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Properties of Self-Consolidating Concrete for Prestressed Members

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Self-consolidating concrete (SCC) mixtures for use in prestressed concrete applications are evaluated in this paper. Twenty-one SCC mixtures were made under laboratory conditions with varying water-to-cementitious materials ratios, sand-to-total aggregate ratios, and cementitious material combinations (Type III cement, Class C fly ash, ground-granular blast-furnace slag, and silica fume). The SCC mixtures achieved prestress transfer compressive strengths between 5470 and 9530 psi (38 and 66 MPa). The moduli of elasticity of the SCC mixtures were in reasonable agreement with the elastic stiffness assumed during the design of conventional-slump concrete structures. The long-term drying shrinkage strain for all the SCC mixtures were approximately the same or less than those measured for the control mixtures. A change in sand-to-total aggregate ratio had no significant effect on the long-term drying shrinkage. At later ages of 56 and 112 days, the measured drying shrinkage corresponded reasonably well to those predicted by the ACI 209 procedure.

Keywords: modulus of elasticity; prestressed concrete; shrinkage; strength.

INTRODUCTION

ACI Committee 237[1] defines self-consolidating concrete (SCC) as "highly flowable, nonsegregating concrete that can spread into place, fill the formwork, and encapsulate the reinforcement without any mechanical consolidation." Contractors are currently exploring the use of SCC because it may produce members with homogeneous quality even in highly congested, narrow members such as prestressed concrete members. The use of SCC may also decrease construction costs due to the reduced number of laborers required to place SCC. Producers in Alabama have experienced many consolidation and finish problems with the use of conventional-slump girder mixtures. Although SCC should mitigate these problems, the Alabama Department of Transportation (ALDOT) has not yet allowed the use of SCC for prestressed girder applications, mainly due to a lack of standardized test procedures and performance data, as well as uncertainty regarding the applicability of current design procedures to members made with SCC. The performance of SCC in prestressed concrete applications has thus far ranged from acceptable[2] to problematic.[3]

It has been reported that the aggregate content and properties affect the magnitude of the modulus of elasticity E_c.[4-6] Bonen and Shah[6] report that because SCC typically has a lower coarse aggregate content than conventional-slump concrete, E_c will be lower for SCC than for conventional-slump concrete of the same strength. Because SCC contains less coarse aggregate than conventional-slump concrete, especially in congested applications, it is important to evaluate the modulus of elasticity at prestress transfer E_{ci} for SCC developed for prestressed concrete applications.

Some prestress losses and long-term deflection changes experienced by prestressed concrete members are the direct result of shrinkage effects.[5] Shrinkage is a paste property, and the aggregate is the most influential restraint on the change in volume within the paste.[4,7] At a constant water-cement ratio (*w/c*), shrinkage increases with an increase in cement content because of the increased volume of hydrated cement paste.[4] In turn, if the water content is held constant and the cement content is increased, the amount of shrinkage can be reduced because the higher strength paste is more able to resist shrinkage.[4] Neville[4] also states that while the size and grading of the aggregate do not have a significant influence on the shrinkage, increasing the maximum aggregate size allows for a leaner mixture, thus reducing the amount of shrinkage. Ozyildirim and Lane[8] recommend a large nominal maximum aggregate size, large amount of coarse aggregate, and low water content to mitigate high drying shrinkage in SCC applications. In congested prestressed concrete applications, however, increasing the nominal maximum size aggregate diminishes the desired filling ability and passability of SCC. According to ACI Committee 209,[9] drying shrinkage increases with an increase in sand-to-total aggregate ratio (*S/Agg*). Thus, it is important to evaluate the drying shrinkage of SCC for use in prestressed concrete applications. For this study, an experimental plan was developed to evaluate some of the hardened properties (at prestress transfer and later ages) of SCC that affect the performance of prestressed members. SCC mixtures were developed to evaluate the effect of the following variables: water-to-cementitious material ratio (*w/cm*), *S/Agg*, and different cementitious material combinations. In this paper, the properties of the SCC mixtures are compared with properties of conventional concrete girder mixtures and those estimated by current design provisions. Cylinders were match-cured in the laboratory to a temperature history that is typical of prestressed concrete operations in the southeastern U.S. Shrinkage prisms were used to evaluate the effect of the test variables on drying shrinkage. The correlation between the modulus of elasticity and compressive strength is evaluated and compared to the predictive equation of ACI 318,[10] which is the same as prescribed in the *AASHTO LRFD Bridge Design Specification*[11] (hereafter called AASHTO LRFD). The drying shrinkage of the SCC is compared with that measured for the control mixtures and to values estimated by applying the well-established predictive models of ACI 209R[9] and AASHTO LRFD.[11]

The primary objectives of the work documented in this paper are as follows:

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- Develop and evaluate SCC mixtures for use in prestressed concrete applications;
- Evaluate the effect of various SCC mixture proportions on the fresh properties of SCC;
- Evaluate the effect of SCC on the strength and modulus of elasticity at prestress transfer; and
- Evaluate the effect of various SCC mixture proportions on the shrinkage behavior of the concrete.

RESEARCH SIGNIFICANCE

The use of SCC may help precast/prestressed plants to produce high-quality prestressed concrete members at reduced labor costs. Concerns about the effects of SCC proportions on hardened properties have limited the widespread use of SCC in precast/prestressed concrete applications. SCC mixtures for use in prestressed concrete applications are evaluated in this paper. Cylinders were match cured to a temperature history that is typical of prestressing operations. This paper provides guidance on the effects that changes in *S*/*Agg* and *w*/*cm* have on properties that could have a major impact on the performance of prestressed concrete members.

EXPERIMENTAL WORK

Industry requirements

Materials local to the Alabama concrete industry were used to produce SCC mixtures to satisfy the requirements of the prestressed concrete industry. A meeting was held in February 2004 between the research team and representatives of ALDOT, FHWA, the precast/prestressed industry, and the chemical admixture industry. The resulting decisions specifically influenced the work documented in this paper:

- Compressive strength at prestress transfer (f'_{ci})—SCC mixtures should be evaluated that have a f'_{ci} range of 5000 to 9000 psi (34 to 62 MPa) at an age of 18 to 21 hours;
- Slump flow requirement—A slump flow of 27 to 28 in. (685 to 710 mm) is desirable for prestressed concrete girders. Experimental SCC mixtures should be developed to have a slump flow at placement of 27 ± 3 in. (685 ± 75 mm). Slump flow ranges for quality control should be determined from field trials;
- Placement duration—Because concrete placement usually begins 15 minutes after water is added to the cement, slump flow values should be evaluated at this time;
- Total air requirements—For the purpose of this project, SCC mixtures should be designed to have a total air content of 4% ± 1%. ALDOT currently requires this total air content for all prestressed concrete mixtures; and
- Control mixture—A conventional-slump concrete mixture with f'_{ci} of approximately 5500 psi (38 MPa) should be used as a control mixture.

