SELF-CONSOLIDATING CONCRETE APPLICATION IN AN ARCH BRIDGE IN VIRGINIA

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ABSTRACT

Self-consolidating concrete (SCC) is a concrete that consolidates under its own weight without any additional consolidation effort. SCC was first used by the Virginia Department of Transportation to make precast arches constructed with locally available materials for a bridge in Fredericksburg, Virginia. This project was an optimal candidate for SCC because the arches are heavily reinforced, thin, curved sections that would be more difficult to construct with conventional concrete. The SCC provided satisfactory strength, permeability, shrinkage, and total air content. However, the concrete had an inadequate air-void system and poor resistance to freezing and thawing at conventional air contents. The bubbles were larger than desired, which was attributed to the use of high-range water-reducing admixtures (HRWRA). Later, concretes with higher air contents or a new formulation of HRWRA were prepared, and a proper air-void system was obtained. In general, the arches had very smooth surface finishes.

Keywords: Concrete, Self-consolidating Concrete, Slump Flow, U-box, Air void, Linear traverse, Segregation, Strength, Permeability, Freezing and Thawing, Shrinkage

INTRODUCTION

Self-consolidating concrete (SCC) is a concrete that consolidates under its own weight without the addition of any supplementary consolidation energy [1]. SCC development began in Japan in the early 1980s when researchers realized that poor concrete consolidation was a major factor in the declining quality of construction work, which raised concerns about concrete durability [2]. Consolidating conventional concrete by internal vibrators is difficult in areas of congested reinforcement and thin sections; inadequate consolidation leads to a large volume of entrapped air. Ultimately, the strength and durability of the concrete are compromised. SCC can eliminate this shortcoming. Also, SCC with high workability eliminates the need for vibrators, resulting in faster construction leading to economic benefits.

BACKGROUND

Ozawa et al. authored the first paper on SCC in 1989*,* and Ozawa and other colleagues presented a paper on the same subject at an international conference on concrete held in Istanbul in 1992 [3,4]. 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 [1,5,6].

Compared to conventional concrete, SCC generally 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 [7]. SCC is a more uniform product; it is relatively homogeneous and is free of large air voids. These qualities result in greater early and ultimate strengths and a much smoother surface finish when compared to conventional concrete [6]. The improved surface finish eliminates the rubbing and patching ordinarily required to fill defects [2].

At high flow values, bleeding and segregation are possible, leading to sand streaks. The flow of mixtures is sensitive to water content. Any deviation in the moisture content of the aggregate can have a large effect on the flow characteristics. Adequate moisture control measures must be taken.

To achieve a high flow rate, to avoid obstruction by closely spaced reinforcing steel, and to avoid segregation, SCC is designed with limits on the nominal maximum size (NMS), 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) [8]. However, care should be exercised when a high fine-to-coarse aggregate ratio is used since shrinkage would increase. SCC mixtures can be produced with normal fine-to-coarse aggregate ratios, typically with viscosity-modifying admixtures (VMA). HRWRA based on polycarboxylates has been an important factor in making SCC a practical reality [2]. VMA are also used to reduce the tendency for segregation and enhance the stability of the air-void system [9,10].

As with other concretes using HRWRA, one note of caution must be heeded when HRWRA is used in an SCC mixture. Interaction of HRWRA and air-entraining admixtures (AEA) would affect the air-void system, resulting in large air voids [11]. Thus, for conventional air contents, proper spacing factor and specific surface may not be achieved. Also, too much HRWRA can actually induce segregation, which would destabilize and reduce the amount of air voids in the concrete. Some AEAs stabilize smaller bubbles than do others. An insufficient air-void system reduces the protection from freezing and thawing damage in a critically saturated concrete. Therefore, the amount, type, and interaction of admixtures must be considered carefully when designing an SCC mixture.

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, SCC typically has higher shrinkage. Increased shrinkage may result in more cracks in the restrained concrete elements, which can accelerate the deterioration of the concrete and the reinforcing steel.

Another issue has been the pressure exerted by the formwork. The lateral pressure exerted by this concrete with high fluidity is not well understood [12]. Currently, conservative designs that assume SCC fluid up to the setting time are used. However, the lateral pressure drops following casting and the rate of drop depend on the thixotropy of SCC. Accounting for the drop in lateral pressure could result in savings in formwork.

PURPOSE AND SCOPE

The purpose of this project was to use SCC to make precast arches for a bridge in Fredericksburg, Virginia. This project was an optimal candidate for SCC because the arches in the design have heavily reinforced, thin, curved sections that would be more difficult to construct with conventional concrete.

