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Eduardo Torres
South Dakota State University

Junwon Seo
South Dakota State University

Rita E. Lederle

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Eduardo Torres, S.M.ASCE[1]; Junwon Seo, Ph.D., P.E., M.ASCE[2]; and Rita E. Lederle, Ph.D.[3]

Abstract: Self-consolidating concrete (SCC) has the potential to increase precast production and quality, especially for production of prestressed concrete (PSC) bridge girders due to its superior workability compared with conventional concrete (CC). To obtain desired fresh and hardened properties for the production of SCC PSC girders, many factors related to material characteristics and mixture proportioning must be considered. An experimental comparison of fresh and hardened properties of SCC mixtures made with different material constituents was conducted in this study. The ultimate objective of this paper is not only to provide an experimental program enabling the investigation of the effect of material constituents on the performance of SCC mixtures but also to gain more knowledge for improved production of SCC PSC girders. The experimental program was established based on technical findings from a literature review and additional input from a survey of several state departments of transportation (DOTs). The mixture constituents used to investigate SCC performance consisted of the type of cement and size and type of coarse aggregate. Testing methods included slump flow, visual stability index (VSI), J-ring, column segregation, and compressive strength. The testing results showed that the type, shape, and size of coarse aggregate have a dominant effect in terms of fresh properties and compressive strength; specifically, mixtures with river gravel had larger spreads than mixtures with crushed limestone. Cement type had the expected effect with mixtures using Type III cement developing higher early strength than those using Type I/II cement. A statistical analysis was performed to determine significant mixture parameters in terms of fresh and hardened properties. It was found that the fine aggregate content was the most significant parameter affecting both fresh and hardened properties' behavior. **DOI: 10.1061/(ASCE)MT.1943-5533.0001968.** © *2017 American Society of Civil Engineers.*

Author keywords: Self-consolidating concrete; Prestressed concrete bridge girders; Experimental program; Material constituents; Fresh and hardened properties; Statistical analysis.

Introduction

Self-consolidating concrete (SCC) has been called a "smart concrete" (Shamsad et al. 2014) because it can effortlessly flow through congested reinforcing bars with no vibration mechanism. SCC has been used throughout Europe and the United States in many cast-in-place and precast applications. Several state departments of transportation (DOTs) have developed guidelines for the use of SCC through extensive research on materials, mixture design, and fresh and hardened properties, though not all states allow its use due to concerns with performance and consistency. Precast producers are interested in using SCC because of its many benefits to the casting process, such as a reduction of labor and construction time, elimination of vibration requirements and noise hazards, and simplification of the placing process (Skarendahl 2003; Naik et al. 2011; Hemalatha et al. 2015; Royce et al. 2015). However, SCC cannot simply be exchanged for conventional concrete (CC) in the construction process due to differences in the mixes, such as higher paste and lower coarse aggregate volumes of SCC compared to CC (Ghezal and Khayat 2002). Differences in the mixture proportions between SCC and CC can result in different fresh and hardened properties and associated structural performance of PSC bridge girders.

To develop guidelines for the use of SCC, extensive research on materials, mixture design, and fresh and hardened properties and the application of SCC on PSC bridge girders has been conducted by the following agencies: The National Cooperative Highway Research Program (NCHRP), Precast/Prestressed Concrete Institute (PCI), and state departments of transportation. NCHRP Report 628 presented findings regarding SCC mixture parameters and fresh and hardened properties for the use of SCC in prestressed structural components (Khayat and Mitchell 2009). PCI has reported recommendations on SCC mixture constituents and guidelines for production, quality control, placing, and finishing of SCC PSC girders (PCI 2003). Several DOTs have performed state-level research projects on SCC to establish their own state guidelines for the implementation of SCC using local aggregates available in their region. For example, Texas DOT reported that SCC has more adequate workability, excellent stability, higher compressive strength, and similar creep values relative to CC (Trejo et al. 2008). Research for the Florida DOT found that there were no notable differences between SCC and CC prestressed bridge girders in terms of prestress transfer length, mean camber growth, flexural capacity, shear capacity, and web cracking (Labonte and Hamilton 2005).

[1]Graduate Research Assistant, Dept. of Civil and Environmental Engineering, South Dakota State Univ., Brookings, SD 57007. E-mail: eduardo.torres@sdstate.edu

[2]Assistant Professor, Dept. of Civil and Environmental Engineering, South Dakota State Univ., 316 Crothers Engineering Hall, Box 2219, Brookings, SD 57007 (corresponding author). E-mail: junwon.seo@sdstate.edu

[3]Formerly, Structural Design Engineer, Wisconsin Dept. of Transportation Bureau of Structures, Madison, WI 53707. E-mail: Rita.Lederle@gmail.com

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In addition to the aforementioned SCC-related research activities in the United States, some relevant studies by European countries have been performed (EFNARC 2006). The European Federation of National Associations Representing Producers and Applicators of Specialist Building Products for Concrete (EFNARC) provides specifications of the constituent materials, mixture design, test methods, and placing of SCC for precasters and bridge engineers in Europe. It was reported from the EFNARC that SCC has better durability, bond strength, lower modulus of elasticity, and slightly higher compressive strength than CC.

Although many national transportation agencies have developed guidelines related to SCC mixture development for PSC bridge girders, producers still struggle with maintaining uniformity in terms of fresh and hardened properties with minimal segregation in the SCC mixture when transporting and placing of SCC which can lead to reluctance on the behalf of some entities to allow the use of SCC (Shen et al. 2015). One major concern is lack of segregation resistance, which can result in poor workability and performance due to internal and external bleeding of water, differential accumulation of light ingredients, and settling of aggregate at the bottom (Bonen and Shah 2004). Meanwhile, numerous studies (Schindler et al. 2007; Khayat and Mitchell 2009; Turkel and Kandemir 2010; Shamsad et al. 2014) regarding the use of mineral fillers to improve overall performance (including segregation resistance) of SCC have been carried out, indicating fillers help enhance the SCC performance. However, several DOTs have only allowed the use of SCC made of 100% cement for the cementitious material content to produce prestressed SCC bridge girders. Hence, a study to better understand the effects of mixture constituents (e.g., size and type of coarse aggregate) within 100% cement SCC mixtures on their fresh and hardened properties, helping local precastors efficiently produce prestressed SCC bridge girders with satisfactory SCC quality, is needed.

This study is intended to experimentally and statistically evaluate fresh and hardened properties of 28 different SCC mixtures composed of 100% cement in the cementitious material content representative of mixtures that could be produced by three different precast plants in Wisconsin. This paper presents background information for SCC characteristics and mixture constituents, an overview of the proposed experimental program to evaluate fresh and hardened properties for the SCC mixtures, and experimental and statistical results along with related discussion.

Background

SCC typically consists of cement, water, aggregates, and chemical admixtures. Each of the components of SCC can affect the characteristics of the mix. A mix design must carefully balance these effects for a successful outcome.