Table 1—Experimental plan with mixture identification numbers

Cementitious material types	Sand/aggregate (by volume)	*w*/*cm*			
		0.28	0.32	0.36	0.40
Type III cement + 30% Class C fly ash	0.38	SCC-1	SCC-2	SCC-3	—
	0.42	SCC-4	SCC-5	SCC-6	—
	0.46	SCC-7	SCC-8	SCC-9	—
Type III cement + 30 to 50% Grade 120 GGBF slag	—	(30% slag)	(40% slag)	(50% slag)	—
	0.42	SCC-10	SCC-11	SCC-12	—
	0.46	SCC-13	SCC-14	SCC-15	—
Type III cement + 22% Class C fly ash + 8% silica fume	0.42	—	SCC-16	SCC-17	SCC-18
	0.46	—	SCC-19	SCC-20	SCC-21

Materials and mixtures used

Twenty-one SCC mixtures and two conventional-slump mixtures were produced for this study. The experimental factorial for all SCC mixtures and the mixture identification numbers are summarized in Table 1. The mixture proportions for all the mixtures are listed in Table 2. Polycarboxylate-based mid-range and high-range water reducing (HRWR) admixtures were used. All mixtures were made with a No. 78-graded (ASTM C 33), crushed dolomitic limestone. The use of Class C fly ash was selected over Class F fly ash, because Class C fly ash is commonly used in the Alabama prestressed concrete industry. Class C fly ash mixtures typically produce more consistent total air contents and higher early-age strengths as compared with mixtures that contain similar dosages of Class F fly ash. The effects of the following variables were evaluated: *w*/*cm* of 0.28, 0.32, 0.36, and 0.40; *S*/*Agg* (by volume) of 0.38, 0.42, and 0.46; and different cementitious material combinations that included the use of Type III cement with 30% Class C fly ash, with 30 to 50% ground-granulated blast-furnace (GGBF) slag, and a ternary blend with 22% Class C fly ash and 8% silica fume. The cement replacement dosages were determined on a mass basis. The following main properties of the cementitious materials were determined by a commercial testing laboratory:

- Type III cement—50.16% tricalcium silicate (C_3S), 19.52% dicalcium silicate (C_2S), 7.34% tricalcium aluminate (C_3A), 11.81% tetracalcium aluminoferrite (C_4AF), 0.27% $Na_2O + 0.658K_2O$, a Blaine specific surface area of 505 m^2/kg, and a specific gravity of 3.15;
- Class C fly ash—24.12% calcium oxide (CaO) and 37.59% silicon dioxide (SiO_2), a Blaine specific surface area of 320 m^2/kg, and a specific gravity of 2.63;
- Grade 120 GGBF slag—Calcium oxide (CaO) of 45.32%, Silicon dioxide (SiO_2) of 32.68%, Blaine specific surface area of 570 m^2/kg, and a specific gravity of 2.91; and
- Densified silica fume—95.57% silicon dioxide (SiO_2) and a specific gravity of 2.30.

SCC mixture proportions were designed to include a viscosity-modifying admixture (VMA) with a maximum *S*/*Agg* of 0.46. The 0.46 limit on the *S*/*Agg* was deemed

Table 2—Mixture proportions

Mixture ID	Water, lb/yd^3	Cement, lb/yd^3	Fly ash, lb/yd^3	GGBF slag, lb/yd^3	Silica fume, lb/yd^3	Coarse aggregate, lb/yd^3	Fine aggregate, lb/yd^3	AEA, oz/cwt	Mid-range WRA, oz/cwt	HRWRA, oz/cwt	VMA, oz/cwt
CTRL-1	260	705	0	0	0	1942	1102	3.00	4.0	6.0	0.0
CTRL-2	270	640	0	0	0	1964	1114	0.33	4.0	5.0	0.0
SCC-1	260	650	279	0	0	1756	1035	0.80	4.0	5.0	2.0
SCC-2	265	580	248	0	0	1807	1065	0.30	4.0	5.0	2.0
SCC-3	270	525	225	0	0	1848	1089	0.35	4.0	5.5	2.0
SCC-4	260	650	279	0	0	1643	1143	0.80	4.0	6.0	2.0
SCC-5	265	580	248	0	0	1690	1177	0.35	4.0	5.5	2.0
SCC-6	270	525	225	0	0	1726	1201	0.00	4.0	7.5	2.0
SCC-7	260	650	279	0	0	1529	1252	0.80	4.0	6.0	2.0
SCC-8	265	580	248	0	0	1574	1289	0.35	4.0	6.0	2.0
SCC-9	270	525	225	0	0	1607	1316	0.40	4.0	6.0	2.0
SCC-10	260	650	0	279	0	1659	1155	3.25	6.0	7.5	2.0
SCC-11	265	497	0	331	0	1702	1185	2.25	6.0	5.5	2.0
SCC-12	270	375	0	375	0	1733	1206	1.50	6.0	5.5	2.0
SCC-13	260	650	0	279	0	1544	1265	3.75	6.0	7.0	2.0
SCC-14	265	497	0	331	0	1584	1297	2.30	6.0	5.5	2.0
SCC-15	270	375	0	375	0	1613	1321	1.50	6.0	5.5	2.0
SCC-16	265	580	182	0	66	1686	1173	0.10	6.0	8.5	0.0
SCC-17	270	525	165	0	60	1721	1198	0.04	6.0	8.5	0.0
SCC-18	275	482	151	0	55	1748	1217	0.00	7.5	7.0	0.0
SCC-19	265	580	182	0	66	1569	1285	0.10	6.0	8.5	0.0
SCC-20	270	525	165	0	60	1603	1312	0.02	6.0	9.0	0.0
SCC-21	275	482	151	0	55	1627	1333	0.00	10.0	5.0	0.0