METHODOLOGY

OVERVIEW

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 span across the creek. Each segment is an ellipsoidal arch measuring 7.5 ft wide and 10 in thick, with an arc length of 45 ft. The bridge has a total width of 188.7 ft and a clearance of 12.5 ft above the creek. Soil has been filled 30 ft above the arch.

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 without requiring manual labor. The concrete was delivered in buckets, each carrying 3 yd^3 of concrete, with each load leveling itself over the previous one. The finished product was smooth and free of surface blemishes.

During construction, the arches were set on masonite sheets that were placed over the footings. Oak wedges held the arches steady until the arches could be fixed into place with grout. Epoxy was applied between the segmental joints, and asphalt strips were placed on top along the joint to prevent leaks. Then soil was placed on top of the arches.

MATERIAL, PROPORTIONING, AND TESTING

Table 1 shows the mixture proportions for the SCC. The cementitious material was a combination of Type III portland cement and slag. Slag was 35 percent of the total cementitious material. Table 1 also includes a plain portland cement SCC batch used for comparison.

Table 1. Mixture Proportions in lb/yd^3

Material	Description	Slag	Plain
Cement	Type III	488	750
Slag	35%, Grade 120	262	0
Sand	Natural sand	1451	1455
Stone	Granite, 19 mm NMS	1451	1475
Water	---	279	270
Air (%)	---	5.5 $\pm$ 1.5	5.5 $\pm$ 1.5
AEA (fl oz/cwt)	Sodium-salt type soap	0.2	0.3
HRWRA (fl oz/cwt)	Polycarboxlyate	8.0	8.0

The fine aggregate was natural sand with an absorption of 0.6 percent, a specific gravity of 2.76, and a fineness modulus of 2.45. The coarse aggregate was crushed granite with a nominal maximum size of ¾ in, an absorption of 0.7 percent, a specific gravity of 2.67, and a dry-rodded unit weight of 99.8 lb/ft^3. The combined fine and coarse aggregate grading is shown in Figure 1. Except for the No. 8 sieve, the grading between the ½ in and No. 50 sieves was fairly uniform. Uniform aggregate blending helps to minimize segregation [13].

Two admixtures were included in the design. One was a commercially available AEA, which was a liquid solution of concentrated organic materials. The second admixture was a polycarboxylate, which is an HRWRA meeting the requirements of ASTM C 494, Type F, expected to provide maximum water reduction without affecting the setting time.

Five batches of SCC were produced and tested during construction at two different times: Batches 1 through 3 at one time and then Batches 4 and 5 at another time. In addition, two batches of SCC, Batches 6 and 7, without slag were tested for comparison.

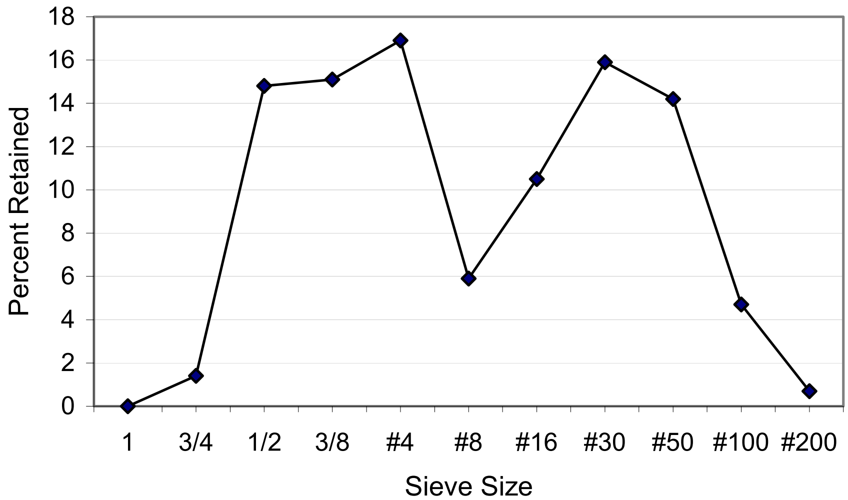

Figure 1: Aggregate Grading

FRESHLY MIXED CONCRETE

The consistency and workability of the freshly mixed concrete were evaluated using the slump flow and the U-box tests. Due to its ease of operation and portability, the slump flow test is the most widely used method for evaluating the consistency of SCC in the laboratory and at construction sites. The Japan Society of Civil Engineers (JSCE) specifies the slump flow test [14]. In this test, the average diameter of the concrete flowing out of the slump cone measured at two perpendicular directions is a measure of the ability of SCC to flow, thus determining the consistency and cohesiveness of the concrete [15]. Generally, slump flow values are around 25.5 in [7,16]. In this study, the desired range for slump flow values was 24 to 28 in. Also, the time the SCC took to reach a diameter of 20 in was recorded during the slump flow test.