Cement

Cement type affects the strength of an SCC girder as well as the workability. For PSC bridge girder applications, Type I/II and Type III cements are most commonly used (Khayat and Mitchell 2009). Type III cement is used when higher early strength is needed, although it tends to have higher water and high range water reducer (HRWR) demands. Type I/II cement has been shown to provide longer durability and more consistency of fresh concrete (Khayat and Mitchell 2009). Several studies (Burgueno and Bendert 2007; Trejo et al. 2008; Khayat and Mitchell 2009) have been performed to investigate the compressive strength of SCC compared to that of CC. For example, Burgueno and Bendert (2007) found that the compressive strength of SCC made with cement Type III showed higher strength than that made with CC, indicating cement content, water to cement ratio (w/c), and coarse aggregate content have an influence on compressive strength.

Aggregates

Coarse aggregate has a significant influence on the workability and strength of SCC. The maximum size of the aggregate (MSA) should be selected depending on the minimum space between reinforcing bars (Sonebi et al. 2007). For example, the Virginia DOT SCC Specifications state that the coarse aggregate size should not exceed 19 mm, not be less than 1/5 of the narrowest dimension between the sides of the forms, and not have less than 19 mm of minimum clear spacing between bars (Torres and Seo 2016). A NCHRP research project performed by Long et al. (2014) suggests that the MSA should be between 19 and 9.5 mm, while EFNARC suggests that the MSA should be between 12 and 20 mm.

The type and size of aggregate have an impact on the strength of SCC. Trejo et al. (2008) and Khaleel et al. (2011) found that mixtures using crushed limestone developed higher strength than those containing crushed or uncrushed gravel, and that the mixtures with coarse aggregate with a MSA of 10 mm had higher compressive strength compared to those with a MSA of larger than 10 mm.

Chemical Admixtures

Chemical admixtures are used to modify the physical and chemical properties of a mix to achieve acceptable SCC performance (EFNARC 2006). Admixtures are able to reduce water content, improve deformability and stability, increase air content, accelerate strength development, and retard setting time (Khayat and Mitchell 2009). The most common admixtures used for SCC are high range water reducer and viscosity modifying admixtures (VMA). The addition of these admixtures depends upon SCC mixture parameters, such as w/c and binder type. For example, HRWR can be added in small amounts to freshly mixed SCC to improve its workability for a short period of approximately 30 min. HRWR can also be added to mixtures with low w/c to obtain higher fluidity and higher strength. VMA can be used to increase the viscosity of the mixture to control segregation (Turkel and Kandemir 2010). According to NCHRP Report 628 (Khayat and Mitchell 2009), VMA should be used for mixtures with less than 425 kg/m^3, or mixtures with w/c values greater than 0.40.

Fillers

Due to its higher amount of cement and lower aggregate volume, SCC tends to be more expensive than CC, thus, many precasters often replace some portion of the cement content with fillers to reduce cost while maintaining satisfactory workability and strength. Fillers, better known as mineral admixtures or supplementary cementitious materials, can also be added to improve workability. Benefits from the use of fillers in SCC applications include the following: (1) increased early compressive strength, bleeding control, viscosity, and workability as well as reduced porosity (Shamsad et al. 2014). Fillers commonly used for SCC production include fly ash, ground granulated blast-furnace slag, silica fume, and limestone powder (Torres and Seo 2016). Suggested percentages of replacement of cement are listed in Table 1.

Material Testing Methods

Material testing methods that have been typically used for the evaluation of fresh and hardened properties of SCC are employed for this study. The ASTM has developed guidelines to evaluate

Table 1. Suggested Cement Replacement Values (Data from Khayat and Mitchell 2009)

Filler	% Replacement
Fly ash[a]	20–40
Limestone	20–30
Blast-furnace slag	30–60
Fly ash/blast-furnace slag	Maximum 50

[a]Classes of fly ashes, including C, D, and F; replacement percentage ranges are identical for fly ash no matter the class.

Table 2. SCC Test Methods with Corresponding Guidelines

Test methods	Fresh properties	Guidelines
Slump flow	Filling ability	ASTM C 1611/PCI/EFNARC
J-ring	Passing ability	ASTM C 1621/PCI/EFNARC
Column segregation	Segregation resistance	ASTM C 1610/PCI/EFNARC

workability and performance of SCC mixtures. NCHRP, EFNARC, and PCI provide technical descriptions for material testing methods for the individual properties of a mix. Table 2 summarizes such testing methods and corresponding guidelines. The workability of SCC is evaluated in terms of flowing ability, passing ability, and segregation, while the performance of SCC is evaluated through compressive strength.

The slump flow test (also called the spread test) is one of the most well-known methods for determining the flow ability of SCC mixtures. This test is frequently used in field work for the evaluation of the consistency of flow ability for target mixtures and is specified by ASTM C1611. Figs. 1(a and b) show photographs for slump flow setup and testing that were done for this study. The ASTM C1611 documentation recommends the SCC diameter to range between 533 and 737 mm. Meanwhile, Khayat and Mitchell (2009) suggests that the slump spread diameter of SCC for prestressed elements range from 597 to 737 mm.

The spread diameter is not the only parameter measured during this test: the T_{50} and visual stability index (VSI) can be obtained. T_{50} is defined as the time it takes the concrete to flow and reach the 508 mm mark. T_{50} values provide information on the flow properties, where longer values correspond to high viscosity. VSI is a visual inspection of the concrete to qualitatively assess the stability of the concrete. VSI is ranked from 0 to 3 according to the presence of bleeding or segregation (ASTM 2011c).

The passing ability and filling capacity of freshly mixed SCC can be evaluated using the J-ring test. ASTM C1621 defines (ASTM 2011b) passing ability as the difference between the spread diameter of J-ring and slump flow. Passing ability is most influenced by MSA, as the coarse aggregate can cause blockage between the reinforcing bars of the ring. Filling capacity is the ability of SCC to flow and fill all existing spaces in the formwork. The J-ring test procedure is similar to that of the slump flow except that a J-ring is placed around the cone, and the SCC passes through the legs of the open circular steel ring, as seen in Figs. 1(c and d). The average of the two orthogonal diameters is recorded and compared to those from the slump flow testing. If the difference is less than 25.4 mm according to ASTM C1621, it means the mix has good passing ability. If the difference is above 50.8 mm, it indicates poor passing ability. The height difference between the concrete inside the ring and concrete outside the ring can also be used to evaluate the passing ability, but it is not specified by ASTM C1621 (ASTM 2011b).

