SELF-CONSOLIDATING CONCRETE IN CONGESTED SECTIONS: MIX CHARACTERISTICS AND ASSESSMENT OF PERFORMANCE

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ABSTRACT

Eight planar 6-in. thick, 6-ft deep and 6-ft wide wall sections and eight 13-ft long BT-72 beam sections were fabricated in two precast plants. All sections had highly congested reinforcement. The wall panels used three different SCC mixes, while four different mixes were used for the BT-72 beams. The main differences among the SCC mixes were the maximum size aggregate and the combinations of coarse and fine aggregate used. Cores were taken at different locations on each of the walls and beams to assess the distribution of compressive strength of the SCC. The specimens were sawn vertically at different locations, and the aggregate distribution of each sawn surface section was quantified to assess segregation of the SCC mixes throughout the depth and length of the elements. Some mixes showed no segregation and excellent surface finish while others resulted in large voids and many surface blemishes.

The SCC mixes had test results with slump flow between 22 and 29 inches, U-flow with depth ratio greater than 85% and L-box result with depth ratio greater than 75%. Yet, such test results were not sufficient for predicting a mix's performance in congested sections. Only construction of mock-up sample sections showed the true self-consolidating performance of a mix. That is, specially developed SCC mixes are required for congested sections as opposed to SCC for slabs or for lightly reinforced beams – all SCC's are not created equal.

KEYWORDS: Prestressed Concrete, Precast Concrete, Self-Consolidating Concrete, SCC, Digital Image Analysis, Segregation, Flowability

INTRODUCTION

There has been a lot written about self-consolidating concrete, SCC. And many are telling us, "SCC is the answer!" SCC promises better quality, better finish, and less labor than conventional concrete. So, the Georgia Department of Transportation sponsored us at Georgia Tech to investigate whether SCC would really work well for construction of highly congested precast concrete bridge structures. What we found was that not all SCC's are created equal. SCC's are a *class* of concrete; one mixture may be applicable to lightly reinforced slabs while a very different mix is applicable to congested bridge girders.

The purpose of the research was to identify the SCC mix designs and quality assurance methods which would best satisfy the State's need for constructing highly congested precast/prestressed concrete bridge girders and for placing congested bridge diaphragms and end walls. Mixes were made in the laboratory and in the field at Tindall Concrete in Conley, Georgia and at Standard Concrete Products in Atlanta, Georgia; and prototype, mock-up specimens were cast at the plants.

In conversations with precasters, we have learned that SCC is being used regularly and successfully at many plants around the nation. Proceedings of the PCI National Bridge Conferences have papers on SCC applications[1, 2]. Summary reports of applications and mix designs have been published[3-6]. And PCI has published its own survey of SCC[7].

So why another research project? Because our preliminary laboratory study showed that mix designs provided by admixture suppliers and given in the literature did not provide a SCC that flowed through congested reinforcement using commonly available Georgia aggregates[8].

Our past laboratory-based research[8] examined fine and coarse aggregates from sources throughout Georgia, use of fly ash and slag, different cements, and SCC admixtures from three different suppliers. Excellent mixtures were developed using the different admixtures, but each of those mixes was different. We found that blending natural and manufactured sands and blending of coarse aggregates created the smoothest gradation which assured good flow, passing ability, and segregation resistance. Use of both Class F fly ash and slag combined up to 40% of cementitious content proved to enhance SCC qualities. A maximum size aggregate greater than ½-in. (No. 7 stone) caused diminished passing ability in the L-box and U-box tests where clear spacing between the bars was 1 ½-in., which modeled the spacing between typical prestressing strands. The three resulting "best" mix designs were used as a basis for the field-based research described herein.

RESEARCH PLAN

We planned the research with the assistance of representatives from precasters, Tindall Concrete and Standard Concrete Products, along with technical representatives of Sika Chemical Corp. and Grace Construction Products. The goals were to develop different SCC mixes which varied from least expensive (most desirable) to complex (those from our previous laboratory study that included blended aggregates and supplementary cementitious materials), which satisfied standard quality control tests for flowability and stability, and which could be cast at the precast plants to fabricate "full size" mock-up samples. The mock-ups would be inspected for surface condition and would be saw cut to examine segregation and filling ability along their length and depth. Cores would be taken from the mock-ups and compared to test cylinders.

The mock-ups were eight planar 6-in. thick, 6-ft deep and 6-ft wide wall sections cast at Tindall Concrete plus eight 13-ft long PCI BT-72 beam sections cast at Standard Concrete Products as shown in Figures 1 and 2.

Figure 1. 6-in. thick wall panel

Figure 2. 13-ft. BT-72 mock-up

WALL PANELS

Table 1 gives the three mix designs used for the wall panels. Mixtures W-1 and W-2 were based on the mixes from the laboratory study[8] while W-3 was the mixture currently used at the plant for casting precast slab sections. Standard slump flow (inverted cone) and U-box and L-box tests were conducted. For the U-box, the ratio of height of the SCC after the gate to that before the gate (H_2/H_1) is given in Table 1. For the L-box, the ratio of the height of the SCC at the end of the box (H_f) to that just after the gate (H_{S1}) is given.

Figure 3 illustrates the reinforcing cage made of ½-in diameter prestressing strand spaced about 9-in. by 11-in. on-center on each face. The SCC was placed at one location through a funnel just toward the middle of the wall adjacent to a lifting hook. Three walls were cast with the W-1 mix, four with the W-2 mix, and one with the W-3 mix. Two walls of each of the first two mixes were vibrated externally for about 5 seconds as was the one wall using W-3. The vibration was planned to determine if it resulted in an improved surface finish.

