Self-Consolidating Concrete for Cast-in-Place Bridge Components

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 819

Self-Consolidating Concrete for Cast-in-Place Bridge Components

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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C O O P E R A T I V E   R E S E A R C H   P R O G R A M S

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The research reported herein was performed under NCHRP Project 18-16 by the University of Nebraska-Lincoln (UNL) and Iowa State University (ISU); Dr. George Morcous, Professor of Construction Engineering at UNL, was the principal investigator. The other authors of this report are Dr. Kejin Wang, Professor of Civil Engineering at ISU; Dr. Peter C. Taylor, Director of the National Concrete Pavement Technology Center at ISU; Dr. Surendra P. Shah, Consultant; Micheal Asaad, Research Assistant and Ph.D. Candidate at UNL; and Xuhao Wang, Post-Doctoral Associate at ISU.

FOREWORD

By Amir N. Hanna
Staff Officer
Transportation Research Board

This report presents recommended guidelines for the use of self-consolidating concrete (SCC) in cast-in-place highway bridge components. These guidelines address the selection of constituent materials, proportioning of concrete mixtures, testing methods, fresh and hardened concrete properties, production and quality control issues, and other aspects of SCC. The report also presents proposed changes to the AASHTO LRFD Bridge Design and Construction Specifications to address use of SCC for cast-in-place highway bridge components. The information contained in the report will guide materials and bridge engineers in evaluating, selecting, and specifying SCC mixtures for use in cast-in-place concrete bridge components, thereby facilitating construction, improving the working environment and safety, and reducing cost. The information contained in the report will be of immediate interest to state materials and bridge engineers and others involved in specifying and evaluating concrete mixtures for use in highway bridges and structures.

SCC is a specially proportioned hydraulic cement concrete that enables the fresh concrete to flow easily into the forms and around the reinforcement and prestressing steel without segregation. Use of this type of concrete for the manufacture of precast, prestressed concrete bridge elements has increased in recent years because it helps increase the rate of production and safety, reduce labor needs, and lower noise levels at manufacturing plants. However, use of cast-in-place SCC in bridge construction has been limited because of the lack of design and construction guidelines and concerns about certain design and construction issues that may influence the structural integrity of the bridge system.

NCHRP Project 18-12 (see *NCHRP Report 628: Self-Consolidating Concrete for Precast, Prestressed Concrete Bridge Elements*) focused on the application of SCC in precast, prestressed bridge elements; some of the findings of this research are applicable to cast-in-place concrete bridge components. However, use of SCC in cast-in-place applications requires the consideration of conditions other than the controlled conditions existing in precast concrete plants and the issues that are perceived to influence constructability, performance, and structural integrity of the bridge system. Thus, research was needed to address the factors that significantly influence the design, constructability, and performance of cast-in-place bridge components manufactured with SCC, such as workability, strength development, creep and shrinkage properties, bond to reinforcement, and durability. Research was also needed to develop guidelines for the use of SCC in these applications and to propose related changes to AASHTO LRFD Bridge Design and Construction Specifications.

Under NCHRP Project 18-16, "Self-Consolidating Concrete for Cast-in-Place Bridge Components," the University of Nebraska-Lincoln worked with the objectives of (1) developing guidelines for the use of self-consolidating concrete in cast-in-place concrete in highway bridge components and (2) recommending relevant changes to the AASHTO LRFD Bridge Design and Construction Specifications. To accomplish these objectives, the researchers reviewed available information on the use of SCC in structural applications and investigated its use in cast-in-place, concrete bridge components. The investigation included an extensive laboratory testing program that covered the types and ranges of materials used in SCC mixtures and considered the properties that affect constructability and performance. The project considered the use of SCC for cast-in-place concrete bridge substructure components (such as piers, pier caps, footings, abutment walls, and wing walls) and superstructure components (such as girders, stringers, floor beams, arches, diaphragms, connections, closure pours, rails, and concrete-filled tubes) but not for other bridge components (such as deep foundations, drilled shafts, bridge decks, and approach slabs). Based on this review and analysis of test results, the research proposed changes to the AASHTO LRFD Bridge Design and Construction Specifications (included as Attachment A) and guidelines for the use of SCC in cast-in-place bridge components (included as Attachment B). The proposed guidelines and changes to LRFD Bridge Design and Construction Specifications will be particularly useful to highway agencies because their use will help identify SCC mixtures that will provide the desired properties and performance and thus accrue the anticipated benefits.

Six appendices contained in the research agency's final report provide detailed information on the different aspects of the experimental program. These appendices are not published herein, but are available online at http://www.trb.org/Main/Blurbs/174472.aspx.

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Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.trb.org) retains the color versions.

SUMMARY

Self-Consolidating Concrete for Cast-in-Place Bridge Components

Research Significance

Self-consolidating concrete (SCC) is a specially proportioned hydraulic cement concrete that enables fresh concrete to flow easily into the forms and around steel reinforcement without segregation and without any mechanical consolidation. Use of this type of concrete in precast, prestressed bridge elements has increased in recent years because of the increased rate of production and safety, reduced labor needs, and lower noise levels at manufacturing plants. However, use of cast-in-place SCC has had limited application in bridge construction because of the lack of design and construction guidelines and concerns about certain design and construction issues that may influence the structural integrity of the bridge system. *NCHRP Report 628* (Khayat and Mitchell, 2009) focused on the application of SCC in precast, prestressed bridge elements; some of the findings are applicable to cast-in-place concrete bridge components, but use of SCC in cast-in-place applications requires the consideration of conditions other than the controlled conditions existing in precast concrete plants. NCHRP Project 18-16 was conducted to address the use of SCC in cast-in-place bridge applications.

Project Objectives and Scope

The objectives of this research were to develop guidelines for the use of SCC in cast-in-place concrete in highway bridge components and recommend relevant changes to the AASHTO LRFD Bridge Design and Construction Specifications. The research included the following:

- Identifying the properties of fresh, early-age, and hardened SCC that are relevant to cast-in-place bridge components and the factors that have significant influence on these properties.
- Developing criteria for evaluating the performance of SCC used in cast-in-place bridge substructure and superstructure components.
- Identifying quality control and quality assurance test methods for fresh SCC (at the ready-mixed plant and on site) and for hardened SCC.
- Evaluating the constructability of a full-scale, cast-in-place bridge pier and a post-tensioned box girder using SCC.
- Developing guidelines for the use of cast-in-place SCC in bridge construction.
- Proposing relevant changes to the 2014 AASHTO LRFD Bridge Design Specifications (7th edition) and the 2010 AASHTO LRFD Bridge Construction Specifications (3rd edition).

The project considered the use of SCC for cast-in-place concrete bridge substructure components (e.g., piers, pier caps, footings, abutment walls, and wing walls) and superstructure components (e.g., girders, stringers, floor beams, arches, diaphragms, connections, closure pours, rails, and concrete filled tubes) but not for other bridge components (e.g., deep foundations, drilled shafts, bridge decks, and approach slabs).

Organization of the Report

This report includes this summary, three chapters, and two attachments. Appendices A through F are available on the TRB website at http://www.trb.org/Main/Blurbs/174472.aspx. This summary presents an overview of the project and its major findings. Chapter 1 summarizes the approach used in conducting the literature review, experimental investigations, and full-scale testing; Chapter 2 discusses test results and their appraisal and interpretation; and Chapter 3 presents the research findings and recommendations for future research. Attachment A presents proposed changes to AASHTO LRFD Bridge Design and Construction Specifications and Attachment B presents proposed guidelines for use of SCC in cast-in-place bridge components. Appendices A through F provide further details on the reviewed literature and survey of state departments of transportation; material properties; fresh, early-age, and hardened concrete properties; and testing of full-scale bridge components.

Overview of the Project

An extensive literature review and a survey of U.S. transportation agencies were conducted to determine the properties of SCC that are relevant to the design and construction of cast-in-place bridge components, the appropriate test methods to evaluate these properties, and the associated target values/ranges. The SCC properties included fresh SCC properties (rheology, filling ability, passing ability, static stability, dynamic stability, and workability retention); early-age SCC properties (formwork pressure, heat of hydration, and time of setting); mechanical properties (compressive strength, modulus of elasticity, tensile strength, modulus of rupture, bond strength, and shear resistance); visco-elastic properties (drying shrinkage, restrained shrinkage, and creep); and durability properties (air void system characteristics and surface resistivity).

Fresh, early-age, and hardened concrete properties were evaluated in a laboratory investigation of forty SCC mixtures and six conventionally vibrated concrete (CVC) mixtures for comparison. The SCC mixtures were proportioned using two types of coarse aggregate: crushed limestone and natural gravel; three nominal maximum sizes of aggregate (NMSAs): ¾, ½, and ⅜ in.; three supplementary cementitious materials (SCMs) and one filler: 25% Class F fly ash, 25% Class C fly ash, 30% ground granulated blast-furnace slag (GGBFS), and 20% Class F fly ash plus 15% limestone powder (LSP); and two levels of slump flow: low (22 to 26 in.) and high (26 to 30 in.). The CVC mixtures were proportioned using the same two types of coarse aggregate and three NMSA used in the SCC mixtures. All CVC mixtures were proportioned with the same SCM (25% Class F fly ash) and medium slump (2 to 4 in.). All SCC and CVC mixtures were air-entrained and contained portland cement Type I/II.

The laboratory tests were conducted according to AASHTO or ASTM methods or according to methods reported in the literature when AASHTO or ASTM procedures were not available. Available test methods were adequate for characterizing SCC properties; no new test methods were developed. Measured properties of SCC mixtures were compared to AASHTO LRFD predicted values/ranges for CVC (current AASHTO LRFD Bridge Design and Construction Specifications do not address SCC) to determine whether AASHTO LRFD provisions for CVC would apply to SCC or whether changes should be proposed to accommodate SCC applications.

Constructability and structural performance of SCC mixtures were evaluated by fabricating and testing two full-scale bridge components (a bridge pier and a post-tensioned box girder) using four ready-mixed SCC mixtures to simulate field applications. Several SCC properties (e.g., formwork pressure, formed surface quality, and air void system) were evaluated when different placement methods and rates were used. Uniformity of SCC consolidation was evaluated by examining cores extracted at different locations in each component.

Research Findings

The following is a summary of the research findings. These findings were obtained for the materials and mixtures used in the project; other materials or mixtures may result in different findings.

- SCC mixtures with satisfactory properties for cast-in-place bridge construction could be proportioned with natural gravel or crushed limestone aggregates (NMSA of ⅜, ½, or ¾ in.), SCMs (Class F fly ash, Class C fly ash, or GGBFS), and fillers (limestone powder).
- Standard test methods, such as slump flow, T_{50}, J-ring, caisson test, visual stability index (VSI), hardened visual stability index (HVSI), penetration, and column segregation were adequate for characterizing the key workability properties of SCC. Slump flow, T_{50}, J-ring, VSI, and penetration tests were suited for job site quality assurance because of their simplicity, rapidness of assessment, and ability to be conducted with a single operator. Caisson, column segregation, flow trough, and HVSI tests were suitable for evaluating trial batches.
- Modifications were made to the flow trough test method used to evaluate the dynamic stability of cast-in-place SCC mixtures to enhance test reliability and ease of use.
- The rate of workability loss of SCC mixtures ranged from 3 to 9 in. per hr and was directly proportional to the initial slump flow but varied widely depending on the mixture composition, temperature, and type of chemical admixtures used.
- Time of initial setting of SCC mixtures ranged from 4 to 11 hr depending on the type of SCM/filler, temperature, and slump flow. SCC mixtures with high slump flow had a longer time of initial setting due to the retarding effects of the high-range water-reducing admixture (HRWRA). SCC mixtures that contained Class C fly ash had the longest time of setting, and those that contained Class F fly ash had the shortest time of setting.
- Temperature rise due to heat of hydration of SCC mixtures ranged from 20 to 40°F (not significantly different from that of CVC mixtures). A slight delay was observed in reaching the peak temperature of SCC mixtures depending on the type of SCM/filler; the longest delay was observed in SCC mixtures containing the Class C fly ash.
- The formwork pressure of SCC mixtures was slightly less than full hydrostatic pressure. The rate of SCC placement, thixotropic effects, and yield stress had significant effect on the maximum formwork pressure and its reduction with time.
- The ratios of compressive strength of SCC at 7, 14, and 56 days to the 28-day compressive strength was accurately predicted using the ACI 209 model developed for CVC.
- The modulus of elasticity (MOE) of SCC was slightly lower than predicted by AASHTO LRFD for CVC. Also, mixtures containing limestone aggregate showed a slightly higher MOE than mixtures containing gravel aggregate.
- The modulus of rupture (MOR) of SCC was within the range predicted by AASHTO LRFD for CVC. However, the splitting tensile strength of SCC was lower than predicted by AASHTO LRFD for CVC.
- The bond strength of deformed steel bars in SCC was lower than that in CVC for vertical bars, but comparable to that in CVC for horizontal bars. Also, the top-bar effect of horizontal bars in SCC decreased as the slump flow of SCC increased.
- The nominal shear resistance of SCC was accurately predicted by AASHTO LRFD for CVC, but the interface shear resistance of SCC with compressive strength less than 6 ksi was lower than predicted by AASHTO LRFD for CVC.

- Drying shrinkage of SCC was significantly higher than predicted by AASHTO LRFD for CVC. The type of SCM had a significant effect on drying shrinkage (e.g., SCC containing Class C fly ash or GGBFS exhibited higher drying shrinkage than SCC containing Class F fly ash).
- Restrained shrinkage of SCC depends on the type of SCM and NMSA (e.g., SCC containing Class C fly ash and/or NMSA of ⅜ in. exhibited higher cracking potential than that for SCC containing Class F fly ash and NMSA of ½ or ¾ in.).
- The creep coefficient of SCC was accurately predicted by AASHTO LRFD provisions for CVC (except for SCC containing 15% limestone powder as a filler, which showed higher creep strains).
- Surface resistivity and air void system parameters of SCC were within the ranges reported in the literature.
- SCC mixtures proportioned with high segregation resistance did not show signs of segregation under a free-fall height of 15 ft and free-flow distance of 20 ft in complex/highly congested sections.
- The formed surface of full-scale bridge components made of SCC has shown low surface void ratio and small surface void diameter. Flow direction during placement influenced the surface voids (e.g., flowing in a bottom-up direction resulted in less and smaller surface voids than flowing in a top-down direction).
- Limited testing of full-scale bridge components fabricated using SCC mixtures yielded structural capacities (i.e., flexure and shear resistance) that are different from those predicted by AASHTO LRFD specifications for CVC. The deformations and cracking patterns of these components appeared comparable to those reported in the literature for similar CVC components.

CHAPTER 1

Research Approach

1.1 Literature Review and Survey

An extensive literature review was conducted to determine the properties of self-consolidating concrete (SCC) that are relevant to the design and construction of cast-in-place bridge components and thus necessary to consider in the experimental investigation; these properties are shown in Figure 1-1. Also, a survey of 17 state departments of transportation was conducted to identify the constituent materials, test methods, and performance requirements that are relevant for cast-in-place bridge construction. Findings of the literature review and survey results are summarized in Appendix A.

1.2 Experimental Investigation

The experimental investigation was conducted on 40 normal-weight SCC mixtures containing two types of coarse aggregate (crushed limestone and natural gravel) with three nominal maximum sizes of aggregate (NMSAs) (¾, ½, and ⅜ in.), three types of supplementary cementitious materials (SCMs) (Class C fly ash, Class F fly ash, and ground granulated blast-furnace slag [GGBFS]), and one filler (limestone powder [LSP]). LSP was included in some mixtures because some earlier studies have indicated a possible synergistic effect/reaction with the C3A in the system that enhances the reactivity of the other constituents, such as cement and fly ash (Cost and Bohme, 2012; Beeralingegowda and Gundakalle, 2013; and Bucher, 2009).

Six normal-weight conventionally vibrated concrete (CVC) mixtures that represent AASHTO LRFD Class A(AE) and Class C(AE) concrete were included in the experimental investigation as examples of mixtures commonly used in cast-in-place bridge design and construction (AASHTO, 2014; AASHTO, 2010). All SCC and CVC mixtures had portland cement type I/II, AASHTO M 6 natural sand, and were air entrained. Table 1-1 lists the chemical composition of the cement, SCMs, and filler, and Figure 1-2 shows the particle size distribution of the fine and coarse aggregates used in the experimental investigation (details of the physical and chemical properties of the constituent materials are presented in Appendix B). The performance of CVC mixtures was compared to the performance of SCC mixtures especially when AASHTO LRFD evaluation criteria were not available. Table 1-2 lists the combination of constituent materials considered in the experimental investigation, each of which represents a concrete mixture for a total of 46 mixtures (40 SCC and 6 CVC mixtures). The procedures for proportioning the SCC mixtures and testing the fresh, early-age, and hardened concrete properties are described in the following sections.

1.2.1 Proportioning SCC Mixtures

Proportioning SCC mixtures is different from proportioning CVC mixtures because workability targets, rather than compressive strength, usually control the proportioning of the mixture. Workability targets were identified for the different geometric characteristics of bridge components and production and placement conditions. The geometric characteristics of a bridge component include length, depth, thickness, shape intricacy, formed surface quality, and level of reinforcement (i.e., intensity and spacing). Production and placement conditions include mixing energy, transport time, placement technique, and temperature. For simplicity, each of the geometric characteristics was classified as either "high" or "low." Table 1-3 shows the value/definition used to describe the classes of each geometric characteristic based on the literature (Daczko, 2012; EFNARC, 2005). Similarly, two classes were used to describe each of the three key workability properties of SCC: filling ability (FA), segregation resistance (SR), and passing ability (PA). Table 1-4 shows the value/range of the parameters used to describe the two classes of each workability property based on the literature (EFNARC, 2005; Daczko, 2012; ACI 237, 2007; Khayat and Mitchell, 2009); these values/ranges might be adjusted according to the production and placement conditions (PCI, 2003).

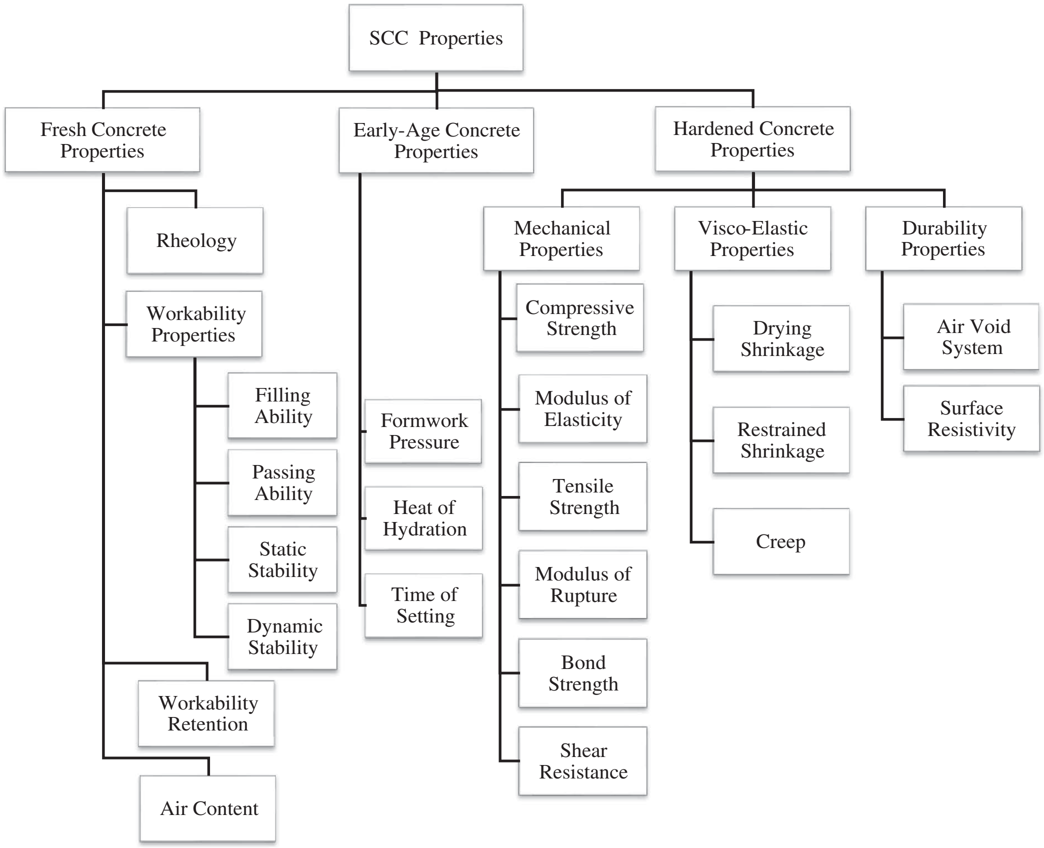


Figure 1-1. SCC properties considered in the experimental investigation.

Table 1-1. Chemical composition of cement, SCM, and filler.

Component	Component Content by Percentage for				
	Type I/II Cement	Class C Fly Ash	Class F Fly Ash	GGBFS	Limestone Powder (coarse)
SiO_2	20.10	42.46	50.87	31.63	1.56
Al_2O_3	4.44	19.46	20.17	11.30	–
Fe_2O_3	3.09	5.51	5.27	0.34	0.48
SO_3	3.18	1.20	0.61	3.30	1.77
CaO	62.94	21.54	15.78	41.31	52.77
MgO	2.88	4.67	3.19	10.77	0.48
Na_2O	0.10	1.42	0.69	0.19	0.03
K_2O	0.61	0.68	1.09	0.36	0.09
P_2O_5	0.06	0.84	0.44	0.02	–
TiO_2	0.24	1.48	1.29	0.56	–
SrO	0.09	0.32	0.35	0.04	–
BaO	–	0.67	0.35	–	–
LOI	2.22	0.19	0.07	–	42.50

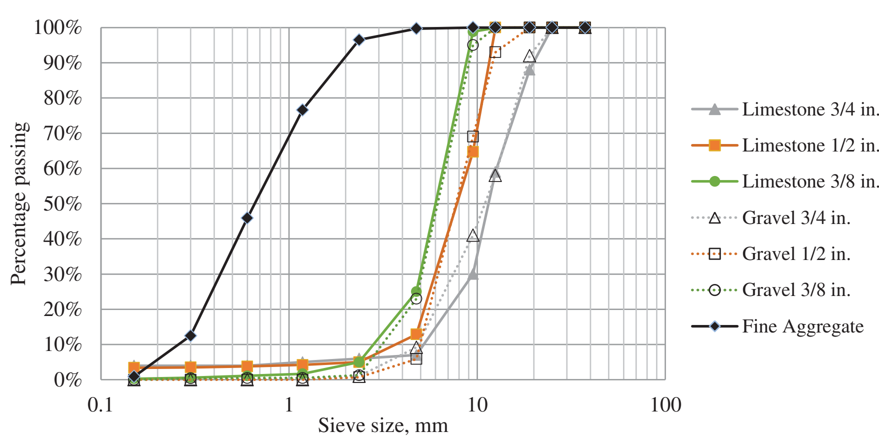


Figure 1-2. Particle size distribution of fine and coarse aggregates.

Table 1-2. Constituent materials of SCC and CVC mixtures.

Coarse Aggregate		SCC Mixtures								CVC Mixtures	Number of Mixtures
Type	NMSA (in.)	Cement Type I/II+ 25% Class C Fly Ash		Cement Type I/II+ 25% Class F Fly Ash		Cement Type I/II+ 30% GGBFS		Cement Type I/II+ 20% Class F Fly Ash + 15% LSP		Cement Type I/II + 25% Class F Fly Ash	
		Low Slump Flow	High Slump Flow	Low Slump Flow	High Slump Flow	Low Slump Flow	High Slump Flow	Low Slump Flow	High Slump Flow		
Crushed Limestone (AASHTO M 43)	3/4 (No. 67)	X	X	X	X	X	X	X	X	X	9
	1/2 (No. 78)	X	X	X	X	X	X	X	X	X	9
	3/8 (No. 8)		X		X		X		X	X	5
Natural Gravel (AASHTO M 43)	3/4 (No. 67)	X	X	X	X	X	X	X	X	X	9
	1/2 (No. 78)	X	X	X	X	X	X	X	X	X	9
	3/8 (No. 8)		X		X		X		X	X	5
Number of Mixtures		4	6	4	6	4	6	4	6	6	46

Table 1-3. Classes of component geometric characteristics.

Component Geometric Characteristic	Class	Value/Definition
Length	Low	≤ 33 ft
	High	> 33 ft
Depth	Low	≤ 16 ft
	High	> 16 ft
Thickness	Low	≤ 8 in.
	High	> 8 in.
Shape Intricacy	Low	Concrete flows in a single direction
	High	Concrete flows around corners and cutouts
Formed Surface Quality	Low	Unexposed to the traveling public
	High	Exposed to the traveling public
Level of Reinforcement	Low	Large spacing between bars (≥ 3 in.)
	High	Small spacing between bars (< 3 in.)

Table 1-4. Classes of SCC workability properties.

Workability Property	Class	Value/Range	Application
Filling Ability (FA)	FA1	22 in. ≤ Slump Flow < 26 in.	Simple sections
	FA2	26 in. ≤ Slump Flow ≤ 30 in.	Complex sections or high formed surface quality
Passing Ability (PA)	PA1	80% > Filling Capacity ≥ 70% 2 in. < J-Ring ΔD ≤ 4 in. 0.6 in. < J-Ring ΔH ≤ 0.8 in.	Wide spacing between reinforcing bars
	PA2	Filling Capacity ≥ 80% J-Ring ΔD ≤ 2 in. J-Ring ΔH ≤ 0.6 in.	Narrow spacing between reinforcing bars
Segregation Resistance (SR)	SR1	10% < Column Segregation ≤ 15% 0.5 in. < Penetration ≤ 1 in. VSI = 1	Short or shallow components
	SR2	Column Segregation ≤ 10% Penetration ≤ 0.5 in. VSI = 0	Long or deep components

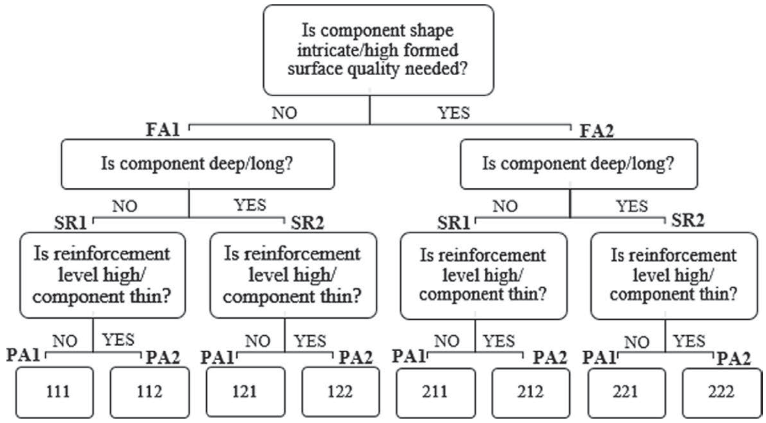


Figure 1-3. Process for determining workability targets.

Figure 1-3 illustrates the process for selecting the workability target value/range for a specific bridge component based on its geometric characteristics. This process results in a three-digit identification (one of the eight identifications shown at the bottom of Figure 1-3) that describes the desired target workability with respect to FA, SR, and PA classes. For example, the 111 identification indicates a mixture with the workability properties FA1, SR1, and PA1. Table 1-5 shows the proposed workability targets for examples of substructure and superstructure bridge components; these workability targets were used to proportion SCC mixtures for the experimental investigation. In addition, requirements for hardened concrete properties, such as compressive strength and air void system, were suggested based on the survey findings and were

Table 1-5. Proposed workability targets for examples of cast-in-place bridge components.

Component Category	Bridge Component	Component Geometric Characteristics						SCC Workability Targets	
		Length	Depth	Thickness	Shape Intricacy	Formed Surface Quality	Level of Reinforcement	Workability Property Classes*	ID
Substructure	Footing	Low	Low	High	Low	Low	Low	FA1, SR1, PA1	111
	Pile Cap	Low	Low	High	Low	Low	High	FA1, SR1, PA2	112
	Wing Wall	Low	Low	High	Low	Low	Low	FA1, SR1, PA1	111
	Abutment Wall	High	High	High	Low	Low	Low	FA1, SR2, PA1	121
	Pier Wall	Low	High	High	High	High	Low	FA2, SR2, PA1	221
	Pier Column	Low	High	High	Low	High	High	FA2, SR2, PA2	222
	Strut or Tie	Low	Low	High	Low	High	Low	FA2, SR1, PA1	211
	Pier Cap	Low	Low	High	Low	High	High	FA2, SR1, PA2	212
Superstructure	Box Girder	High	Low	Low	High	High	High	FA2, SR2, PA2	222
	Stringer	Low	Low	High	Low	Low	High	FA1, SR1, PA2	112
	Floor Beam	Low	Low	High	Low	Low	Low	FA1, SR1, PA1	111
	Girder	High	Low	Low	Low	High	High	FA2, SR2, PA2	222
	Arch	High	High	High	Low	High	Low	FA2, SR2, PA1	221

* For long/deep components, SR1 could be acceptable if free-fall height/free-travel distance are controlled (e.g., tremie pipe).

considered in proportioning the SCC mixtures. Also, the properties of constituent materials, such as aggregate shape, angularity and absorption, and SCM/filler type and fineness, could affect the proportioning of the mixtures.