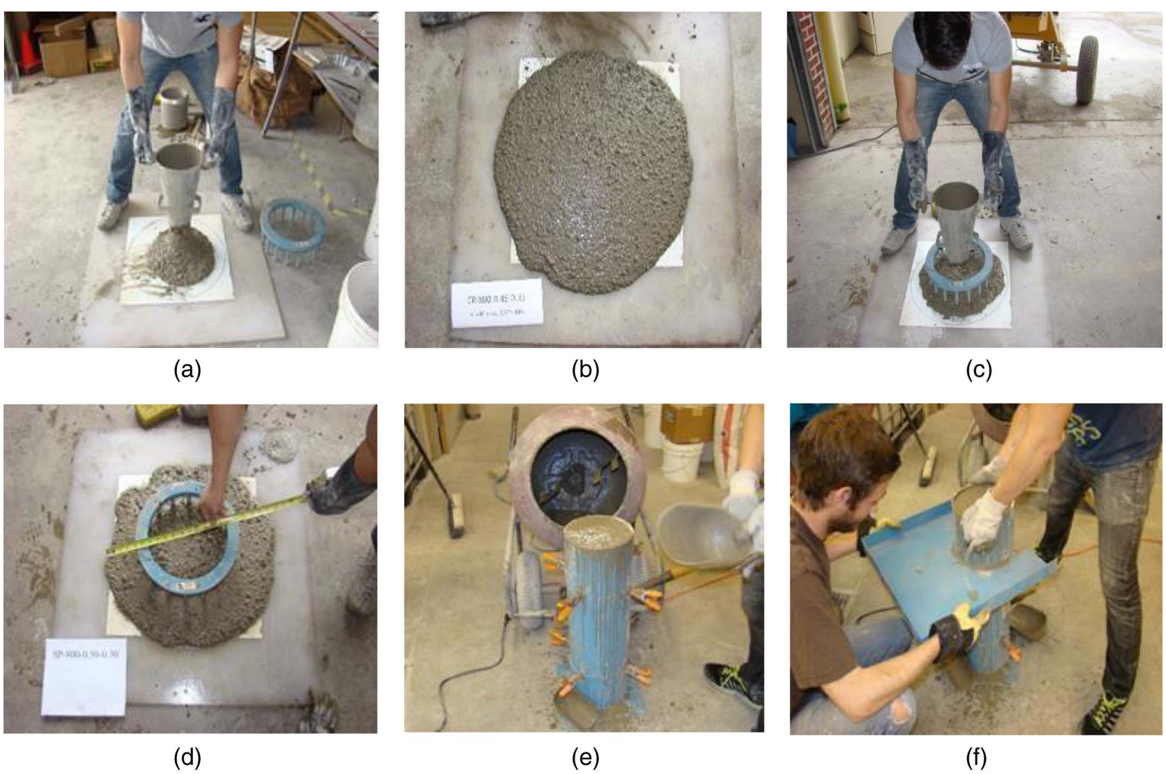
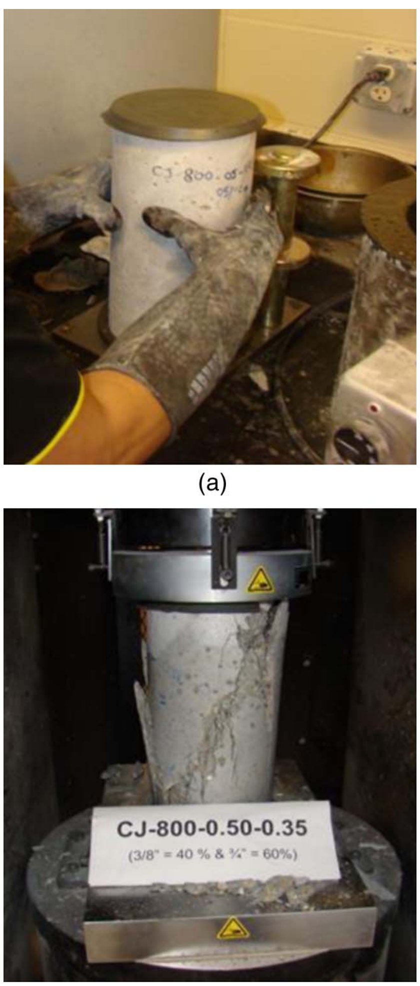


Fig. 1. Workability test methods: (a) slump flow setup; (b) slump spread diameter measurement; (c) J-ring setup; (d) J-ring spread diameter measurement; (e) column segregation set up; (f) collecting top section of cylinder

The column segregation test is used to determine the segregation potential of SCC mixtures. In accordance with ASTM C1610, the SCC mixture is poured into the test cylinder, [Fig. 1(e)]. The SCC mixture rests for 15 min without any disturbance, then the SCC at the top and bottom segments of the cylinder are collected and placed in different containers, as shown in Fig. 1(f). The SCC mixtures from the top and bottom segments were washed to discard any particles passing the No. 4 sieve. The column segregation is expressed as the percentage ratio difference of aggregate mass between the bottom and top segments to the total aggregate mass in the two segments (ASTM 2011d).

Strength Testing

Compressive strength of SCC mixtures was tested according to ASTM C39 using SCC cylinders of 304.8 × 152.5 mm as shown in Fig. 2. Fig. 2(a) shows a picture where a cylinder of the SCC mixtures is capped with a sulfur cap to ensure that compressive loads are uniformly distributed on the surface. Fig. 2(b) displays a cylinder that was fractured after 16 h of curing necessary for PSC application. The compressive load rate was 0.23 MPa/s in accordance with ASTM C39 (ASTM 2011a) until failure.



(a)

(b)

Fig. 2. Compressive strength test: (a) sulfur cap top/bottom of a sample cylinder; (b) diagonal crack of a sample cylinder

Experimental Program

An experimental program accounting for various SCC mixture parameters is established herein. The following subsections describe material testing methods, testing matrix, fresh property criteria, and mixing and curing procedures as part of the experimental program.

Fresh and Hardened Property Requirements

In this study, a survey collected the requirements for SCC workability and strength from each of the contacted state DOTs. The values required by the contacted DOTs for slump flow ranged from 457.2 to 762 mm. For the J-ring test, the most common value specified was a difference between the spread diameter of the J-ring test and slump flow test no greater than 50.8 mm. For the VSI test, the requirements from the DOTs are consistent throughout the states, with a maximum index of 1. For the column segregation test, the maximum percent of segregation allowed is 15%. A summary of the requirements of each DOT for each test method can be seen in Table 3. More details regarding the survey can be found in Torres and Seo (2016).

Target Values

The results of the DOT survey and recommendations from the ASTM/PCI test method guidelines were used to determine specific target values for each test method. If SCC mixtures do not meet the workability criteria shown in Table 4, it is necessary to adjust parameters of the SCC mixture design. For instance, by amending the dosage of admixtures, the viscosity and flow ability of the mixture can be improved without modification of other mixture parameters. By decreasing the size of the coarse aggregate, the passing ability can be improved, and segregation of the mixture will decrease. For compressive strength, the target values for 16 h and 28 days are included in Table 4. The target compressive strength is set to be the highest value used by certain DOTs to avoid concrete crushing due to the prestress force induced to the girder.