Table 1. Mix proportions for SCC used in Wall Panels

Mix Components	Mix W-1	Mix W-2	Mix W-3
	S-Slag/Ash	**G-Slag**	**T-Cement**
Cementitious, lb/cy [kg/m^3]			
Cement Type I	720 [427]	730 [433]	750 [445]
Slag	200 [119]	225 [133]	-
Fly Ash, Class F	90 [53]	-	-
Water, lb/yd^3 [kg/m^3]	306 [182]	350 [208]	288 [171]
w/cm	*0.30*	*0.37*	*0.38*
Coarse Aggregate, lb/cy [kg/m^3]			
# 67 stone (max. size 3/4-in.)	-	-	1465 [870]
# 7 stone (max. size 1/2-in.)	1030 [611]	910 [540]	-
# 89 stone (max. size 3/8-in.)	555 [329]	485 [288]	-
Fine Aggregate, lb/cy [kg/m^3]			
Natural sand (FM= 2.35)	615 [365]	600 [356]	1331 [790]
Manufactured sand (FM= 2.90)	395 [234]	580 [344]	-
Admixtures, fl oz./cwt [mL/100 kg]			
HRWR (polycarboxylate base)	Type 1* 7.1 [463]	Type 2† 6.9 [450]	Type 2† 5.5 [360]
Air-entrainer (Daravair 1000 ®)	-	-	0.4 [26]
SCC Properties			
Slump flow diameter, in. [mm]	34 [834]	26 [660]	18 [457]
U-Box (H_2/H_1)	100%	100%	50%
L-Box (H_f / H_{S1})	100%	75%	50%
VSI	1	0	1.5
Compressive strength, f_c', psi, [Mpa]	11,600 [80]	8,600 [59]	8,600 [59]
Compressive strength cores psi [MPa]	11,000 [76]	8,600 [59]	6,650 46]

* Sika ViscoCrete 6100 ®

† Grace ADVA Cast 540 ®

Surface Finish Evaluation. Both a visual and quantitative inspection of the SCC wall panels were used to assess the quality of their surface finishes. The walls cast with mixes W-1 and W-2 displayed an excellent surface finish; the external vibration did not make any difference in finish. The wall cast with the W-3 mix exhibited a poor concrete consolidation and honeycombing. As seen in Figure 4, the large aggregates of the W-3 mix got trapped among the wall's reinforcement, thus blocking the flow.

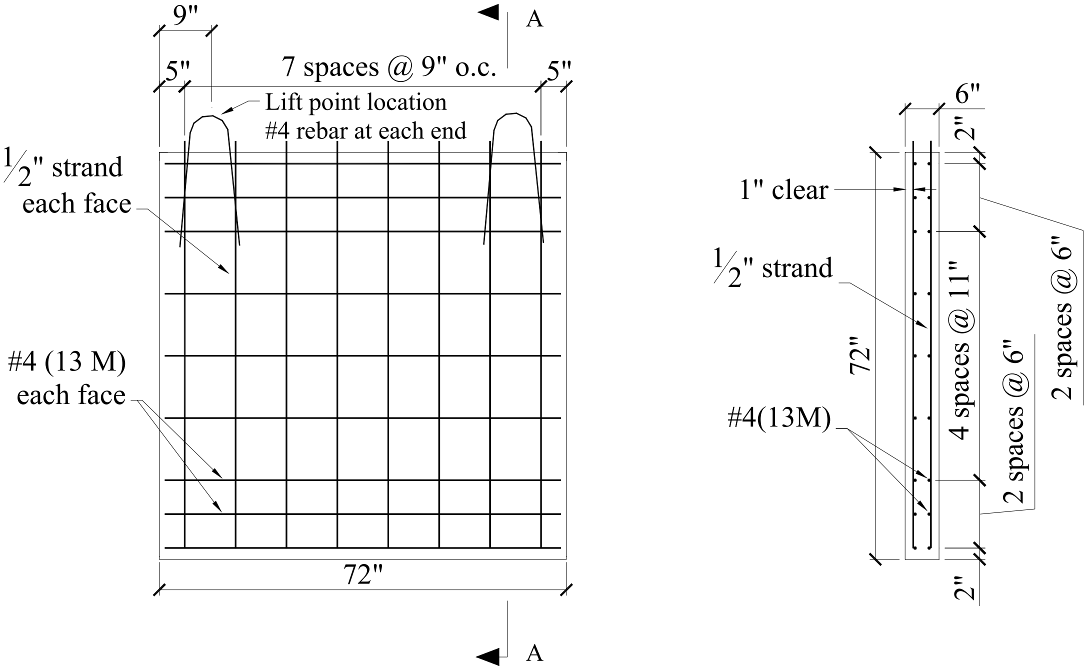

Figure 3. Reinforcement layout for wall panels.

Figure 4. Poor filling and flow of Mix W-3 in wall panel

Compressive Strength of Cores Samples. To evaluate the in-place properties of the SCC mixes, 3-in. diameter cores were taken at nine locations on each wall, three across the length and three through the height. The cores were drilled and tested 56 days after casting of the walls. Figure 5 gives the strength the cores. A single core was taken at each position; the “near” end was that where the SCC was placed.

A statistical analysis showed that for W-1 (S-Slag/Ash) and W-2(G-Slag) mixes neither the vibration, horizontal location, or vertical location of the cores were significant factors in the results. That is, the strength could be considered consistent throughout the wall panels. The W-3 (T-Cement) mix showed significant horizontal and vertical variation in strength. It was concluded that the reinforcement significantly inhibited the flow of the W-3 mix with its larger aggregate and lower slump flow.