Several approaches for proportioning SCC mixtures reported in the literature were reviewed and evaluated (Okamura and Ozawa, 1995; EFNARC, 2002; Bui, Akkaya, and Shah, 2002; PCI, 2003; GRACE, 2005; ACI 237, 2007; Koehler and Fowler, 2007; Domone, 2009; Kheder and Al Jadiri, 2010). The mixture proportioning procedure for SCC proposed by Koehler and Fowler (2007) was chosen for cast-in-place bridge application because it considers the effect of aggregate gradation, shape, and angularity and uses standard workability test methods to identify necessary parameters. However, consideration was given to the water content requirement for different NMSAs proposed in ACI 211 (2008); and the powder content and aggregate volume recommended in ACI 237 (2007). CVC mixtures were proportioned according to ACI 211.4R-08 procedures.

The selected SCC mixture proportioning procedure uses the 0.45 power curve (Shilstone, 1990) to determine the sand-to-aggregate (S/A) ratio that provides the optimum combined gradation of fine and coarse aggregates. This gradation produces a high packing density, reduces the demand for high-range water-reducing admixture (HRWRA), and improves plastic viscosity. The optimal S/A ratios for the mixtures used in the project were 0.45 for ¾ in. NMSA, 0.47 for ½ in. NMSA, and 0.5 for ⅜ in. NMSA (more information on this procedure is provided in Attachment B).

Tables 1-6 and 1-7 show the proportions of SCC and CVC mixtures containing limestone and gravel aggregate, respectively, used in the experimental investigation. Aggregate weights shown in these tables were calculated using saturated surface dry conditions. The unit weight measured for the mixtures ranged from 135 to 146 lb/ft^3, which meets the AASHTO LRFD definition for normal-weight concrete. The weight of the limestone powder was included in the total powder content and in calculating the water/powder (W/P) ratio. Table 1-8 lists the proposed test methods, test standard/source, target values/ranges, and time(s) of testing, which were selected based on the literature review findings and current practices of state departments of transportation. Table 1-9 lists the properties tested and the number of specimens for each test for the mixtures containing one type of aggregate; the same test matrix was conducted for the mixtures containing the other type of aggregate.

1.2.2 Fresh Concrete Properties

Rheology

Rheological properties of all SCC and CVC mixtures were characterized using mortar and concrete rheometers (one sample for each rheometer). Mortar samples were sieved using a No. 4 sieve and tested using a mortar rheometer according to ASTM C1749 to determine the Bingham model parameters—dynamic yield stress and plastic viscosity (ACI 237, 2007). Other rheological properties, such as static yield stress and thixotropy, were also determined using the mortar rheometer. The sample was placed in a 2 in. diameter by 4 in. tall cylindrical vessel and sheared by a 0.6 × 1.2 in. vane spindle using a predetermined loading history. The rheological properties of the mortar were determined from the shear stress versus shear rate relationship.

For the concrete rheometer, each concrete sample was poured in a bowl for testing using an H-shaped impeller (Hu and Wang, 2011). To obtain a uniform sample, the concrete sample was pre-sheared at 0.2 rev/sec for 25 sec, stopped for 25 sec, loaded for 100 sec by increasing impeller speed from 0 to 1 rev/sec, and finally unloaded for 100 sec by decreasing impeller speed to 0. Basic concrete rheological properties (i.e., yield stress and viscosity) were determined from the flow curve for each sample obtained by plotting the torque versus speed.

Workability Properties

The key workability properties of SCC mixtures are FA, PA, and stability (static and dynamic). These properties (except dynamic stability) were evaluated using the standard test method (no standard test method is available for dynamic stability).

The FA of SCC mixtures was determined according to the slump flow test method (AASHTO T 347) using the inverted mold procedure. The average final diameter of SCC spread in two perpendicular directions (slump flow) and the time it takes the outer edge of concrete to reach the 20 in. diameter mark on the base plate (T_{50}) were determined.

The PA of all SCC mixtures was determined using the J-ring test method (AASHTO T 345) and described by two parameters: ΔD—the difference between the slump flows measured in restrained and unrestrained conditions (i.e., with and without J-ring) and ΔH—the difference between the height of the concrete patty in the middle of the J-ring and the average height at four points around the perimeter of the J-ring.

The caisson test method (AASHTO T 349) was used to measure the filling capacity of SCC, which is the ability of fresh SCC to fill the forms while passing through cross bars located at 2 in. spacing in the horizontal and vertical directions without segregation. This test is suited for reinforced concrete sections with congested reinforcement.

The static stability of SCC mixtures was determined using four test methods: penetration (ASTM C1712), column segregation (ASTM C1610), visual stability index (VSI) (AASHTO T 351), and hardened visual stability index (HVSI) (AASHTO PP 58). The penetration test was conducted twice: one time

Table 1-6. Proportions of SCC and CVC mixtures containing limestone aggregate.

Mixture Type	SCC Mixtures																				CVC Mixtures		
SCMs/Fillers	**25% Class C Fly Ash**					**25% Class F Fly Ash**					**30% GGBFS**					**20% Class F Fly Ash + 15% LSP**					**25% Class F Fly Ash**		
Flowability	**Low slump flow**		**High slump flow**			**Low slump flow**		**High slump flow**			**Low slump flow**		**High slump flow**			**Low slump flow**		**High slump flow**			**2 - 4 in. slump**		
NMSA, in.	**3/4**	**1/2**	**3/4**	**1/2**	**3/8**	**3/4**	**1/2**	**3/4**	**1/2**	**3/8**	**3/4**	**1/2**	**3/4**	**1/2**	**3/8**	**3/4**	**1/2**	**3/4**	**1/2**	**3/8**	**3/4**	**1/2**	**3/8**
Mixture ID	**111**	**121**	**211**	**221**	**222**	**111**	**121**	**211**	**221**	**222**	**111**	**121**	**211**	**221**	**222**	**111**	**121**	**211**	**221**	**222**	**No. 67**	**No. 78**	**No. 8**
Cement Type I/II, lb/cy	531	535	568	572	587	531	535	568	572	587	521	525	539	543	558	456	460	488	491	504	494	553	572
SCM, lb/cy	177	178	189	191	196	177	178	189	191	196	223	225	231	233	239	140	141	150	151	155	165	184	191
Filler, lb/cy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	105	106	113	113	116	0	0	0
Coarse Agg., lb/cy	1,542	1,462	1,518	1,439	1,334	1,542	1,462	1,518	1,439	1,334	1,542	1,462	1,530	1,450	1,345	1,542	1,462	1,518	1,439	1,334	1,674	1,485	1,350
Natural Sand, lb/cy	1,262	1,297	1,242	1,276	1,334	1,262	1,297	1,242	1,276	1,334	1,262	1,297	1,252	1,286	1,345	1,262	1,297	1,242	1,276	1,334	1,193	1,271	1,356
Water, lb/cy	280	295	280	295	305	280	295	280	295	305	280	295	280	295	305	280	295	280	295	305	280	295	305
HRWRA, oz/cwt	12.0	14.0	12.0	16.0	13.0	6.0	4.0	8.0	8.0	13.0	12.0	10.0	18.0	16.0	15.0	11.0	9.0	12.0	12.0	15.0	0.0	0.0	0.0
VMA, oz/cwt	0.0	0.0	6.0	0.0	0.0	3.0	0.0	3.0	6.0	0.0	0.0	0.0	3.0	3.0	0.0	0.0	0.0	3.0	6.0	0.0	0.0	0.0	0.0
AEA, oz/cwt	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Total Weight, lb/cy	3,792	3,767	3,797	3,772	3,756	3,792	3,767	3,797	3,772	3,756	3,828	3,803	3,832	3,807	3,792	3,786	3,761	3,790	3,765	3,749	3,806	3,788	3,774
Total Aggregate, lb/cy	2,804	2,759	2,760	2,714	2,669	2,804	2,759	2,760	2,714	2,669	2,804	2,759	2,782	2,737	2,691	2,804	2,759	2,760	2,714	2,669	2,867	2,756	2,706
Total Powder, lb/cy	708	713	757	763	783	708	713	757	763	783	744	750	770	776	797	702	707	751	756	776	659	738	763
W/P Ratio	0.40	0.41	0.37	0.39	0.39	0.40	0.41	0.37	0.39	0.39	0.38	0.39	0.36	0.38	0.38	0.40	0.42	0.37	0.39	0.39	0.43	0.40	0.40
S/A Ratio	0.45	0.47	0.45	0.47	0.50	0.45	0.47	0.45	0.47	0.50	0.45	0.47	0.45	0.47	0.50	0.45	0.47	0.45	0.47	0.50	0.42	0.46	0.50
Paste Volume %	37.0%	38.0%	38.0%	39.0%	40.0%	37.0%	38.0%	38.0%	39.0%	40.0%	37.0%	38.0%	37.5%	38.5%	39.5%	37.0%	38.0%	38.0%	39.0%	40.0%	36.0%	38.5%	39.6%
Coarse Agg. Vol. %	34.4%	32.6%	33.9%	32.1%	29.8%	34.4%	32.6%	33.9%	32.1%	29.8%	34.4%	32.6%	34.1%	32.4%	30.0%	34.4%	32.6%	33.9%	32.1%	29.8%	37.4%	33.1%	30.1%

AEA = air-entraining admixture

Table 1-7. Proportions of SCC and CVC containing gravel aggregate.

Mixture Type	SCC Mixtures																				CVC Mixtures		
SCMs/Fillers	**25% Class C Fly Ash**					**25% Class F Fly Ash**					**30% GGBFS**					**20% Class F Fly Ash + 15% LSP**					**25% Class F Fly Ash**		
Flowability	**Low slump flow**		**High slump flow**			**Low slump flow**		**High slump flow**			**Low slump flow**		**High slump flow**			**Low slump flow**		**High slump flow**			**2 - 4 in. slump**		
NMSA, in.	**3/4**	**1/2**	**3/4**	**1/2**	**3/8**	**3/4**	**1/2**	**3/4**	**1/2**	**3/8**	**3/4**	**1/2**	**3/4**	**1/2**	**3/8**	**3/4**	**1/2**	**3/4**	**1/2**	**3/8**	**3/4**	**1/2**	**3/8**
Mixture ID	**111**	**121**	**211**	**221**	**222**	**111**	**121**	**211**	**221**	**222**	**111**	**121**	**211**	**221**	**222**	**111**	**121**	**211**	**221**	**222**	**No. 67**	**No. 78**	**No. 8**
Cement Type I/II, lb/cy	494	498	568	572	587	494	498	568	572	587	485	489	539	543	558	440	444	488	491	504	459	516	534
SCM, lb/cy	165	166	189	191	196	165	166	189	191	196	208	209	231	233	239	135	137	150	151	155	153	172	178
Filler, lb/cy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	102	102	113	113	116	0	0	0
Coarse Agg., lb/cy	1,580	1,497	1,530	1,450	1,344	1,580	1,497	1,530	1,450	1,344	1,580	1,497	1,543	1,462	1,355	1,567	1,486	1,530	1,450	1,344	1,674	1,485	1,350
Natural Sand, lb/cy	1,292	1,328	1,252	1,286	1,344	1,292	1,328	1,252	1,286	1,344	1,292	1,328	1,262	1,296	1,355	1,282	1,317	1,252	1,286	1,344	1,277	1,358	1,455
Water, lb/cy	280	295	280	295	305	280	295	280	295	305	280	295	280	295	305	280	295	280	295	305	260	275	285
HRWRA, oz/cwt	5.0	5.0	9.0	5.0	8.0	7.0	4.0	7.0	5.0	5.5	6.0	5.0	10.0	7.0	7.5	3.0	3.0	6.0	7.5	6.0	0.0	0.0	0.0
VMA, oz/cwt	0.0	0.0	3.0	0.0	3.0	0.0	0.0	2.0	3.0	3.0	0.0	0.0	3.0	0.0	0.0	0.0	0.0	2.0	3.0	0.0	0.0	0.0	0.0
AEA, oz/cwt	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Total Weight, lb/cy	3,811	3,784	3,819	3,793	3,776	3,811	3,784	3,819	3,793	3,776	3,844	3,818	3,854	3,829	3,812	3,807	3,781	3,813	3,787	3,769	3,823	3,806	3,803
Total Aggregate, lb/cy	2,872	2,825	2,782	2,736	2,688	2,872	2,825	2,782	2,736	2,688	2,872	2,825	2,805	2,758	2,711	2,849	2,803	2,782	2,736	2,688	2,951	2,843	2,805
Total Powder, lb/cy	659	664	757	763	783	659	664	757	763	783	692	698	770	776	797	677	683	751	756	776	612	688	713
W/P Ratio	0.43	0.44	0.37	0.39	0.39	0.43	0.44	0.37	0.39	0.39	0.40	0.42	0.36	0.38	0.38	0.41	0.43	0.37	0.39	0.39	0.43	0.40	0.40
S/A Ratio	0.45	0.47	0.45	0.47	0.50	0.45	0.47	0.45	0.47	0.50	0.45	0.47	0.45	0.47	0.50	0.45	0.47	0.45	0.47	0.50	0.43	0.48	0.52
Paste Volume %	36.0%	37.0%	38.0%	39.0%	40.0%	36.0%	37.0%	38.0%	39.0%	40.0%	36.0%	37.0%	37.5%	38.5%	39.5%	36.5%	37.5%	38.0%	39.0%	40.0%	33.9%	36.3%	37.4%
Coarse Agg. Vol. %	34.7%	32.9%	33.6%	31.9%	29.5%	34.7%	32.9%	33.6%	31.9%	29.5%	34.7%	32.9%	33.9%	32.1%	29.8%	34.5%	32.7%	33.6%	31.9%	29.5%	37.4%	33.1%	30.1%

AEA = air-entraining admixture

Table 1-8. SCC test methods and target values/ranges.

	Property	Test Method	Standard/Source	Target Values/Ranges	Time(s) of Testing
Fresh Concrete Properties	**Rheology**	Mortar Rheometer	ASTM C1749	For Comparison Only	Immediate
		Concrete Rheometer	Hu and Wang (2011)	For Comparison Only	Immediate
	Filling Ability	Slump Flow and T_{50}	AASHTO T 347	22 - 30 in., 1 - 6 sec	Immediate
	Passing Ability	J-Ring	AASHTO T 345	$\Delta D \leq 2$ in., $\Delta H \leq 0.6$ in.	Immediate
		Caisson	AASHTO T 349	≥ 70%	Immediate
	Static Stability	Visual Stability Index (VSI)	AASHTO T 351	0 , 1	Immediate
		Hardened Visual Stability Index (HVSI)	AASHTO PP 58	0 , 1	28 days
		Column Segregation	ASTM C1610	≤ 15%	Immediate
		Penetration	ASTM C1712	≤ 1 in.	Immediate
	Dynamic Stability	Flow Trough	Lange, et al. (2008)	≤ 20%	Immediate
	Workability Retention	Slump Flow Retention	Khayat and Mitchell (2009)	≤ 2.5 in. per 30 min	30, 60, 90 min
	Air Content	Pressure Method	AASHTO T 152	6 ± 1.5%	Immediate
Early-Age Concrete Properties	**Formwork Pressure**	Pressure Vessel	Assaad, et al. (2003)	$P <= P_{hydrostatic}$	1 - 12 hr
	Heat of Hydration	Isothermal Calorimetry	ASTM C1702	For Comparison Only	0 - 24 hr
		Semi-Adiabatic Calorimetry	RILEM 119-TCE	For Comparison Only	0 - 24 hr
	Time of Setting	Penetration Resistance	AASHTO T 197	For Comparison Only	3 - 12 hr
Hardened Concrete Properties	**Compressive Strength**	Compressing 4x8 in. Cylinders	AASHTO T 22	min 4,000 - 6,000 psi	7, 14, 28, 56 days
	Modulus of Elasticity	Compressometer for 4x8 in. Cylinders	ASTM C469	AASHTO LRFD 5.4.2.4	28 days
	Tensile Strength	Splitting 4x8 in. Cylinders	AASHTO T 198	AASHTO LRFD 5.4.2.7	28 days
	Modulus of Rupture	Simple Beam with Third-Point Loading	AASHTO T 97	AASHTO LRFD 5.4.2.6	28 days
	Bond Strength	Pull-out of Vertical Bars	RILEM/CEB/FIB. 1970	Comparison to CVC	28 days
		Pull-out of Horizontal Bars	RILEM/CEB/FIB. 1970	Comparison to CVC	28 days
	Shear Resistance	Push-off Test	Mattock and Hawkins, 1972	AASHTO LRFD 5.8.4.1	28 days
		Beam Test	Lachemi, et al., 2005	AASHTO LRFD 5.8.3.3	28 days
	Shrinkage	Drying Shrinkage	AASHTO T 160	AASHTO LRFD 5.4.2.3.3	7, 14, 28, 56 days
		Restrained Shrinkage	ASTM C1581	Comparison to CVC	28 days
	Creep	Two 6x12 in. Cylinders	ASTM C512	AASHTO LRFD 5.4.2.3.2	28 - 365 days
	Air Void System	Linear-Traverse Method	ASTM C457	For Comparison Only	28 days
	Surface Resistivity	Four Point Wenner Array Probe	AASHTO TP 95	For Comparison Only	28 days

while performing the slump flow test and another time while performing the J-ring test as recommended in practice. The HVSI test was conducted on three hardened concrete cylinders for quality assurance.

The flow trough test was selected to evaluate the dynamic stability of SCC mixtures because of its simplicity (Lange et al., 2008). Twelve high slump flow SCC mixtures with ¾, ½, and ⅜ in. nominal maximum size limestone aggregate were tested using the original flow trough test. The test was then modified, and 12 high slump flow SCC mixtures with ¾, ½, and ⅜ in. nominal maximum size gravel aggregate were tested using the modified flow trough test. The original trough is made of wood with internal dimensions of 6 × 6 × 72 in. and an inclined angle of 7°. SCC samples are taken using 4 × 8 in. cylinders before and after flowing in the trough, and the paste is washed on a No. 4 sieve. The dynamic segregation index is determined from change in coarse aggregate content between the two samples (similar to the column segregation procedure). Two modifications were proposed to make the test more operator friendly and enhance the sampling quality. These modifications, shown in Figure 1-4, include using 6 in. diameter PVC half pipe inside the form to accelerate the concrete flow and reduce the amount of concrete needed to conduct the test and using 6 in. × 6 in. cylinders to collect concrete before and after flowing, which simplifies the sampling process and increases the sample size. With these modifications,

Table 1-9. Test matrix for SCC and CVC mixtures for each aggregate type.

	Mixtures Type	SCC Mixtures																				CVC Mixtures		
	SCMs/Fillers	25% Class C Fly Ash					25% Class F Fly Ash					30% GGBFS					20% Class F Fly Ash + 15% LSP					25% Class F Fly Ash		
	Flowability	Low slump flow		High slump flow			Low slump flow		High slump flow			Low slump flow		High slump flow			Low slump flow		High slump flow			2 - 4 in. slump		
	NMSA, in.	3/4	1/2	3/4	1/2	3/8	3/4	1/2	3/4	1/2	3/8	3/4	1/2	3/4	1/2	3/8	3/4	1/2	3/4	1/2	3/8	3/4	1/2	3/8
	Mixture ID	111	121	211	221	222	111	121	211	221	222	111	121	211	221	222	111	121	211	221	222	No. 67	No. 78	No. 8
Fresh Concrete Properties	Rheology (Mortar rheometer)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Rheology (Concrete rheometer)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Filling Ability (Slump flow)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1			
	Passing Ability (J-Ring)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1			
	Passing Ability (Caisson)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1			
	Static Stability (VSI)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1			
	Static Stability (HVSI)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3			
	Static Stability (Column segregation)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1			
	Static Stability (Penetration)	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2			
	Dynamic Stability (Flow trough)			1	1	1			1	1	1			1	1	1			1	1	1			
	Workability Retention**		3		3			3		3			3		3			3		3				
	Air Content (Pressure method)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Early-Age Concrete Properties	Formwork Pressure		1	1		1		1	1		1		1	1		1		1	1		1	1	1	1
	Heat of Hydration (Isothermal)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Heat of Hydration (Adiabatic)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Time of Setting		1		1			1		1			1		1			1		1			1	
Hardened Concrete Properties	Compressive Strength	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
	Splitting Strength	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	Modulus of Rupture	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	Modulus of Elasticity	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	Bond Strength (Pull-out of vertical bars)								3	3	3											3	3	3
	Bond Strength (Pull-out of horizontal bars)*							18		18													18	
	Shear Resistance (Push-off)								2	2	2											2	2	2
	Shear Resistance (Beam test)*							6		6													6	
	Drying Shrinkage	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	Restrained Shrinkage	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	Creep					2					2					2					2			2
	Air Void System	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	Surface Resistivity	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3

Shaded cells indicate the mixtures tested for the corresponding property and the number inside each cell represents the number of tested specimens.

* Test was conducted on ready-mixed concrete mixtures containing limestone aggregate only

** Test was conducted on mixtures containing limestone aggregate only

Figure 1-4. Original (left) and modified (right) flow troughs used for evaluating dynamic stability.

the test has shown higher repeatability than the original test. Figure 1-5 shows a sketch of the modified flow trough with dimensions.

Workability Retention

The rate of workability loss was determined for eight SCC mixtures containing ½ in. nominal maximum size crushed limestone aggregate, four different SCM/fillers, and two levels of flowability. The slump flow test (AASHTO TP 74) was conducted at 8, 30, 60, and 90 minutes after adding the water to the mixtures (Khayat and Mitchell, 2009). The relationship between initial slump flow and rate of losing slump flow with time was determined to evaluate the effect of initial slump flow on workability retention.

1.2.3 Early-Age Concrete Properties

Formwork Pressure

The lateral pressure of concrete was monitored for CVC mixtures and a set of SCC mixtures with different rheological properties using the device shown in Figure 1-6. The device consists of a 3 ft tall, 8-in. diameter PVC rigid pipe with removable steel end caps. Three flush diaphragm pressure sensors were installed along the side of the pipe to measure the pressure distribution over the height of the column. An air pressure gauge and an air valve were installed at the top cap to increase the air pressure at the top portion of the concrete column (Assaad, Khayat, and Mesbah, 2003). Approximately 40 minutes after mixing, concrete was poured in the pipe at a rate of 6 in./min to simulate a common concrete placement rate in column applications of 30 ft/hr. The CVC mixtures were consolidated with an internal vibrator in 12 in. lifts; no mechanical consolidation was used for the SCC mixtures. When the concrete was filled up to 12 in. above the top sensor, air was pumped into the pipe at the same rate up to 30 psi to simulate 30 ft of concrete head. The pressure at each sensor was recorded every minute until the lateral pressure reached a constant value. The ratio of maximum lateral pressure to hydrostatic pressure was compared for the different concrete mixtures to evaluate the effects of time and rheological properties on formwork pressure.

Heat of Hydration

Semi-adiabatic and isothermal calorimeters were used to assess the heat emissions during cement hydration of the SCC and CVC mixtures. The semi-adiabatic calorimeter was used to monitor temperature changes of four concrete cylinders from each mixture for 24 hr after mixing (RILEM TC 119-TCE, 1997). The increase in temperature and the time elapsed to reach the maximum temperature for different mixtures were examined to study the effect of different SCMs/fillers. The

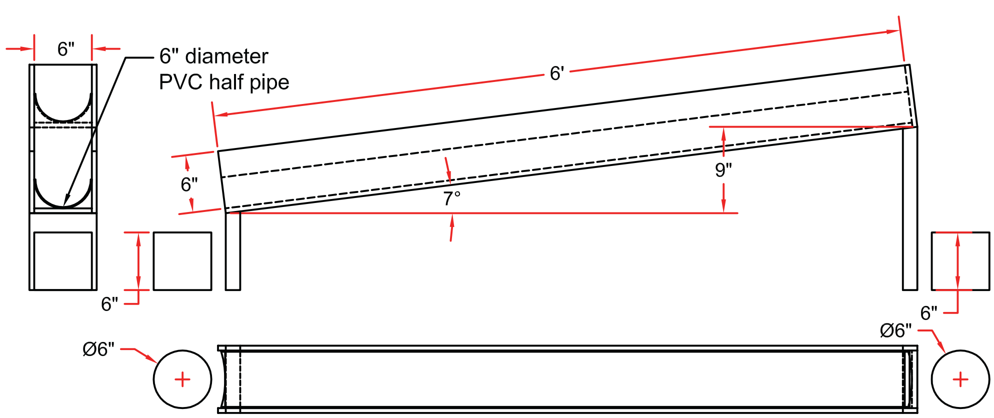


Figure 1-5. Modified flow trough used for evaluating dynamic stability.

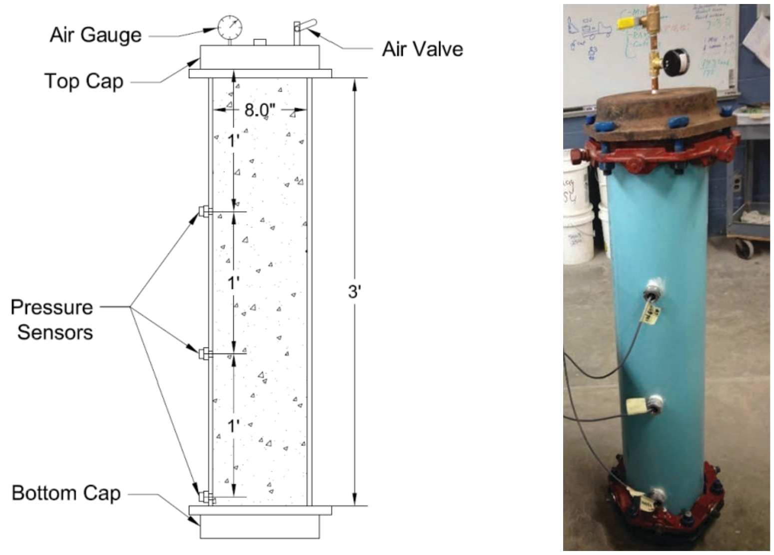


Figure 1-6. Form pressure device.

isothermal calorimeter was used to monitor the rate of energy generation in a temperature control chamber for four mortar samples sieved from each concrete mixture. Approximately 100 g of mortar was poured into each 125 ml plastic cup and then each cup was placed onto the sample holders of the calorimeter in accordance with ASTM C1702. The readings were recorded every 30 sec up to 24 hr. The rate of energy generation and the time elapsed to reach the peak value for different mixtures were examined to study the effect of different SCMs/fillers.

Time of Setting

The time of initial setting of 16 SCC mixtures and two CVC mixtures was measured according to AASHTO T 197. All mixtures had ½ in. NMSA, half of which contained crushed limestone aggregate while the other half contained gravel aggregate. The mixtures had different SCMs/fillers and levels of flowability to evaluate their effects on the time of initial setting. The time of initial setting for each mixture was obtained by sieving a sample of fresh concrete on a No. 4 sieve and measuring the mortar resistance to penetration at different times. The time of initial setting was that corresponding to a penetration stress of 500 psi.

1.2.4 Hardened Concrete Mechanical Properties

Compressive Strength

Compressive strength (f_c) of the SCC and CVC mixtures was determined at ages 7, 14, 28, and 56 days according to AASHTO T 22 as the average value of three tests on 4 in. × 8 in. cylinders. The average ratios of the 7-day, 14-day, and 56-day compressive strength of SCC to compressive strength at 28-days were compared to those predicted by the ACI 209 model for CVC. The effect of aggregate type and SCM/filler type on the compressive strength was also examined. The modulus of elasticity (MOE) (E_c) and split tensile strength (f_t) were determined at 28 days according to ASTM C469 and AASHTO T 198, respectively, as the average value of three tests on 4 in. × 8 in. cylinders. The modulus of rupture (MOR) (f_r) was also determined at 28 days according to AASHTO T 97 as the average value of three tests on 6 in. × 6 in. × 20 in. prisms. The purpose of the f_c, E_c, and f_r tests was to determine whether AASHTO LRFD models for predicting CVC properties are appropriate for predicting SCC properties or whether changes are necessary.

Bond Strength

Pull-out tests were conducted on three specimens of each of six SCC mixtures and six CVC mixtures (i.e., a total of 36 specimens) to evaluate the bond strength of uncoated, deformed, vertical reinforcing steel bars in tension according to RILEM/CEB/FIP (1970). For each concrete type, three mixtures contained crushed limestone aggregate with ¾, ½, and ⅜ in. NMSA, and the other three mixtures contained gravel aggregate with ¾, ½, and ⅜ in. NMSA; all mixtures had the same SCM (25% Class F fly ash).