During the slump flow test, a visual inspection for segregation is routinely made. This inspection involves observing the mortar halo around the spread and the aggregate distribution within the spread. If a mortar halo forms around the spread or if the coarse aggregate is not uniformly distributed, the concrete has segregated.

The consistency of SCC was also measured using the U-box test. This test indicates if the SCC will pass around the reinforcement or other restrictions easily. The U-shaped container has of the container a vertical wall separating the two legs of the “U.” This wall extends for most of the height except for at 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-box is about 14 in. Concrete was considered SCC if the flowing height was more than 70 percent of this equilibrium height (i.e., 10 in) [17].

In addition to slump flow, the freshly mixed concrete was measured for density (ASTM C 138) and air content (ASTM C 231). The specified air content for precast members is 5.5 ± 1.5 percent when an HRWRA is used. These arches were precast members, and the requirement for average air content is lower than the requirement for regular cast-in-place bridge elements.

To determine if aggregate settlement occurred after placement, SCC was cast in a 4-in-diameter, 4-ft-long plastic tube and kept vertical while curing. After one week, the tube was cut in half longitudinally to determine the percentage of paste, fine aggregate, coarse aggregate, and air content in both the top and bottom 6 in of the tube.

HARDENED CONCRETE

Specimens were made for tests in the hardened state. Most specimens were placed in molds without any consolidation effort; however, additional specimens were consolidated by rodding. These extra specimens helped to verify whether or not additional consolidation effort would yield any improvements in compressive strength. Samples were tested for permeability, shrinkage, freeze-thaw resistance, and air-void analysis, as summarized in Table 2. Table 2 also includes specified or desired limits for different properties. The specified minimum 28-day design strength was 5,000 psi. The permeability value was not specified but was expected to be less than 2,500 coulombs, as in bridge decks.

Table 2. Hardened Concrete Tests and Specifications

Test	Specification	Age (d)	Size (in)	Limits
Compressive Strength	AASHTO T 22	[a]	4 x 8	Minimum of 5000 psi
Permeability	AASHTO T 277	28[b]	2 x 4	Maximum of 2500 Coulombs
Drying Shrinkage	ASTM C 157	28	3 x 3 x 11 ¼	Maximum of 400 microstrain
Freeze-Thaw Analysis	ASTM C 666	[c]	3 x 4 x 16	Weight loss ≤ 7%; durability factor ≥ 60; surface rating ≤ 3
Air-Void Analysis	ASTM C 457	28	4 x 8	(voids > 1 mm) < 2%; spacing factor < 0.008 in; specific surface > 600 in^2/in^3

[a] At 1,7, and 28 days.
[b] One week at 73°F and 3 weeks at 100°F.
[c] Procedure A except moist cured for 2 weeks and air dried at least 1 week before testing, and the test water contained 2 percent NaCl..

For the air-void analysis, samples were subjected to a linear traverse analysis (ASTM C 457). In this analysis, air bubbles less than 1 mm in diameter define spherical air-entrained bubbles, and bubbles greater than 1 mm in diameter are considered to be entrapped air due to lack of consolidation or extra water. Properly consolidated concrete should contain less than 2 percent entrapped air [18].

RESULTS AND DISCUSSION

FRESHLY MIXED CONCRETE

Of approximately 100 batches made for the arches, 5 were tested. The fresh concrete properties are summarized in Table 3 along with the plain mixtures used for comparison. The fresh properties were similar in the slag and the plain mixtures. The slump flow values were in the desired 24 to 28 in range, except for one that was marginal. The air contents were within the specifications. The time for the spread to reach 20 in was at most 3.6 seconds, which was satisfactory. There was no mortar halo present during the slump flow test, and the coarse aggregate and paste were uniformly distributed throughout the spread. Thus, the SCC was free of segregation.

Table 3. Fresh Concrete Properties

SCC	Batch	Slump Flow (in)	Time to 20 in (s)	U-box (in)	Density (lb/ft^3)	Air (%)
Slag	1	24.8	2.6	12	144	5.3
	2	25.0	2.9	13	146	4.4
	3	24.0	3.6	14	146	6.6
	4	25.5	2.2	11	140	6.3
	5	27.3	2.2	NA	141	5.0
Plain	6	23.8	2.5	NA	141	6.2
	7	25.0	2.2	NA	142	6.0

The U-box test was conducted on the first 4 batches and the filling height ranged from 11 to 14 in. Thus, all four samples exceeded the suggested height of 10 in (70 percent of equilibrium height) expected to provide sufficient ability to flow past the reinforcement. The decision to require a 70 percent rise was an arbitrary one. Some research has suggested that the rise should be 90 percent of the equilibrium height [19], which is more than 12 in [1]. Other research has suggested that the rising height actually should not be the arbiter of the ability of SCC to flow. Instead, the qualitative results, such as whether or not the aggregate is able to flow past the reinforcement, serve as better criteria [14]. More work is needed to determine the lowest rising height for different applications. Different equilibrium heights may prove satisfactory for SCC, depending on the material, distance between concrete production and placement, structural design, and the environmental conditions.