Aggregate Distribution throughout Cross Sections. All wall panels were sawn vertically in order to analyze the distribution of aggregates throughout their cross-sections. A vertical cut was made approximately 1 ft away from each end of each wall. When looking at the walls cast with S-Slag/Ash and G-Slag mixes, an even distribution of the aggregates was noticed for all sections. No voids were found beneath or around the reinforcement at any level, indicating that there was excellent consolidation and that there was no bleeding. For the T-Cement, W-3 mix, the far end surface was characterized by large air voids and loose aggregate without surrounding paste.

	Near End	Center	Far End
Top	10,900	10,500	9,800
Middle	11,500	11,300	11,000
Bottom	11,400	11,500	11,200

Vibrated

	Near End	Center	Far End
Top	11,400	9,700	10,700
Middle	11,500	10,900	10,900
Bottom	11,400	11,000	11,200

Vibrated

	Near End	Center	Far End
Top	11,700	10,100	10,700
Middle	11,200	11,000	10,700
Bottom	11,200	10,800	10,700

Non-Vibrated

S-Slag/Ash mix. Control cylinder strength 11,600 psi @ 56 days

	Near End	Center	Far End
Top	9,850	2,200	3,700
Middle	2,900	5,900	9,300
Bottom	9,300	8,000	8,800

Vibrated

T-Cement Mix

Control cylinder strength 8,600 psi @ 56 days

	Near End	Center	Far End
Top	8,800	8,600	8,800
Middle	9,600	9,500	9,000
Bottom	9,500	8,700	8,800

Non-Vibrated

	Near End	Center	Far End
Top	8,600	8,500	8,400
Middle	8,200	8,200	8,500
Bottom	8,200	8,400	8,100

Non-Vibrated

	Near End	Center	Far End
Top	7,800	7,700	8,200
Middle	8,200	8,300	8,100
Bottom	8,100	7,900	8,000

Vibrated

	Near End	Center	Far End
Top	9,300	9,100	9,000
Middle	8,600	8,600	9,000
Bottom	8,900	8,800	8,800

Vibrated

G-Slag mix. Control cylinder strength 8,600 psi @ 56 days

Figure 5. Core compressive strength of the SCC wall panels.

BULB-TEE MOCK-UPS

Eight 13-ft. long PCI BT-72 mock-ups were constructed at Standard Concrete Products as illustrated in Figure 6. The bottom flange was reinforced with 26 0.6-in. diameter strands; an additional 14 0.6-in. strands were draped to a mid-point harp, and two strands were in the top flange. Cover was 1-in.; #5 bar two-leg stirrups were spaced 12-in.on centers; five #6 stirrups were spaced 3-in. on centers at each end. Each end also was reinforced with five horizontal layers of #4 bars, four "dog house" bars at 12-in. on center, plus lifting loops made of 3 ½-in. strand. A diaphragm pocket was located at the center. This section was considered to represent a typical, heavily reinforced GDOT bridge girder.

Figure 6. BT-72 mock-up beams with 42 0.6-in. strands.

Five trial SCC mixes were made in the laboratory and at the precasting plant. Slump flow, L-box, and U-box tests were conducted, and the surface finishes of highway barriers cast with the SCC's were inspected. Class C fly ash and Type III cement were used rather than Class F ash and Type I cement because the precaster wanted to assure rapid curing. The four mixes given in Table 2 were selected to make the mock-ups – two beams for each mix. An external vibrator was attached to one form for each mix and activated for 5 seconds. The mixes were designed such that "7" means #7 stone and "67" means #67 stone, ½-in. and ¾- in. maximum size aggregate, respectively; “N” means a natural sand, “M” a manufactured sand, and “BL” a blend of the two to achieve an more uniform gradation. The “v” indicates that the beam was externally vibrated.

Table 2. Mix proportions for BT-72 mock-up beams

	Mix 1		Mix 2		Mix 4		Mix 5	
Mix Components	7N	7Nv	67N	67Nv	7BL	7BLv	67M	67Mv
Cementitious (lb/yd^3)								
Cement Type III	780	765	780	750	776	754	770	768
Fly Ash, Class C	166	163	156	146	163	147	153	156
Total Powder	*946*	*928*	*936*	*896*	*939*	*901*	*923*	*924*
Water (lb/yd^3)	297	300	277	293	305	308	294	303
w/cm	*0.31*	*0.32*	*0.30*	*0.33*	*0.32*	*0.34*	*0.32*	*0.33*
Coarse aggregate (lb/yd^3)								
# 67 stone	-	-	1164	1176	-	-	1439	1443
# 7 stone	1254	1250	-	-	1259	1223	-	-
# 89 stone	194	208	215	218	204	182	-	-
Total Coarse	*1448*	*1458*	*1379*	*1394*	*1463*	*1405*	*1439*	*1443*
Fine aggregate (lb/yd^3**)**								
Natural sand (FM=)	1210	1280	1339	1320	199	211	-	-
Manufactured sand (FM=)	-	-	-	-	1139	1155	1357	1206
Total Fine	*1210*	*1280*	*1339*	*1320*	*1338*	*1366*	*1357*	*1206*
Total Aggregates	*2658*	*2738*	*2718*	*2714*	*2801*	*2771*	*2796*	*2649*
Admixtures (fl oz./cwt)								
HRWR (ViscoCrete 6100)	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
LRWR (Plastiment)	2.1	1.9	2.1	1.9	2.1	1.9	2.0	2.0
Air entrainer (AEA-14)	0.15	0.11	0.18	0.18	0.15	0.18	0.18	0.33
SCC fresh state properties								
Slump-flow (in.)	23	27	22	25	29	28	27	27
VSI	1	1.5	1.5	0	1.5	1	1	1
U-box (H_2/H_1 %)	100	100	86	100	100	100	100	100
L-box (H_f/H_{S1} %)	75	75			75	100		

Based on visual inspection and testing (Slump-flow, Visual Stability Index (VSI), U-box, and L-box results are reported in Table 2), each mix was considered a good quality SCC.