Each specimen was prepared by placing a #6 Grade 60 deformed bar vertically (as in columns) in the center of an 8 in. wooden cube, attaching a rigid plastic sheathing to the top 4.25 in. of the bar, and then placing the concrete in the form (resulting in a bonded length of 3.75 in.). Forms were stripped after 24 hr and the specimens were moist cured until 28 days. A pull-out force was applied at a rate of 0.05 in./min, and the slip at the other end of the bar was measured using two linear variable differential transformers (LVDTs) as shown in Figure 1-7. The average compressive strength of the specimens at the time of testing ranged from 4.0 to 8.7 ksi. The bond strength of each specimen was calculated at different slippage values (0.01 in. and 0.1 in.) and the ultimate force was recorded.

The bar direction has a significant effect on the bond strength (CEB-fib, 2000). Horizontal bars have a large area under which bleed water could accumulate. To evaluate the bond strength of horizontal bars (such as in beams) as well as the top-bar effect, six wall specimens were cast, each measuring 48 in. × 48 in. × 8 in. Two of the specimens were cast with high slump flow SCC, two with low slump flow SCC, and two with CVC. Each wall specimen had nine #6, Grade 60, uncoated, deformed horizontal steel bars located horizontally in three rows, as shown in Figure 1-8. The concrete was cast from the top using ready-mixed concrete that had an average compressive strength ranging from 7.1 to 8.3 ksi at the time of testing. Using the same test setup and procedures used for pull-out of vertical bars, each of the 54 #6 steel bars were pulled out to evaluate the effect of bar location and concrete type on the bond strength of horizontal bars.

Shear Resistance

Push-off tests were conducted on two specimens of each of the six SCC mixtures and six CVC mixtures (i.e., a total of 24 specimens) to evaluate the interface shear resistance according to Mattock and Hawkins (1972). Three of the mixtures of each concrete type contained crushed limestone aggregate with ¾, ½, and ⅜ in. NMSA and the other three mixtures contained gravel aggregate with ¾, ½, and ⅜ in. NMSA; all mixtures had the same SCM (25% Class F fly ash).

Figure 1-9 shows the test setup. Each specimen had two #3, Grade 60, deformed bars across a shear plane that was approximately 9 in. deep and 5 in. wide (i.e., the reinforcement ratio was about 0.5%). An additional 16 specimens were cast using ready-mixed concrete, half of which were cast without reinforcement across the shear plane while the other half were cast with two #3 bars. Forms were stripped after 24 hr and specimens were moist cured for 28 days. A push-off force was applied at a rate of 0.05 in./min and the horizontal and vertical displacements across the shear plane were monitored using three LVDTs. Average compressive strength ranged from 4.0 to 8.7 ksi at the time of testing. Interface shear resistance of SCC mixtures was compared to that of CVC mixtures and to the values predicted by AASHTO LRFD for CVC with and without interface shear reinforcement.

Tests were conducted on 18 beam specimens (6 with high slump flow SCC, 6 with low slump flow SCC, and 6 with CVC) to evaluate the shear resistance at different levels of transverse reinforcement according to Lachemi, Hossain, and Lambros (2005). The six beams of each concrete mixture included two beams with no transverse reinforcement, two beams with two #3 stirrups at 8 in. spacing (reinforcement ratio = 0.35%), and two beams with two #3 stirrups at 4 in.

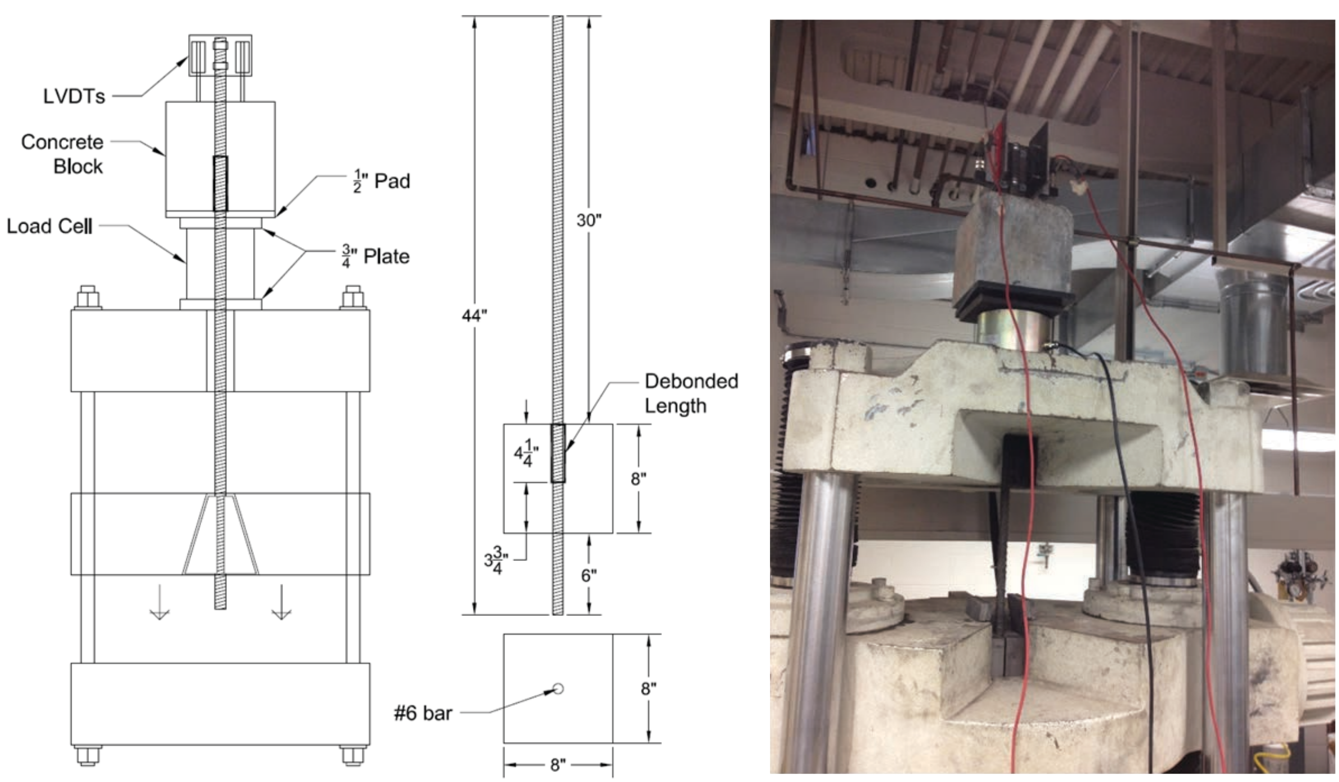


Figure 1-7. Pull-out test setup.

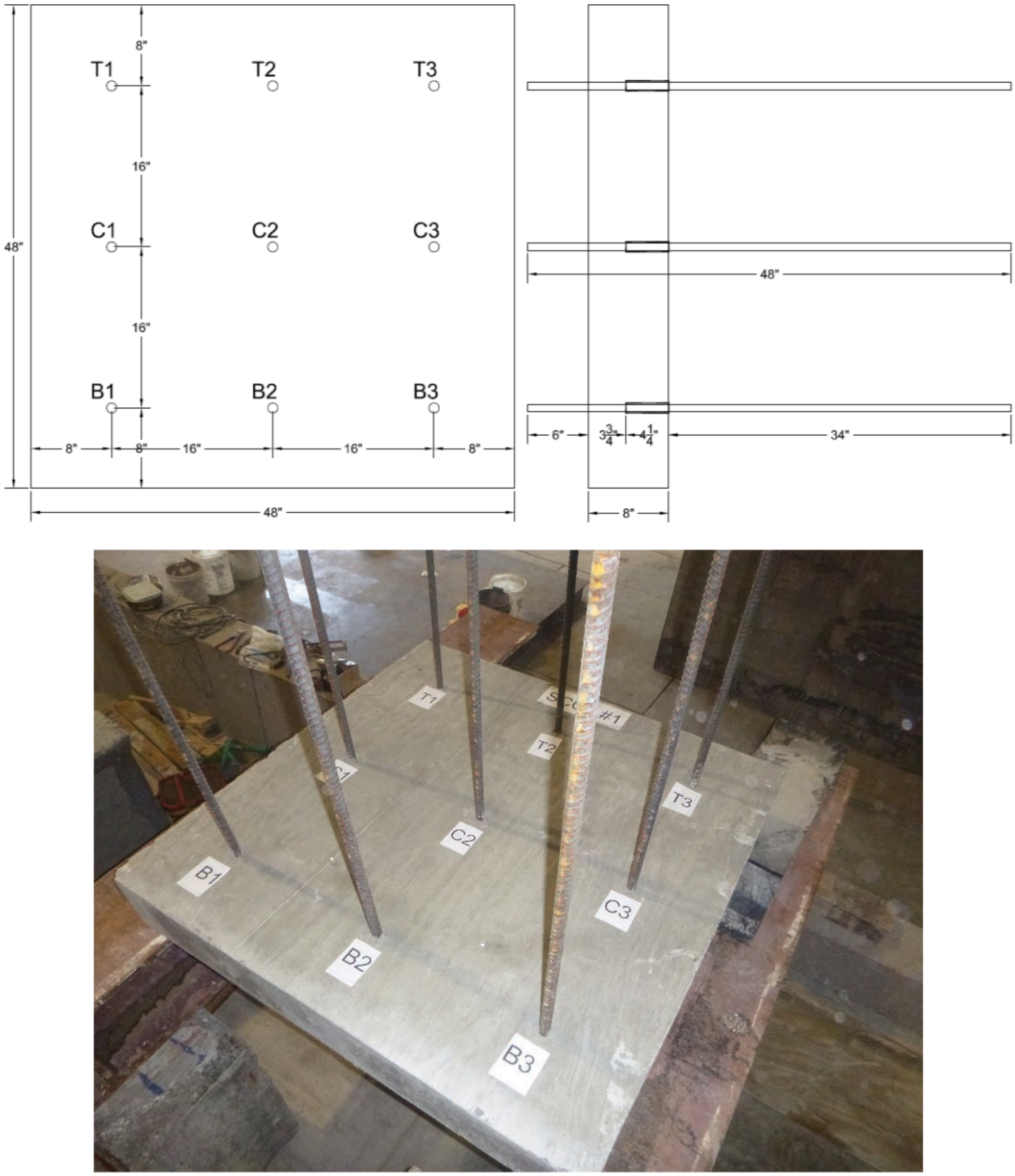


Figure 1-8. Details of wall-out wall specimens.

spacing (reinforcement ratio = 0.69%). Each beam specimen was 60 × 12 × 8 in. and longitudinally reinforced using two #6 Grade 60 bars at the bottom and two #4 Grade 60 bars at the top (Figure 1-10). The specimens were cast using ready-mixed concrete; the average concrete strength at the time of testing ranged from 7.1 to 8.3 ksi. Tests were conducted using a three-point loading arrangement; mid-span deflection and bottom bar slippage were monitored using LVDTs. Test results were compared to the values predicted by AASHTO LRFD for CVC at different levels of transverse reinforcement.

1.2.5 Hardened Concrete Visco-Elastic Properties

Drying (Free) Shrinkage

The change in length of hardened concrete due to drying shrinkage was measured for the SCC and CVC mixtures according to AASHTO T 160. Three 4 × 4 × 11.25 in. concrete prisms were cast from each mixture, moist cured for 7 days (Figure 1-11), and then stored for 56 days in a drying room maintained at 50% ± 4% relative humidity and

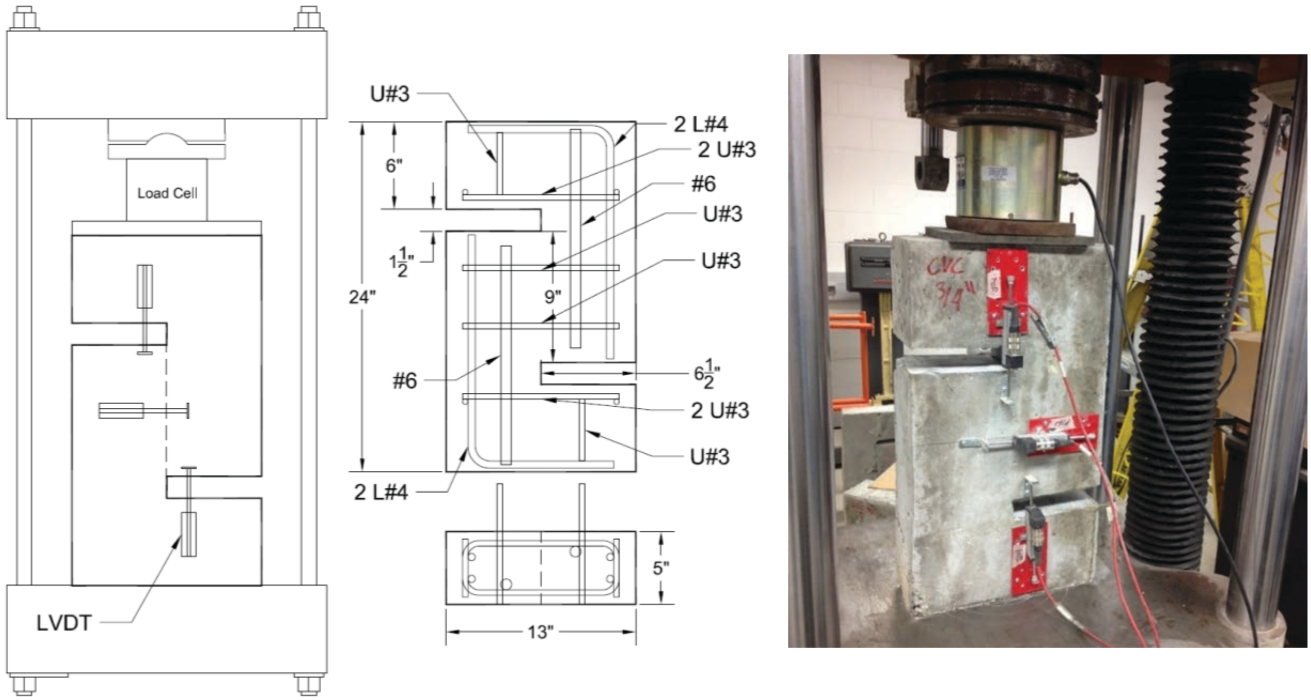


Figure 1-9. Push-off test setup.

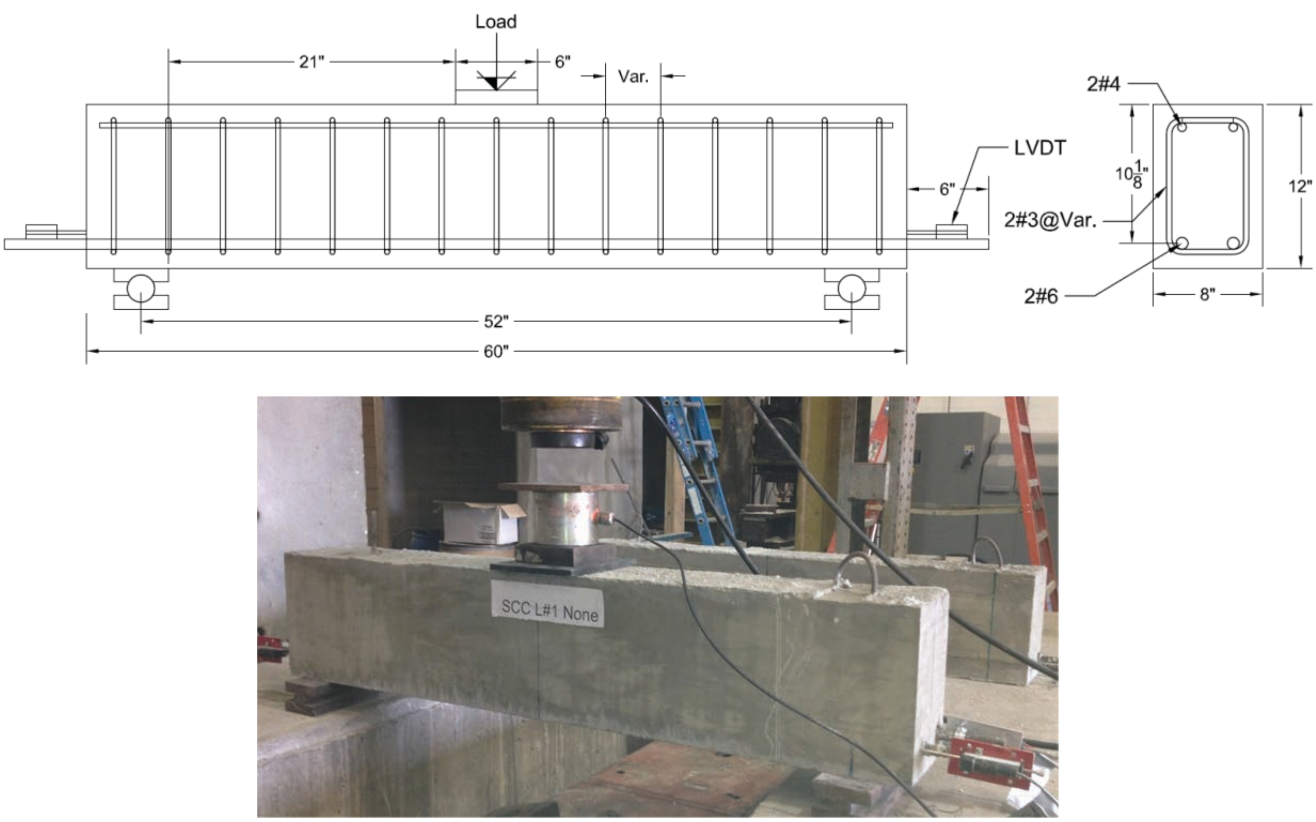


Figure 1-10. Beam shear test setup.

Figure 1-11. Drying shrinkage specimens.

73 ± 2°F temperature. Length change readings were taken at 3, 7, 14, 28, and 56 days after the curing period. The average shrinkage strain of each set of three prisms at different ages was compared to the values predicted by the AASHTO LRFD model for CVC. Also, the effect of SCM/filler and aggregate type/size on the drying shrinkage was studied.

Restrained Shrinkage

Restrained shrinkage tests were performed to assess the cracking potential of SCC and CVC mixtures using a modified ASTM C1581 procedure. Two concrete rings (Figure 1-12) were made from each mixture; paraffin wax was used to seal the top surface of the ring and allow moisture loss only from the side. The changes in steel strain due to concrete shrinkage were monitored by two strain gauges mounted on the inner face of the ring. Data were recorded every 1 min (until the concrete cracked or the test terminated at 28 days) to calculate the average stress rate (psi/day) and the time of cracking (day) for each mixture—indicators of the cracking potential of that mixture. Mixtures with a time-to-cracking duration of less than or equal to 7 days and an average stress rate greater than or equal to 50 (psi/day) have high cracking potential (ASTM C1581). The effects of SCMs/fillers and NMSA on the cracking potential of SCC were examined.

Figure 1-12. Restrained shrinkage specimen.

Creep

Creep was measured for eight SCC mixtures and two CVC mixtures according to ASTM C512 (half of the mixtures of each concrete type contained ⅜ in. nominal maximum size gravel aggregate and the other half contained ⅜ in. nominal maximum size limestone aggregate). These mixtures were expected to have the highest creep strains because of their high paste volume. Specimens from six SCC mixtures and the two CVC mixtures were loaded at an age of 28 days. The specimens from the other two SCC mixtures (both contained gravel—one contained fly ash Type F and the other contained slag) were loaded at an age of 56 days to ensure that the compressive strength had reached the specified value prior to loading. Two sets, each consisting of two 6 × 12 in. cylinders, were obtained from each mixture; one set was loaded to 40% of its 28-day or 56-day average compressive strength, and the other set was kept unloaded and monitored for deformations due to shrinkage and temperature effects (Figure 1-13). All cylinders were instrumented using three pairs of detachable mechanical gauges distributed around the cylinders to measure the length change over 8 in. distance using a dial gauge. The deformations for both sets were recorded every day for a week, then every 7 days for a month, and then every 30 days up to 230–360 days after time of loading. Average creep strains were calculated by subtracting the average deformation of the unloaded cylinders from those of the loaded cylinders. Also, measurements from the three pairs of gauges were compared to check the uniformity of loading. The relative humidity of the creep specimens was also recorded and considered in predicting the creep coefficient according to AASHTO LRFD.

1.2.6 Hardened Concrete Durability Properties

Air Void System

The parameters of the air void system in hardened concrete (i.e., air content, spacing factor, and specific surface) were determined for the SCC and CVC mixtures using the linear-traverse method (ASTM C457). For each mixture, two square samples were taken from the top and bottom of a 28-day old cylinder and tested using the Rapid Air 457 air void analyzer. Air content of 6±1.5%, specific surface ≥ 24 mm^2/mm^3, and spacing factor ≤ 0.20 mm were proposed as guidelines for proportioning of mixtures as they are expected to result

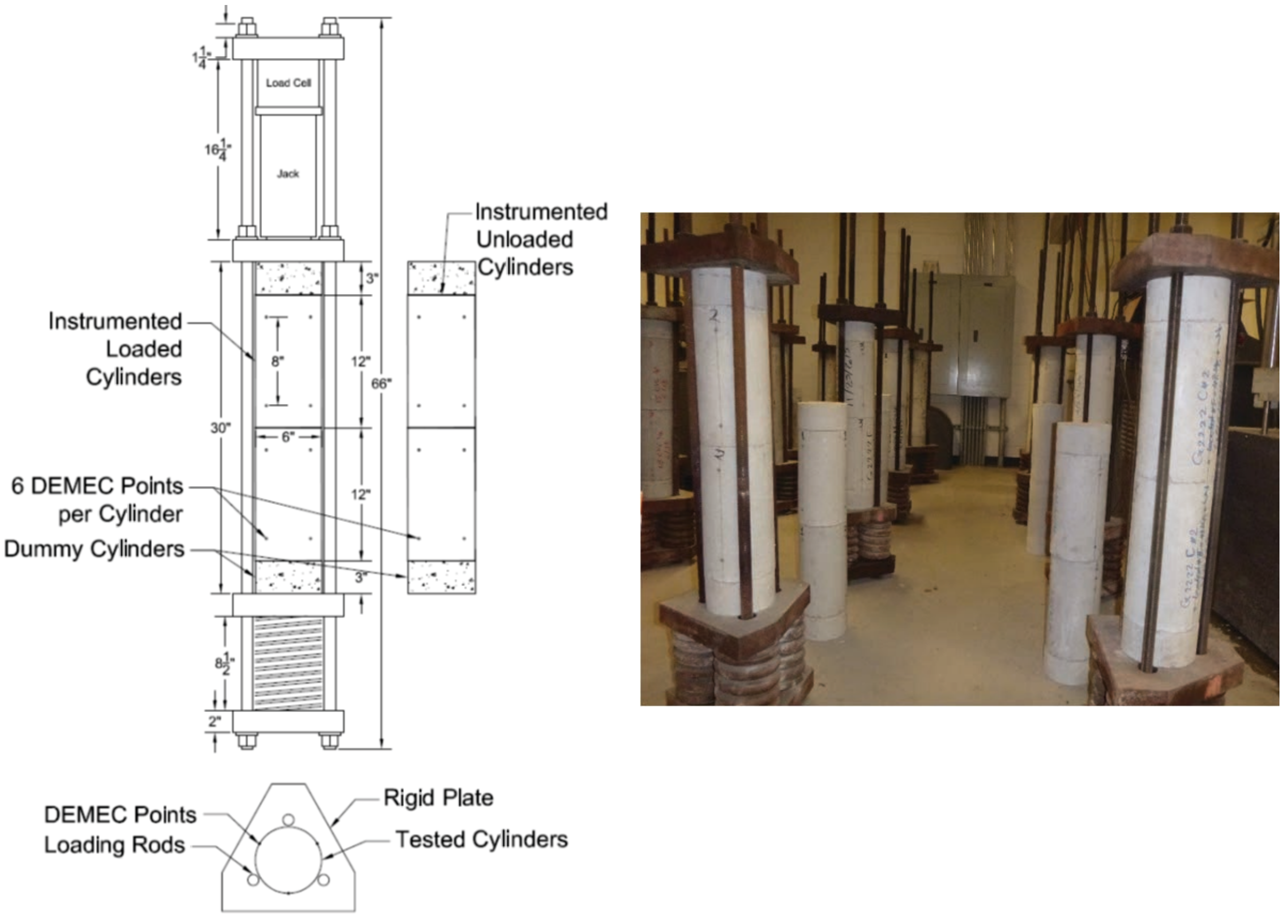


Figure 1-13. Creep test setup.

in adequate freeze-thaw resistance (PCA, 2009; FHWA, 2006). Other values may be proposed for different exposure categories.

Surface Resistivity

Results obtained from surface resistivity tests (AASHTO TP 95) have been shown to have a strong correlation with the results obtained from rapid chloride penetrability tests (RCPTs) (AASHTO T 277; LADOTD, 2011; FDOT, 2011; INDOT, 2013; FHWA, 2013). Also, surface resistivity tests provide faster results and are simpler to conduct. Surface resistivity tests were conducted on the SCC and CVC mixtures using a four-point Wenner probe array. Three 4 × 8 in. concrete cylindrical specimens were prepared from each mixture and stored in a moisture room at 73°F after casting. The test was conducted at 1, 3, 7, 28, and 56 days and results were recorded as the average value of three specimens. Table 1-10 shows proposed RCPT classes for 28-day surface resistivity ranges according to AASHTO standards.

Table 1-10. Correlation between RCPT and surface resistivity results.

AASHTO T 277 RCPT class	AASHTO T 277 charge passed (Coulombs)	AASHTO TP 95 28-day surface resistivity (kΩ-cm)
High	> 4,000	< 12
Moderate	2,000 – 4,000	12 – 21
Low	1,000 – 2,000	21 – 37
Very Low	100 – 1,000	37 – 254
Negligible	<100	> 254

1.3 Full-Scale Bridge Components

To evaluate the constructability and structural performance of cast-in-place bridge components made using SCC, one full-scale substructure specimen (bridge pier) and one full-scale superstructure specimen (post-tensioned box girder) were fabricated. The 19.5 ft high bridge pier consisted of a footing, two columns, and a pier cap; dimensions and reinforcement details are shown in Figures 1-14 and 1-15. The 40 ft long box girder consisted of a tub section and top flange; dimensions and reinforcement details are shown in Figures 1-16 and 1-17. The box girder specimen was fabricated with two 3 in. diameter post-tensioning corrugated metal ducts at the bottom flange and anchor blocks at each end to accommodate 18 Grade 270 low

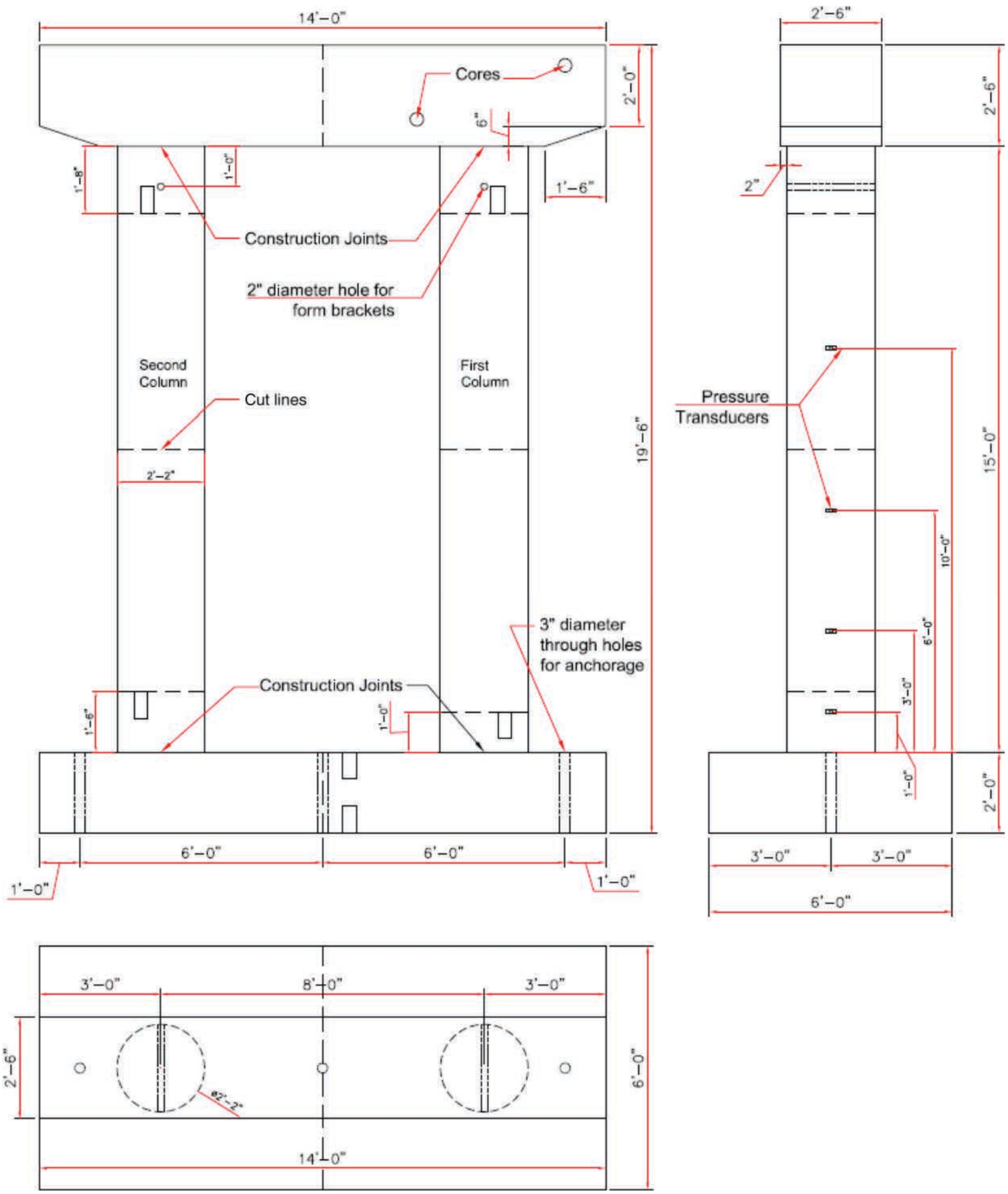


Figure 1-14. Views of the bridge pier specimen.