For this project, all of the concretes were considered to be SCC, since the differences in strength between the consolidated and unconsolidated specimens were small (see Table 4) and the concrete traveled the entire arch length past the reinforcements in the arch without any blocking or lift lines. Since the U-box test is cumbersome, once the mixture is established for satisfactory flow, the slump flow test may be used for quality control without the U-box.

Table 4. Hardened Concrete Properties

SCC	Batch	Strength (psi)				Perm	Shrinkage[b]		
		1 d	7 d	28 d	28 d, R[a]	(Coul)	28 d	4 mo.	8 mo.
Slag	1	3380	6160	7610	-	815	330	440	475
	2	-	6490	7300	-	882	400	510	545
	3	-	6600	7270	-	1002	310	400	420
	4	3040	5740	7720	7870	1690	395	505	500
	5	2720	5620	7630	8180	1758	345	475	475
Plain	6	4330	6280	7630	7500	2503	335	505	515
	7	4880	6690	7870	7650	2281	340	530	540

[a] Rodded.
[b] Shrinkage in microstrain.

SCC from B5 had a high slump flow and was cast in a 4-in-diameter, 4-ft-high plastic tube to determine if any settlement occurred. Table 5 shows the percentage of paste, fine aggregate, coarse aggregate, and air found in the top and bottom 6 inches of the tube. The percentages for the individual materials were fairly similar in the top and the bottom; therefore, segregation was not expected in similar batches.

Table 5. Analysis of 4-ft Cylinder

Material	Percentage	
	Top 6 in	Bottom 6 in
Paste Volume	32.8	35.3
Fine Aggregate Volume	28.8	29.0
Coarse Aggregate Volume	31.7	31.4
Air Content	6.7	4.3

HARDENED CONCRETE PROPERTIES

The hardened concrete properties are summarized in Table 4. The compressive strengths for the plain mixtures at 1 day were higher than those for the slag mixtures; however, at 28 days, the mixtures had similar strength. At 28 days, all of the specimens exceeded the 5,000-psi minimum compressive strength by at least 45 percent. The strength of the additional specimens that were consolidated by rodding was similar to that of specimens that were not rodded, indicating that all the batches were self-consolidating. The permeability values were lower in slag mixtures, as expected. Plain mixtures were associated with marginal permeability values. The 28-day shrinkage values for all of the samples were similar between mixture designs and less than or equal to the recommended 400-microstrain maximum at 28 days [20].

Table 6 displays freeze-thaw data for specimens from Batches 5 (slag) and 6 (plain). The acceptance criteria for adequate freeze-thaw resistance are a maximum weight loss of 7 percent, a minimum durability factor of 60, and a maximum surface rating of 3. Both batches had a high weight loss and surface rating and a low durability. Table 7 summarizes the air-void parameters. Typically, the spacing factor should be less than 0.008 in and the specific surface should be more than 600 in^2/in^3 for adequate resistance to freezing and thawing in a severe environment [21]. The results indicate a high spacing factor and a low specific surface, indicative of large bubbles. Because of failing freeze-thaw results, further work was planned. However, this arch structure is not expected to suffer from damage from cycles of freezing and thawing. It is not expected to be critically saturated because of the low-permeability concrete and the ability to dry from inside the arch, and it is not exposed to deicing salts. The structure will be monitored to determine its performance over time.

Table 6. Freeze Thaw Analysis

SCC	Batch	Weight Loss (%)	Durability Factor	Surface Rating
Slag	5	27.4	18	5
Plain	6	42.7	14	5

Table 7. Linear Traverse Analysis

Material	Batch	Air Content (%)			Specific Surface (in^2/in^3)	Spacing Factor (in)
		<1 mm	>1 mm	Total		
Slag	5	3.3	2.0	5.3	307	0.0151
Plain	6	3.3	3.0	6.3	269	0.0159

Two approaches are possible to achieve the desired air-void parameters that will improve the resistance to freezing and thawing. The first approach is to increase the air content to entrain enough bubbles in the concrete. After the completion of the arch, two additional mixtures of concrete were prepared at the same plant. The mixture proportions are given in Table 8. The fresh properties of these batches are given in Table 9, and the 7- and 28-day strengths in Table 10. More AEA was added and a higher air content was obtained compared to the earlier batches. The freeze-thaw results summarized in Table 11 indicate satisfactory values.