Each 3.0 yd^3 batch was delivered from the batch location about 300 ft. to the beam using a Tucker-built truck. The SCC was placed in each beam at a single point about 20-in. from one end, between the pick-up loops and the #6 stirrups. The pick-up loops did inhibit flow of the SCC.

Surface Finish. In all beams, except mix 7BL (Mix 4), air bubbles as well as bleeding marks were clustered around the areas of heavier reinforcement, particularly the lifting loops and the draped strands. The bleeding marks were thicker and more common at the end of the beams where the SCC was placed (termed “near end”). In general, vibrated and non-vibrated beams presented similar surface finish quality.

Mixes 67M and 67Mv (Mix 5) both showed a particularly poor surface finish. Large voids (honeycombing) and bleeding lines around the area of the draped strands were observed for both beams. However, the central area of the web of these beams displayed a smooth, good quality surface finish. This difference in the quality of the surface finish within the beams showed that mixes 67M and 67Mv were self-flowing, but showed limited ability to flow in the highly congested reinforcement of the BT-72 sections.

Mixes 7BL and 7BLv (Mix 4) presented similar surface finishes to one another. Both beams showed smooth and clean surfaces with minimal presence of air bubbles, especially mix 7BLv. The bottom flanges of these beams appeared to be of the highest quality, as compared with the rest of the mixes. Although the finish of the bottom flanges was not completely air-void free, the sizes of the bubbles were small and reduced in number. Materials engineers with GDOT as well as production personnel with Standard Concrete products stated that the surface finish of the beams with 7BL and 7BLv was superior to that obtained in vibrated beams using conventional concretes.

As shown in Figure 7, four 1-ft. square zones were selected for a bubble-count quantitative surface analysis, near top, center web, far bottom and top of bottom flange. The number of surface bubbles within ± 1/16-in. of the following were recorded and plotted in Figures 8 through 11: ⅛-in., ¼ , ⅜, and >7/16-in.

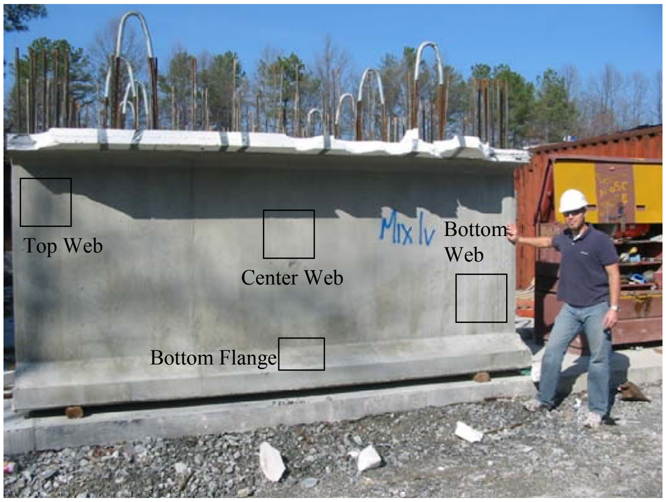

Figure 7. Locations for bubble-count analysis.