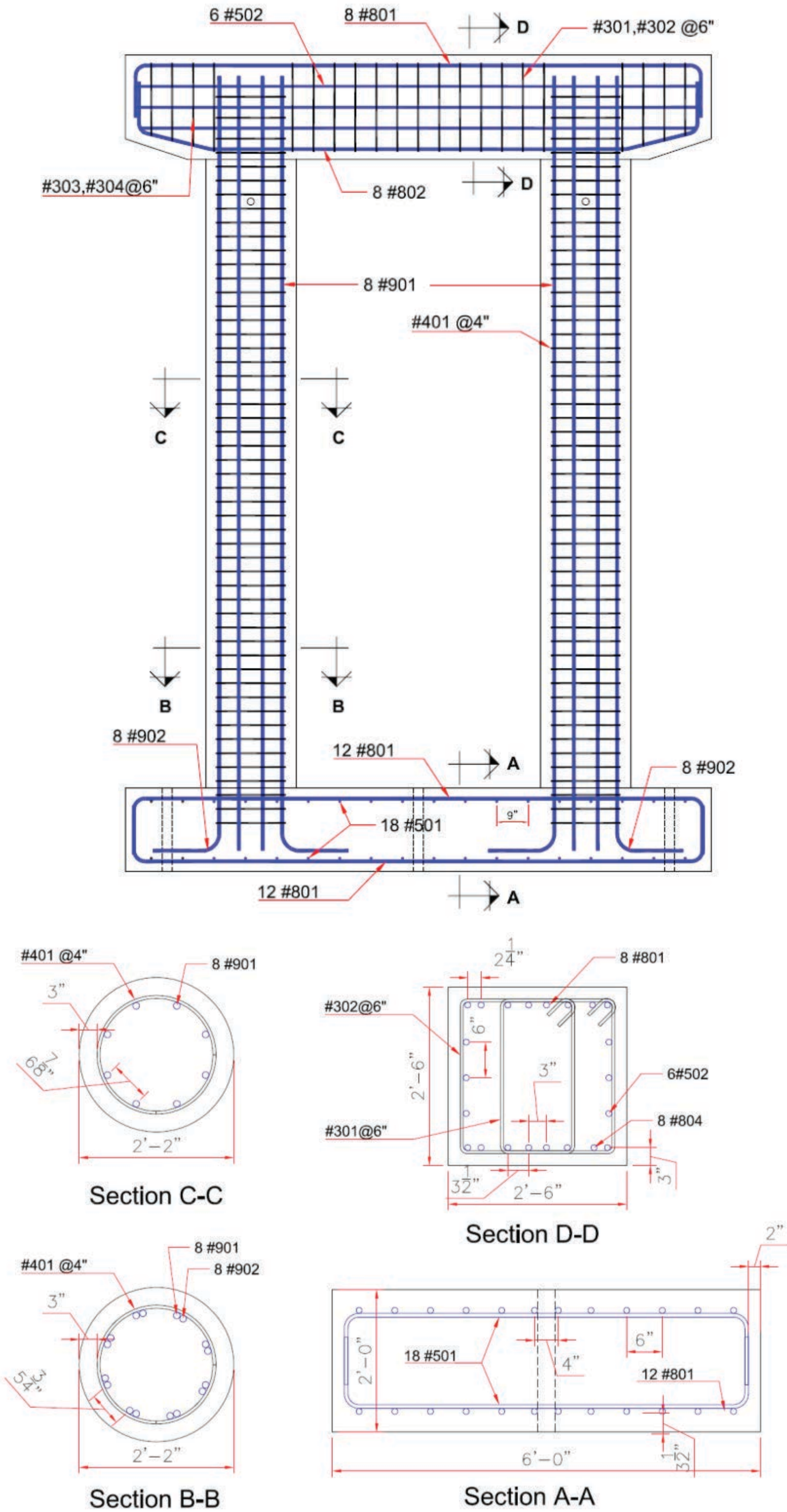


Figure 1-15. Reinforcement details and cross sections of the bridge pier specimen.

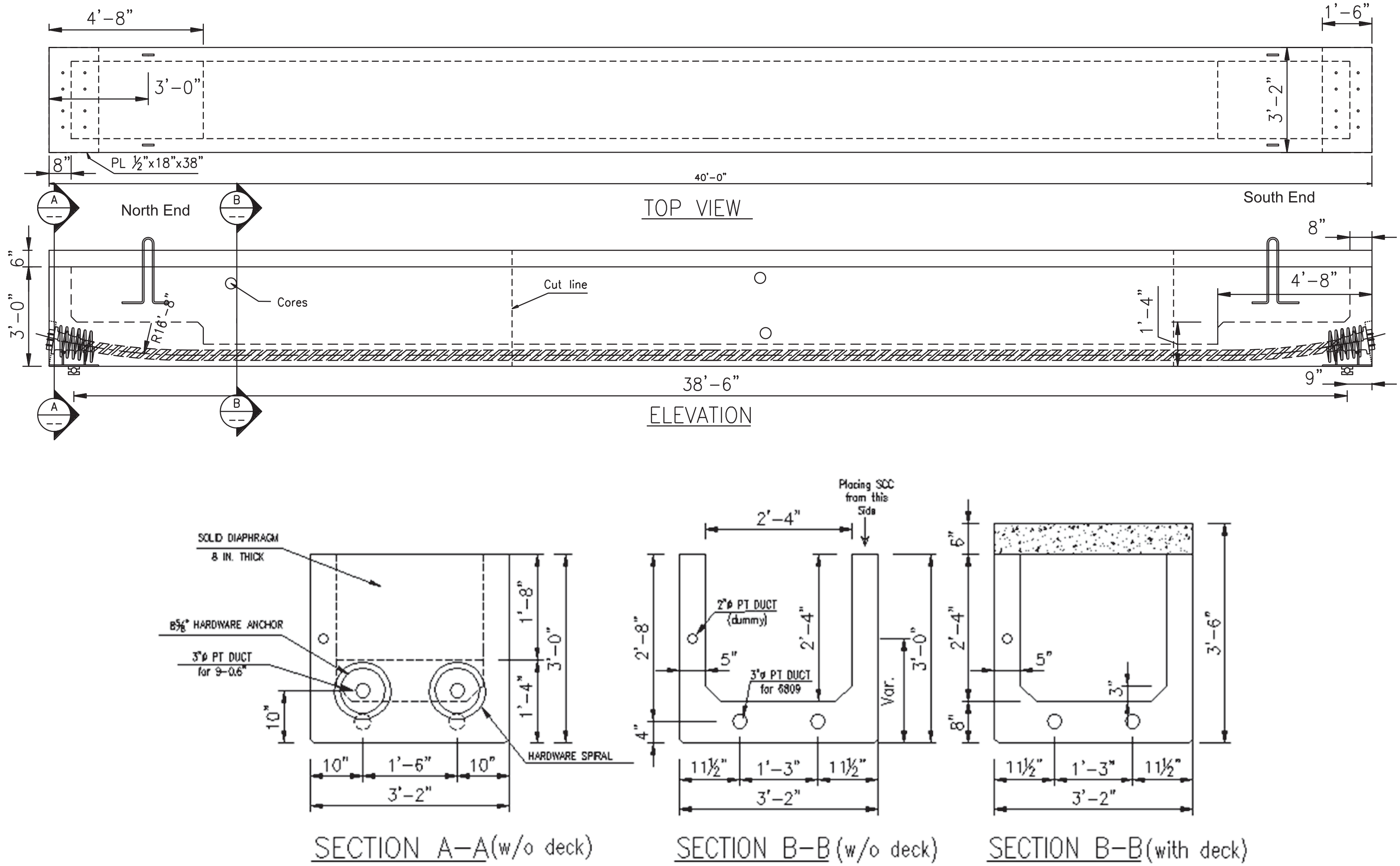


Figure 1-16. Views of the bridge post-tensioned box girder specimen.

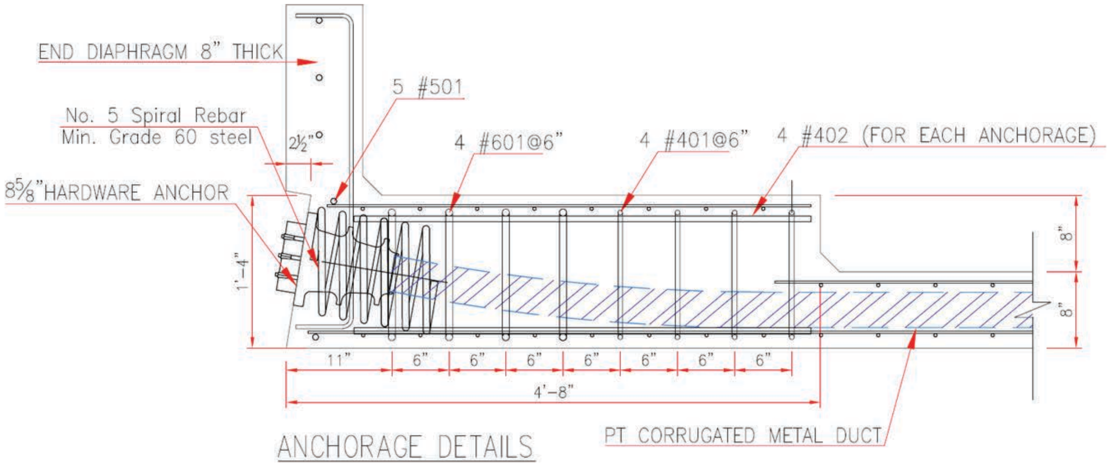


Figure 1-17. Reinforcement details of the box girder specimen.

relaxation strands, each with a diameter of 0.6 in. (9 strands per duct). Anchorage blocks were detailed according to AASHTO LRFD specifications to evaluate the performance of SCC in highly disturbed regions (local zone and global zone). In addition, a 2 in. diameter dummy corrugated metal duct was installed in the 5 in. thick web to investigate concrete flow and consolidation in tight spaces. Column and tub sections were dimensioned and reinforced to simulate cases of narrow sections with congested reinforcement and evaluate concrete consolidation.

Table 1-11 lists the mixture used in each component along with the placement method and rate, required and ordered concrete quantity, and duration of casting. All mixtures were proportioned using crushed limestone coarse aggregate, natural sand, and Type IPF cement (a pre-blended Type I portland cement with 25% Class F fly ash). This type of cement was used because of its availability at the nearby ready-mixed concrete plant and its common use in cast-in-place bridge construction in the state of Nebraska. Because a blockage of the 2 in. diameter pump hose occurred during concrete placement in the tub section, the tub section was not completely filled in one batch (a large concrete quantity had to be disposed of and the remaining concrete was not sufficient). The remaining portion of the tub section (approximately two-thirds of the web along 12 ft from one end) and the top flange were filled with a second batch of the same SCC mixture using a 3 in. diameter pump hose.

All batches were mixed at the same ready-mixed concrete plant and transported to the fabrication location using mixing trucks. Table 1-12 lists the SCC properties that were measured, the test method used, and the frequency/location of testing.

Table 1-11. Materials and placement details for SCC used in full-scale bridge components.

Component	Mixture ID	NMSA (in.)	Ordered Quantity (cy)	Required Quantity (cy)	Duration of Casting (min)	Placement Details	
						Method	Rate
Footing	111	3/4	7	6.2	5	Truck chute (one location discharge)	1.3 cy/min
First Column	221	1/2	3	2.05	35	½ cy bucket with tremie pipe (5 ft free fall)	26 ft/hr (0.06 cy/min)
Second Column	221	1/2	3	2.05	15	½ cy bucket without tremie pipe (15 ft free fall)	60 ft/hr (0.14 cy/min)
Pier Cap	121	1/2	4	3.15	45	½ cy bucket (3 ft free fall)	0.07 cy/min
Tub Section	222	3/8	7	5.0	40	Pumping with 2 then 3 in. diameter hose (one location discharge)	0.13 cy/min
Top Flange	222	3/8	7	3.35	25	Pumping with 3 in. diameter hose (multiple locations discharge)	0.13 cy/min

Table 1-12. Tests for the SCC mixtures used in fabricating full-scale specimens.

Property	Test Method	Test Location (Frequency per batch)
Rheology	Concrete Rheometer (Koehler and Fowler, 2004)	Job site (1)
Filling Ability (FA)	Slump Flow (AASHTO T 347)	Plant and Job site (2)
Passing Ability (PA)	J-Ring (AASHTO T 345)	Job site (1)
	Caisson (AASHTO T 349)	Job site (1)
Static Stability	Visual Stability Index (AASHTO T 351)	Plant and Job site (3)
	Hardened Visual Stability Index (AASHTO PP 58)	Lab (3)
	Column Segregation (ASTM C1610)	Job site (1)
	Penetration (ASTM C1712)	Job site (2)
Dynamic Stability	Flow Trough (Lange et al., 2008)	Job site (1)
Air Content	Pressure Method (AASHTO T 152)	Plant and Job site (2)
Formwork Pressure*	Pressure Transducers (AASHTO T 352)	Job site (4)
Compressive Strength	Compressing 4 x 8 in. Cylinders (AASHTO T 22)	Lab (15)
Tensile Strength	Splitting 4 x 8 in. Cylinders (AASHTO T 198)	Lab (3)
Flexural Strength	Simple Beams with Third-Point Loading (AASHTO T 97)	Lab (3)
Modulus of Elasticity	Compressometer for 4 x 8 in. Cylinders (ASTM C469)	Lab (3)
Drying Shrinkage **	Length Change of 4 x 4 x 11.25 in. Prisms (AASHTO T 160)	Lab (6)
Air Void System	Linear-Traverse Method (ASTM C457)	Lab (2)

* for column batches only
** for batches of different mixtures only

Rheology of each SCC batch was measured at the job site using a concrete rheometer. Test results were used to characterize the mixture in terms of dynamic yield stress and plastic viscosity. All other workability properties were measured only once at the job site except FA and static stability: these were measured at the plant and job site when a dosage of HRWRA was added. Air content was also measured using the pressure method at the plant and at the job site to evaluate the effect of transportation and HRWRA dosage. Formwork pressure was measured during SCC placement in the two columns using four pressure transducers located at different heights, as shown in Figure 1-14. Formwork pressure data were recorded for up to 75 minutes after concrete placement. Two different concrete placement rates (26 ft/hr and 60 ft/hr) were used in the two columns to evaluate the effect of the SCC placement rate on formwork pressure. The pressure transducer located at 3 ft from the bottom of each column did not function properly; its readings were not included in the analysis.

Six prisms were made from each of the four SCC mixtures used for fabricating full-scale bridge components to evaluate the drying shrinkage (24 total). Three prisms of each mixture were moist cured for 7 days and the other three were moist cured for 28 days to evaluate the effect of the curing period. After curing, all specimens were stored in a drying room at 20% ± 4% relative humidity and 73°F ± 2°F temperature (the same conditions as those of the fabricated full-scale bridge components). Shrinkage measurements were recorded for up to 150 days after the end of curing and compared to the shrinkage predicted using the proposed model.

The quality of the formed surface for SCC components was evaluated according to ACI 347.3R-13. Two 24 in. × 24 in. areas were selected on the surface of each component to determine the surface void ratio and maximum void diameter for different mixtures and placement methods.

Each full-scale component was tested twice to evaluate structural performance under different cases of loading. In the first test of the bridge pier specimen, the pier cap was loaded at mid-span with a point load to evaluate its capacity (see Figure 1-18). In the second test, a lateral load was applied at mid-height of the pier cap to evaluate the flexural behavior of the columns (see Figure 1-19). For the bridge superstruc-

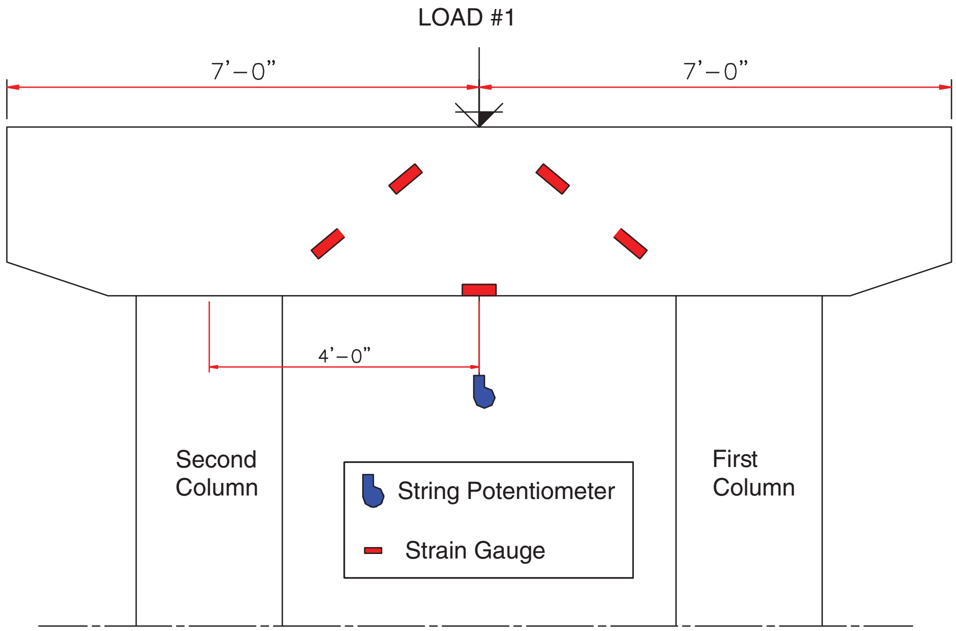


Figure 1-18. Pier cap test setup.

ture specimen, the box girder was post-tensioned to 75% of the strand ultimate strength with a mono-strand jack, and the ducts were grouted using flowable cementitious grout to allow for structural testing of a girder with bonded strands. Anchorage zones were inspected visually immediately after post-tensioning. In the first structural test, a vertical load was applied at the mid-span section to evaluate its flexural capacity (see Figure 1-20). In the second test, a vertical load was applied 8 ft from the girder end to evaluate its shear capacity (see Figure 1-21). In all tests, loading was stopped when the ultimate design capacity calculated according to AASHTO LRFD was reached to maintain the specimen stability and integrity for further testing.

All components were saw cut at different locations, as noted in Figures 1-14 and 1-16, to evaluate the uniformity of coarse aggregate distribution (i.e., HVSI) and consolidation of concrete around the reinforcement. Also, 3 in. diameter cores were extracted from different locations, as noted in Figures 1-14 and 1-16, to evaluate the effect of the placement method and rate on the air void system of the hardened SCC. The cores extracted from the pier cap were damaged during handling and were not used for air void system measurements.

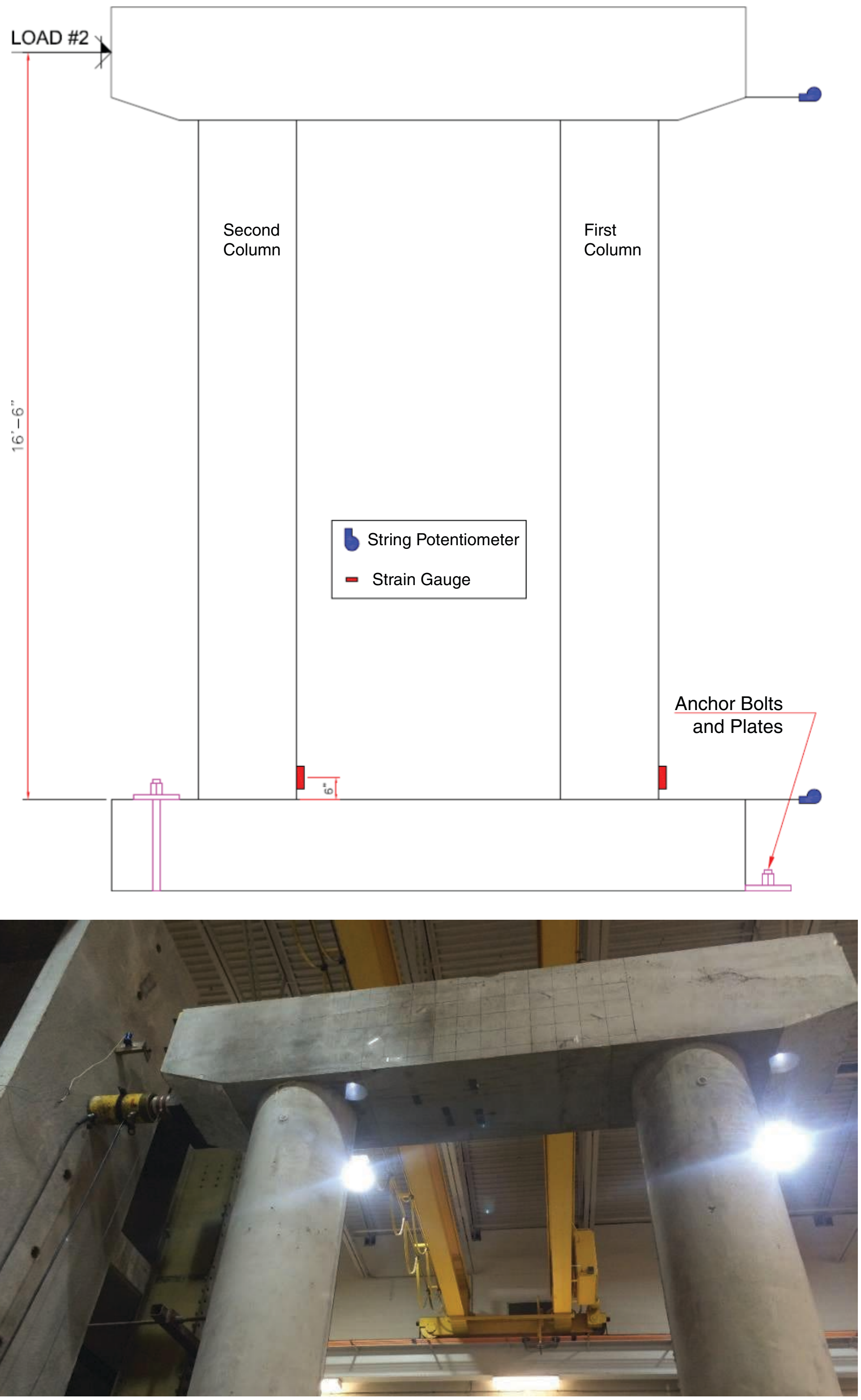


Figure 1-19. Column test setup.

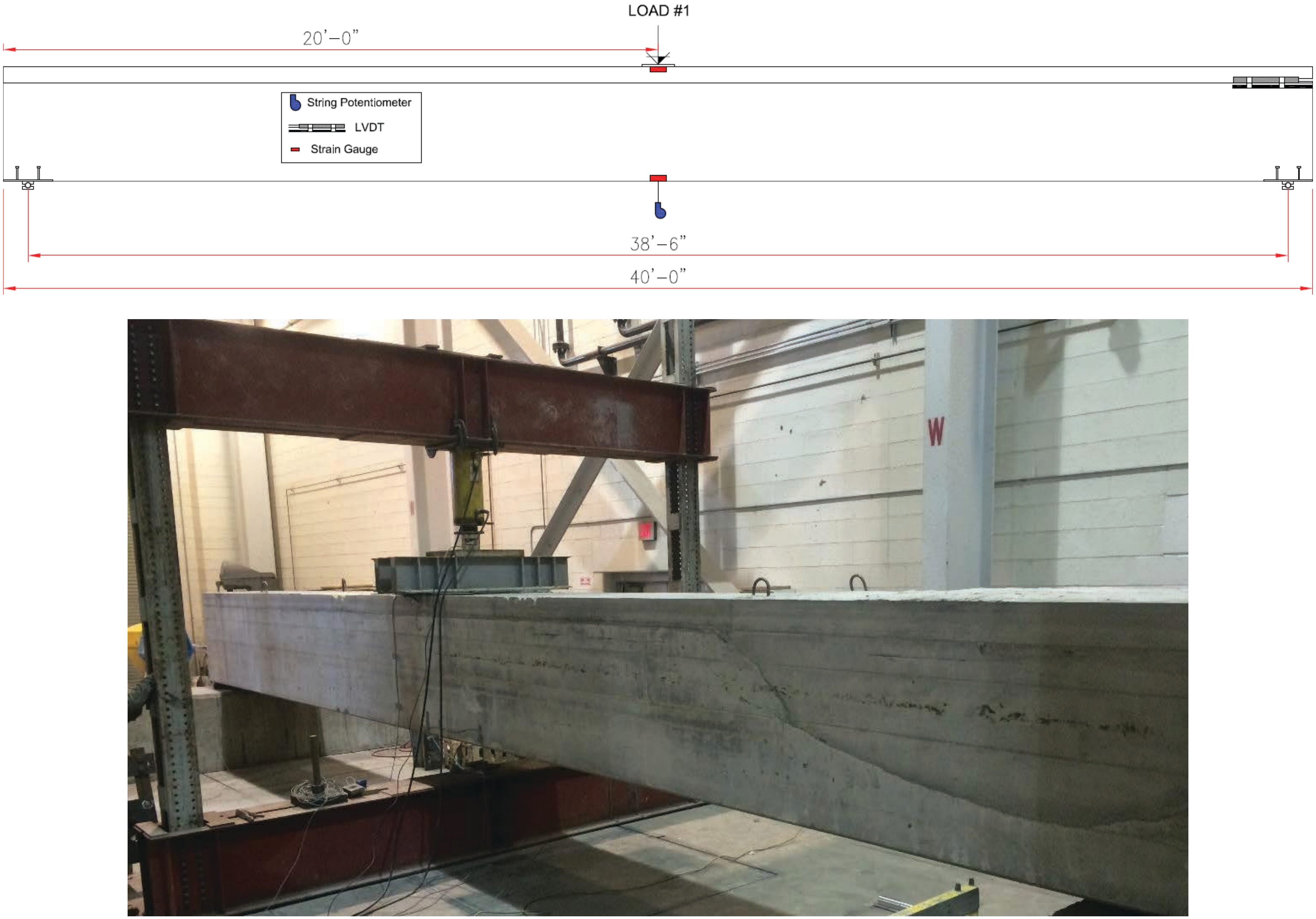


Figure 1-20. Setup of the flexure test of box girder specimen.