Testing Matrix

For this research, a testing matrix for SCC mixtures to be evaluated in terms of workability and strength according to the predetermined target values was created to consider the parameters of cement type, aggregate type and size, and blending configuration. The two types of cement considered were Type I/II and Type III, while the two types of coarse aggregate were crushed limestone and rounded river gravel, as they are widely used in the Wisconsin precast concrete industry. Note that three different providers of coarse aggregate were selected from different regions in Wisconsin. The aggregate size used was 19 and 9.5 mm as recommended by NCHRP Report 628 (Khayat and Mitchell 2009). To improve the workability of the mixtures, several blending configurations combining both the sizes were included in the test matrix to study their impact on the workability and compressive strength. The blending configuration was established using intervals of 20% from 100 to 0% of 19 mm combined with 9.5 mm. Grain size distribution curve for the 19-mm aggregate size was plotted against the ASTM upper and lower limits (ASTM 2013). Fig. 3 shows that for Plant B, the percent passing of 12.5 mm or less exceeded the allowed ASTM upper limit. On the other hand, Plant C aggregate was under the lower limit at 19 mm meaning that Plant C had larger aggregate size.

Table 5 presents the 28 mixtures tested in this research. These mixes can be divided into three groups to systematically evaluate the influence of binder type, type and size of coarse aggregate, w/c,

Table 3. DOT Requirements for Fresh Properties Test Methods (Data from Torres and Seo 2016)

State	Slump flow (mm)	J-ring (mm)	VSI	L-box	Column segregation
Alabama	635–736.6	±76.2	0–1	N/A	N/A
Florida	685.8 ± 63.5	±50.8	0–1	N/A	Maximum 15%
Georgia[a]	Minimum 508	N/A	N/A	Minimum 0.8	N/A
Illinois[a]	508–711.2	Maximum 101.6	0–1	Minimum 0.6	Maximum 15%
Iowa	Maximum 685.8	N/A	N/A	N/A	N/A
Kentucky[a]	N/A	N/A	N/A	N/A	N/A
Louisiana	508–711.2	N/A	N/A	N/A	N/A
Michigan	685.8 ± 25.4	±15.24	0–1	Minimum 0.8	N/A
Minnesota	Maximum 711.2	±50.8	0–1	N/A	N/A
Nebraska	ASTM C1611	N/A	ASTM C1611	N/A	N/A
Nevada[a]	N/A	N/A	N/A	N/A	N/A
New York[a]	±50.8 target	±50.8	0–1	N/A	Maximum 15%
North Carolina	609.6–762	±50.8	N/A	Minimum 0.8	N/A
Ohio	685.8 ± 50.8	N/A	N/A	N/A	N/A
Pennsylvania[a]	508–762	±50.8	0–1	N/A	N/A
Rhode Island	508–660.4	±50.8	N/A	N/A	N/A
South Carolina	N/A	N/A	N/A	N/A	N/A
South Dakota	508–711.2	±50.8	0–1	N/A	N/A
Texas[a]	558.8–685.8	±50.8	0-1	N/A	Maximum 10%
Utah	457.2–812.8	±25.4	0–1	N/A	Maximum 10%
Virginia	660.4 ± 76.2	±50.8	0–1	N/A	Maximum 15%
Washington	±50.8 target	±38.1	0–1	N/A	Maximum 10%

[a]Required values were obtained from state-DOT specification as detailed below: (1) Georgia: Special Provisions Section 500 Concrete Structures; (2) Illinois: Specifications for Precast Products Section II.3.1 SCC; (3) Kentucky: II.4.1 Method for Approval of Using SCC: Provide Spread Limits, Production Records and Quality Control Procedures; (4) Nevada: Section 501 Portland Cement Concrete: No specific guidelines; (5) Nebraska: Section 1002 in the Standard Specification; (6) New York: Self Consolidating Concrete Mix Design Qualification Procedure for Precast Work Performed under the QC/QA Program; (7) Pennsylvania: Section 714—Precast Concrete Products; (8) South Carolina: Precasters are hesitant to use SCC; (9) Texas: Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges Section 4.2.8.

and sand-to-aggregate ratio (S/Agg). Each group of mixtures corresponds to the combination of cement type and aggregate available at each precast plant. These groups are designated as Plant A, Plant B, and Plant C. Plant A mixtures used Type III cement and crushed limestone. Plant B mixtures used Type I/II cement and crushed limestone. Plant C mixtures used Type III cement and river gravel. Plant A and B mixtures used chemical admixtures provided by Grace Construction Products, while Plant C mixtures were developed using admixtures provided by SIKA. Table 6 indicates the material properties of each plant used for mixture design.

The cement content for all mixtures was fixed at either 445 or 474 kg/m^3 to ensure a higher compressive strength needed for prestress bridge girders. It should be noted that the mixtures had only cement as cementitious materials, filler was not part of the testing. Referring to Table 7, details for the mixture designs are presented. To facilitate the interpretation of the data in both Tables 5 and 7, there is a letter next to the mixture number, which is the letter A, B, or C that was included to denote to which plant each mixture belongs.

Table 4. Target Values for Specific Test Methods

Evaluation table for fresh properties		
Fresh properties tests	Acceptable range	Target value
Slump flow (mm)	558.8–711.2	635
J-ring (mm)	Maximum 50.8	Maximum 50.8
Column segregation (%)	≤15	Close to 10
T_{50} (s)	3–10	<6
VSI	≤1	≤1
Compressive strength (16 h) (MPa)	N/A	46.88
Compressive strength (28 days) (MPa)	N/A	55.15

Mixing and Curing Procedures

All the SCC mixtures were made in batches of 0.14 m^3 (5 ft^3) using a drum mixer. Mixing procedure was consistent for every mixture according to the procedure provided by the Portland Cement Association (PCA 2005). Sand, coarse aggregate, and cement were placed in the drum and left to be mixed for 30 s, then the water was slowly added to the mix ensuring equal distribution. After 1 min of mixing, the admixtures were added to the mix. It was specified by the admixture provider that the admixtures not be combined with the water. Once the admixtures were added, the concrete was remixed for 8 min. Fresh properties were measured immediately after mixing was complete. Slump flow, J-ring, and column

