1})	Spacing Factor (in)
		< 1 mm	> 1 mm	Total		
Laboratory	7	7.1	1.0	8.1	465	0.0083
	8	9.8	0.2	10.0	564	0.0059
P1	1	4.6	0.5	5.1	518	0.0099
Criteria					≥ 600	≤ 0.008

Table 8. Freeze Thaw Data

Location	Batch No.	Weight Loss (%)	Durability Factor	Surface Rating
	3	0.7	106	0.9
Laboratory	5	1.0	108	0.8
	6	2.3	96	1.2
	1	16.5	43	3.4
P1	2	12.0	91	2.6
	3	29.9	43	4.7
P2	1 moist cured	4.9	113	1.4
Criteria		≤ 7	≥ 60	≤ 3

Plant Phase

Freshly Mixed Concrete

The plant mixtures had smaller aggregates than the laboratory mixtures to improve flow characteristics and to reduce segregation. For the P1 mixture, the slump flow values ranged from 22.5 to 26 in (572 to 660 mm), as shown in Table 9. The slump flow value for the P2 mixture was 22.5 in (572 mm), slightly lower than the 23 in (585 mm) planned. Table 9 also shows that the U-tube test values were 11.5 in (292 mm) or above, with one value below the planned value of 12 in (300 mm). There was no visible segregation or bleeding, and the air contents were satisfactory, ranging from 5.1 to 7.0 percent.

Table 9. Fresh Concrete Properties of Plant Phase

Plant No.	Batch No.	Spread (in)	U-Tube (in)	Air (%)	Unit Weight (lb/ft^3)
P1	1	22.5	12.0	5.1	----
	2	24.0	11.5	7.0	136.6
	3	26.0	13.0	5.2	140.2
P2	1	22.5	12.5	6.2	----

Hardened Concrete

As with the laboratory samples, 28-day strengths for the plant specimens exceeded the 4,000 psi (27.6 MPa) minimum, and the permeability values were well below the 2500 coulomb maximum. Table 10 shows that the P1 and P2 samples had similar compressive strengths regardless of whether they were rodded, thus indicating the SCC was well consolidated. As expected, moist-cured samples of P2 had lower 7-day strengths but had higher 28-day strengths when compared to the steam-cured specimens. Table 10 also shows that the shrinkage values varied from 420 to 495 microstrain at 28 days, which were higher than the desired 400 microstrain. The higher shrinkage values result from the smaller NMS, the smaller amount of coarse aggregate, and the increased amount of cementitious material and water used, which increase paste content.[19]

Table 10. Hardened Concrete Properties of Plant Phase

Plant No.	Batch No.	Permeability (coulomb)	Strength (psi)			Shrinkage (microstrain)		
			1 day	7 day	28 day	28 day	4 mo	8 mo
P1	1 not rodded	786	2880	4230	5740	420	590	610
	1 rodded	----	----	----	5560	----	----	----
	2 not rodded	923	2410	3540	4970	415	----	605
	2 rodded	----	----	----	4970	----	----	----
	3 not rodded	1145	2400	3800	5130	465	720	720
P2	Moist cured, rodded	----	4742	4830	7650	470	650	725
	Moist cured, not rodded	----	4763	4790	7810	490	650	730
	Steam cured	1624	----	6010	6710	495	655	695

The P1 concretes had low freeze-thaw resistance, as seen in Table 8. All specimens had weight loss that was significantly higher than the acceptable value of 7 percent. Batches 1 and 3 had durability values less than the minimum acceptable value of 60, had surface ratings greater than the acceptable limit of 3, and failed to complete the 300-cycle test. On the other hand, the SCC made at P2 had desirable freeze-thaw resistance properties in all three categories of weight loss, durability, and surface rating.

Samples from P1, Batch 1, were subjected to linear traverse analysis. The larger bubbles accounted for only 0.54 percent of the air content, thus satisfying the 2 percent maximum, as shown in Table 7. Further, the 5.1 percent total air content in this batch was within the 4 to 8 percent range required for satisfactory performance. However, the spacing factor exceeded the 0.008 in (0.20 mm) required to resist the cycles of freezing and thawing in a severe environment, [17] and the specific surface was less than the minimum required value of 600 in^{-1} (24 mm^{-1}). These results appear marginal at best and raise concerns about achieving the proper void system in SCC with HRWRA when conventional total air contents are specified.