Notes: AEA = air-entraining admixture; WRA = water-reducing admixture; VMA = viscosity-modifying admixture; HRWRA = high-range water-reducing admixture; 1 yd^3 = 0.765 m^3; 1 lb/yd^3 = 0.593 kg/m^3; 1 fl oz = 29.57 mL.

sufficiently high for SCC designed specifically for prestressed concrete applications. The main concern was that higher *S/Agg* might lead to decreased modulus of elasticity, as well as increased creep and drying shrinkage, three factors that greatly affect prestress losses as well as member deflections. The proportions of the first conventional-slump mixture (CTRL-1) are routinely used for the manufacture of prestressed girders; this mixture was developed during a past high-performance concrete study at Auburn University.[12] Mixture CTRL-1 has a w/c of 0.37 and a *S/Agg* of 0.37. Strengths obtained after 18 hours of match curing revealed that this mixture had a f'_{ci} of 7480 psi (52 MPa). Because this strength was significantly higher than the target of 5500 psi (38 MPa), the w/c of this mixture was increased to 0.42 to produce a second conventional-slump mixture, Mixture CTRL-2. The 18-hour f'_{ci} of Mixture CTRL-2 was 6280 psi, which was deemed appropriate for comparison to the SCC mixtures. Mixture CTRL-2 is thus used for comparison purposes based on the assumption that mixtures should be compared at comparable f'_{ci} and water content, and not equivalent w/cm.

Each SCC mixture was made with the proportions indicated in Table 1. Adjustment to the HRWR admixture dosage was necessary to obtain a slump flow range between 24 and 30 in. (610 and 760 mm). The air-entraining admixture dosage also required adjustment to keep the total air content within the quality control range of 3 to 5%. Some specific adjustments are discussed in the Results section.

Mixing procedures

Different mixing procedures were evaluated to determine the most efficient procedure to introduce the cementitious materials and chemical admixtures. Applying the recommendations of cementitious material and chemical admixture representatives, trial batches were employed to determine the best mixing procedure for each cementitious material combination. Mixing procedures that do not meet the requirements of ASTM C 192 were used. The laboratory mixing procedure outlined in ASTM C 192 did not allow the HRWR admixtures to be as effective as the modified procedures outlined in the following.

The following laboratory mixing procedure was found to produce reliable results for the fly ash and GGBF slag SCC mixtures:

1. Butter the mixer with a representative w/cm mortar;
2. Add 80% of mixing water;
3. Add all the fine and coarse aggregate;
4. Add the air-entraining admixture and mix for 1 minute;
5. Add all cementitious materials and remaining mixing water;
6. Mix the concrete for 2 minutes;
7. Add all HRWR admixtures and VMA (if necessary) and mix for 3 minutes;
8. Stop mixing and rest for 3 minutes;
9. Mix concrete for 2 minutes;
10. Stop mixing and test the slump flow;
11. If the slump flow is too low, add more HRWR admixtures, mix for 3 minutes, and re-test the slump flow. Add HRWR admixture until the target slump flow is reached; and
12. Once the target slump flow has been reached, perform remaining quality control tests and cast all specimens for hardened property tests.

When the aforementioned mixing procedure was applied to the ternary mixtures with densified silica fume, excessive (>10%) total air contents were obtained. Representatives of the Silica Fume Association indicated that longer mixing times are required to disperse the conglomerates of densified silica fume particles before the addition of all other cementitious materials. The mixing procedure outlined previously was thus modified by adding the silica fume to all the aggregates (Step 3), and then these materials were mixed for 5 minutes. After 5 minutes of mixing, the air-entraining admixture was added and the remaining procedure (Steps 5 to 12), as outlined previously, was followed. This modification successfully resulted in SCC mixtures that repeatedly had total air contents within the required range of 3 to 5%.

Curing procedures

Four-by-eight in. (100 x 200 mm) cylinders were match-cured to a temperature history that is typical of prestressed concrete operations in the southeastern U.S. The target match-curing profile required a 4-hour preset period at 73 °F (22.8 °C), then the concrete was heated at a rate of 20 °F/hour (11.1 °C/hour) until 150 °F (65.6 °C) was reached. The temperature of 150 °F (65.6 °C) was reached at a concrete age of approximately 8 hours, and this temperature was held until an age of 24 hours. After 24 hours, all the remaining specimens were stripped and placed in a moist-curing room that was maintained at 73 °F (22.8 °C). With this curing profile, f'_{ci} and E_{ci} could be determined at 18 and 21 hours. All 6 x 12 in. (150 x 300 mm) cylinders were made under laboratory conditions, stripped after 24 hours, and placed in a moist-curing room that was maintained at 73 °F (22.8 °C).

Tests conducted

Slump flow, T-50, and visual stability index (VSI) tests were performed to characterize the fresh properties of the SCC. The slump flow is a measure of the filling ability, or how far the concrete will flow into the formwork. The T-50 is the time that it takes the concrete to reach a slump flow 20 in. (50 cm) and provides an indication of the viscosity of the mixture. The VSI is a subjective visual assessment of the dynamic stability of the slump flow patty.[13] Because no standardized test procedures were available, all these tests were performed as outlined in the Interim PCI Guidelines for SCC.[14] The slump flow, T-50, and VSI were assessed just prior to fabrication of all test specimens, approximately 15 minutes after mixing was started. The total air content, unit weight, and fresh concrete temperature were also collected. The slump flow was tested with the slump cone in the inverted position. This test configuration was used because it is easily performed by one technician and has been found to produce similar slump flow results as when the cone is used upright.[15] Note that T-50 times are increased when the slump cone is used in the inverted position. Specimens were made for the following tests:

Compressive strength development (ASTM C 39)—

- 4 x 8 in. (100 x 200 mm) match-cured cylinders. Two cylinders were tested at 18 hours, 21 hours, 7 days, and 28 days.
- 6 x 12 in. (150 x 300 mm) moist-cured cylinders. Three cylinders were tested at 3, 7, 28, and 56 days.

Modulus of elasticity development (ASTM C 469)—

- 4 x 8 in. (100 x 200 mm) match-cured cylinders. Two cylinders were tested at 18 hours, 21 hours, 7 days, and 28 days.
- 6 x 12 in. (150 x 300 mm) moist-cured cylinders. Three cylinders were tested at 3, 7, 28, and 56 days.