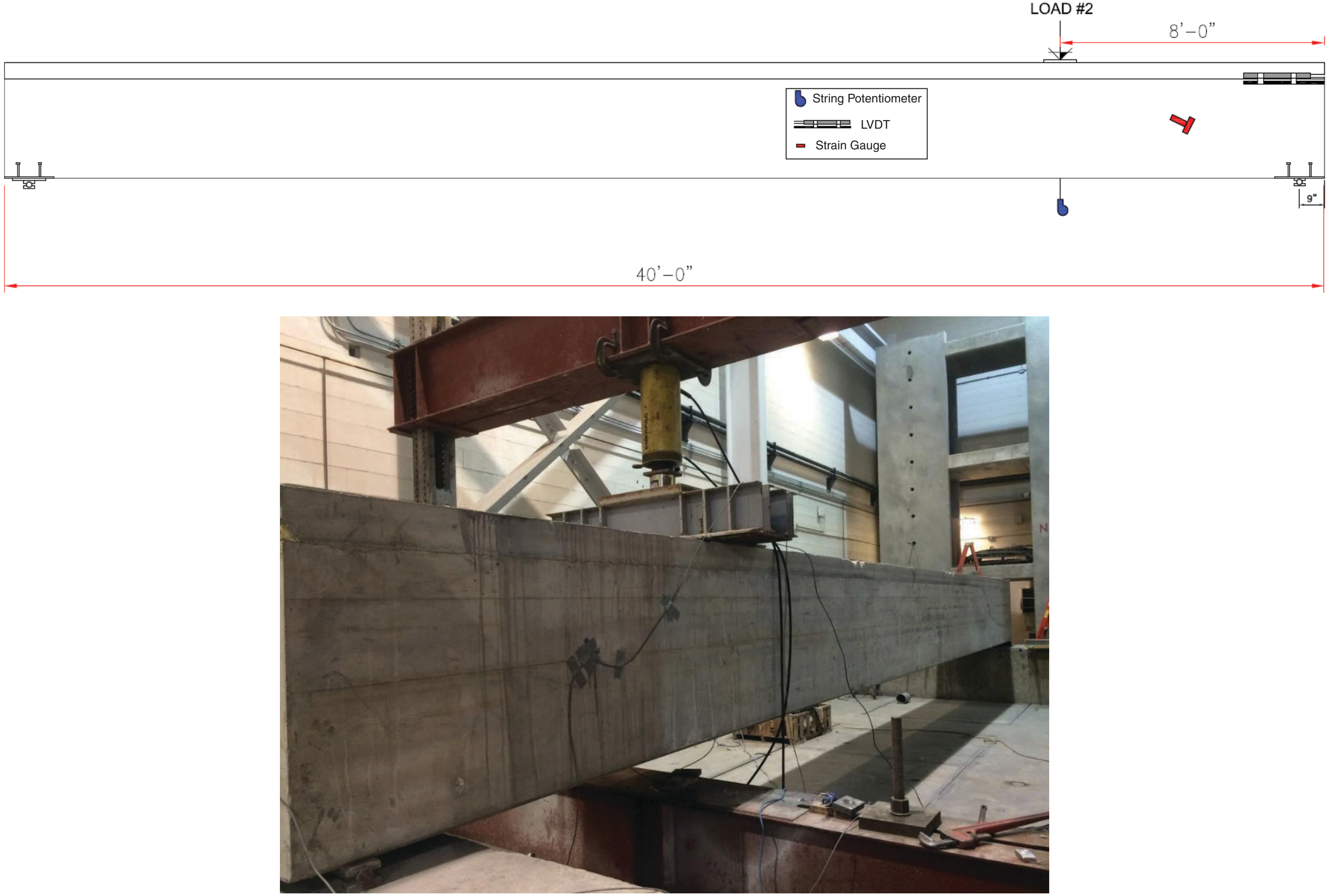


Figure 1-21. Setup of the shear test of box girder specimen.

CHAPTER 2

Results, Interpretation, and Application

This chapter presents test results and provides interpretation of the findings. Proposed changes to the current AASHTO LRFD design and construction specifications are presented in Attachment A. Proposed guidelines for proportioning, quality control testing, and acceptance criteria for SCC applications in cast-in-place bridge components are provided in Attachment B. Details of test results are presented in Appendices C, D, E, and F.

2.1 Fresh Concrete Properties

2.1.1 Rheology

Figure 2-1 shows the rheological properties of the SCC and CVC mixtures obtained from a mortar rheometer after sieving out the coarse aggregate. Figure 2-1 indicates that the dynamic yield stress of SCC mixtures is significantly lower than that of CVC mixtures, which makes them flow more easily. SCC mixtures also have a wider range of plastic viscosity compared to CVC mixtures because of the larger range of water-powder ratios and SCM/filler types used. Figure 2-2 shows rheological properties of the SCC and CVC mixtures obtained using a concrete rheometer (including the coarse aggregate). In comparison to CVC mixtures, SCC mixtures have lower yield torque (which represents yield stress) and a wider range of slope (which indicates plastic viscosity). Also, Figure 2-2 shows that the SCC mixtures containing gravel aggregate had higher yield torque and lower viscosity than the SCC mixtures containing limestone aggregate. In comparison to the round shape of gravel particles, the angularity of limestone particles causes more particle-to-particle interlock, which results in higher viscosity and increased packing density improving the flow and reducing the yield torque (Erdogan and Fowler, 2005; Lu, 2008). The flow curves for the SCC and CVC mortar and concrete mixtures are provided in Appendix C.

2.1.2 Workability Properties

Tests were conducted to evaluate the FA, PA, and stability of the SCC mixtures; the results are presented in Figures 2-3 through 2-8. Figures 2-3 and 2-4 show the ΔD and ΔH versus slump flow for the J-ring test on SCC mixtures with different NMSA. Figures 2-3 and 2-4 indicate that most mixtures had high PAs ($\Delta D \leq 2$ in. and $\Delta H \leq 0.6$ in.). A few mixtures, mostly those with ¾ in. NMSA, had low PAs ($\Delta D = 2$ to 4 in. and $\Delta H = 0.6$ to 0.8 in.). These mixtures may not be suitable for components with high congestion of reinforcement and/or narrow sections (e.g., box girder), but may be appropriate for components with large sections and a low level of reinforcement (e.g., footing) (Khayat and Mitchell, 2009). Figure 2-5 shows filling capacity versus slump flow obtained from the caisson test on SCC mixtures with different NMSA. Figure 2-5 indicates that all mixtures had either high (> 80%) or moderate (70 to 80%) filling capacity. Figure 2-6 shows penetration depth versus slump flow for SCC mixtures with different NMSA. Figure 2-6 indicates that most SCC mixtures had high static stability (penetration ≤ 0.5 in.), only a few mixtures had moderate static stability (penetration of 0.5 to 1.0 in.), and most mixtures with low slump flow had higher static stability than those with high slump flow. Figure 2-7 shows the column segregation versus slump flow for SCC mixtures with different NMSA. Figure 2-7 indicates that the majority of SCC mixtures had high static stability (column segregation ≤ 10%), and only a few mixtures (mostly with ¾ in. NMSA) had moderate static stability (column segregation between 10% and 15%) or low static stability (column segregation between 15% and 20%). These mixtures might be suitable for shallow and short components with simple and uncongested sections (e.g., grade beam). All SCC mixtures had VSI and HVSI values of 0 or 1, indicating adequate static stability in both fresh and hardened conditions. Figure 2-8 shows dynamic stability measured using a modified flow trough for SCC mixtures with high slump flow only. Figure 2-8 indicates that most mixtures exhibited either high dynamic stability (segregation ≤ 20%) or moderate dynamic stability (segregation ≤ 30%). Most SCC mixtures with high slump flow

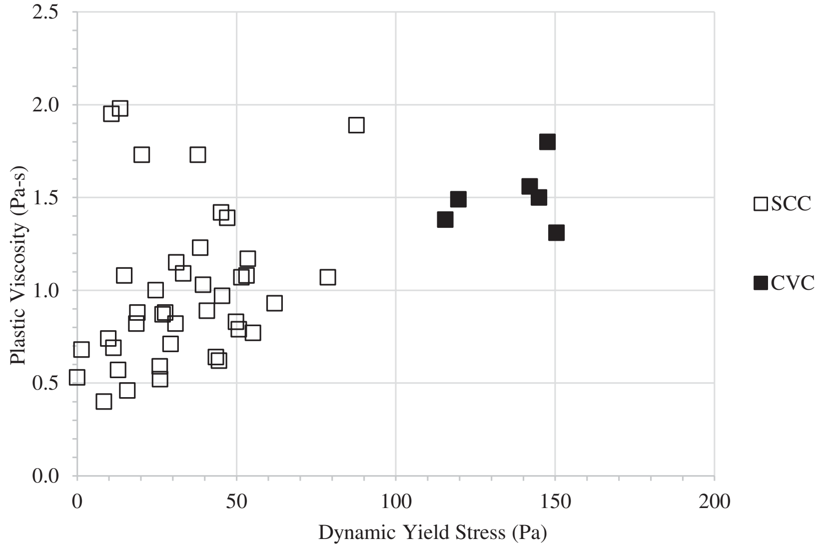


Figure 2-1. Rheological properties of mortar mixtures.

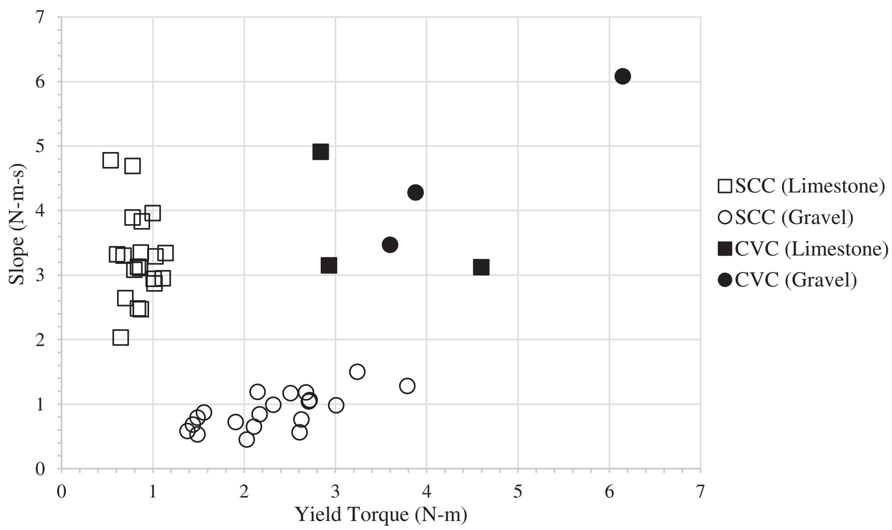


Figure 2-2. Rheological properties of concrete mixtures.

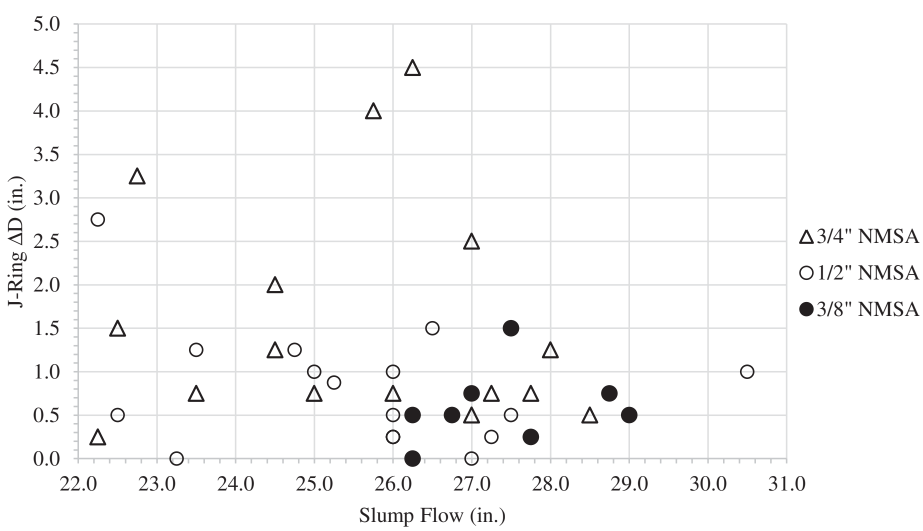


Figure 2-3. J-ring reduction in slump flow diameter (ΔD) of SCC versus slump flow.

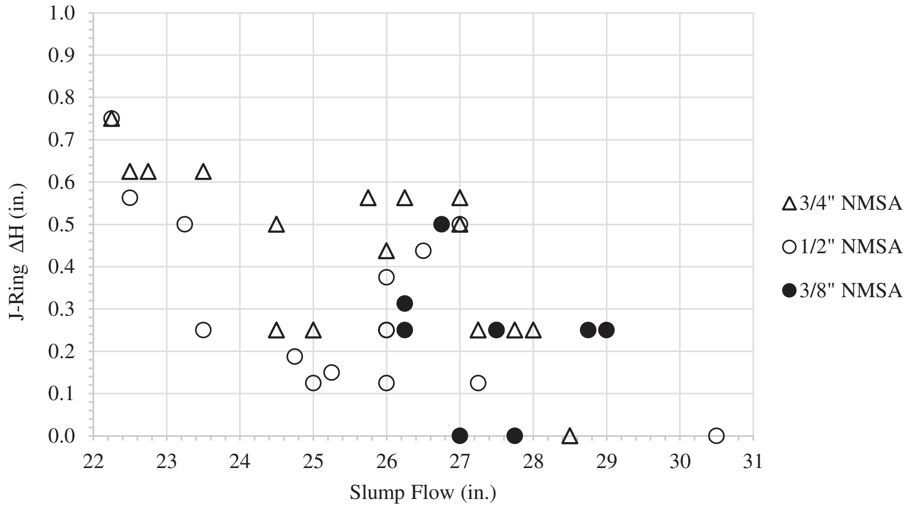


Figure 2-4. J-ring difference in average height (ΔH) versus slump flow.

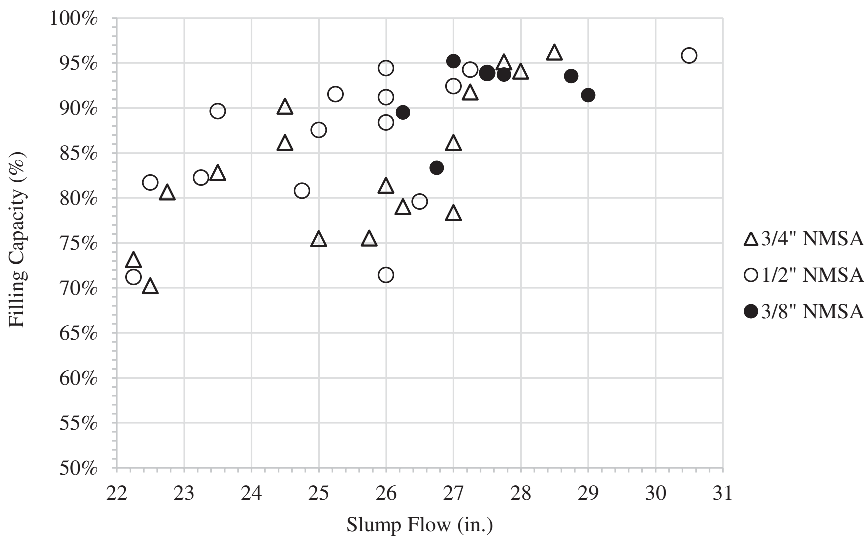


Figure 2-5. Caisson filling capacity of SCC versus slump flow.

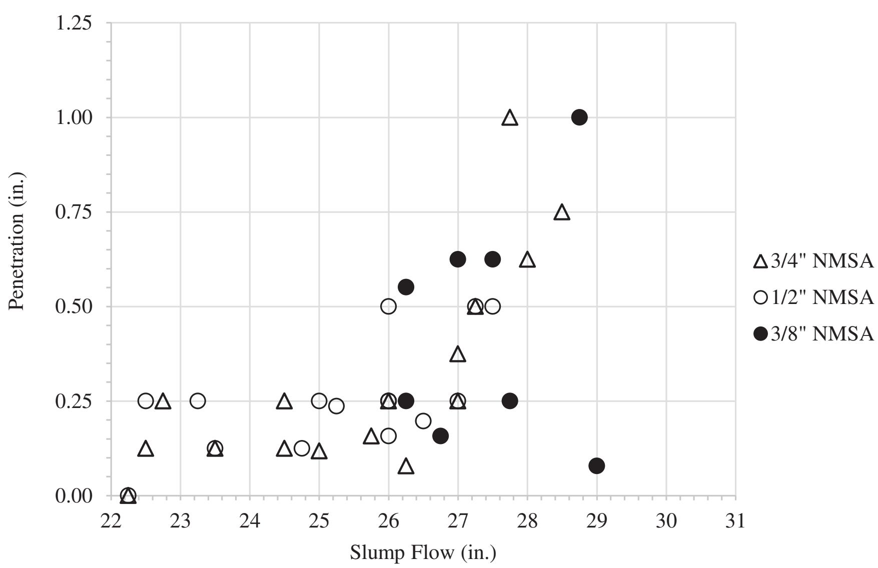


Figure 2-6. Penetration versus slump flow.

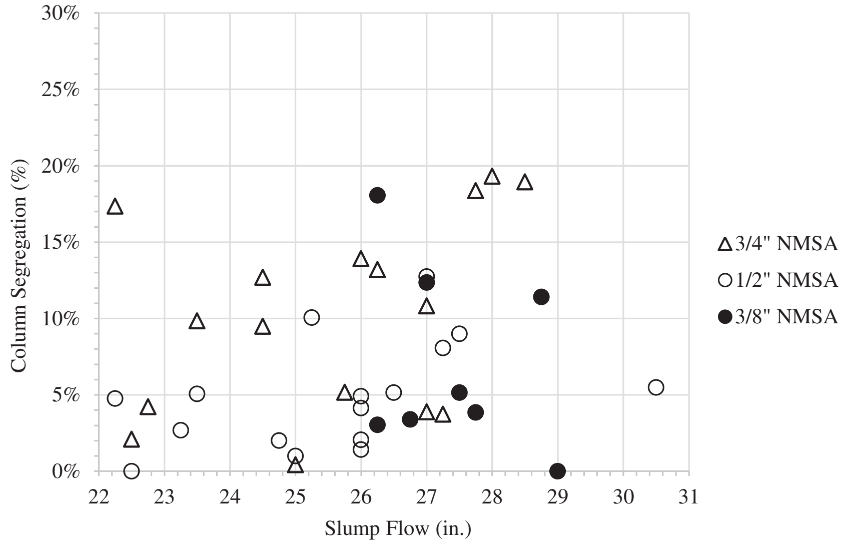


Figure 2-7. Column segregation versus slump flow.

and ¾ in. NMSA showed poor dynamic stability, making them inappropriate for long or deep components. The T_{50} values for all mixtures were very close (approximately 2 sec), which helps speed placement and produce a formed surface with a good quality.

2.1.3 Workability Retention

This investigation showed that the rate of slump flow loss is directly proportional to the initial slump flow when no workability retaining admixtures (WRAs) or additional dosage of HRWRA are used. Figure 2-9 shows that the rate of workability loss for SCC mixtures with initial slump flow of 30 in. and 24 in. averaged 7 and 3.5 in. per hr, respectively. These rates could vary depending on the mixture composition, temperature, and type of chemical admixtures used. Using WRAs during batching is a recommended practice for cast-in-place applications requiring workability retention for an extended period (e.g., 90 minutes). Adding dosages of HRWRA at the job site is not desired and should only be used to address unexpected interruptions to SCC placement operations.

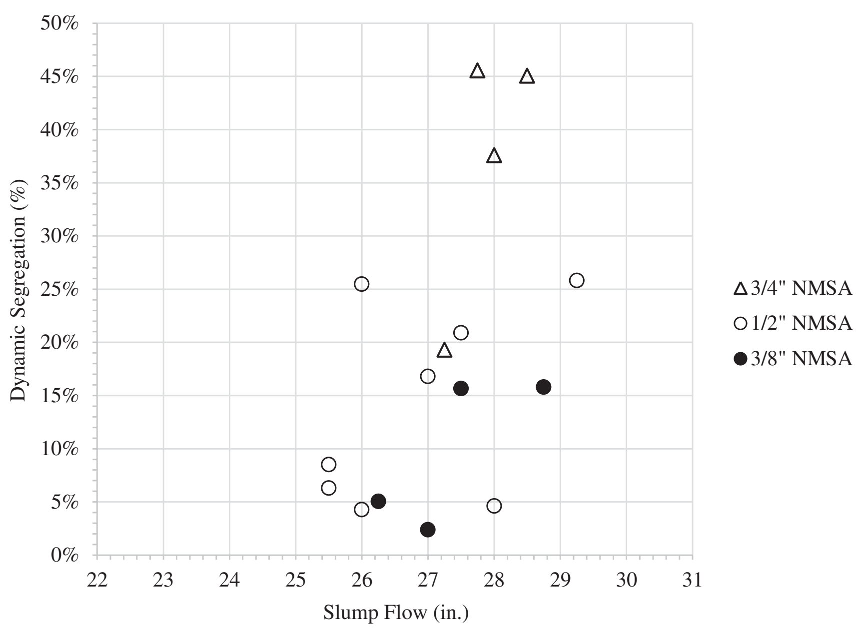


Figure 2-8. Flow trough dynamic segregation versus slump flow.

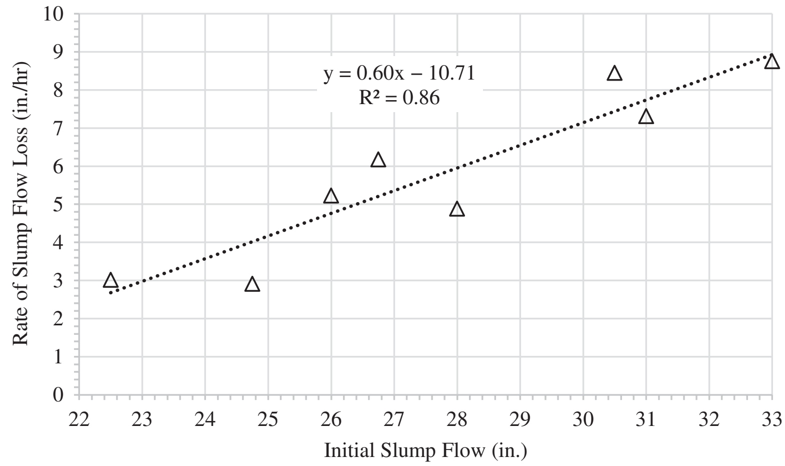


Figure 2-9. Initial slump flow versus rate of slump flow loss.

2.2 Early-Age Concrete Properties

2.2.1 Formwork Pressure

Figure 2-10 shows the ratio of maximum exerted lateral pressure to hydrostatic pressure ($P_{maximum}/P_{hydrostatic}$) for SCC and CVC mixtures. Generally, SCC mixtures generated higher lateral pressure (93 to 100% of the hydrostatic pressure) than CVC mixtures (88 to 95% of the hydrostatic pressure). Larger differences between the lateral pressure of SCC and CVC mixtures are expected when low placement rates (< 15 ft/hr) are used. Figure 2-10 also indicates linear relationships between the ratio of $P_{maximum}/P_{hydrostatic}$ and thixotropy and yield torque for all mixtures as reported in the literature (Assaad, Khayat, and Mesbah, 2003; Khayat and Assaad, 2012). Mixtures with high thixotropy and yield torque exerted lower lateral pressure than those with low thixotropy and yield torque. These relationships support the use of rheological properties of SCC mixtures to predict formwork pressure.

2.2.2 Heat of Hydration

Figure 2-11 shows the maximum increase in temperature obtained from semi-adiabatic calorimetry versus time for SCC and CVC mixtures. Figure 2-11 indicates that the temperature rise for SCC and CVC mixtures was similar (20 to 40°F) but SCC mixtures generally took a longer time to reach peak temperature. The difference in time needed to reach peak temperature depends on the type of SCM/filler (relationships of temperature change versus time for different types of SCMs/fillers are provided in Appendix D). Also, it was observed that using Class C fly ash delays the start of the acceleration phase (Figure 2-12) as reported in earlier studies (Schindler and Folliard, 2005). Figure 2-13 shows the peak rate of energy generation during hydration obtained from isothermal calorimetry for mortar sieved from SCC and CVC mixtures. There was no significant difference in the peak rate of energy generation for CVC and SCC mortar mixtures, but there was a significant delay in reaching the peak value for SCC mixtures. The temperature rise and rate of energy generation of all mixtures over a 24-hr period are provided in Appendix D.

2.2.3 Time of Setting

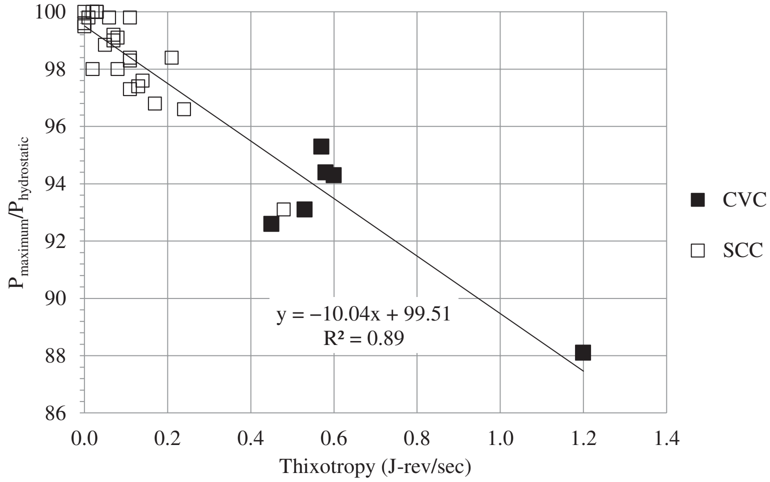
Figure 2-14 shows the time of initial setting for SCC mixtures versus slump flow at two ambient temperatures (60 and 80°F). Figure 2-14 indicates that SCC mixtures with high slump flow have longer time of setting than SCC mixtures with low slump flow, possibly due to the retarding effects of HRWRA. The ambient temperature has also a significant effect on the time of setting as higher temperatures result in shorter times of setting. The wide range in time of setting for SCC mixtures (4.5 to 11 hr) may be attributed to the effect of SCM/filler type (a similar range was reported by Khayat and Mitchell, 2009). Mixtures with Class C fly ash had the longest time of setting and those with Class F fly ash had the shortest. For purposes of comparison, CVC mixtures had an average time of initial setting of 6 hr at 80°F and 7 hr at 60°F.

2.3 Hardened Concrete Properties

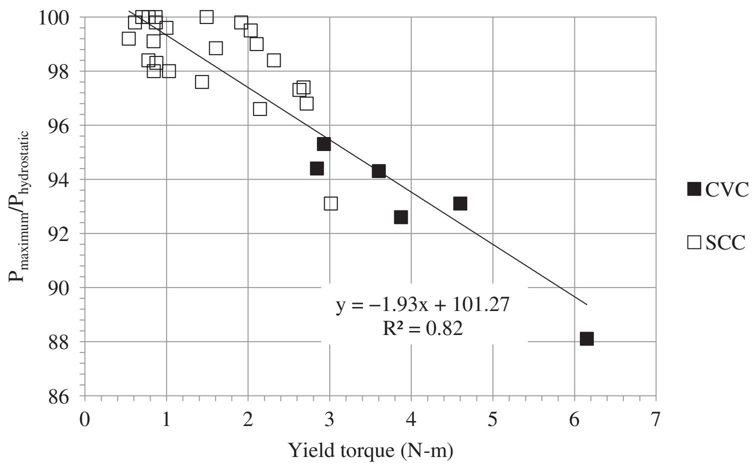
2.3.1 Mechanical Properties

Compressive Strength

Figure 2-15 shows the relationships between the average 28-day compressive strength and the average compressive strength at 7, 14, and 56 days for all SCC mixtures. The best fit lines indicate that the average ratios of 7-day, 14-day, and 56-day compressive strength to 28-day compressive strength were 0.77, 0.88, and 1.12 respectively; these values are close to the values of 0.70, 0.88, and 1.09 predicted by the ACI 209 model (ACI



(a) Ratio of $P_{maximum}/P_{hydrostatic}$ versus thixotropy.



(b) Ratio of $P_{maximum}/P_{hydrostatic}$ versus yield torque.

Figure 2-10. Ratio of $P_{maximum}/P_{hydrostatic}$ versus thixotropy and yield torque.

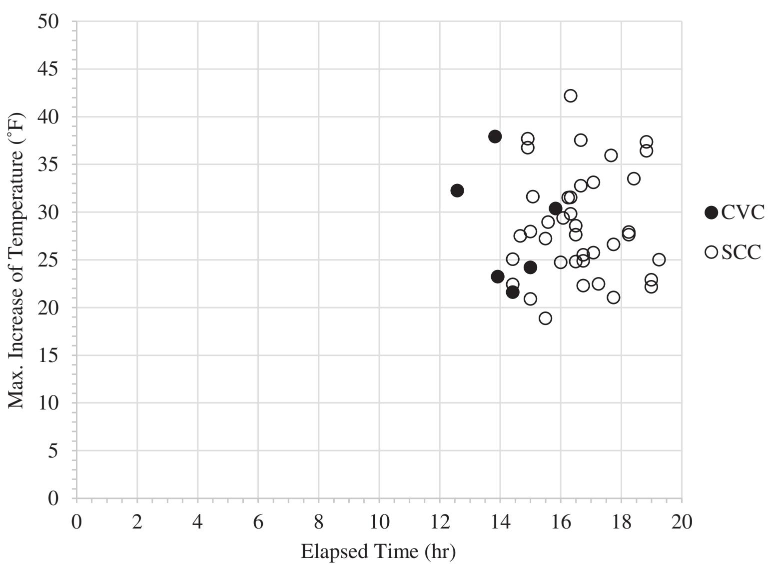


Figure 2-11. Maximum increase of temperature in semi-adiabatic condition.