Table 8. Mixture Proportions, Increased Air Content (per yd^3)

Material	B 8	B 9
Cement	508	750
Slag	127	0
Water	254	270
Coarse Aggregate (lb)	1535	1475
Fine Aggregate (lb)	1530	1428
AEA (fl oz/cwt)	0.4	0.4
HRWRA (fl oz/cwt)	8	8
w/cm	0.40	0.36

Table 9. Fresh Concrete Properties, Increased Air Content

Batch	Flow (in)	Air (%)	Concrete Temp. (°F)	Density (lb/ft^3)
8	24	10.0	80	136
9	26.5	7.0	79	135

Table 10. Hardened Concrete Properties, Increased Air Content

Batch	Strength (psi)	
	7 day	28 day
8	4890	6030
9	7360	8600

Table 11: Freeze-Thaw Analysis, Increased Air Content

Batch	Weight Loss (%)	Durability Factor	Surface Rating
8	0.0	97	0.5
9	0.0	96	0.2

The second approach is to use a new formulation of HRWRA that contained a defoamer. One of the problems with the use of HRWRA has been that it alone, without the AEA, entrains large bubbles, necessitating that low dosages of AEA be added so that the total air content would not be increased. Defoamer would minimize the air-entraining capabilities of the HRWRA and enable the addition of a sufficient amount of AEA to entrain small bubbles for an adequate air-void system. Two batches of concrete were prepared using the mixture proportions given in Table 12 at the same plant. The differences between the two batches were in the amount of AEA added. These batches had Class N natural pozzolan (ASTM C 618), a calcined shale.

Table 12. Mixture Proportions, New HRWRA (lb/yd^3)

Material	Amount (lb/yd^3)
Cement	476
Calcined shale	204
Water	270
Coarse Aggregate	1450
Fine Aggregate	1392
AEA (oz/cwt)	0.4 and 0.5
New HRWRA (oz/cwt)	8
w/cm	0.40

The fresh and hardened properties of these batches are given in Table 13 and were satisfactory. The air-void analyses as summarized in Table 14 indicate that air voids were smaller than those obtained earlier during the construction of the arch, since the specific surface values were smaller. This indicates that smaller bubbles can be obtained by this new admixture. The spacing factors of these mixtures were satisfactory.

Table 13. Fresh Concrete Properties, 28-Day Strength and Permeability, New HRWRA

Batch	Air (%)	Flow (in)	Compressive (psi)	Permeability (Coul)
10	7.4	25.5	5850	1107
11	8.0	26.5	5260	1335

Table 14. Linear Traverse Analysis, New HRWRA

Material	Batch	Air Content (%)			Specific Surface (in^{-1})	Spacing Factor (in)
		<1 mm	>1 mm	Total		
Calcined shale	10	6.6	0.3	6.9	686	0.0065
Calcined shale	11	8.9	0.3	9.2	615	0.0056

CONCLUSIONS

1. SCC that flows into formwork only under the influence of its own weight can be produced using locally available materials.

2. Tests for slump flow and time of flow are good indicators of the ability of SCC to flow. The U-box test indicates the ability of the concrete to pass around the reinforcing steel.

3. The standards for the U-box tests may need to be reconsidered; different equilibrium heights may prove satisfactory for SCC, depending on the material, distance between concrete production and placement, structural design, and environmental conditions.

4. Strength, permeability, and shrinkage were satisfactory.

5. Although the SCC had a satisfactory air content, the material had an inadequate air-void system and poor resistance to freezing and thawing. However, increasing the air content of the concrete and using new formulations of HRWRA with defoaming agents were both viable solutions to the freeze-thaw problems with the original batches.

6. Strict moisture control is necessary since SCC is highly sensitive to slight variations in water content that may lead to bleeding and segregation.

7. Very smooth surface finishes were achieved.

RECOMMENDATIONS

SCC should be considered for future projects, especially for those involving thin sections and dense reinforcement.

More research on the flow tests should be conducted with regard to the extreme ranges for height rise in the U-box test or spread in the slump flow test. A lower limit should be determined such that the concrete does not require mechanical vibration and flows easily past steel reinforcement. To test if a mixture is SCC, specimens with and without consolidation can be tested for strength. The upper limit should be established such that the concrete is stable (i.e., no segregation).

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