Drying shrinkage development (ASTM C 157)—

- 3 x 3 x 11.25 in. (75 x 75 x 286 mm) prisms were cured in a lime-bath for 7 days prior to drying. Length change readings were recorded on three prisms at drying ages of 1, 2, 3, 4, 7, 14, 28, 56, and 112 days.

Table 3—Summary of fresh concrete properties

Mixture ID	Slump flow, in.	T-50, seconds	VSI	Total air, %	Unit weight, lb/ft^3	Temperature, °F
CTRL-1	9.5*	—	—	3.0	151.5	76
CTRL-2	9.0*	—	—	3.8	148.8	—
SCC-1	28.0	5.3	1.5	3.8	151.7	75
SCC-2	29.0	4.2	1.0	3.0	151.8	76
SCC-3	27.5	2.8	1.0	4.3	148.5	81
SCC-4	29.0	5.5	1.5	3.2	150.9	76
SCC-5	28.5	5.4	1.5	3.9	150.4	78
SCC-6	26.0	2.8	0.5	2.7	150.9	69
SCC-7	29.0	5.3	1.5	3.0	151.2	77
SCC-8	29.0	2.7	1.5	4.6	148.0	76
SCC-9	27.75	3.3	1.5	4.7	148.0	74
SCC-10	28.0	13.4	1.5	3.0	152.0	76
SCC-11	28.0	12.3	1.0	3.4	150.0	76
SCC-12	28.0	5.1	1.0	3.8	148.5	83
SCC-13	29.0	13.0	1.0	3.6	150.3	76
SCC-14	27.0	11.5	1.0	3.9	148.4	76
SCC-15	27.75	4.1	2.0	4.8	146.6	76
SCC-16	27.0	4.3	1.0	3.3	149.8	71
SCC-17	26.5	3.0	1.5	5.3	146.2	71
SCC-18	26.5	3.7	1.5	3.8	147.8	73
SCC-19	26.5	5.6	0.5	4.1	148.6	72
SCC-20	26.0	3.4	1.5	4.2	147.9	72
SCC-21	26.0	2.6	0.5	2.5	149.2	74

*Conventional slump test results.

Notes: 1 in. = 25.4 mm;1 lb/ft^3 = 16.02 kg/m^3; °F = 1.8 °C + 32.

RESULTS AND DISCUSSION

Fresh properties

The fresh properties are summarized in Table 3. The slump flow, after approximately 15 minutes of mixing, ranged between 26.0 and 29.0 in. (660 and 735 mm). It may be seen that the T-50 times, which provide an indication of the relative viscosity of the SCC,[13] increase with a decrease in the *w/cm*. This is in agreement with results found in previous research.[13] The increase in viscosity will help to minimize the risk of segregation during and after placement. The fresh properties also show that most of the mixtures had a VSI between 1.0 and 1.5, indicating that these mixtures should have adequate dynamic stability. The dynamic and static stability of some of these SCC mixtures should be evaluated during placement of full-scale, plant-cast members.

Adjustment of the chemical admixture dosages was required to achieve the desired air content and slump flow. Increased dosage of HRWR admixture was required for the GGBF slag and ternary mixtures to obtain the required slump flow. The required amount of air-entraining admixture was significantly affected by the cementitious material type, the dosage of HRWR admixture, the *w/cm*, and the mixing sequence. For each cementitious material combination, larger dosages of air-entraining admixture were required as the *w/cm* was decreased. Increased HRWR admixture dosages generally tended to increase the total air content of the SCC mixtures, and thus required a reduction in air-

Table 4—Summary of hardened concrete test results

Mixture ID	4 x 8 in. match-cured cylinder results								6 x 12 in. moist-cured cylinder results						Drying shrinkage strain, $\times 10^{-6}$	
	Compressive strength, psi				Modulus of elasticity, ksi				Compressive strength, psi			Modulus of elasticity, ksi				
	18 hour	21 hour	7 day	28 day	18 hour	21 hour	7 day	28 day	7 day	28 day	56 day	7 day	28 day	56 day	28 day	112 day
CTRL-1	7480	7880	9700	10,500	6100	5750	6850	7000	8880	10,250	11,190	7350	7250	7000	330	477
CTRL-2	6280	6310	7940	9550	5330	5300	6650	6500	7670	8850	9510	6150	7100	6500	353	520
SCC-1	9000	9110	10,970	12,410	5750	5100	6400	6848	10,660	12,510	13,080	6300	7000	7150	307	400
SCC-2	7000	7430	9540	11,760	4950	5450	6000	7100	9450	11,090	12,070	6150	7300	7150	297	382
SCC-3	5790	6490	7500	9220	5000	5250	5700	6500	8020	10,150	10,900	5450	6500	6700	293	440
SCC-4	8820	9410	10,520	12,700	5450	6050	6600	7400	11,390	13,600	14,080	6350	7050	7400	293	402
SCC-5	7140	7530	9220	10,490	5150	5350	6350	6650	9250	11,580	12,380	6200	7000	7600	343	432
SCC-6	5470	5750	7150	9110	4850	5100	5850	6250	7800	10,330	10,350	5650	6400	6900	422	475
SCC-7	8860	9580	10,950	12,520	5900	6050	6250	6350	11,060	13,300	13,930	6450	7350	7900	293	400
SCC-8	7780	7930	10,050	10,970	5200	6050	6350	6900	9290	11,550	12,100	5,75	6800	6850	357	482
SCC-9	5800	6100	7650	9280	4700	5000	5400	5900	7990	10,060	11,000	5650	6350	6650	420	470
SCC-10	8350	8470	10,020	10,510	5870	5950	7450	7750	9950	11,620	12,540	6950	7050	7200	330	423
SCC-11	7610	8120	8930	10,650	5430	5550	6200	7000	8850	10,750	11,260	5800	6950	7050	290	470
SCC-12	6490	6650	8610	9740	5350	5450	6100	6800	7660	9880	10,250	6000	6600	6800	327	415
SCC-13	8800	8950	9950	11,740	5750	5750	6650	7300	10,020	11,580	12,290	7200	7000	7100	290	420
SCC-14	7090	7430	8850	10,130	5150	5600	6100	6600	8350	10,390	10,690	5750	6500	6650	347	500
SCC-15	5780	6290	8060	8610	4800	4900	6100	6200	7360	8960	9570	5100	7000	6650	280	457
SCC-16	9470	9480	10,270	11,160	5600	5850	6850	6650	9370	12,240	13,390	6000	6850	6950	372	418
SCC-17	8310	8790	8860	10,090	5600	5900	6200	6200	8140	10,760	12,430	5450	6550	6850	410	445
SCC-18	6880	7420	8190	8840	5400	5550	6150	6200	7410	11,020	11,800	5700	6700	6800	398	415
SCC-19	9530	9700	10,700	11,060	5700	5900	6500	6850	9620	12,470	13,160	6000	6700	7000	377	460
SCC-20	8320	8570	9680	9840	5500	5650	6050	6100	8260	11,840	12,650	5800	6700	6800	437	480
SCC-21	7750	8000	8470	8600	5750	5700	5850	6200	7830	11,630	12,130	5850	6550	6750	373	390

Note: 1 psi = 6.89 kPa; 1 ksi = 6.89 MPa.

entraining admixture to meet the target air content. The GGBF slag SCC mixtures required much higher dosages of air-entraining admixture as compared to the other types of SCC mixtures.