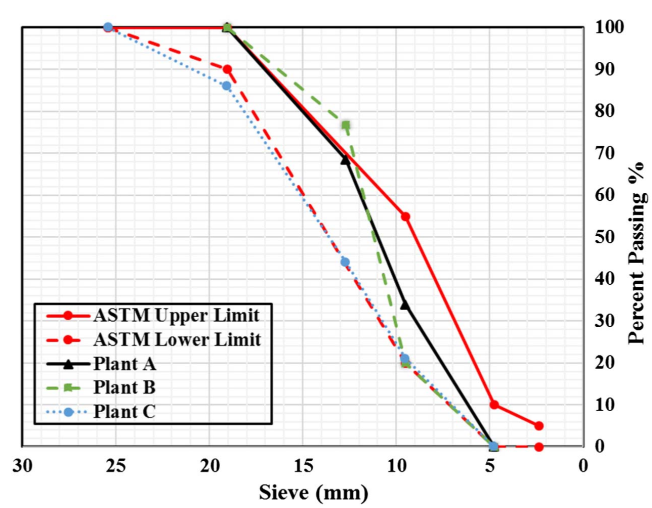


Fig. 3. Grain size distribution

Table 5. Parametric Testing Matrix

Aggregate type	Mixture number	Aggregate size 100% 9.5 mm	80% 9.5 mm	60% 9.5 mm	40% 9.5 mm	20% 9.5 mm	0% 9.5 mm	Cement type Type III	Type I/II	w/c 0.35	0.33	S/Agg 0.50	0.45
Crushed limestone	1	X	—	—	—	—	—	X	—	X	—	X	—
	2	X	—	—	—	—	—	X	—	X	—	—	X
	3	—	X	—	—	—	—	X	—	X	—	X	—
	4	—	—	X	—	—	—	X	—	X	—	X	—
	5	—	—	X	—	—	—	X	—	X	—	—	X
	6	—	—	—	X	—	—	X	—	X	—	X	—
	7	—	—	—	X	—	—	X	—	X	—	—	X
	8	—	—	—	—	X	—	X	—	X	—	X	—
	9	—	—	—	—	X	—	X	—	X	—	—	X
	10	—	—	—	—	—	X	X	—	X	—	X	—
	11	—	—	—	—	—	X	X	—	X	—	—	X
	12	X	—	—	—	—	—	—	X	X	—	X	—
	13	—	X	—	—	—	—	—	X	X	—	X	—
	14	—	—	X	—	—	—	—	X	X	—	X	—
	15	—	—	—	X	—	—	—	X	X	—	X	—
	16	—	—	—	X	—	—	—	X	—	X	X	—
	17	—	—	—	X	—	—	—	X	—	X	—	X
	18	—	—	—	—	X	—	—	X	X		X	—
	19	—	—	—	—	X	—	—	X	—	X		X
	20	—	—	—	—	X	—	—	X	—	X	X	—
	21	—	—	—	—	—	X	—	X	X	—	X	—
Round gravel	22	—	—	—	X	—	—	X	—	X	—	X	—
	23	—	—	—	X	—	—	X	—	X	—	—	X
	24	—	—	—	X	—	—	X	—	X	—	—	X
	25	—	—	—	—	X	—	X	—	X	—	X	—
	26	—	—	—	—	—	X	X	—	X	—	—	X
	27	—	—	—	—	—	X	X	—	X	—	—	X
	28	—	—	—	—	—	X	X	—	—	X	X	—

Table 6. Material Properties for Each Plant

Material constituent	Aggregate properties	Plant A	Plant B	Plant C
Cement	Specific gravity	3.15	3.14	3.15
Coarse aggregate	Specific gravity	2.66	2.59	2.77
	Percent absorption	1.52	2.64	1.73
Fine aggregate	Specific gravity	2.65	2.65	2.76
	Percent absorption	0.59	0.69	0.73

segregation tests were completed in the respective order within 30 min of mixing. A certain testing time window is required to ensure that the admixtures consistently affect each mixture. For each mixture, compressive strength was tested at 16 h to simulate time of curing used at prestressed plants before strands release. To simulate steam curing temperatures, cylinders were placed in a water bath for 16 h at a temperature of 43.3°C as shown in Fig. 4. Note that the water bath had constant temperature, meaning that it was different to the curing regime normally used in the precast industry.

Results and Discussion

Fresh Properties

The overall fresh properties of the SCC mixtures were evaluated by comparing the test results against the target values that were determined based upon inputs from the survey and literature review. The resulting fresh properties for each mixture, including slump flow, J-ring, passing ability, filling capacity, T_{50}, and column segregation, are summarized in Table 8. Note that the results of the compressive strength are also included in the table and some tests, such

Table 7. Composition for Selected SCC Mixtures

Mixture number	Water (kg/m^3)	Cement (kg/m^3)	Coarse aggregate (kg/m^3) 9.5 mm	19 mm	Fine aggregate (kg/m^3)	HRWR (L/m^3)	VMA (L/m^3)
1A	166	474	645	0	640	1.18	0.24
2A	166	474	763	0	621	1.18	0.47
3A	166	474	516	129	640	1.42	0.47
4A	166	474	387	258	640	1.18	0.00
5A	166	474	467	305	621	1.18	0.24
6A	166	474	258	387	640	1.30	0.71
7A	166	474	305	471	635	1.42	0.54
8A	166	474	129	516	640	1.42	0.24
9A	166	474	152	610	621	1.66	0.35
10A	166	474	0	645	640	1.42	0.24
11A	166	474	0	763	621	1.18	0
12B	166	474	662	0	640	1.18	0
13B	166	474	530	132	640	1.42	0
14B	166	474	397	264	640	1.18	0.24
15B	166	474	264	397	640	1.18	0.24
16B	156	474	264	397	640	1.42	0.35
17B	156	474	264	397	621	1.18	0.35
18B	166	474	132	530	640	1.18	0.24
19B	156	474	132	530	621	1.42	0.47
20B	156	474	132	530	640	1.18	0.35
21B	166	474	0	662	640	1.18	0.47
22C	166	474	288	432	719	1.42	0.47
23C	166	474	317	402	647	0.95	0.47
24C	166	445	324	409	662	1.42	0
25C	166	474	144	576	719	1.42	0
26C	166	445	0	808	662	1.66	0.47
27C	166	474	0	794	647	1.66	0.47
28C	156	474	0	720	719	2.13	0.24

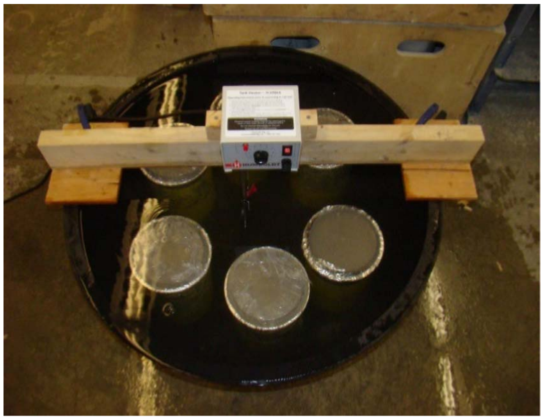


Fig. 4. Water bath to simulate steam curing

as column segregation, were not performed for all the mixtures due to limited availability of materials. The current tabulated data set allowed for reasonable examination of the effect of SCC mixture constituents on the fresh properties of SCC.

Though the slump flow values are consistent for all the mixtures, it can be seen that the mixtures from Plant C having rounded gravel (i.e., 22C to 28C) have higher spread diameter than those from Plants A and B. This behavior can be attributed to the smoother surface of the gravel aggregate facilitating movement, while limestone is flaky and elongated, making it hard for the wet SCC to flow freely. Recall from Table 4 that the target value for slump flow was 635 mm. To study the effect of blending configurations on slump flow, S/Agg was fixed at 0.5 and w/c at 0.35. The dosage of admixtures was slightly modified to have a stable mixture. Fig. 5 shows that the size of the coarse aggregate had an impact on the slump flow results. Mixtures containing 40% of 9.5 mm (5A, 15B, and 22C) showed consistently larger spread diameters than the target value of 635 mm. This can be attributed to the fact that as the percentage of 9.5 mm increased, the mixture had higher viscosity, while as the percentage of 19 mm increased, less movement of particles was observed due to larger particle size. Minor difference was observed when comparing the effect of Type III cement (Plant A) with Type I/II cement (Plant B) in terms of slump flow values.