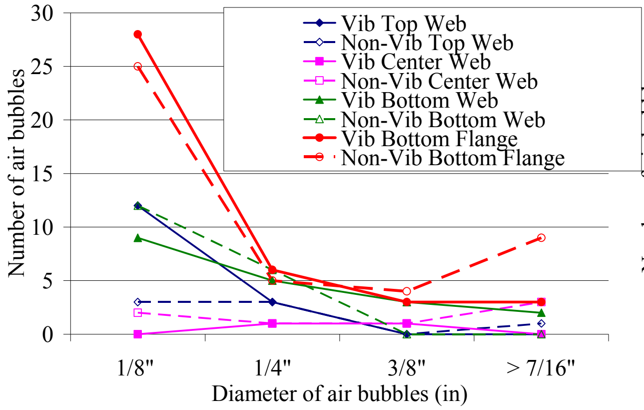

Figure 8. Mix 1, 7N & 7Nv

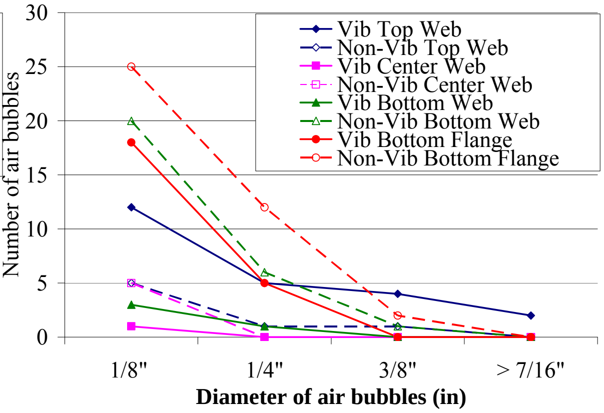

Figure 9. Mix 4, 7BL & 7BLv

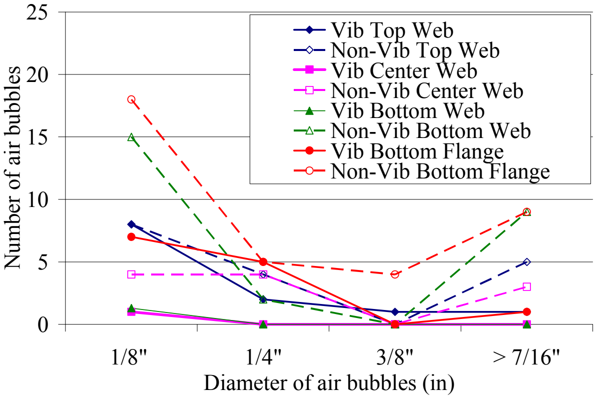

Figure 10. Mix 2, 67N & 67Nv

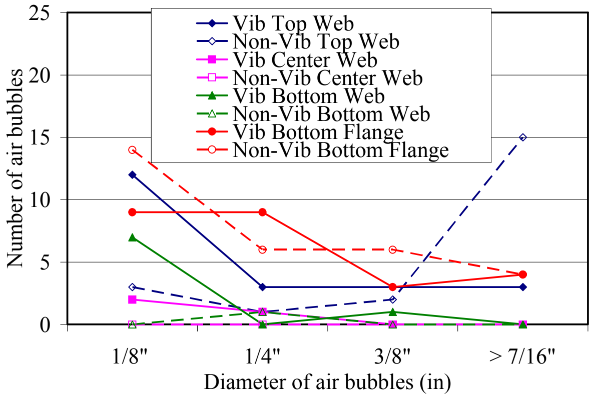

Figure 11. Mix 5, 67M & 67Mv

The region with the greatest number of air bubbles was the bottom flange location for all beams. The greater presence of large bubbles in mixes 67N and 67M, including 3/8-in. and >7/16-in. diameter, were an indication of poor consolidation of these mixes. The maximum area fraction of air bubbles to surface of the beams for mixes 67N and 67M were 2.11% and 3.41%, respectively, both greater than the 2% maximum of entrapped air typical for properly consolidated concrete.[9] For mixes 7N and 7BL the maximum air-bubbles to surface ratio were only 0.90% and 0.45%.

<u>Compressive Strength of Control Cylinders and Core Samples</u>. Compressive strengths of the various mixes were determined using laboratory-cured 4x8 in. control cylinders and by testing 3x6 in. cores taken from the beams. The compressive strength of the mixes was tested at 1, 3, 7, 28 and 56 days according to ASTM C39 specifications. The average of four cylinders was reported at each time period for every mix. Figure 12 shows the mean compressive strength achieved by all mixes used in casting of the beams at different ages. Differences in strength as well as SCC qualities were mainly attributed to differences in adsorbed water on the aggregate.

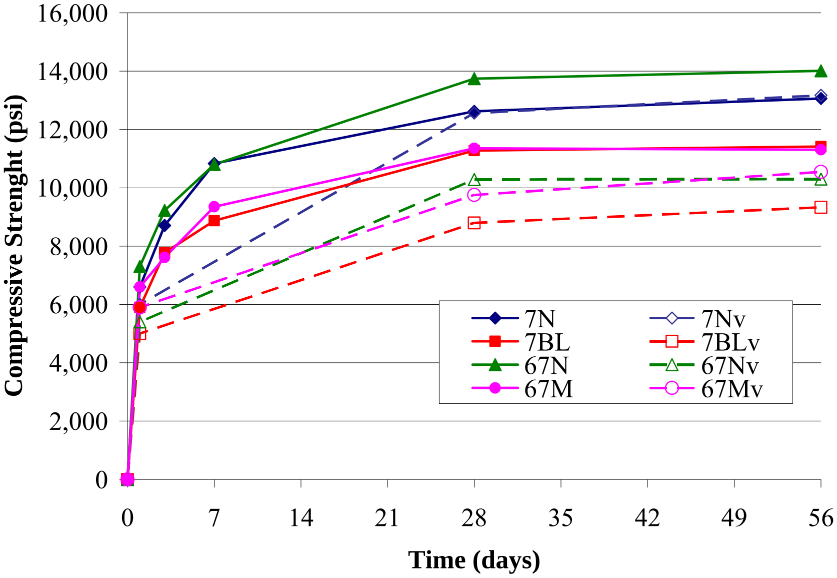

Figure 12. Compressive strength for 4x8-in. control cylinders, ASTM curing.

Nine 3-in. diameter cores were taken from the web of each beam in order to evaluate the in-place properties of the SCC. The surface of the cores mirrored the surface finish of the beams. The coefficient of variation (COV) of the compressive strength of the cores within a given beam varied among the mixes, but all remained below 9.5% indicating a good reproducibility of the test results. The majority of the mixes displayed a COV that ranged in between 4.6% and 6.4%, including 67M and 67Mv (Mix 5). The compressive strengths are given in Figure 13. Difference in the water-cementitious materials ratio (w/cm) was determined to be the main cause of differences between the SCC of the beams. There was not a statistically significant difference within any single beam.

No significant differences were observed between the strength of cores and laboratory cured cylinders, except for mixes 7N, 7Nv and 67N (Table 3). For these last three mixes, the cores' adjusted compressive strengths were about 15% weaker than the control cylinder strengths. The compressive strength of core sample from mixes 67M and 67Mv (Mix 5) was very similar to that of their control cylinders. This confirmed that proper consolidation was achieved by these mixes in the upper areas of the beams, where less congested reinforcement was present.