Compressive strength

The compressive strength results are summarized in Table 4. The 18-hour f'_{ci} of the SCC mixtures varied between 5470 and 9530 psi (38 and 66 MPa), which slightly exceeded the target range of 5000 to 9000 psi (34 and 62 MPa). The two control mixtures had f'_{ci} values of 6280 and 7480 psi (43 and 52 MPa).

The effect of *S/Agg* on f'_{ci} is evaluated in Fig. 1 for all three supplementary cementing material (SCM) types relative to the results obtained for the control mixtures. *S/Agg* has little to no effect on f'_{ci}. From Table 4 it may also be concluded that the *S/Agg* has little to no effect on the long-term compressive strength.

In Fig. 1 it may be seen that for the same *w/cm*, f'_{ci} for the fly ash SCC mixtures is similar to the strength obtained from the GGBF slag SCC mixtures. At a *w/cm* of 0.36, f'_{ci} values of the fly ash and GGBF slag SCC mixtures are significantly less than that of the control mixture made with a *w/c* of 0.37 (CTRL-1). At a *w/cm* of 0.32, however, f'_{ci} values of the fly ash and GGBF slag SCC mixtures are approximately the same as for Mixture CTRL-1. Therefore, replacing Type III cement with high dosages of Class C fly ash or GGBF slag reduces the f'_{ci} of SCC mixtures. Higher f'_{ci} values can be obtained by using a decreased *w/cm.* The ternary SCC mixtures exhibited higher f'_{ci} values at a given *w/cm* than the fly ash or GGBF slag SCC mixtures. The effect of *w/cm* on f'_{ci} of the ternary SCC mixtures matches that obtained for the two control mixtures. The introduction of 8% silica fume thus significantly increased f'_{ci} of the SCC mixtures that contained only Type III cement and Class C fly ash.

Modulus of elasticity

The modulus of elasticity E_c results are summarized in Table 4. Eighteen-hour E_{ci} values of the SCC mixtures ranged from 4700 to 5900 ksi (32 and 41 GPa), while the two control mixtures had E_{ci} values of 5330 and 6100 ksi (37 and 42 GPa). Fifty-six-day E_c values of the SCC mixtures ranged from 6650 to 7600 ksi (46 and 52 GPa), while the two control mixtures had 56-day E_c values of 6500 and 7000 ksi (45 and 48 GPa).

The E_{ci} values for all the SCC mixtures are less than E_{ci} of the control mixture made with a *w/c* of 0.37 (CTRL-1). The E_c values of Mixture CTRL-1 will be compared to SCC Mixtures 2, 5, 8, 11, 14, 18, and 21 because these mixtures have f'_{ci} values within –4% to +6% of Mixture CTRL-1. These SCC mixtures have E_{ci} values between 6 to 19% less than Mixture CTRL-1; however, at 56-days, these SCC mixtures have E_c values within –9% to +5% of Mixture CTRL-1. Similarly, the E_c values of Mixture CTRL-2 will be compared with SCC Mixtures 3, 6, 9, 12, and 15 because these mixtures have f'_{ci} values within –3% to +13% of Mixture CTRL-2. These SCC mixtures have E_{ci} values between 0 to 12% less than Mixture CTRL-2; however, at 56-days these SCC mixtures have E_c values between 2 to 6% greater than Mixture CTRL-2. It may be concluded that the E_{ci} values of the SCC mixtures are less than that of the control mixtures with comparable f'_{ci}. At later ages of 56 days,

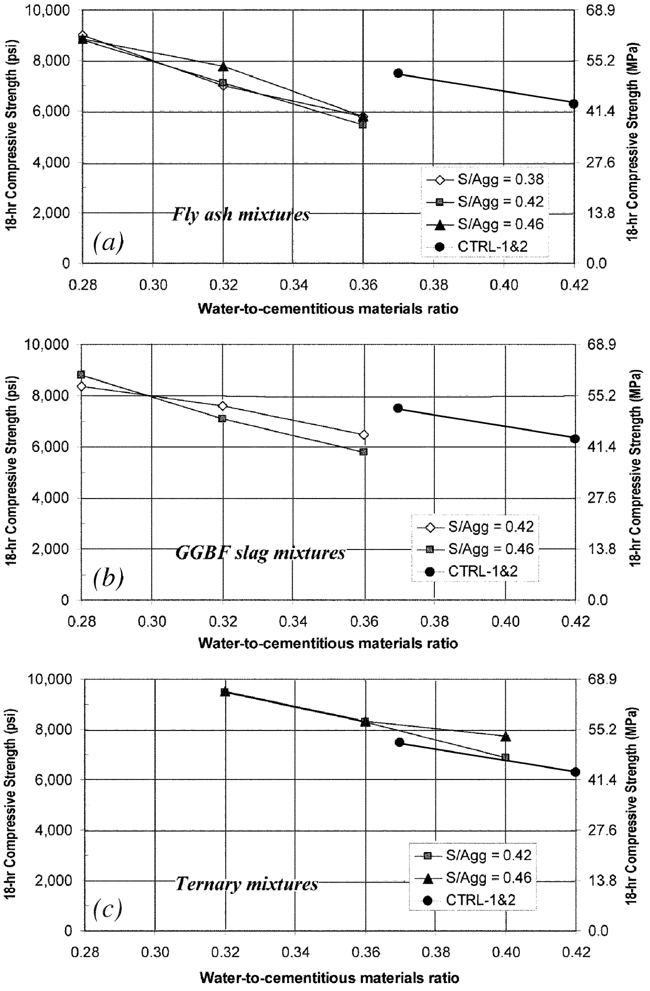

Fig. 1—Compressive strength values determined at release (18 hours): (a) fly ash mixtures; (b) GGBF slag mixtures; and (c) ternary mixtures.

however, the E_c values of the SCC mixtures are similar to that of the control mixtures with comparable f'_{ci}. The higher E_{ci} values of the control mixtures may be due to the use of only Type III cement.