J-ring spread diameters with varying blending configuration are shown in Fig. 6. While the results for Plants A and B do not show the effects of change in blending, for Plant C the spread diameters increased as the blending percent of 9.5 mm increased. The J-ring values were used to determine the passing ability and filling capacity of the SCC mixtures. Mixtures 8A, 12B, and 24C exceeded the predetermined target value of ±51 mm, as shown in Table 8. Fig. 7(a) shows the passing ability trend of each plant versus the respective blending configuration. From this figure, it was observed that the mixtures representing Plant B made of Type I/II cement exhibited better results compared to Plants A and C, which used Type III cement. This observation was expected as Type I/II cement tends to develop better workability than Type III cement due to lower water demand.

The literature (Long et al. 2014; Khayat and Mitchell 2009) indicates that the filling capacity values are considered acceptable if they are equal to or larger than 80%. As seen in Fig. 7(b) and Table 8, most mixtures meet the filling capacity requirements, with the exception of Mixtures 12B, 24C, and 26C. These mixtures had a large difference in spread diameters between slump flow and J-ring due to a higher percentage of 19-mm coarse aggregate,

Table 8. Summary of Results

Mixture number	Slump flow (mm)	J-ring (mm)	Passing ability (mm)	Filling capacity (%)	VSI	T_{50}	Column segregation (%)	Compressive strength (MPa) 16 h	Compressive strength (MPa) 28 days
1A	610	622	12	84,8	0	9.4	2.7	44.42	82.73
2A	610	—	—	—	0	7.4	—	41.00	—
3A	603	610	0	83,1	0	5.3	6.3	48.45	81.87
4A	622	610	12	83,7	0.5	12.0	6.4	46.58	76.23
5A	622	—	—	—	0.5	8.5	—	44.71	—
6A	629	622	7	85,7	1	3.9	2.8	47.98	70.08
7A	629	610	19	84,0	1	5.2	4.7	49.20	68.10
8A	578	635	57	85,0	0	10.6	9.1	58.14	—
9A	641	622	19	86,3	1	4.8	4.2	48.60	65.00
10A	635	610	25	84,3	1	4.6	6.3	48.22	63.72
11A	584	622	0	85,4	0	7.3	10.1	49.94	68.32
12B	622	571	51	78,2	0	6.3	1.6	36.00	55.59
13B	660	622	38	87,3	1	7.1	3.3	38.06	60.13
14B	622	597	25	81,9	0	9.3	5.1	42.66	62.39
15B	643	622	21	86,4	1	13.6	8.0	48.25	—
16B	629	597	32	82,2	0.5	3.4	2.0	49.05	60.33
17B	625	603	22	82,9	0	3.6	10.1	47.98	71.66
18B	622	597	25	81,9	0	8.2	9.5	40.81	—
19B	635	597	38	82,5	0.5	5.9	—	46.11	—
20B	622	610	12	83,7	0	4.8	9.9	49.29	68.91
21B	660	616	44	86,4	1	5.7	11.8	40.47	67.08
22C	667	635	19	83,5	1	6.1	5.1	46.45	57.28
23C	641	603	38	83,7	1	5.8	3.4	47.73	61.58
24C	622	565	57	77,4	0	5.3	2.2	46.26	58.72
25C	667	622	45	87,6	1	3.1	9.9	47.31	62.58
26C	610	571	39	77,6	0	2.5	4.7	34.77	46.38
27C	610	597	13	82,1	0	3.4	3.1	37.59	46.98
28C	610	603	7	84,8	0	4.0	12.2	41.22	49.17

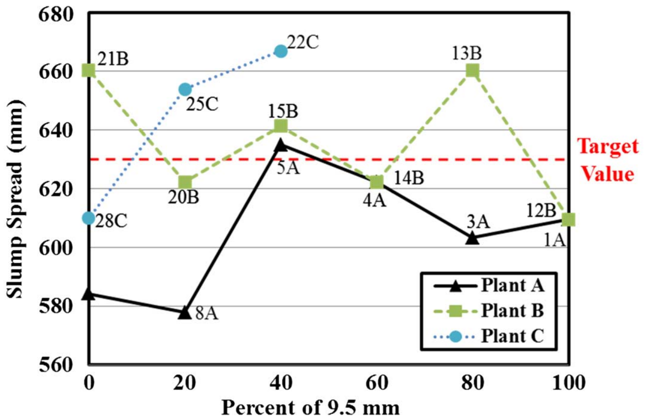


Fig. 5. Slump flow spread diameter results with w/c 0.35 and S/Agg 0.50

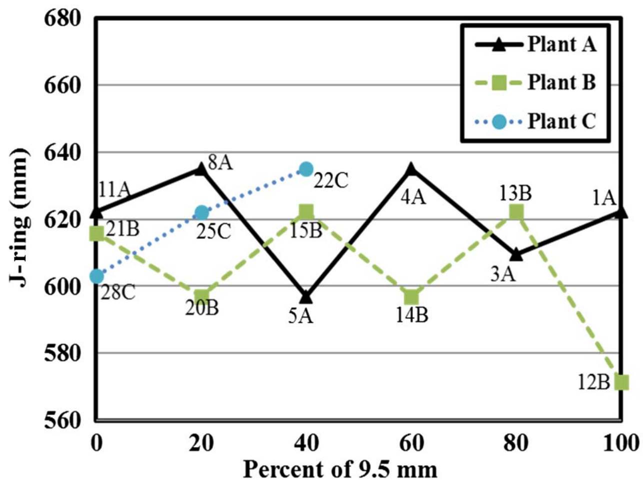


Fig. 6. J-ring spread diameters with w/c 0.35 and S/Agg 0.50

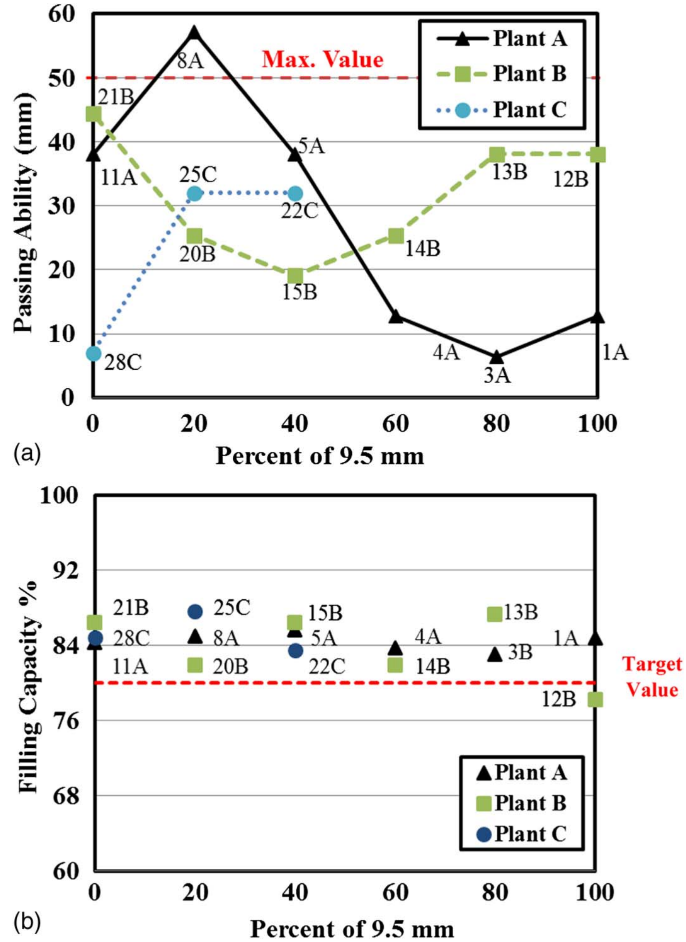


Fig. 7. Workability assessment of mixtures with w/c 0.35 and S/Agg 0.50: (a) passing ability; (b) filling capacity

resulting in higher blockage. Overall, higher values of filling capacity were observed by the mixtures made of crushed limestone (Plants A and B) compared to mixtures made with rounded gravel (Plant C).