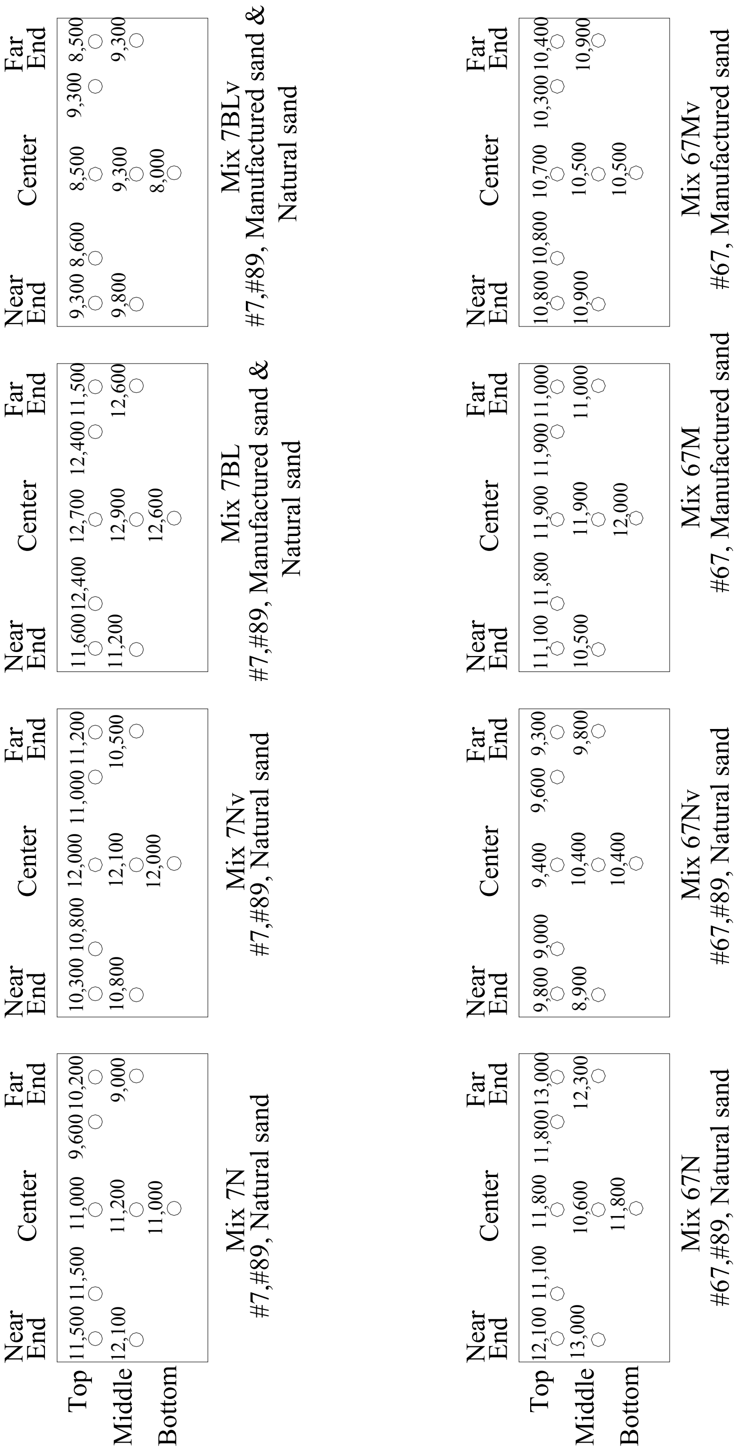

Figure 13. Compressive strength of individual cores taken from the eight beams.

Table 3. Comparison of average compressive strength at 56 days of control cylinders versus core samples* of SCC beams

Mix	4x8 in. Control cylinders (psi)	3x6 in. Cores (psi)	Cores/Control
7N	13,000	10,600	81.5%
7Nv	13,200	11,000	83.3%
7BL	11,400	12,000	105.3%
7BLv	9,300	8,800	94.6%
67N	14,000	11,800	84.3%
67Nv	10,300	9,500	92.2%
67M	11,300	11,200	99.1%
67Mv	10,600	10,500	99.1%

*3x6 in. core strength were adjusted to equivalent 4x8 in. cylinder strength by multiplying the strength by a factor of 0.98

Aggregate Distribution throughout Cross Sections. The beams were sawn vertically at three locations, two at 24 in. away from each end, and a third cut at mid-length. The cut closer to the casting point was defined as the "near end" surface; the cut at the opposite end was labeled "far end". A visual inspection of the sawn surfaces revealed no significant differences in the aggregate distribution for any of the beams, except mix 67M (Mix 5). No major variations were observed between top and bottom areas of a given cross section (Figure 14), nor between near and far end surfaces. Also, no voids were observed around the reinforcement in any of the beams, except mix 67N and 67M, indicating very good consolidation of the concrete and no evidence of internal bleeding.

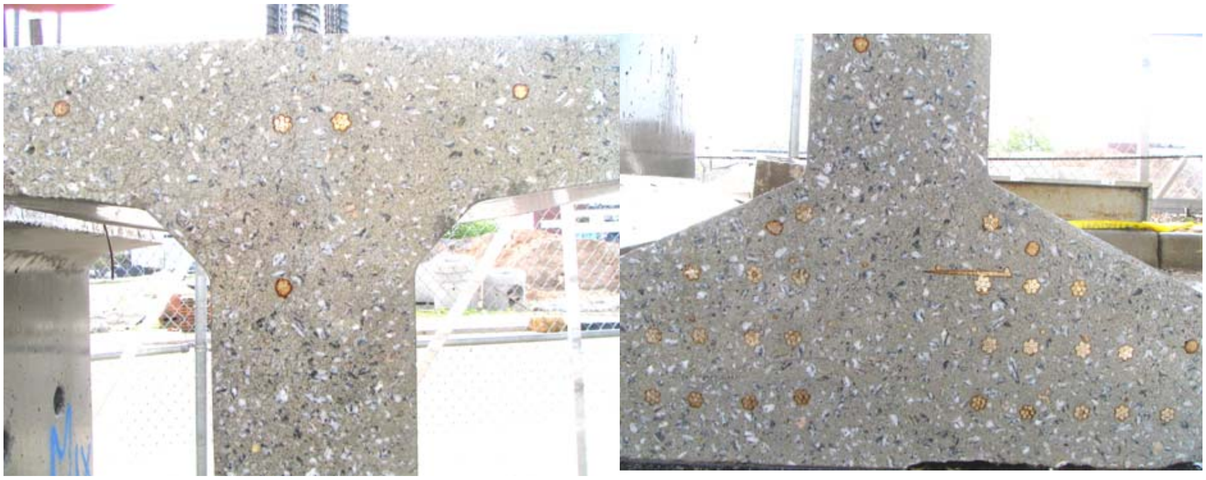

Figure 14. Far end cut of beam 7N top (left) and bottom (right).