The effect of *S/Agg* and *w/cm* on E_{ci} can be evaluated in Fig. 2 for each of the SCM types relative to the results for the control mixtures. E_{ci} of the control mixtures, as well as the fly ash and GGBF slag SCC mixtures, decreases with an increase in *w/cm*. Note that E_{ci} values of the ternary SCC mixtures are not affected by a change in *w/cm*. E_{ci} values for the ternary SCC mixtures are higher than the values obtained for the fly ash and GGBF slag mixtures. It may be seen in Fig. 2(b) that the *S/Agg* has a small effect on E_{ci} for the GGBF slag SCC mixtures. The GGBF slag mixtures with a *S/Agg* of 0.46 have a 2 to 12% lower E_{ci} than the mixtures with a *S/Agg* of 0.42. The *S/Agg* has no distinct effect on E_{ci} of the fly ash and ternary SCC mixtures. These findings are in agreement with those of Su et al.,[16] who evaluated the effect of *S/Agg* from 0.30 to 0.55 on E_c. They concluded that when the fine and coarse aggregate have comparable elastic moduli, and the total volume of aggregate is held constant, the *S/Agg* does not significantly affect the modulus of elasticity of the concrete.

Modulus of elasticity comparison with ACI 318 formulation—According to the ACI 318[10] Building Code, Section 8.5.1, E_c can be estimated using Eq. (1). This formulation is also used to estimate E_c with the AASHTO LRFD,[11] Section 5.4.2.4.

$$E_c = 33 w_c^{1.5} \sqrt{f_c} \qquad (1)$$

where E_c is the modulus of elasticity (psi), w_c is the unit weight of the concrete (lb/ft^3), and f_c is the compressive strength (psi).

To determine if the E_c values obtained for the SCC mixtures correspond to the behavior of conventional-slump concrete, the E_c values measured in this research are compared with those estimated by using the ACI 318 formulation in Fig. 3. The ACI 318 E_c formulation generally underestimates E_c of the SCC mixtures; however, the majority of the errors fall within the 0% to –10% error range. The E_c values of these SCC mixtures thus generally slightly exceed what one would estimate with the ACI 318 E_c formulation. The E_c values obtained for the SCC mixtures are in reasonable agreement with the elastic stiffness assumed during the design of conventional-slump concrete structures.

Drying shrinkage

The 28- and 112-day drying shrinkage strain ε_{SH} data are summarized in Table 4. Because the long-term shrinkage has the most impact on prestress losses and camber development in beams, only the magnitude of the shrinkage at 112 days will be evaluated in this paper. The 112-day ε_{SH} of the SCC mixtures varied between 382 and 500 microstrain while the two control mixtures had 112-day ε_{SH} values of 477 and 520 microstrain.

The effect of *S/Agg* on the 112-day ε_{SH} is evaluated in Fig. 4 for each of the three SCM types relative to the values measured for the control mixtures. The 112-day ε_{SH} for all the SCC mixtures are approximately the same or less than the 112-day ε_{SH} of both control mixtures. It may also be seen in Fig. 4 that there is no fixed trend in the change in 112-day ε_{SH} relative to a change in *S/Agg*. In the fly ash SCC mixtures made with a *w/cm* of 0.32, the 112-day ε_{SH} increases by up to 26% as the *S/Agg* is increased from 0.38 to 0.46. At a *w/cm* of 0.28 and 0.36, however, the *S/Agg* has no effect on the 112-day ε_{SH} of the fly ash SCC mixtures. In the case of the GGBF slag SCC mixtures, there is an increase of –1 to 10% in the 112-day ε_{SH} as the *S/Agg* is increased from 0.42 to 0.46. In the case of the ternary SCC mixtures, there is no specific trend in the change in 112-day ε_{SH} as the *S/Agg* is increased from 0.42 to 0.46. In all these cases, this change is reasonably small, and these mixtures exhibited a 112-day ε_{SH} that was similar to or less than that measured for the control mixture (CTRL-1) with a *S/Agg* of 0.38. From these results, it may be concluded that a change in *S/Agg* from 0.38 to 0.46 had no significant effect on the 112-day drying shrinkage strain of these SCC mixtures.

Drying shrinkage comparison with ACI 209R and AASHTO LRFD estimates—To determine if the ε_{SH} values obtained for the SCC mixtures correspond to behavior currently assumed during design, the ε_{SH} values collected in this research are compared to those estimated by ACI 209R[9] and AASHTO LRFD.[11] The ACI 209R drying shrinkage formulation accounts for the humidity, volume-to-surface ratio, fine aggregate percentage, slump, cement content, air content, curing method and duration, and age of the specimen. The water slump (slump prior to the addition of water-reducing admixtures) was used as the slump input in the ACI