Field Application

Results from laboratory and field testing indicated that the use of SCC was feasible, which led to a field application involving an arch bridge in Fredericksburg, Virginia. This project was an excellent candidate for SCC because the arches in the bridge are heavily reinforced, thin, curved sections that would be difficult to construct with conventional concrete.

The bridge carries traffic over a small creek in a residential area. A total of 25 precast arch segments were placed side by side to create a single 30-ft (9.14-m) span across the creek. Each segment is an ellipsoidal arch measuring 7.5 ft (2.29 m) wide and 10 in (254 mm) thick, with an arc length of 45 ft (13.72 m). The bridge has a total width of 188.7 ft (57.51 m) and a clearance above the creek of 12.5 ft (3.81 m). The roadbed is supported by 30 ft (9.14 m) of soil filled vertically above the arch.

The cementitious material was a combination of Type III portland cement and slag, which was added at 35 percent of the total cementitious material. The coarse aggregate was crushed granite with an NMS of ¾ in (19 mm); the fine aggregate was natural sand. The P1 grading given in Figure 1 was used. Two admixtures were included in the design. One was a commercially available AEA. The other was a polycarboxylate-based HRWRA.

During casting, each steel arch mold was placed on its side and SCC was poured at one end of the arch. The SCC spread from the point of pouring for an arc distance greater than 40 ft (12.19 m) without requiring manual labor. The concrete was delivered in buckets carrying 3 yd^3 (2.3 m^3) of concrete, with each load leveling itself and the subsequent load flowing over the previous one without leaving any marks. The formed surface of the arch units was very smooth.

To determine if settlement occurred after placement, SCC was cast in a 4-ft (1.25-m) high, 4-in (100-mm) diameter tube that was kept vertical while curing. After 1 week, the tube was cut in half longitudinally to determine the percentage of paste, the distribution of fine and coarse aggregate, and the air content in the top and bottom 6 in (150 mm) of the tube. From the results shown in Table 11, the distribution was found to be uniform, indicating no segregation.

The facts that no segregation occurred in the 4-ft (1.25-m) cylinder and the concrete was easily poured into the arch molds indicate that SCC can be used successfully in commercial processes and in a large scale production.

Table 11. Point Count data For Top and Bottom Sections

Material	Top (%)	Bottom (%)
Paste Volume	32.8	35.3
Fine Aggregate Volume	28.8	29.0
Coarse Aggregate Volume	31.7	31.4
% Hardened Air	6.67	4.33

CONCLUSIONS

- *SCC that flows into formwork and through reinforcement under the influence of its own weight can be made such that no external vibration is required.* Although careful proportioning and batching are needed, SCC can be produced with locally available materials.

- *Concretes with a high slump flow are prone to segregation and bleeding.* Tests should be conducted with the material used for a specific project to establish that the SCC flows sufficiently but will not segregate, bleed, or require additional consolidation. To minimize segregation, a large amount of fine material, a small NMA size, uniform grading, and low water-cementitious material ratios are needed or conventional mixtures with VMAs may be used.

- *SCC can have high compressive strength and low permeability for use in bridge structures.*

- *To mitigate high drying shrinkage, a large NMA size, a large amount of coarse aggregate, and a low water content are needed.*

- *To avoid an improper air-void system that would reduce freeze-thaw resistance, either a large air content or a conventional air content with the proper selection of admixtures that will lead to a reduced void size and spacing is needed.*

- *The use of SCC has the potential to provide initial savings because of the reduction in labor required to place the concrete. Further savings can be obtained because structures constructed with SCC should last longer.*

RECOMMENDATIONS

- *Specific test procedures should be followed to determine if concretes are self-consolidating or segregating.* Specimens should be tested for strength and permeability made with and without consolidation to determine if they are self-consolidating. The slump flow test should be used to detect segregation based on aggregate distribution and a mortar halo around the spread. The U-tube or a similar test should be used to show that SCC can flow through the reinforcement and provide high workability without segregation.

- *Rheometers should be used to provide data on yield stress and viscosity and to describe the flow characteristics while the mixtures are being developed.* Low viscosity values indicate adequate flow characteristics. However, there is no correlation between the viscosity number and segregation or equilibrium height or spread in this limited study. Further work in this area is recommended.

- *SCC is recommended for use in transportation structures that can benefit from concretes with high workability, particularly in thin sections and areas with dense reinforcement.*

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