However, Mixes 5, 67M and 67Mv, presented noticeable differences in coarse aggregate distribution throughout the beams. Although no perceptible differences were observed within a given sawn surface, considerable change in the aggregate-to-concrete area ratio was detected when comparing the near end surface with the far end surface. Coarse aggregate at the near end surface occupied a larger percentage of the area of the bottom flange of the beam, and a similar amount was present at the middle surface of the beams. However, the bottom flange at the far end surface showed a considerable reduction of the area occupied by the aggregate.

Every beam cross-section was divided into five regions, top and bottom flanges, and three 18-in. long regions in the depth of the web. The regions were labeled and studied using a Digital Image Analysis (DIA) method.[10] Figure 15 illustrates the results obtained for aggregate distribution from the DIA for every beam. The theoretical value for the coarse aggregate-to-concrete ratio of the mixes by volume was 32.7%, except for mixes 67N and 67Nv (Mix 2) which was 31.5%.

The general trend found with the DIA method was that the greatest differences in percentage of aggregate were between the bottom flange at the near end and the top flange at the far end. The maximum COV within a beam was 9.4% for mix 67M (Mix 5 not vibrated), which was greater than the required 6% specified in ASTM C94 for uniformity of the concrete. For the rest of the beams, the COV remained around 3.5%, except for mix 7N that showed a COV equal to 6%.

The quantitative results obtained in the DIA corresponded with the qualitative visual inspection of the sawn surfaces. No significant aggregate segregation was found in the studied cross-sections, except for those of mixes 67M and 67Mv (Mix 5). For the beams where no segregation was observed, the maximum difference obtained between the theoretical and in-place aggregate percentage was 4.6%, which is about equal to the COV obtained for these beams.

In general, the aggregate-to-concrete ratio was lower at the far end than at the near end. Also, the ratio was lower at the top than at the bottom. These two trends showed that there was some, though slight, aggregate segregation as the SCC flowed from near end to far end and as it filled the beam from bottom to top. The difference within a column or level was less than the COV.

	Near End	Center	Far End
TF	30.7%	27.9%	24.0%
TW	29.2%	27.8%	26.4%
MW	28.1%	28.6%	26.3%
BW	29.3%	29.7%	28.7%
BF	29.5%	30.1%	28.6%

Mix 7N

	Near End	Center	Far End
TF	29.6%	28.7%	29.1%
TW	29.7%	29.3%	30.8%
MW	29.5%	29.3%	30.2%
BW	31.6%	31.7%	29.2%
BF	32.4%	31.65	30.7%

Mix 7Nv

	Near End	Center	Far End
TF	32.4%	29.2%	30.9%
TW	31.4%	29.8%	30.4%
MW	32.1%	30.0%	30.5%
BW	32.5%	30.8%	30.8%
BF	32.3%	31.9%	31.2%

Mix 7BL

	Near End	Center	Far End
TF	30.0%	32.3%	31.2%
TW	31.9%	31.7%	31.8%
MW	32.2%	31.8%	31.3%
BW	32.3%	32.1%	32.8%
BF	32.2%	32.7%	32.6%

Mix 7BLv

	Near End	Center	Far End
TF	28.7%	28.9%	27.4%
TW	27.9%	29.5%	27.7%
MW	28.7%	30.2%	28.1%
BW	29.3%	30.0%	29.6%
BF	30.9%	30.5%	30.0%

Mix 67N

	Near End	Center	Far End
TF	29.4%	26.9%	28.1%
TW	29.6%	29.6%	29.2%
MW	30.3%	29.5%	29.7%
BW	30.5%	30.3%	30.7%
BF	30.6%	29.8%	30.9%

Mix 67Nv

	Near End	Center	Far End
TF	31.5%	30.4%	26.2%
TW	32.8%	30.7%	26.3%
MW	32.5%	31.8%	23.6%
BW	32.8%	28.7%	29.3%
BF	32.5%	32.4%	29.1%

Mix 67M

	Near End	Center	Far End
TF	31.1%	28.9%	28.4%
TW	31.2%	30.7%	30.4%
MW	30.3%	29.7%	31.0%
BW	30.4%	30.8%	30.1%
BF	32.5%	31.1%	32.4%

Mix 67MV

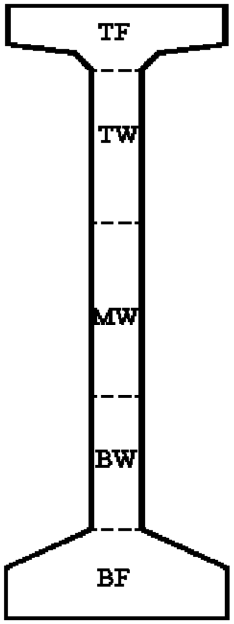

Figure 15. Aggregate distribution for SCC beams, aggregate-to-total concrete area ratio.

DISCUSSION

The mock-up tests using the wall panels and using the PCI BT-72 sections showed the same general results; they were separated and used different mix designs because the two plants used different aggregate sources and different admixture manufacturers. The use of either Type I (walls) or Type III (BT-72) cement did not significantly influence the flowability or passing ability of the mixes. Different supplementary cementitious materials (SCMs) were used with no significant differences in flow and filling ability of the SCC mixes depending on the type or percentage of SCM employed. That is, the slag and slag-Class F fly ash mixtures in the walls worked as well as the just the Class C ash used in the BT-72 sections. Initial and final compressive strengths were dependent on the water content (w/cm ratio) and not on the class of fly ash or whether slag or fly ash was the SCM used.