T_{50} values for all the mixtures (Table 8) were within the acceptable ranges listed in Table 4 except for Mixtures 4A, 8A, and 15B. Generally, there were no noticeable trends in terms of T_{50}. Segregation resistance was investigated using the column segregation test. The cement and aggregate type did not have a significant influence on the segregation resistance of the mixtures. However, it should be mentioned that from the perspective of the coarse aggregate size, it was clear that as the percent of 9.5 mm decreases, segregation (%) increases, leading to lesser segregation resistance as shown in Fig. 8(a). This is attributed to the fact that the weight of the aggregate increases, and a higher settlement rate occurs. All the mixtures (Table 8) experienced segregation below the pre-established limit of 15%.

A pair of specific mixtures for each plant was selected to study the effects of S/Agg in terms of percent segregation of the mixtures. Mixtures included were 6A, 7A, 16B, 17B, 22C, and 23C, which had a blending configuration fixed at 40% of 9.5-mm aggregate and a w/c of 0.35 for Plants A and C and 0.33 for Plant B. Fig. 8(b) shows the percent segregation as the S/Agg changes from 0.45 to 0.50. It was observed that the segregation increases as S/Agg reduces from 0.50 to 0.45. This behavior was expected as the higher amount of fine aggregates is directly related to the viscosity of the mixture.

Compressive Strength

Compressive strength of all the mixtures at 16 h for Plant A were higher than those from Plants B and C. This was to be expected for Plant B because it used Type I/II cement, which does not develop strength as quickly as the Type III cement used at Plants A and C. The mixtures of Plant C made of rounded river gravel developed lower compressive strength than those from Plant A, which used limestone. This occurred because of the smooth surface of the rounded gravel, which results in a weak interfacial transition zone. Fig. 9(a) shows the compressive strength results for 16 h of Plants A, B, and C with w/c of 0.35 and S/Agg of 0.50. As the percent of 9.5-mm coarse aggregate decreased, the compressive strength of Plants A and B mixtures tended to increase. Compressive strengths of Plant A mixtures range from 41.0 to 58.1 MPa; the values are larger than those from Plant B (36.0–49.3 MPa) and Plant C (37.6–47.7 MPa). Fig. 9(b) illustrates the compressive strength for Plant B mixtures 15B, 16B, 18B, and 20B with w/c of either 0.33 or 0.35, which were selected to explore the effect of w/c on the strength. As expected, when the w/c ratio increased, the compressive strength decreased. However, the decrease in strength is more abrupt for the mixtures (18B and 20B) using 20% of 9.5 mm [Fig. 9(b)]. From the results, it can be inferred that for SCC mixtures using Type I/II cement, the w/c ratio may be less than 0.35 to meet the required

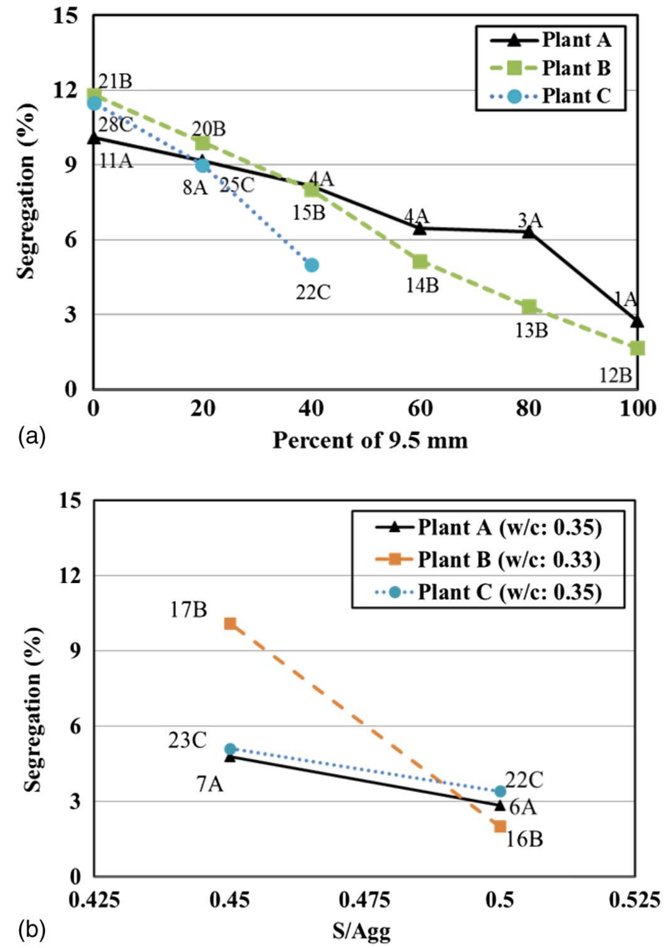


Fig. 8. Percent segregation analysis: (a) column segregation results based on blending configurations; (b) percent segregation for S/Agg 0.45–0.50

strength shown in Table 4 for SCC PSC girder fabrication. It should be noted that the testing matrix for cement Type III mixtures did not have variability in w/c ratios.

The compressive strength for all the mixtures at 28 days was above the required 49 MPa, as shown in Fig. 10. Similar to the results for 16 h strength, Plant A mixes had higher strength than those from Plants B and C. It appears that 28-day compressive strength for Plant A is almost proportional to the percent of 9.5 mm, though the relationship is the opposite to what occurred for strength at 16 h. For Plant B, this figure shows that the compressive strength decreased as the percent of 9.5 mm aggregate increased for both the 16-h and 28-day results. At 0 and 20% of 9.5 mm, the compressive strength of both Plants A and B were similar, whereas for 40–100% of 9.5 mm, the difference in strength between Plants A and B mixes increased. Plant C mixes had lower 28-day compressive strength relative to the other plants, and the difference in strength can be attributed to the aggregate type as previously discussed.