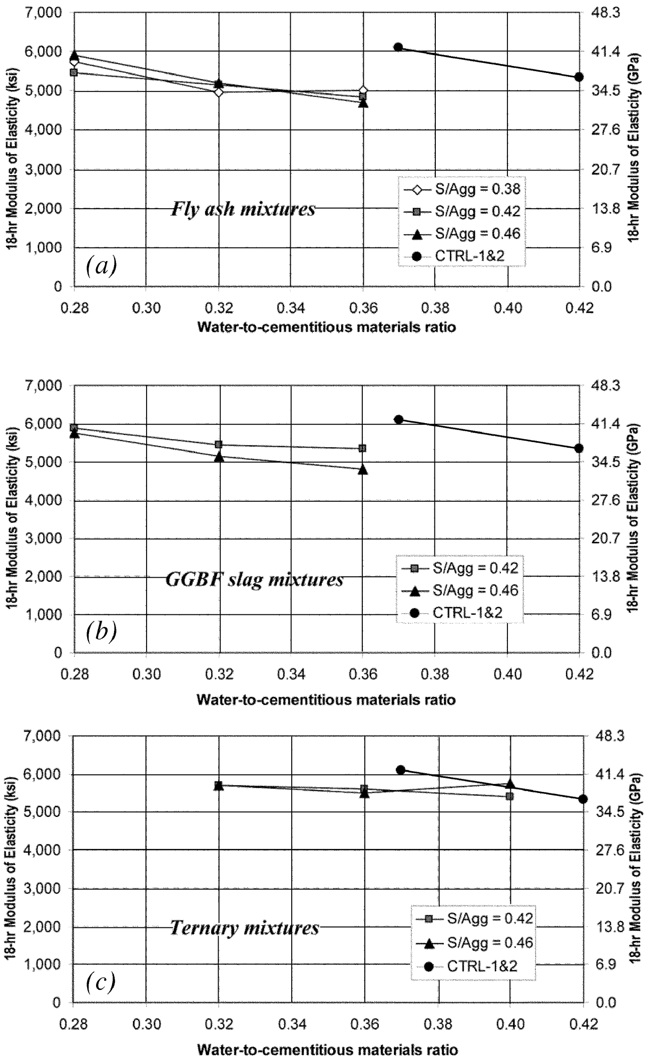

Fig. 2—Modulus of elasticity values determined at release (18 hours): (a) fly ash mixtures; (b) GGBF slag mixtures; and (c) ternary mixtures.

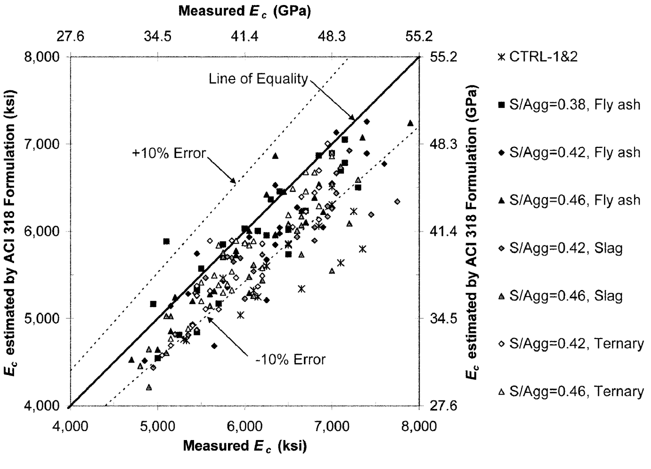

Fig. 3—Measured E_c *versus* E_c *estimated by ACI 318*[10] *(or AASHTO LRFD).*[11]

209R procedure. This approach was deemed conservative, as this would yield the lowest estimate of the ε_{SH} by the ACI 209R procedure. The water slump for all SCC mixtures was less than 0.5 in. (12.7 mm) due to their low water contents and low *w/cm* values. The AASHTO LRFD shrinkage prediction formulation (Section 5.4.2.3.3) only accounts for the humidity, volume-to-surface ratio, curing method, and age of the specimen.

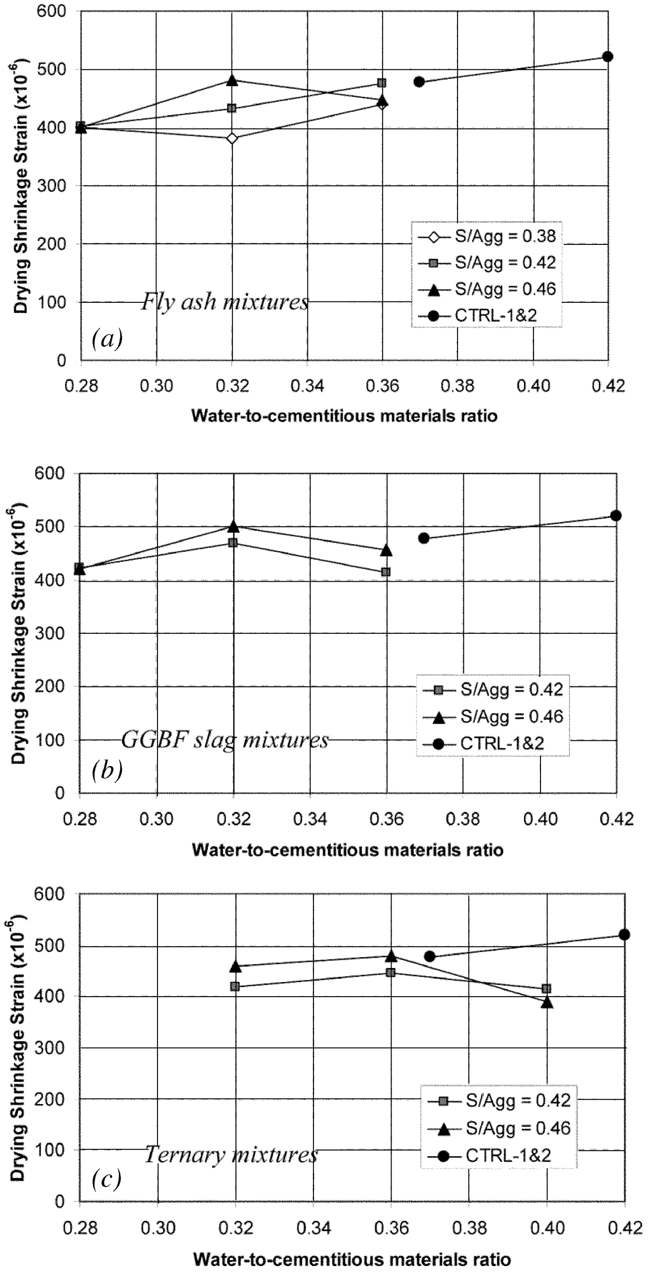

Fig. 4—Measured 112-day drying shrinkage strain results: (a) fly ash mixtures; (b) GGBF slag mixtures; and (c) ternary mixtures.

As stated in AASHTO LRFD, it is expected that: "Large concrete members may undergo substantially less shrinkage than that measured by laboratory testing of small specimens of the same concrete." It is expected, however, that if the shrinkage estimates from using these two procedures are of the same order of magnitude as those measured, then the shrinkage of full-scale members should be less than those estimated by these procedures.