The size and gradation of the aggregates were considered the most important factors affecting the performance of SCC mixes. Not only the individual gradation of each aggregate, but the combined gradation of both coarse and fine aggregates should be taken into account when designing a workable SCC mix. Figure 16 illustrates the gradation by weight retained of selected mixes. Mixes with a good performance in wall panels and beams were represented in solid lines, while those mixes with poor performance were represented in dashed lines.

The mixes with the best plastic performance showed a lower percentage of stones retained on large size sieves, such as ¾-in. (19 mm) and ½-in. (13 mm), than those mixes with a poor performance. This was intuitive: the larger the size of the stone used, the greater the blockage potential of the mix when flowing through congested reinforcement. In addition, larger stones are likely more susceptible to segregation, as evidenced by the DIA data for mixes with larger MSA coarse aggregate, such as Mix 67M.

Also, the workable mixes displayed a more uniform gradation of the fine aggregate, with a maximum difference of 7% between the weight of aggregates retained on sieve No. 16 and that retained on sieve No. 50. This uniform gradation was not achieved by the W-3 (T-Cement) mix, which displayed large gaps for both coarse and fine aggregates and which corresponded with its poor performance in field applications. Poor performing Mix 67M showed similar uniform fine aggregate gradation as that of good performance mixes; yet, it slightly differed with those in its coarse aggregate gradation, demonstrating the importance in limiting the maximum aggregate size to produce good quality SCC.

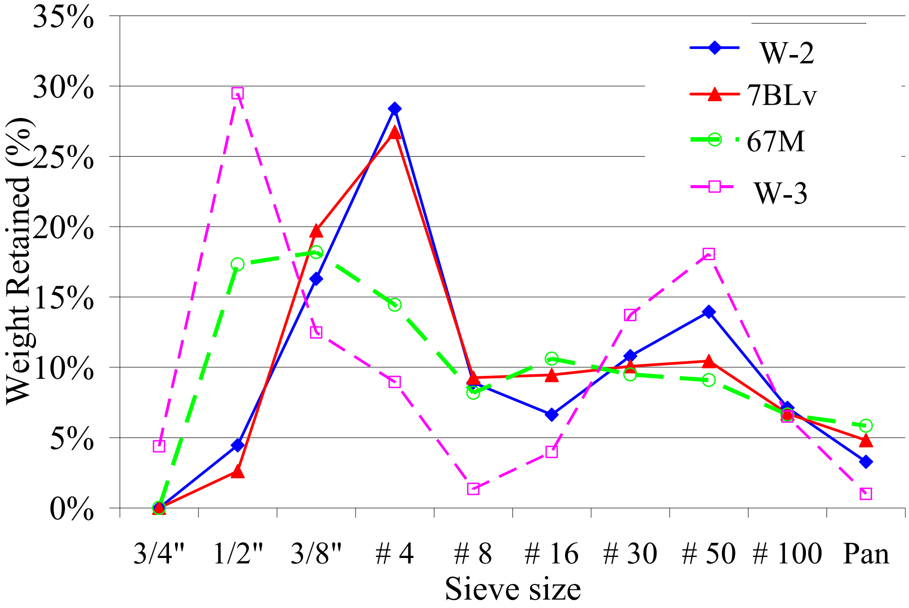

Figure 16. Gradation comparison of mixes with good performance (solid lines) versus mixes with poor performance (dashed lines)

Indicators proposed by Ramage et al.[8] for good stability and self-consolidating abilities of SCC, including fresh VSI numbers between 0 and 1, slump flow spread between 22 and 28 in. (560 to 711 mm), and over 85% H_2/ H_1 in the U-flow test, agreed with the results of good quality SCC mixes in field applications; yet, those measurements were not sufficient for predicting a mix's performance in congested sections.

As an example, trial batches at Standard Concrete Products (SCP) Atlanta plant of a mix with only #67 stone as coarse aggregate and manufactured sand as fine aggregate (Mix 5, mixes 67M and 67Mv), showed very good results in fresh state testing. Nevertheless, casting of BT-72 mock-up beam sections using these mixes produced honeycombing and multiple air-voids in the surface finish of the beams.

Evidence from this research and other research by Horta[10] would indicate that the performance of bridge girders made with SCC would be the same as girders made from normal concrete of the same strength.

CONCLUSIONS

The acceptance criteria for SCC mixes are dependant on the specific application, and not on fixed parameters of mix proportions or levels of workability of the mix. Performance criteria of the structural component rather than mix design and fresh state testing criteria should be considered when assessing the quality of SCC mixes.

The maximum size and combined gradation of the aggregates were considered the most important factors affecting the performance of SCC mixes. Good quality SCC mixes used a blend of coarse and fine aggregates, which created a more uniform aggregate gradation than those mixes using a single type of stone. The good mixes included a blend of #7 (1/2-in.) stone and #89 (3/8-in.) stone, and also a blend of fine aggregates including natural and manufactured sand. The use of #67 (3/4-in.) stone was proven to be inappropriate when the clear distance between reinforcement was 1.5 in. or less. Aggregate segregation and honeycombing was apparent when this type of mix was used in the end-wall panels and BT-72 beam sections.

The five seconds of external vibration on the forms did not change the external surface finish as compared to samples with no vibration. Whether further vibration would improve surface finish or cause segregation is unknown.

While the use of aggregate gradation and standard slump flow, L-box and U-box tests are recommended for development of good SCC mix designs, construction and inspection of mock-up, prototype samples is required to assure a good quality constructed product. Digital image analysis methods may also be used to quantitatively assess the quality of in-place SCC. Highly congested reinforcement in deep sections proved a difficult test for SCC which passed the standard laboratory type evaluations.

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