Statistical Results

A multivariable regression model was created and simulated to statistically determine the significant mixture constituents on the tested mixture fresh and hardened properties. Five mixture constituent variables were considered in the statistical model, including percent of 9.5- and 19-mm coarse aggregate, content of fine aggregate, and

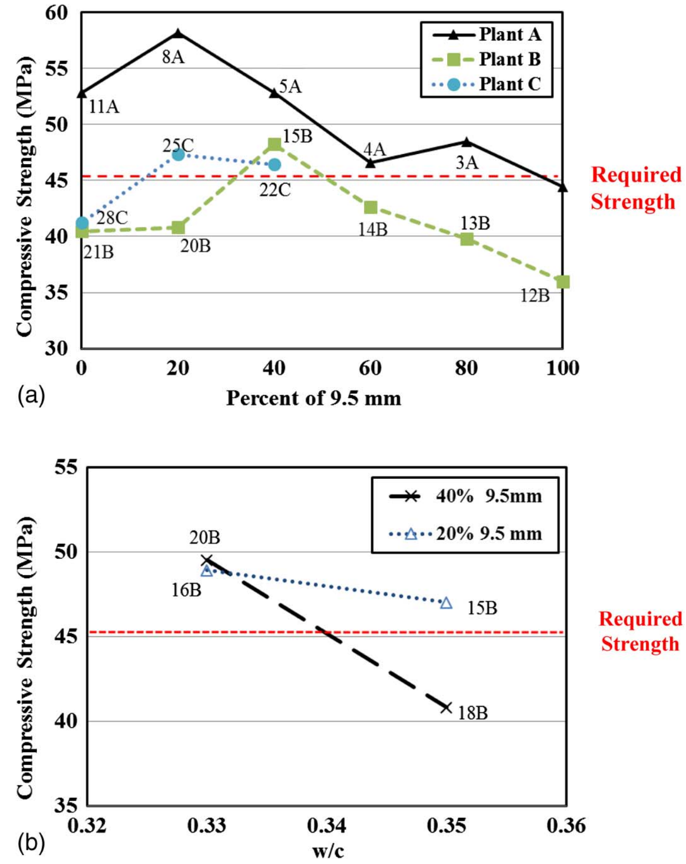


Fig. 9. Release compressive strength: (a) compressive strength for blending configurations; (b) compressive strength for Plant B using 0.33 and 0.35 w/c

dosages of HRWR and VMA. The selection of the mixture constituents was based on the ability of the local precasters to modify mixture constituents. For cost and practical reasons, aggregates and admixtures tend to be the primary alternative chosen by the local precasters to efficiently control the desired SCC quality. The standard level of significance was set at $\alpha = 0.05$, and the intercept was set to be zero for this analysis. The statistical models were validated by performing analysis of variance (ANOVA) in the multi-crossvalidation mode where *P*-values less than 0.05 were considered significant.

Table 9 shows the resulting *P*-value of each mixture constituent variable with respect to the fresh and hardened properties. Based on

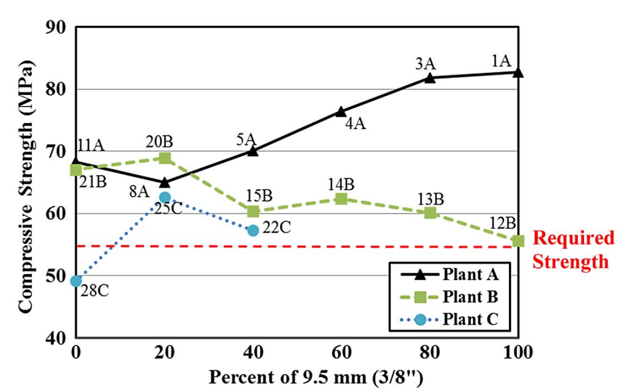


Fig. 10. Compressive strength at 28 days

Table 9. *P*-Values Obtained from the Regression Statistical Analysis to Evaluate Fresh and Hardened Properties of SCC

Parameter	Slump flow	J-ring	Column segregation	Compressive strength (16 h)	Compressive strength (28 days)
Coarse aggregate (9.5 mm)	0.227	0.352	**0.008**	0.830	0.653
Coarse aggregate (19 mm)	0.280	0.378	0.062	0.965	0.937
Fine aggregate	$\mathbf{3.8 \times 10^{-9}}$	$\mathbf{3.1 \times 10^{-6}}$	**0.001**	**0.001**	**0.026**
HRWR	0.052	0.171	0.282	0.193	0.118
VMA	0.278	0.273	0.307	0.528	0.394

Note: Bold indicates the variables with significant effect.

the investigation of the *P*-values, it was found that fine aggregate was the most significant variable affecting all the fresh and hardened properties for all the mixtures and that the content of 9.5-mm aggregate has a significant effect on segregation. It was not clear why only the content of 9.5 mm was significant, as it directly relates to the content of 19 mm. The reason why the content of fine aggregate considered statistically significant is that it has a direct impact on the viscosity of the mixture, resulting in the substantial change of slump flow, J-ring, and segregation.

Conclusions

The paper investigated the effect of material constituents on fresh and hardened properties of SCC mixtures to improve fabrication of SCC PSC girders. An experimental program considering different constituent materials and methods along with target values obtained from the survey and literature review was developed. The material constituents consist of type of cement and size and type of coarse aggregate, and testing methods include slump flow, VSI, J-ring, column segregation, and compressive strength. Experimental and statistical comparisons of the fresh and hardened properties among SCC mixtures made with different material constituents representative of different precast plants located in a different area in Wisconsin were performed. The following conclusions were drawn based on the experimental and statistical results:

1. Slump flow results showed that the mixtures made with river gravel (Plant C) achieved larger spread diameters than those mixes made with limestone (Plants A and B) due to the rounded shape of the river gravel, which resulted in less blockage compared to the flakiness and angular shape of the crushed limestone. Mixes from Plants B and C showed slump flow values close to or above the target value of 635 mm, while Plant A mixes had values below the target value, resulting in unsatisfactory flow ability.
2. Passing ability and filling capacity were evaluated using the results from slump flow and J-ring. As expected, the best passing ability results were seen by the mixtures of Plant A, which contained larger percentages of 9.5 mm. Most mixtures resulted in similar filling capacity with values above 80%; therefore, no effect was observed of the material constituents studied.
3. All mixtures exhibited acceptable segregation characteristics, though as the percent of 9.5 mm decreased, more segregation was seen. This was expected as large-size particles settle at a faster rate. Additional segregation was also observed for some mixtures using 0.45 S/Agg compared to those with 0.50 S/Agg due to lower viscosity.
4. The effects of blending aggregate sizes were mostly observed in segregation performance. Mixtures with 20, 40, and 60% of 9.5 mm indicated better performance compared to mixtures with either 0 or 100% of 9.5 mm.
5. Higher compressive strength was found in the mixtures of Plant A, which used Type III cement. It can be concluded from the results that the mixtures using crushed limestone developed higher compressive strength compared to those made of river gravel. For the mixtures made of cement Type I/II, it was observed that a change of w/c ranged from 0.35 to 0.33 considerably increased strength.
6. *P*-values obtained from the statistical analysis indicated that fine aggregate is the parameter having the most significant effect on the fresh and hardened properties, though aggregate size and blending were also found to affect segregation.

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