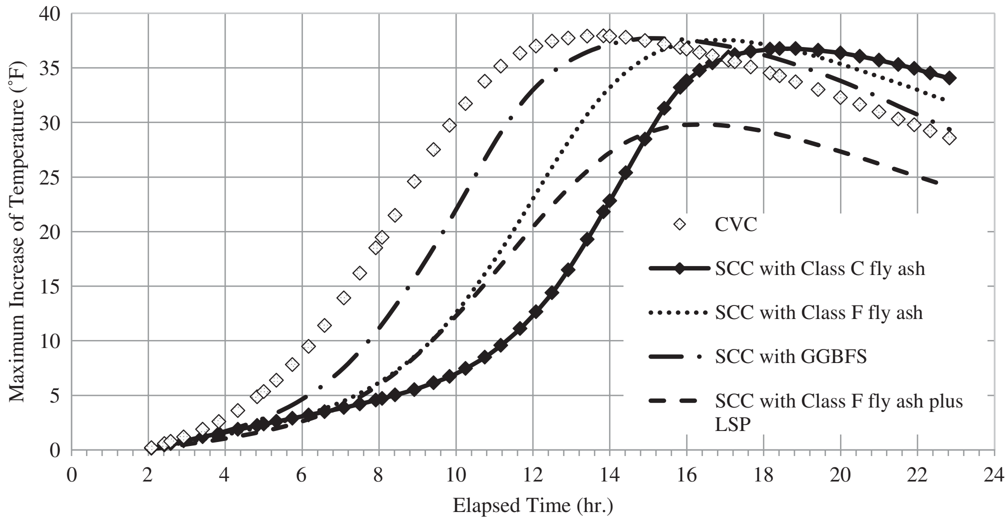


Figure 2-12. Semi-adiabatic calorimetry test results for mixtures containing ½ in. nominal maximum size limestone aggregates.

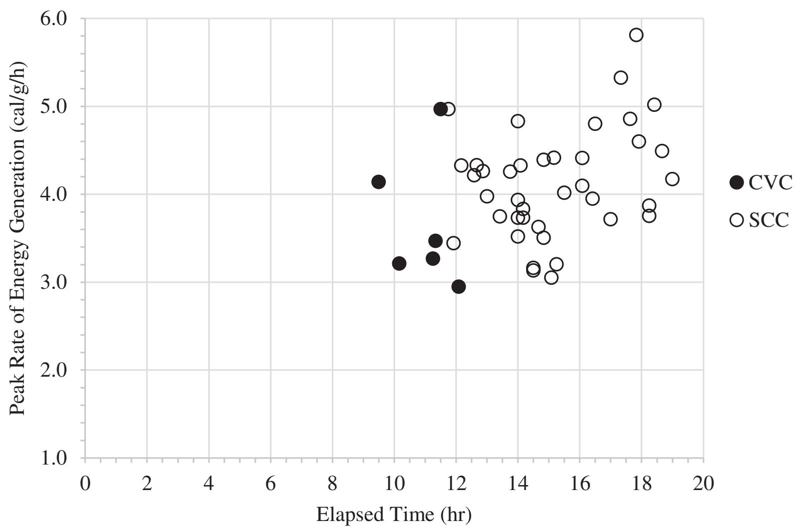


Figure 2-13. Peak rate of energy generation in isothermal condition.

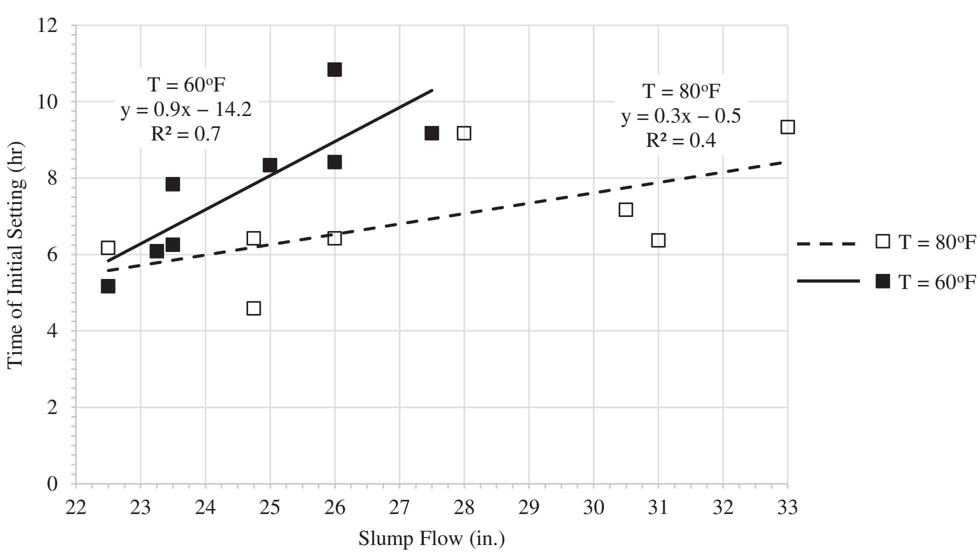


Figure 2-14. Time of initial setting versus slump flow for SCC mixtures.

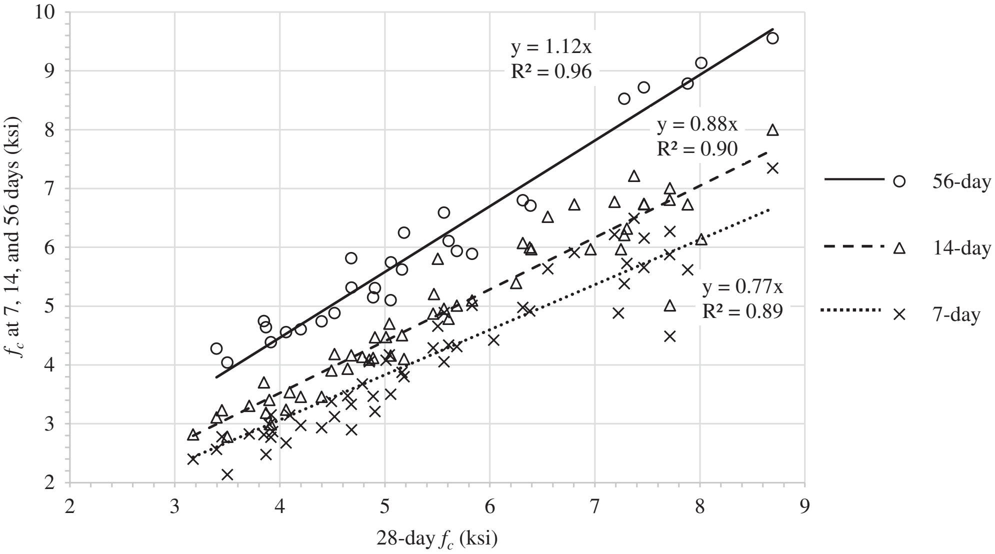


Figure 2-15. Relationships between average compressive strength at 7, 14, and 56 days and average compressive strength at 28 days for SCC mixtures.

209, 1997) for CVC with cement type I/II and moist curing conditions. The average compressive strength versus age values for all SCC mixtures are provided in Appendix E. These data indicated that SCC mixtures containing limestone aggregate had higher compressive strength than SCC mixtures containing gravel aggregate, possibly because the interfacial transition zone (ITZ) is weaker in gravel particles than it is in limestone particles (Ozturan and Cecen, 1997). These data also indicated that SCC mixtures containing limestone powder had lower compressive strength than those without limestone powder (possibly due to the coarseness of the limestone powder used in this study). The particle size of limestone powder has a significant effect on compressive strength because coarser limestone particles reduce the reactivity of the system and, consequently, the compressive strength (Bentz et al., 2015).

Modulus of Elasticity (MOE)

The AASHTO LRFD Equation 5.4.2.4-1, for predicting MOE of CVC ($E_c = 33{,}000\ K_1\ w_c^{1.5}\sqrt{f_c}$ [ksi]), includes a correction factor for source of aggregate (K_1) to be taken as 1.0 unless determined by physical test. Since two different types of coarse aggregate were used in this study, the K_1 factor was first determined by comparing the MOE values of SCC mixtures containing limestone aggregate to those of SCC mixtures containing gravel aggregate to determine their relative stiffness. Figure 2-16 shows the average measured MOE for SCC mixtures containing the two aggregate types versus the square root of compressive strength times the unit weight of concrete (0.143 and 0.140 kcf for limestone and gravel mixtures, respectively) raised to the power of 1.5. Figure 2-16 indicates that the MOE of SCC

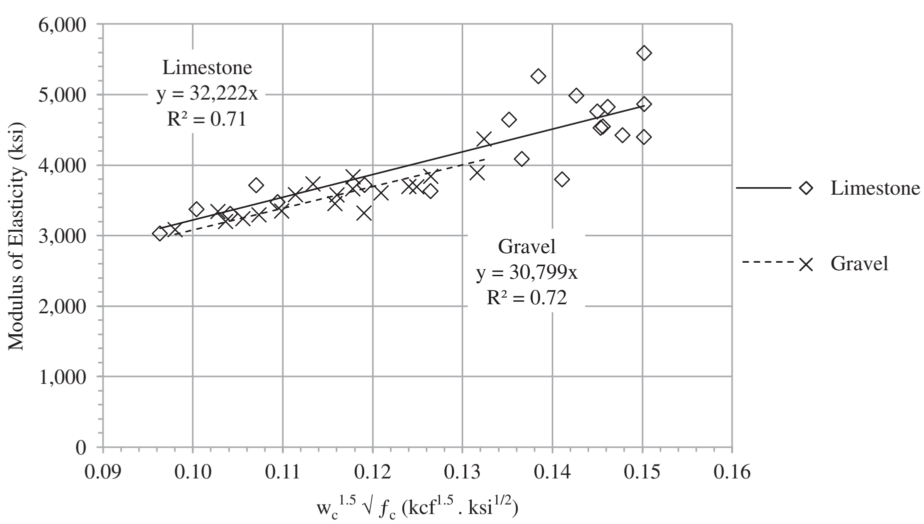


Figure 2-16. Comparing MOE of SCC mixtures containing gravel and limestone aggregates.

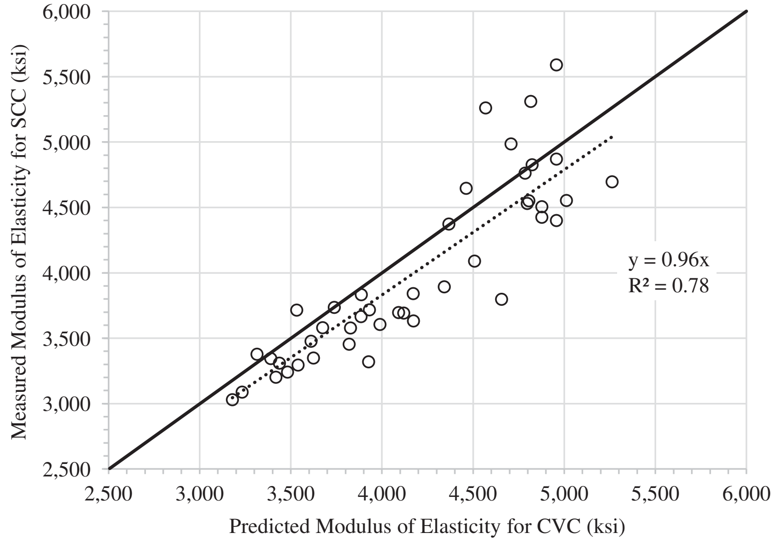


Figure 2-17. AASHTO predicted MOE CVC versus measured MOE for SCC.

mixtures containing limestone aggregate was slightly higher than the MOE of SCC mixtures containing gravel aggregate, as reported by an earlier study (Mokhtarzadeh and French, 2000); K_1 values of 1.0 and 0.95 are proposed for the limestone and gravel aggregates used in this study, respectively.

Figure 2-17 shows the measured MOE values of all SCC mixtures versus those predicted by AASHTO LRFD Equation 5.4.2.4-1, using the proposed K_1 values (1.0 for limestone mixtures and 0.95 for gravel mixtures). Figure 2-17 indicates that MOE of SCC mixtures was slightly lower than predicted (a similar observation was reported by Khayat and Mitchell, 2009), which may be attributed to paste-to-coarse aggregate volume, which is higher in SCC than it is in CVC. Therefore, a modification factor ($K_2 = 0.96$) is proposed for SCC ($E_c = 33{,}000\ K_1\ K_2\ w_c^{1.5}\sqrt{f_c}$ [ksi]).

Tensile Strength

Figure 2-18 shows the average measured splitting tensile strength for SCC mixtures versus the values predicted by AASHTO LRFD Provision C5.4.2.7 for CVC ($f_t = 0.23\sqrt{f_c}$ [ksi]). Figure 2-18 indicates that the splitting tensile strength of SCC

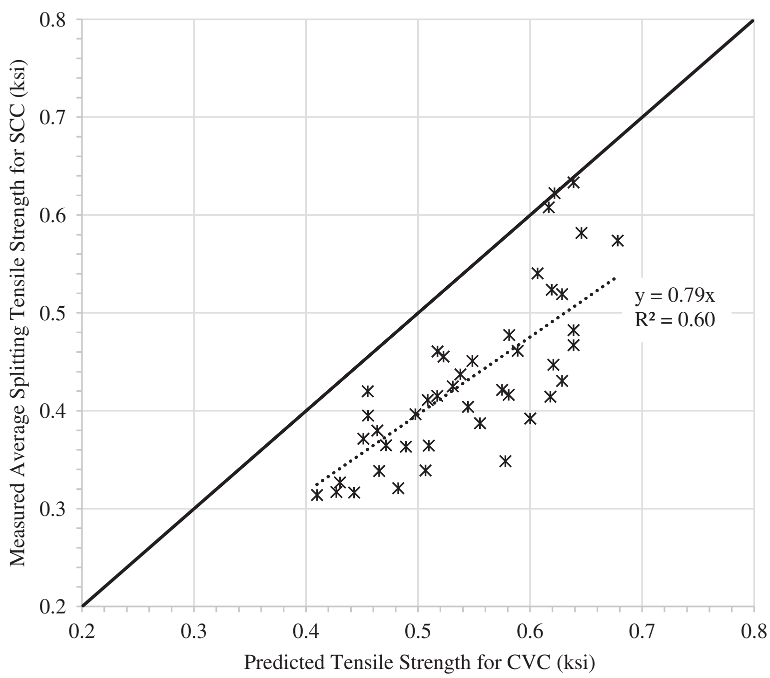


Figure 2-18. AASHTO predicted tensile strength for CVC versus measured tensile strength for SCC.

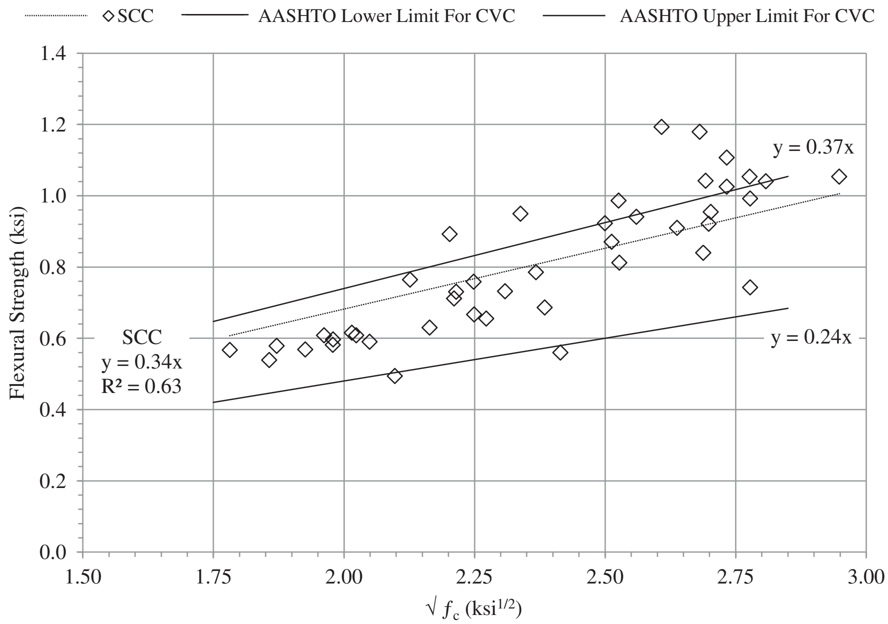


Figure 2-19. Average measured flexural strength of SCC mixtures versus square root of average 28-day compressive strength.

mixtures was approximately 20% less than that predicted for CVC (an earlier study, Parra, Valcuende, and Benlloch, 2007, reported 18% lower tensile strength). Therefore, a modification factor of 0.8 is proposed for estimating the splitting tensile strength of SCC ($f_t = 0.8 \times 0.23\sqrt{f_c}$ [ksi]).

Modulus of Rupture (MOR)

Figure 2-19 shows the average measured MOR versus the square root of the average compressive strength for SCC mixtures and the range predicted by AASHTO LRFD Provision C5.4.2.6 for CVC ($0.24\sqrt{f_c}$ to $0.37\sqrt{f_c}$ [ksi]). Figure 2-19 indicates that the MOR of SCC was within the predicted range for CVC but closer to the upper limit (similar results were reported by Mokhtarzadeh and French, 2000). Thus, the AASHTO LRFD provision for CVC could be applied to SCC.

Bond Strength

Figure 2-20 shows the pull-out bond strength versus the square root of the average compressive strength of SCC and CVC mixtures for 36 vertical deformed reinforcing bars. The

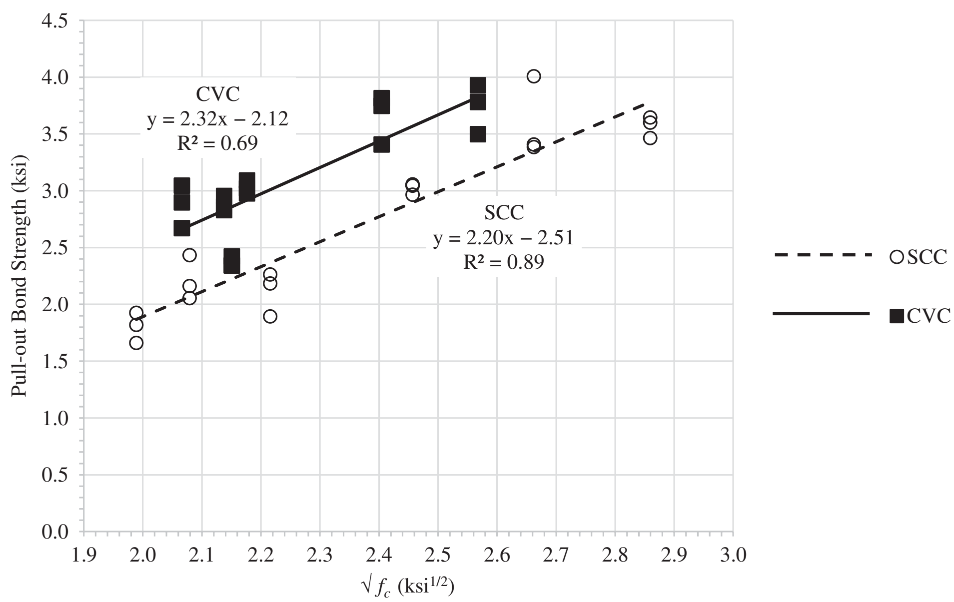


Figure 2-20. Pull-out bond strength versus $\sqrt{f_c}$ of SCC and CVC mixtures.

trend shown indicates that the pull-out bond strength of SCC was consistently lower than that of CVC (similar results were reported by König et al., 2001 and 2003 and Almeida, Nardin, and Gresce, 2005). Also, analysis of variance (ANOVA) of pull-out test data for the two groups of mixtures confirmed this finding at 95% confidence level. Therefore, it appears appropriate to propose a development length modification factor of 1.3 to AASHTO LRFD Bridge Design Specifications Section 5.11.2.1.2 for vertical bars in SCC mixtures.

Figure 2-21 shows the ratios of pull-out bond strength to the square root of average compressive strength for 54 horizontal deformed reinforcing bars located at different heights in six wall specimens: two made of SCC with high slump flow, two made of SCC with low slump flow, and two made of CVC. Figure 2-21 indicates no significant difference in the bond strength of horizontal bars between low slump flow SCC and CVC mixtures, but shows a slight difference between low slump flow SCC and high slump flow SCC. ANOVA of pull-out test data for the three groups of mixtures confirmed this finding at a 95% confidence level. Figure 2-21 also shows a reduction in bond strength as the distance from the bottom of the form increases (top-bar effect), particularly for CVC and low slump flow SCC mixtures, suggesting that the top-bar effect was dependent on the rheological properties of SCC. Therefore, it appears appropriate to propose a development length modification factor of 1.4 in. to AASHTO LRFD Section 5.11.2.1.2 for top horizontal bars with more than 12 in. of fresh SCC cast below regardless of the slump flow.

Shear Resistance

Figure 2-22 shows the push-off interface shear resistance versus the square root of the average compressive strength for 20 SCC and 12 CVC specimens reinforced with two #3 bars across the shear plane. The developed relationships indicate that the interface shear resistance of SCC was very close to that of CVC; ANOVA results confirmed this finding at a 95% confidence level. Figure 2-23 shows a similar interface shear cracking pattern at failure in SCC and CVC specimens. Push-off test results and ANOVA data provided in Appendix E indicate that mixtures containing limestone aggregate exhibited slightly higher interface shear resistance than mixtures containing gravel aggregate.

Figure 2-24 shows the measured interface shear resistance of the 20 SCC specimens reinforced with two #3 bars across the shear plane versus that predicted by AASHTO LRFD Section 5.8.4.1 for CVC with and without the cohesion factor (i.e., c = 0.4 and 0 ksi, respectively). Figure 2-24 indicates that the measured interface shear resistance of SCC was higher than that predicted by AASHTO except for specimens with average compressive strength less than 6 ksi. Therefore, it is proposed that the cohesion factor, c, in the AASHTO LRFD provisions for reinforced normal-weight concrete placed monolithically be 0.0 for SCC with average compressive strength that is less than 6 ksi.

Figure 2-25 shows the average of push-off interface shear resistance of two specimens of each of four bridge components made using ready-mixed SCC and without reinforcement across the shear plane. Figure 2-25 indicates that the measured interface shear resistance of SCC was significantly higher than that predicted by AASHTO LRFD for unreinforced normal-weight concrete placed monolithically (c = 0.4 ksi).

Figure 2-26 shows the ratio of shear resistance to the square root of average compressive strength for 18 beam specimens made of SCC and CVC with different levels of shear reinforcement. It indicates similar shear resistance values for low slump

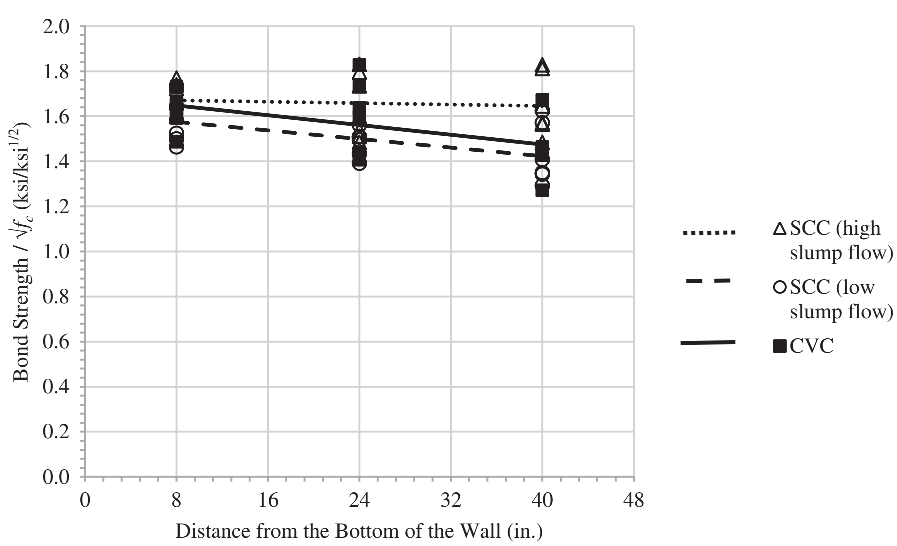


Figure 2-21. Top-bar effect on bond strength of horizontal bars in CVC and SCC mixtures.

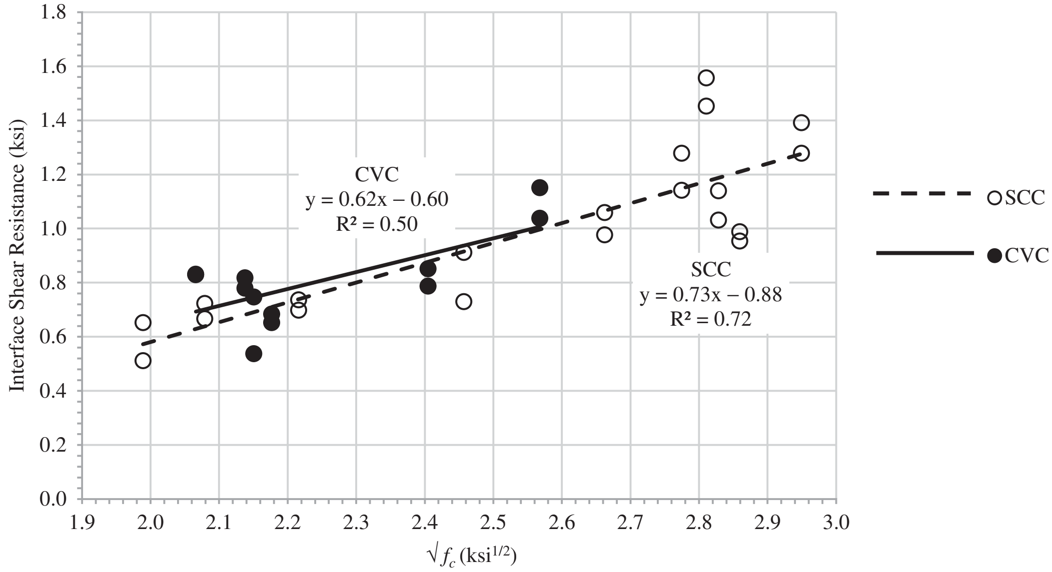


Figure 2-22. Interface shear resistance versus $\sqrt{f_c}$ of SCC and CVC mixtures.

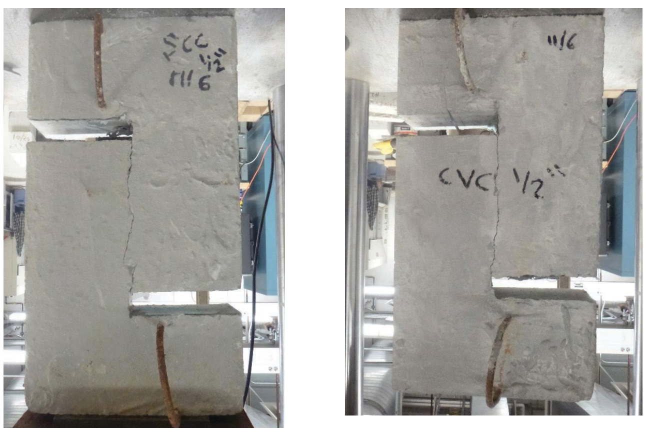


Figure 2-23. Interface shear cracking of SCC and CVC push-off specimens.

flow SCC, high slump flow SCC, and CVC beams with the same reinforcement level. ANOVA data also indicated that the shear resistance of SCC and CVC mixtures was not significantly different at various reinforcement levels (similar to earlier results reported by Ebrahimi and Beygi, 2009). Figure 2-26 also indicates higher shear resistance values for all specimens without shear reinforcement and those with two #3 bars at 8 in. than those predicted by AASHTO LRFD Section 5.8.3.3 (sectional design method). These specimens exhibited typical shear cracking and failure with no significant difference between SCC and CVC beams (see Figures 2-27 and 2-28). Specimens with two #3 bars at 4 in. had reached their ultimate flexure resistance before reaching their ultimate shear resistance and exhibited flexural cracking and failure.