Comparisons of the measured ε_{SH} to the ε_{SH} estimated by ACI 209R and AASHTO LRFD are summarized in Fig. 5 and 6, respectively. From Fig. 5 it may be seen that the ACI 209R procedure underestimates the drying shrinkage at 7

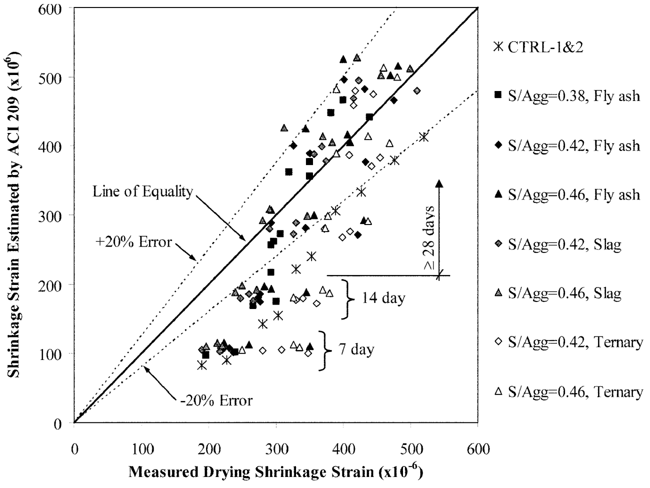

Fig. 5—Measured versus estimated drying shrinkage strains calculated with ACI 209R method.[9]

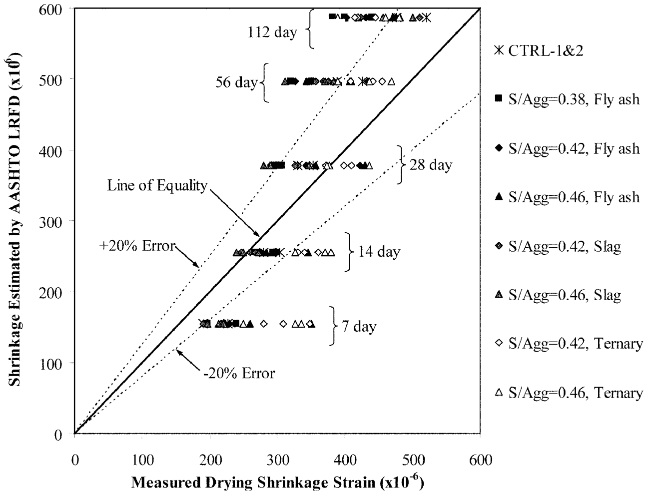

Fig. 6—Measured versus estimated drying shrinkage strains calculated with AASHTO LRFD method.[11]

and 14 days for all SCC and conventional-slump mixtures. At later ages of 56 and 112 days, the measured ε_{SH} values correspond reasonably well to those predicted by the ACI 209R procedure. Note that the 112-day ε_{SH} of the conventional-slump mixtures is underestimated by 20% or more by the ACI 209 procedure.

AASHTO LRFD only provides a single drying shrinkage strain at each age for all the mixtures tested in this study. In Fig. 6, it may be seen that the AASHTO LRFD procedure underestimates the drying shrinkage at 7 days for all SCC and conventional-slump mixtures. At later ages of 56 and 112 days, the ε_{SH} values estimated by AASHTO LRFD are more than the measured ε_{SH} for all SCC and conventional-slump mixtures. From this it may be concluded that the ε_{SH} obtained for the SCC mixtures should be adequate for use during the construction of full-scale prestressed members. Further evaluation of the dimensional stability of SCC mixtures in full-scale prestressed members is recommended.

CONCLUSIONS

Fresh and hardened properties of 21 SCC mixtures and two conventional-slump mixtures are presented and discussed in this paper. All mixtures were produced under laboratory conditions. The experimental program included cylinders that were match-cured to a temperature history typical of prestressed concrete operations in the southeastern U.S. The properties of the SCC mixtures were compared with the properties of conventional-slump prestressed concrete and those estimated by current design provisions. The results of this study support the following primary conclusions.

Fresh properties

Air-entraining admixture dosage was significantly affected by the cementitious material types, the water reducing admixture dosage, *w/cm*, and the mixing sequence. Increased dosages of polycarboxylate-based water-reducing admixtures generally increased the total air content of the SCC mixtures, and a reduction in air-entraining admixture was required to meet the specified air content.

The GGBF slag SCC mixtures required much higher dosages of air-entraining admixture as compared to the other types of SCC mixtures.

When compared with the fly ash SCC mixtures, increased dosages of polycarboxylate-based water reducing admixtures were required for the GGBF slag and ternary mixtures to obtain a slump flow within the specified range.

Hardened properties

1. *S/Agg* had little to no effect on concrete compressive strength at time of f'_{ci} or at later ages. The value f'_{ci} ranged between 5470 and 9530 psi (38 and 66 MPa) for the SCC mixtures;

2. Replacing Type III cement with high dosages of Class C fly ash or GGBF slag reduced the f'_{ci} of SCC mixtures. The ternary SCC mixtures exhibited higher f'_{ci} values at a given *w/cm* than the fly ash or GGBF slag SCC mixtures;

3. The 18-hour moduli of elasticity E_{ci} values of the SCC mixtures were less than that of the control mixtures with comparable f'_{ci}. At later ages of 56 days, the modulus of elasticity values of the SCC mixtures were similar to that of the control mixtures with comparable f'_{ci}. The higher E_{ci} values of the control mixtures may have been due to the use of only Type III cement;

4. A change in *S/Agg* had no distinct effect on E_{ci} of the fly ash and ternary SCC mixtures. The GGBF slag SCC mixtures with a *S/Agg* of 0.46 had slightly lower E_{ci} values than mixtures with a *S/Agg* of 0.42;

5. Modulus of elasticity E_c values obtained from these SCC mixtures generally exceeded those estimated with the ACI 318 or AASHTO LRFD formulations. E_c values obtained for the SCC mixtures were in reasonable agreement with the elastic stiffness assumed during the design of conventional-slump concrete structures;

6. The 112-day drying shrinkage strains for all the SCC mixtures were of the same order of magnitude or less than the 112-day drying shrinkage strains measured for both control mixtures;

7. A change in *S/Agg* from 0.38 to 0.46 had no significant effect on the 112-day drying shrinkage strain of the SCC mixtures considered; and

8. Excessive drying shrinkage is not expected for full-scale members constructed with the SCC mixtures used in this study.

Further research is required to evaluate the creep behavior of the SCC mixtures discussed in this paper, and this work is ongoing. The effect of these SCC mixtures on the transfer and development length of prestressed tendons is also being evaluated. The performance of some of these SCC mixtures should be evaluated during the construction of full-scale, plant-cast prestressed members.

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