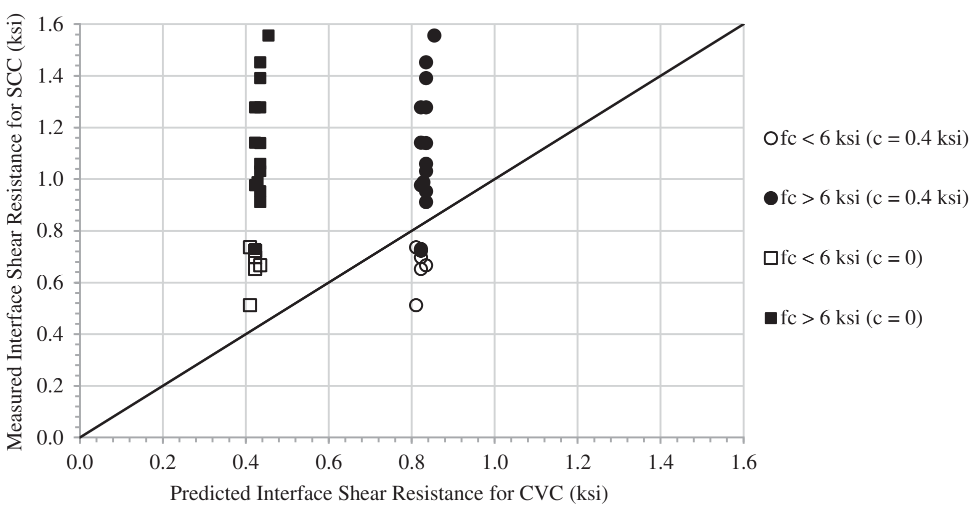


Figure 2-24. Measured interface shear resistance for SCC versus that predicted by AASHTO LRFD for CVC.

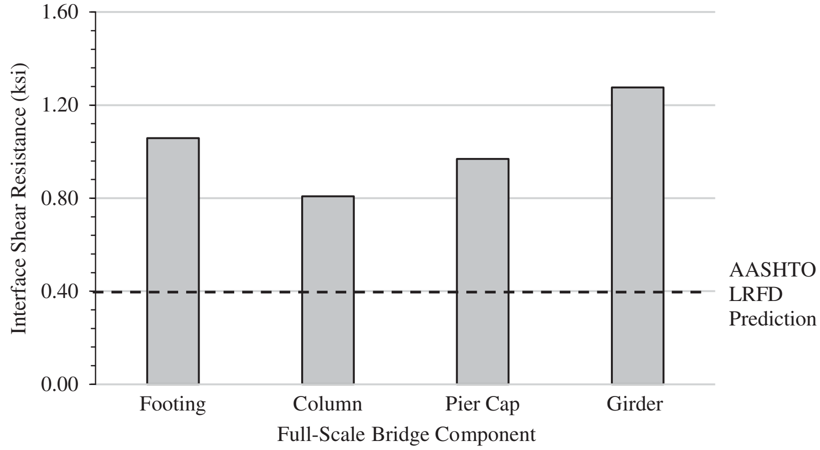


Figure 2-25. Interface shear resistance of unreinforced SCC push-off specimens.

2.3.2 Visco-Elastic Properties

Drying (Free) Shrinkage

Figure 2-29 shows the measured drying shrinkage of SCC mixtures versus that predicted by AASHTO LRFD Equation 5.4.2.3.3-1 for CVC. Figure 2-29 indicates significantly higher shrinkage values for SCC than those predicted for CVC (similar results were reported by Khayat and Mitchell, 2009). Figure 2-29 also indicates that the type of SCM/filler had a large effect on drying shrinkage. Therefore, a modification factor (k_p) to AASHTO LRFD Equation 5.4.2.3.3-1 is proposed to consider SCC mixtures with different types of SCM/filler. This SCC powder composition modification factor is estimated at 1.6 for SCC with cement type I/II and 25% Class C fly ash; 1.4 for SCC with cement type I/II and 30% GGBFS; and 1.3 for SCC with cement type I/II and 25% Class F fly ash or 20% Class F fly ash and 15% limestone powder. These values were derived from the slopes of the best fit straight lines shown in Figure 2-29. All other parameters of AASHTO LRFD Equation 5.4.2.3.3-1 remain the same (i.e., k_p should be 1.0 for CVC). Figure 2-30 shows the average and standard deviation of 56-day drying shrinkage for SCC and CVC mixtures grouped by SCM/filler type.

Restrained Shrinkage

Figure 2-31 shows the time to cracking versus average stress rate for SCC and CVC mixtures in a restrained condition for up to 28 days. It appears that the time to cracking decreased as the average stress rate increased. About 50% of the mixtures did not crack during the 28-day test period (these are not shown in Figure 2-31). Figure 2-32 shows the average stress rate and standard deviation of SCC and CVC mixtures grouped by SCM/filler type. Figure 2-32 indicates that the

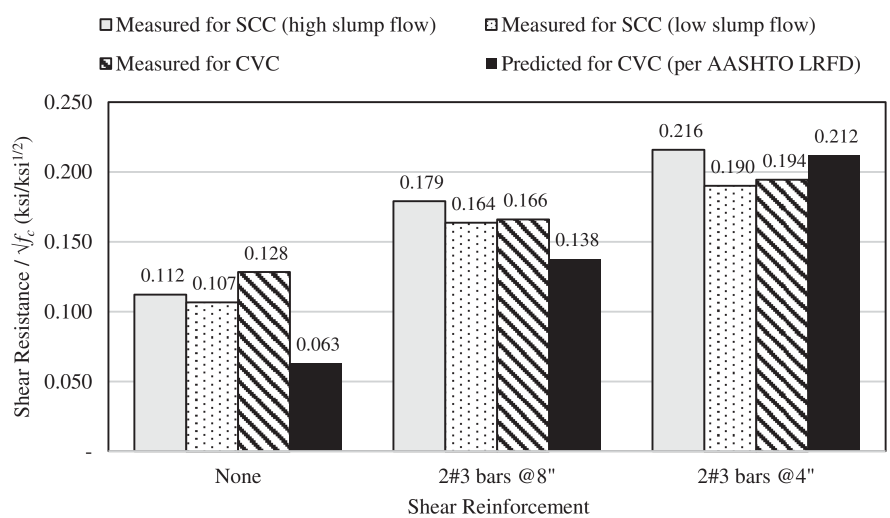
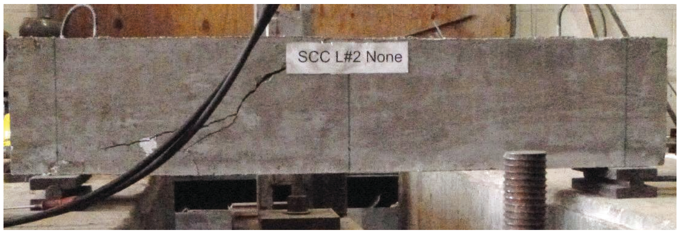


Figure 2-26. Shear resistance of SCC and CVC mixtures with different reinforcement.

(a) Shear cracking in a CVC beam.

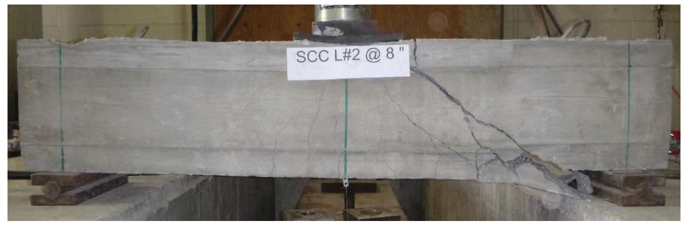


(b) Shear cracking in a low slump flow SCC beam.

(c) Shear cracking in a high slump flow SCC beam.

Figure 2-27. Shear cracking of beams with no transverse reinforcement.

(a) Shear cracking in a CVC beam.



(b) Shear cracking in a low slump flow SCC beam.

(c) Shear cracking in a high slump flow SCC beam.

Figure 2-28. Shear cracking of beams transversely reinforced with two #3 bars at 8 in.

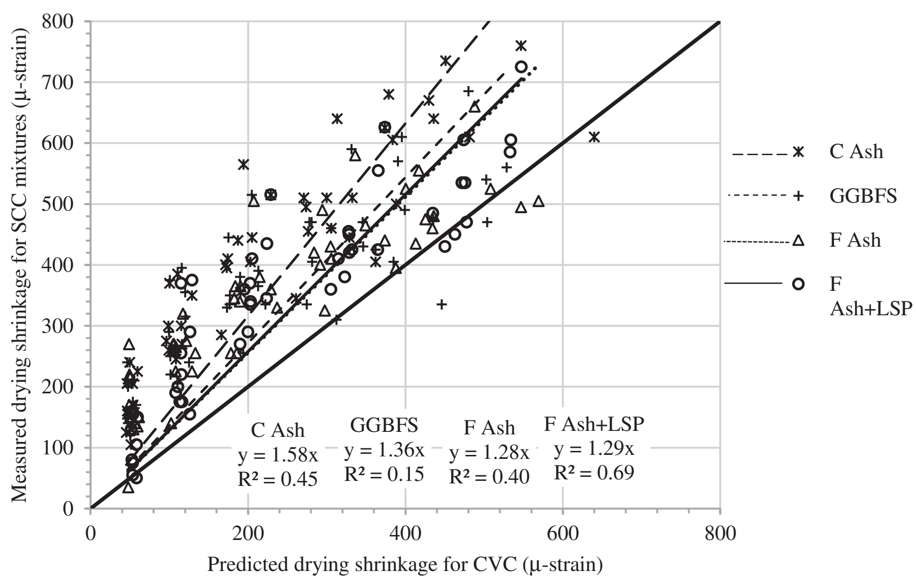


Figure 2-29. AASHTO LRFD predicted drying shrinkage for CVC versus measured drying shrinkage for SCC mixtures.

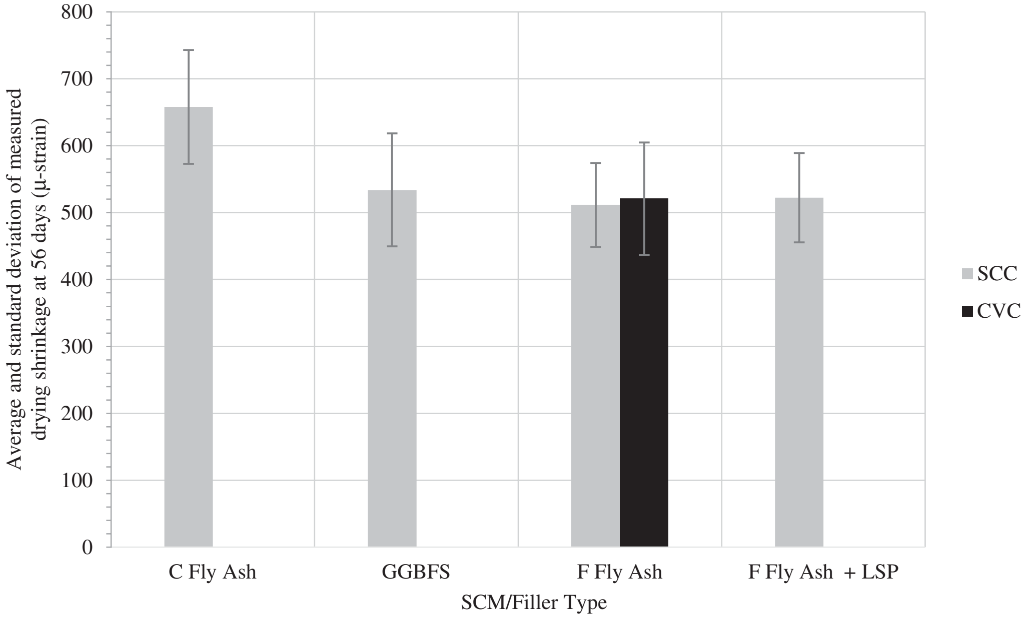


Figure 2-30. Average and standard deviation of measured 56-day drying shrinkage for CVC and SCC mixtures.

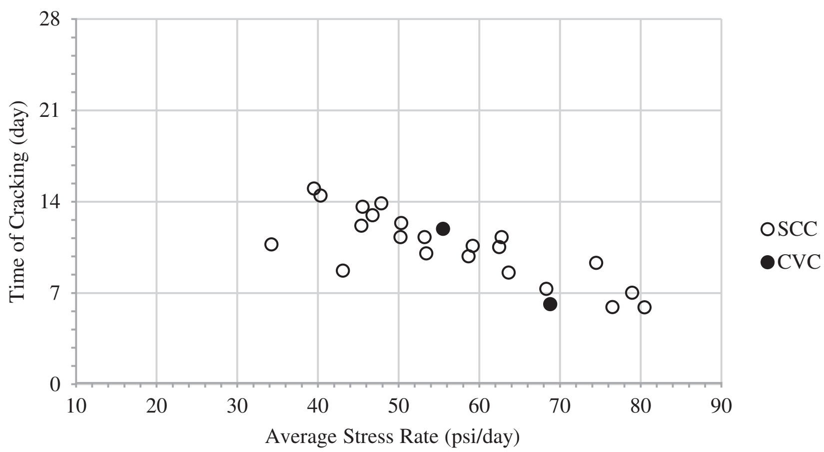


Figure 2-31. Restrained shrinkage test data for SCC and CVC mixtures.

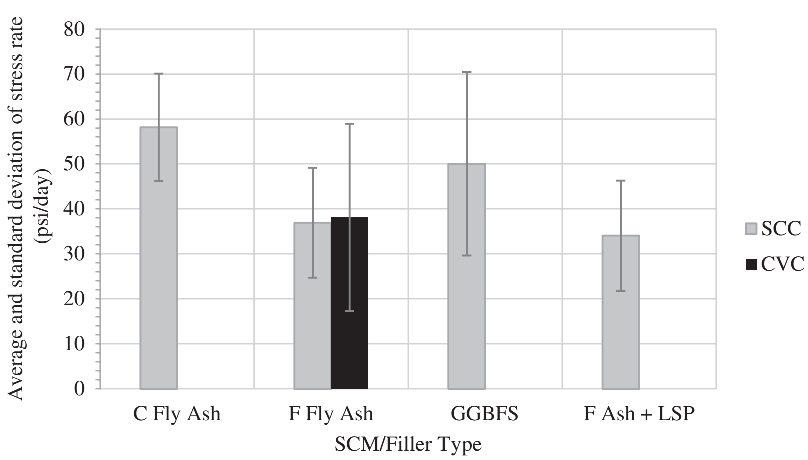


Figure 2-32. Average and standard deviation of stress rate for CVC and SCC mixtures with different types of SCM/filler.

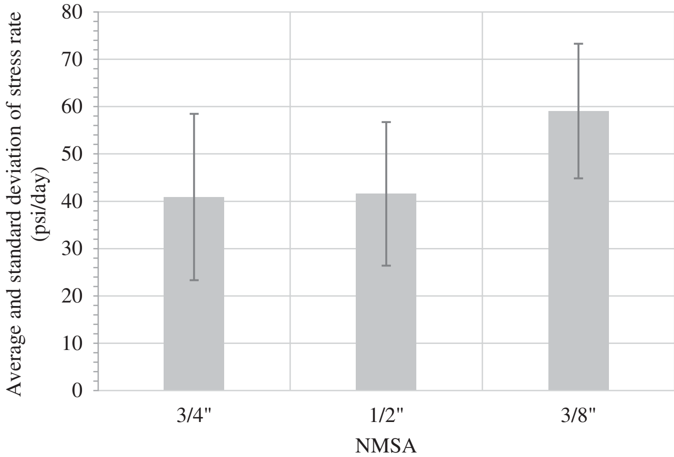


Figure 2-33. Average and standard deviation of stress rate for SCC mixtures with different NMSA.

cracking potential of SCC mixtures was not significantly different from that of CVC mixtures with the same SCM (similar results were reported by See and Attiogbe, 2005). However, the type of SCM/filler had a significant effect on the cracking potential of SCC mixtures; mixtures containing Class C fly ash exhibited the highest potential to crack. Figure 2-33 shows the effect of NMSA on cracking potential. It indicates that SCC mixtures containing ⅜ in. NMSA exhibited higher potential to crack than mixtures containing ¾ or ½ in. NMSA.

Creep

Figure 2-34 shows the measured creep coefficients for SCC mixtures at different ages versus the coefficients predicted by AASHTO LRFD provisions for CVC. All SCC mixtures exhibited the same creep trend except those with limestone powder (similar results were reported by Heirman et al., 2008). Figure 2-34 indicates that for all SCC mixtures, except those with limestone powder, the creep coefficient can be accurately predicted using the AASHTO LRFD equation for CVC. However, a 1.2 modification factor, proposed as a multiplier to AASHTO LRFD Equation 5.4.2.3.2-1, would be required for estimating the creep coefficient of SCC mixtures containing 15% limestone powder. Charts showing creep strain versus age of loading for all SCC and CVC mixtures and charts showing the AASHTO LRFD predicted creep strains versus age of loading are provided in Appendix E. These data show an agreement between measured and predicted creep curves for all mixtures except for mixture G222S (possibly due to errors in loading specimens and/or recording of test data).

2.3.3 Durability Properties

Air Void System

Figure 2-35 shows the air void system parameters for the hardened SCC and CVC mixtures. Figure 2-35 indicates that the spacing factor and specific surface of most SCC and CVC mixtures were within the values recommended by PCA (2009) and FHWA (2006). However, the variation in the air content of SCC mixtures was higher than that of CVC mixtures; some values were outside the target range of 6 ± 1.5%. This variation may be caused by variations in the HRWRA dosage used in SCC mixtures.

Surface Resistivity

Figure 2-36 shows the 28-day surface resistivity of SCC and CVC mixtures. Figure 2-36 indicates that the variation in surface resistivity was more related to the SCM/filler type than to the aggregate type (limestone or gravel) or concrete type (SCC

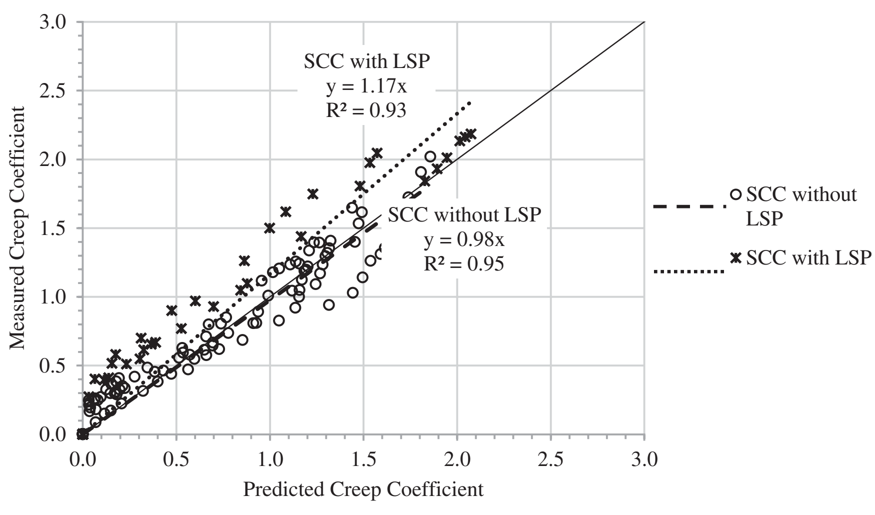
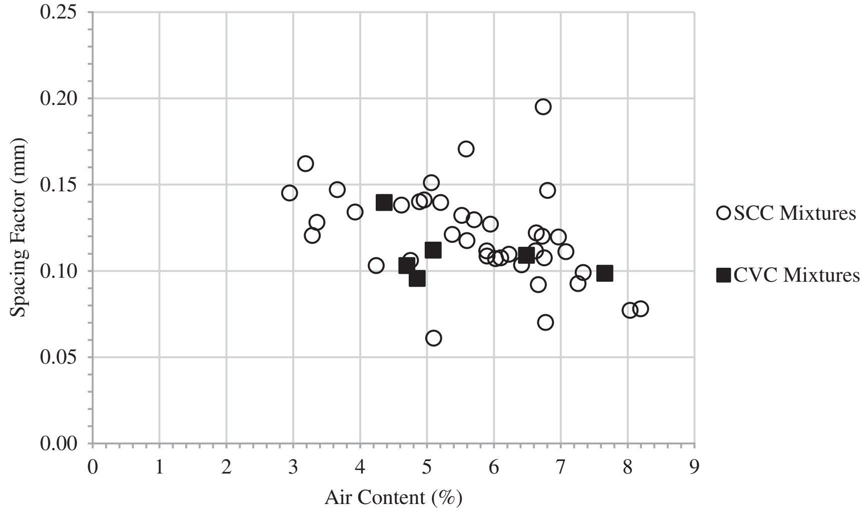
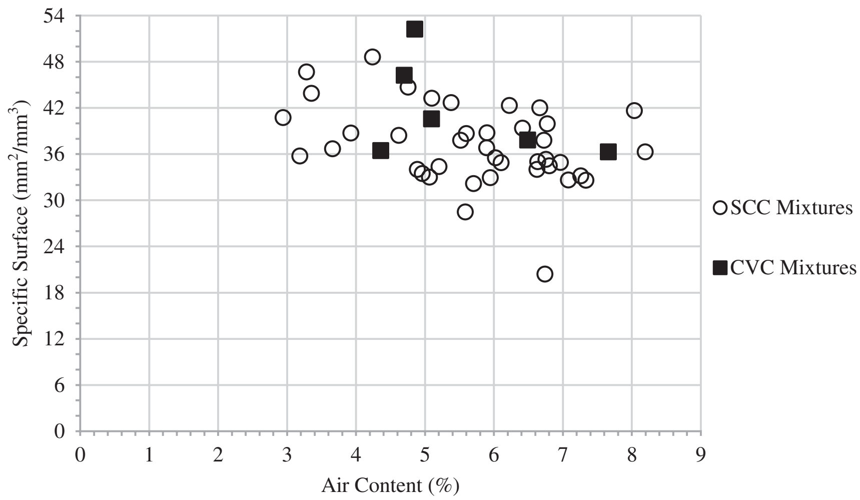


Figure 2-34. Predicted creep coefficient for CVC versus measured creep coefficient for SCC mixtures.



(a) Air content versus spacing factor.



(b) Air content versus specific surface.

Figure 2-35. Air void system parameters for hardened SCC and CVC.

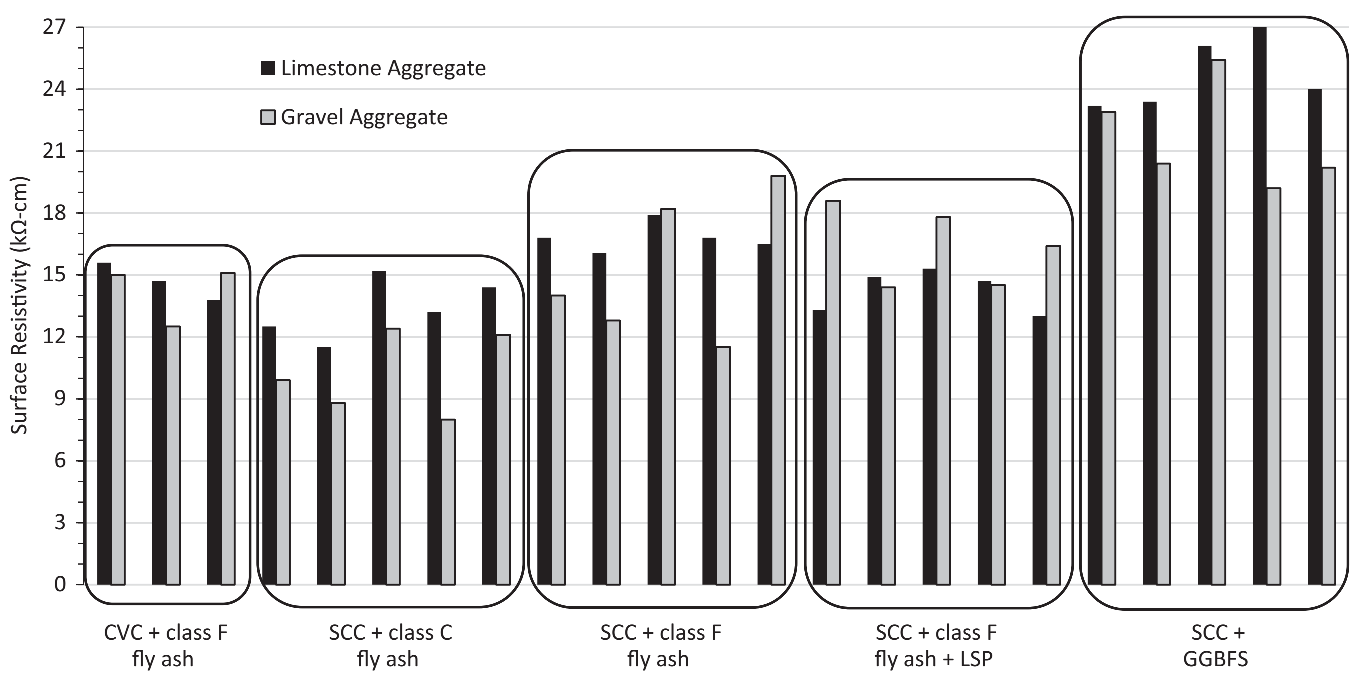


Figure 2-36. Surface resistivity of SCC and CVC mixtures.

or CVC); similar findings have been reported by Tang and Zhu (2007). Mixtures with Class C fly ash exhibited the lowest surface resistivity (high penetrability), and mixtures with GGBFS exhibited the highest surface resistivity (low penetrability). In general, SCC mixtures exhibited higher surface resistivity than CVC mixtures with the same type of SCM. Details of surface resistivity measurements for all mixtures are provided in Appendix E.

2.4 Full-Scale Bridge Components

Several constructability and structural performance issues associated with using SCC in cast-in-place bridges were investigated by constructing and testing two full-scale bridge components; details of forming, reinforcing, placing, and testing each component are provided in Appendix F. The findings are summarized in the following sections.

2.4.1 Formwork Pressure

Figure 2-37 shows the measured SCC formwork pressure versus time (up to 75 minutes) at three locations in the two pier columns. SCC was placed in each column using a bucket (i.e., discrete placement), which resulted in the steps shown in Figure 2-37. The time interval between successive placements determined the placement rate as column dimensions and bucket size were the same. Figure 2-37 indicates a slight reduction in the maximum pressure with time. Figure 2-38 shows the full hydrostatic pressure and the peak pressure values measured at different heights in the two pier columns constructed using placement rates of 26 ft/hr and 60 ft/hr. Figure 2-38 indicates that the maximum SCC formwork pressure was very close to hydrostatic pressure, especially for high placement rates (similar to the findings of the laboratory investigation). A significant reduction in SCC formwork pressure can be obtained by reducing

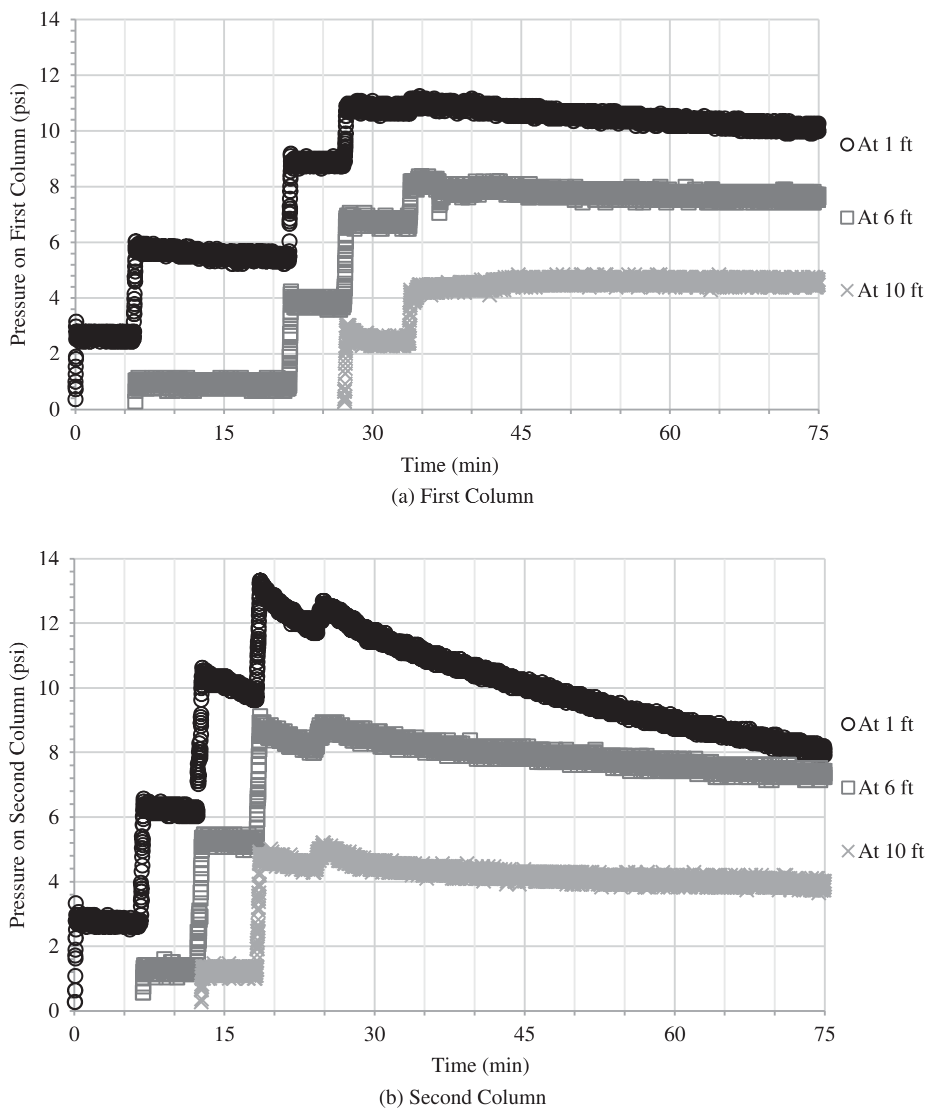


Figure 2-37. Measured SCC formwork pressure versus time for the two pier columns.

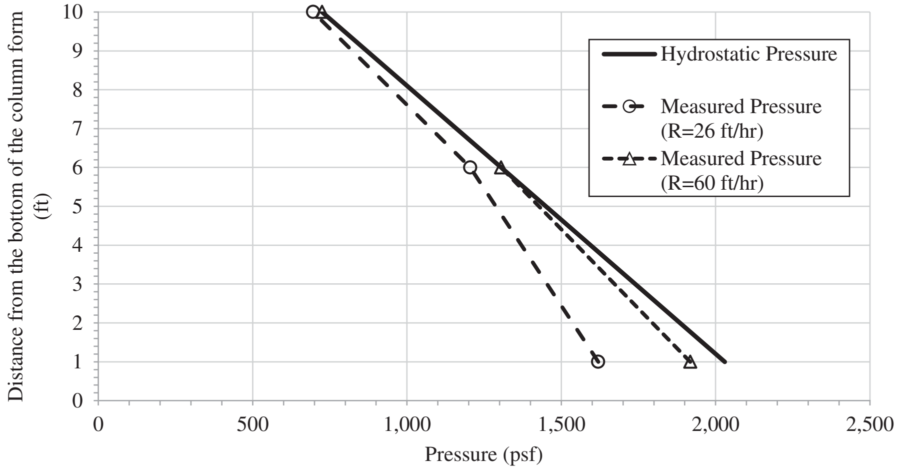


Figure 2-38. Measured SCC formwork peak pressure for different placement rates.

placement rates, especially for mixtures with high thixotropy and high yield stress. The rheological properties of the SCC mixture used in column fabrication are provided in Appendix F.

2.4.2 Drying Shrinkage

Figure 2-39 shows measured drying shrinkage for ready-mixed SCC used in fabricating the full-scale bridge components versus that predicted by the AASHTO LRFD equation, using the proposed powder composition modification factor for SCC (Section 2.3.2). Figure 2-39 shows that introducing the proposed modification factor improves the predictability of drying shrinkage of SCC for the different curing conditions.

2.4.3 Formed Surface Quality

The formed surface quality of the components was evaluated according to ACI 347.3R-13 guidance for formed concrete surfaces. Only the surface void ratio criterion was used because it reflects concrete consolidation; not form quality. Table 2-1 lists the maximum surface void diameter, surface void area, and the corresponding surface void ratio class for different formed surfaces of each component. These results indicate that all of the formed surface resembled concrete surface category (CSC) 3 or 4 (categories for exposed surfaces where visual appearance is important). High slump flow SCC, short free-fall distance, or concrete moved in a bottom-up direction provided the highest surface void ratio classes.

2.4.4 Structural Performance

Table 2-2 summarizes the results of four structural tests conducted on the full-scale bridge components made of SCC. In each test, the nominal resistance of the component was predicted by AASHTO LRFD equations for CVC, assuming a resistance factor of 1.0 and using the measured compressive

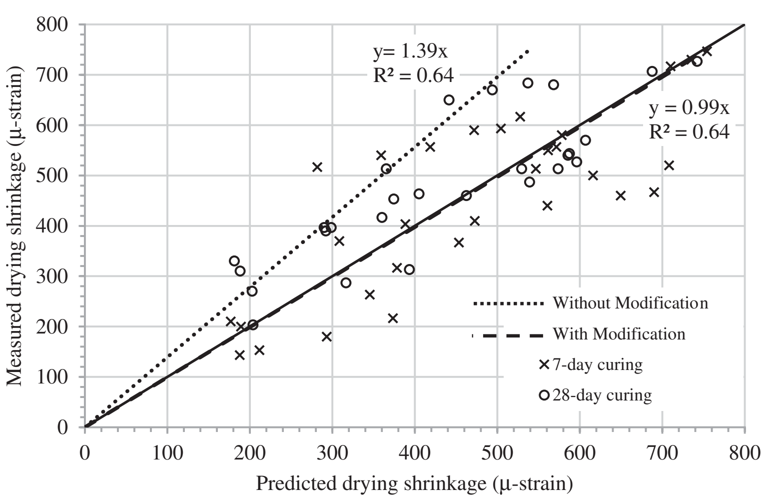


Figure 2-39. Measured versus predicted drying shrinkage for SCC mixtures.

Table 2-1. Measured surface void size and ratio in the formed SCC surfaces.

Formed SCC Surface	Max. Void Diameter (D_{max}), in.	Surface Void Area (%)	Surface Void Ratio Class
Footing (short side)	3/8	0.16%	SVR3
Footing (long side)	3/8	0.31%	SVR3
First Column (at 1.5 ft from the bottom)	3/8	0.14%	SVR3
First Column (at 11.3 ft from the bottom)	3/8	0.25%	SVR3
Second Column (at 8.5 ft from the bottom)	5/8	0.19%	SVR2
Second Column (at 10 ft from the bottom)	5/8	0.31%	SVR2
Pier Cap (at the pour line)	5/8	0.68%	SVR2
Pier Cap (away from the pour line)	5/8	0.54%	SVR2
Top of the Girder (pouring side)	1/2	0.40%	SVR3
Bottom of the Girder (pouring side)	1/2	0.51%	SVR3
Bottom of the Girder (opposite side)	1/4	0.20%	SVR4
Girder End (at the construction joint)	1/4	0.02%	SVR4

Table 2-2. Results of testing full-scale bridge components.

Component	Test Type	Age at Testing (day)	Actual Compressive Strength (ksi)	Predicted Ultimate Load (kip)	Cracking Load (kip)	Applied Load (kip)
Pier Cap	Strut-and-Tie Resistance	33	7.5	380.0	150	451.0*
Column	Flexural Resistance	103	8.5	94.5	40	101.5*
Box Girder	Flexural Resistance	39	8.2	297.0	200	301.5*
	Shear Resistance	39	8.2	353.0	250	400.4*

* Loading was stopped to maintain specimen stability and integrity for further testing.

strength. The predicted nominal resistance was then used to predict the ultimate load, as shown in Table 2-2. All components showed a higher resistance than predicted and a behavior similar to that expected for components made of CVC. Also, no relative displacement (i.e., slippage) between the SCC top flange and tub section was detected and no cracking or signs of damage were observed at the anchorage zones of the post-tensioned SCC girder. The limited data obtained from these tests suggest that SCC components can be expected to exhibit similar behavior to that of CVC components and the possible applicability of AASHTO LRFD interface shear design and anchorage zone design provisions to SCC components.

2.4.5 Segregation Resistance

The stability of SCC used in the construction of full-scale bridge components was evaluated by making several saw cuts at different sections and obtaining specimens for examination. Figure 2-40 shows a mid-section across the width of the footing, Figure 2-41 shows the sections taken at the bottom, middle, and top portions of the two columns of the bridge pier. Figure 2-42 shows a mid-section across the pier cap, and Figures 2-43 and 2-44 show sections taken near the ends of the box girder specimen. For all these sections, the distribution of the coarse aggregate from top to bottom and thickness of the mortar layer at the top of the section were evaluated using the rating criteria of HVSI. Figures 2-40 through 2-44 indicate that the SCC mixtures were stable (HVSI 0 or 1), and no signs of segregation, bleeding, or lack of consolidation around the reinforcing bars were observed.

Figure 2-40. Saw cut at the middle of the bridge pier footing.

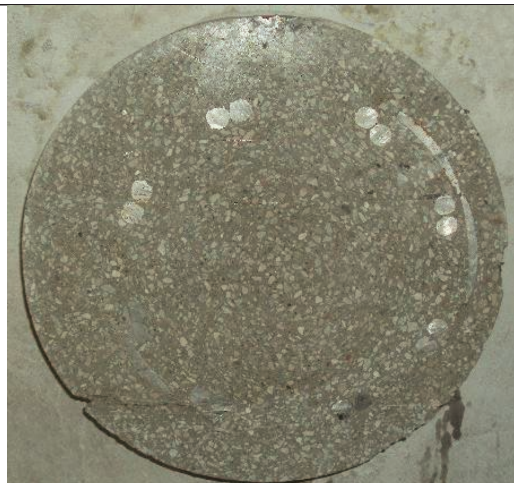
Location	First Column	Second Column
Bottom		
Middle		
Top		

Figure 2-41. Saw cuts at the bottom, middle, and top of the two pier columns.

Figure 2-42. Saw cut at the middle of bridge pier cap.

Figure 2-43. Saw cut in the bridge box girder specimen.

Figure 2-44. Saw cut in the bridge box girder specimen showing top and bottom corners.

Limited mechanical vibration of the concrete surface prior to placing the next lift is a common practice used to avoid the formation of pour lines. To investigate the SR of SCC mixtures handled in this way, three 6 in. × 12 in. cylinders were made using low slump flow SCC. SCC in one cylinder was not vibrated, but SCC in the other two cylinders was subjected to low (2 sec) and moderate vibration (8 sec). The three cylinders were saw cut after hardening to examine the distribution of coarse aggregate. Figure 2-45 shows that the resistance to segregation was not affected by the level of vibration (HVSI of the three cylinders was 1).

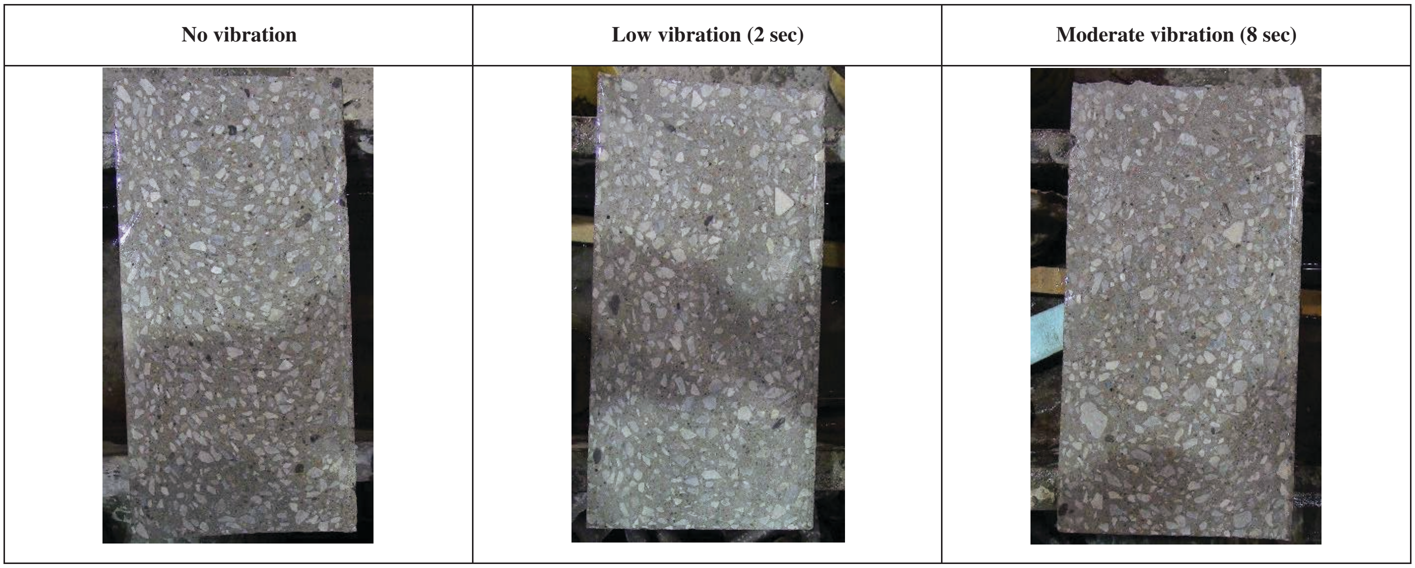


Figure 2-45. Saw cuts of three cylinders with different levels of vibration.

Table 2-3. Air void system in fresh and hardened SCC used in full-scale specimens.

Component	Fresh SCC			Placement method	Hardened SCC					
	% Air content at plant*	Dosage of HRWRA added at jobsite (oz/cwt)	% Air content at jobsite		Measured on 4 x 8 in. cylinders			Measured on 3 in. diameter cores		
					% Air content	Spacing factor (mm)	Specific surface (mm^2/mm^3)	% Air content	Spacing factor (mm)	Specific surface (mm^2/mm^3)
Footing	4.5	2.3	2.5	Truck Chute	4.1	0.17	32.8	2.9	0.23	22.5
First Column	4.5	2.0	4.0	Bucket and Tremie Pipe	5.7	0.17	26.4	4.2	0.18	31.0
Second Column	6.2	1.0	4.0	Bucket (free fall)	4.9	0.15	27.2	5.2	0.15	32.7
Pier Cap	6.4	4.0	4.0	1/2 cy Bucket	4.3	0.22	24.3	–	–	–
Box Girder	6.0	1.5	4.5	Pumping (2 and 3 in. hose)	4.0	0.16	34.0	5.2	0.14	29.0
Top Flange	4.5	1.5	3.5	Pumping (3 in. hose)	5.0	0.13	33.1	4.6	0.17	31.9
AVERAGE	**5.35**	**2.05**	**3.75**	**–**	**4.7**	**0.17**	**29.6**	**4.4**	**0.18**	**29.4**

* Measured by plant technician

2.4.6 Air Void System

Table 2-3 lists the air content measurements for the ready-mixed fresh SCC at the plant and at the job site after adding an additional dosage of HRWRA (the target air content was 6±1.5%). The air void system parameters for the hardened concrete were measured on cylinders and cores extracted from the full-scale components. These data indicated a significant difference between the air content in fresh concrete at the plant and that at job site (more than 1.5%) due to time, transportation, and addition of HRWRA. A comparison of the air void system parameters for the cylinders and cores indicates no significant difference, suggesting that placement method did not have a significant effect on the air void system in SCC.

CHAPTER 3

Conclusions and Recommendations for Research

This chapter summarizes the major findings of the research and presents suggestions for future research. The findings presented in this report were based on the investigations performed using specific materials; other materials may result in different findings.

3.1 Mix Proportions and Fresh and Early-Age Concrete Properties

The tests on SCC mixtures proportioned for cast-in-place bridge components indicated the following:

1. SCC mixtures with satisfactory properties for cast-in-place bridge components could be proportioned using the procedure proposed by Koehler and Fowler (2007). These mixtures had a water-powder ratio ranging from 0.37 to 0.44, powder content ranging from 650 to 760 lb/cy, and sand-to-aggregate ratio ranging from 0.45 to 0.50.
2. SCC mixtures with satisfactory properties for cast-in-place bridge components could be produced with replacements with 25% Class C fly ash, 25% Class F fly ash, 30% GGBFS, or 20% Class F fly ash and 15% limestone powder.
3. SCC mixtures with satisfactory properties for cast-in-place bridge components could be produced using natural gravel and crushed limestone aggregates with ¾, ½, and ⅜ in. NMSA.
4. Workability targets of SCC mixtures depend on the geometric characteristics of cast-in-place bridge components.
5. Table 3-1 shows examples of bridge components, their geometric characteristics, and the proposed workability targets of SCC mixtures.
6. SCC mixtures with high filling ability (FA2) are appropriate for cast-in-place bridge components with intricate shape and/or when high formed surface quality is desired (e.g., for box girders and pier walls); SCC mixtures with low filling ability (FA1) are appropriate for components with simple shape and when formed surface quality is not a concern (e.g., pile caps and floor beams).
7. SCC mixtures with high resistance to segregation (SR2) are appropriate for cast-in-place bridge components that are either deep or long (e.g., arches and abutment walls); SCC mixtures with moderate resistance to segregation (SR1) are appropriate for cast-in-place bridge components that are shallow and short (e.g., pier caps).
8. SCC mixtures with low passing ability (PA1) are appropriate for thick components with a low level of reinforcement (e.g., footings); SCC mixtures with high passing ability (PA2) are appropriate for thin components and/or those with a high level of reinforcement (e.g., girders and pier columns).
9. The dosage of HRWRA required to achieve specific workability targets varied based on the type of aggregate and SCM/filler. SCC mixtures with crushed limestone aggregate and GGBFS required a higher dosage of HRWRA than those with natural gravel aggregate and fly ash to achieve the same workability targets.
10. For SCC mixtures with relatively low powder content and/or high W/P ratio, viscosity-modifying admixture (VMA) was needed to enhance mixture stability.
11. SCC mixtures designed for cast-in-place bridge components exhibited a wide range of viscosity and yield stress depending on the type of SCM/filler, W/P ratio, and type and size of coarse aggregate.
12. The rate of workability loss of SCC mixtures was directly proportional to the initial slump flow; use of WRAs would help maintain the workability for an extended period of time. A late addition of a small dosage of HRWRA helped improve SCC workability when slump flow was below 22 in.
13. Time of initial setting of SCC mixtures was highly dependent on the temperature and type of SCM/filler. Mixtures containing Class C fly ash had the longest time

Table 3-1. Proposed SCC workability targets for examples of cast-in-place bridge components.

Component Category	Bridge Component	Component Geometric Characteristics												SCC Workability Targets					
		Length		Depth		Thickness		Shape Intricacy		Formed Surface Quality		Level of Reinforcement		Filling Ability		Segregation Resistance*		Passing Ability	
		Short	Long	Shallow	Deep	Thin	Thick	Simple	Complex	Low	High	Low	High	FA1	FA2	SR1	SR2	PA1	PA2
Substructure	Footing	■		■			■	■		■		■		■		■		■	
	Pile Cap	■		■			■	■		■			■	■		■			■
	Wing Wall	■		■			■	■				■		■		■		■	
	Abutment Wall		■		■		■	■		■		■		■			■	■	
	Pier Wall		■		■		■		■		■	■			■		■	■	
	Pier Column	■			■		■	■			■		■		■		■		■
	Strut or Tie	■		■			■	■			■	■			■		■	■	
	Pier Cap	■		■			■	■			■		■		■	■			■
Superstructure	Box Girder		■	■		■			■				■		■		■		■
	Stringer	■		■			■	■		■			■	■		■			■
	Floor Beam	■		■			■	■				■		■		■		■	
	Girder		■	■		■		■			■		■		■		■		■
	Arch		■		■		■	■			■	■			■		■	■	

Note: Shaded cells represent selected component geometric characteristics and SCC workability targets.

* For deep/long components, SR1 could be acceptable if free-fall height/free-travel distance is controlled (e.g., tremie pipe).

of initial setting, and those containing Class F fly ash had the shortest time of initial setting. Also, high slump flow SCC mixtures exhibited a longer time of initial setting than that of low slump flow SCC mixtures due to the retarding effects of HRWRA.

14. The heat of hydration of SCC mixtures was similar to that of CVC mixtures but SCC experienced a slight delay in reaching the peak temperature (the longest delay was observed in mixtures containing Class C fly ash).
15. The formwork pressure of SCC was slightly less than full hydrostatic pressure. The placement rate, thixotropy, and yield stress of SCC had a significant effect on the maximum formwork pressure.

3.2 Mechanical, Visco-Elastic, and Durability Properties

The following findings were based on the properties of hardened SCC mixtures proportioned for cast-in-place bridge components:

1. The compressive strength of SCC at any age was accurately predicted using the ACI 209 model for CVC. The ratios of 7-day, 14-day, and 56-day compressive strength to 28-day compressive strength were 0.77, 0.88, and 1.12, respectively for SCC mixtures.
2. MOE of SCC was slightly lower than that predicted by AASHTO LRFD Equation 5.4.2.4-1 for CVC (33,000 $K_1 w_c^{1.5} \sqrt{f'_c}$). A modification factor of 0.96 would account for the effect of high paste-to-aggregate volume of SCC mixtures on MOE. Also, the MOE of SCC mixtures containing crushed limestone aggregate was slightly higher than that of mixtures containing natural gravel aggregate. Use of the AASHTO aggregate source factor (K_1) of 1.0 and 0.95 for limestone and gravel aggregate, respectively, would account for aggregate stiffness.
3. The splitting tensile strength of SCC mixtures was lower than that estimated by AASHTO LRFD Section C5.4.2.7 for CVC (0.23 $\sqrt{f'_c}$); a correction factor of 0.8 would account for tensile forces that are caused by effects other than flexure, such as anchorage zone design.
4. The MOR of SCC mixtures was within the range predicted by AASHTO LRFD Section C5.4.2.6 for CVC (0.24 $\sqrt{f'_c}$ to 0.37 $\sqrt{f'_c}$).
5. The pull-out bond strength of vertical reinforcing steel bars cast in SCC was lower than that of bars cast in CVC; a development length modification factor of 1.3 would account for the difference.
6. The pull-out bond strength of horizontal reinforcing steel bars cast in SCC was similar to that of bars cast in CVC, but the top-bar effect was lower in high slump flow SCC than it was in low slump flow SCC and CVC.
7. The interface shear resistance of SCC obtained from push-off testing was lower than that predicted by AASHTO

LRFD Section 5.8.4.1 for CVC only for compressive strength less than 6 ksi; using a cohesion factor (c) of 0.0 for SCC with compressive strength less than 6 ksi would account for this difference.

8. The nominal shear resistance of SCC beams with different levels of transverse reinforcement was accurately predicted by AASHTO LRFD Section 5.8.3.3 for CVC.
9. Drying shrinkage of SCC mixtures was higher than that predicted by AASHTO LRFD Equation 5.4.2.3.3-1 for CVC and highly dependent on the type of SCM/filler. A powder composition modification factor for SCC containing Class C fly ash, GGBFS, and Class F fly ash with/without limestone powder would account for this difference. Also, increasing the curing period from 7 to 28 days significantly reduced drying shrinkage of SCC mixtures.
10. Restrained shrinkage of SCC mixtures was highly dependent on the type of SCM/filler and NMSA. SCC mixtures containing Class C fly ash and/or ⅜ in. NMSA exhibited high cracking potential, but mixtures containing Class F fly ash and/or ¾ in. NMSA exhibited low cracking potential.
11. The creep coefficient of SCC mixtures (except those containing limestone powder) was accurately predicted by AASHTO LRFD Equation 5.4.2.3.2-1 for CVC. SCC mixtures with 20% Class F fly ash and 15% limestone powder exhibited higher creep strains; a modification factor of 1.2 would account for this difference.
12. The air void system of hardened SCC indicated adequate freeze and thaw resistance for most mixtures. However, the wide variation in HRWRA dosages used in SCC mixtures resulted in a large difference in the air content between fresh and hardened conditions.
13. Surface resistivity of SCC mixtures indicated low-to-moderate chloride ion penetrability depending on the type of SCM/filler. SCC mixtures containing Class C fly ash had the lowest surface resistivity (higher penetrability), and mixtures containing GGBFS had the highest surface resistivity (lower penetrability).

3.3 Full-Scale Bridge Components: Constructability and Structural Performance

Observations made during the construction and testing of full-scale bridge components indicated the following:

1. SCC proportioned for shallow and short bridge components (e.g., footings) was satisfactorily placed continuously at a high placement rate (e.g., 1.3 cy/min) from one location using the truck chute.
2. SCC proportioned for deep components (e.g., columns) was satisfactorily placed at a high placement rate (e.g., 60 ft/hr) using a crane and bucket with a free-fall height of 15 ft. For deeper components, a tremie pipe would be necessary to reduce the free-fall height.
3. Maximum formwork pressure of SCC was very close to full hydrostatic pressure for high placement rates (e.g., 60 ft/hr). Slower placement rates (e.g., 26 ft/hr) resulted in a lower formwork pressure depending on the temperature and thixotropic characteristics of SCC.
4. Interrupting the placement of SCC for an extended period (e.g., 20 minutes or more) may result in forming pour lines (i.e., lift lines) between consecutive pours due to the thixotropic behavior of SCC. Agitating the top surface of the first lift by limited vibration immediately before placing the next lift can reduce or eliminate the formation of pour lines without negatively affecting the stability of SCC.
5. SCC was pumped satisfactorily from one location at one side (i.e., web) of a 40 ft long tub girder that was heavily reinforced. SCC flowed horizontally under its own weight for 20 ft in each direction, filling the bottom flange, encapsulating reinforcing bars and post-tensioning ducts, and rising up to fill the opposite web up to its mid-height (1.5 ft).
6. A maximum surface void ratio of 0.6% and maximum surface void diameter of ⅜ in. (i.e., CSC 3) were observed on all formed surfaces of the fabricated SCC bridge components. A lower surface void ratio can be achieved by controlling the direction of flow so that it is bottom-up rather than top-down, further reducing the entrapped air during SCC placement.
7. Visual examination of coarse aggregate distribution in saw cut bridge components at different locations indicated high stability and consolidation of SCC around reinforcing bars, with no signs of segregation or bleeding.
8. No cracking or signs of damage were observed around post-tensioning anchorages of the box girder specimen indicating a satisfactory application of SCC in highly disturbed regions (i.e., local zone and general zone).
9. Air void system parameters measured on SCC cylinders and cores extracted from fabricated components were not significantly different (< 1.5%) indicating that placement methods (i.e., truck chute, bucket and tremie pipe, free fall, and pumping) did not significantly affect the air void system parameters in SCC.
10. A significant difference (>1.5%) was observed between the air content measured at the plant and that measured at the job site in fresh SCC, probably resulting from transportation, haul time, and the addition of HRWRA at the job site to improve workability.
11. Limited structural testing of full-scale bridge components fabricated using four SCC mixtures yielded structural capacities (i.e., flexure resistance and shear resistance) that

are different from those predicted by AASHTO LRFD specifications for CVC.

3.4 Recommendations for Future Research

NCHRP Project 18-16 examined the properties of SCC intended for use in cast-in-place bridge components. However, further research is needed to address several issues pertaining to SCC applications, including the following:

- Investigating the effect of chemical admixtures (e.g., air-entraining admixtures, shrinkage-compensating admixtures, WRAs, and VMAs) on fresh, early-age, and hardened SCC properties.
- Developing specifications for achieving entrained air content and addressing the effect of adding a later dosage of HRWRA on that entrained air content.
- Investigating the effect of other SCMs (e.g., silica fume and metakaolin and fillers) on the fresh, early-age, and hardened SCC properties.
- Investigating the influence of SCM sources and replacement levels on fresh, early-age, and hardened SCC properties.
- Developing test methods for evaluating the dynamic stability and thixotropic property of SCC at a job site.
- Developing methods for predicting the formwork pressure of SCC considering the rate of placement, temperature, and rheological properties of SCC.
- Investigating use of SCC in cast-in-place bridge deck construction, drilled shafts, and deep foundations.

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Glossary

Admixture: A material other than water, aggregates, cementitious materials, filler, and fiber reinforcement that is used as an ingredient of a cementitious mixture to modify its freshly mixed, setting, or hardened properties and that is added to the batch before or during its mixing.

Aggregate blocking: The situation in which coarse aggregate particles jam between reinforcing steel bars or other obstacles within the form and prevent free flow of SCC.

Air content: The volume of air voids in cement paste, mortar, or concrete, exclusive of pore space in aggregate particles, usually expressed as a percentage of total volume of the paste, mortar, or concrete.

Angularity: The sharpness of the corners and edges of a particle (shape describes a particle on the coarsest scale, angularity on an intermediate scale, and texture on the finest scale).

Bleeding: The autogenous flow of mixing water within, or its emergence from, newly placed concrete or mortar that is caused by the settlement of the solid materials within the mass, also called water gain.

Bulk specific gravity (saturated surface dry): The ratio of the mass of a volume of a material including the mass of water within the pores in the material, (but excluding the voids between particles) at a stated temperature, to the mass of an equal volume of distilled water at a stated temperature.

Cement: A binding material that sets and hardens by chemical reaction with water and is capable of doing so underwater.

Chloride penetrability: The rate of ingress of chloride ions into concrete, which depends on the pore structure of concrete

Concrete, conventionally vibrated (CVC): A composite material that consists essentially of a binding medium within which are embedded particles or fragments of aggregate; in hydraulic cement concrete, the binder is formed from a mixture of hydraulic cement and water and is consolidated using mechanical vibration.

Concrete, self-consolidating (SCC): Fresh concrete that can flow around reinforcement and consolidate within formwork under its own weight without vibration and that exhibits no defect due to segregation or bleeding.

Consolidation: The process of inducing a closer arrangement of the solid particles in freshly mixed concrete or mortar during placement by the reduction of voids—usually in non-SCC by vibration, centrifugation, rodding, tamping, or some combination of these actions. In SCC, consolidation is achieved by gravity flow of the material.

Creep coefficient: The ratio of the creep strain at a certain age after loading to the elastic strain at loading.

Filler: Finely divided inert material, such as pulverized limestone, added to portland cement to reduce shrinkage and improve workability.

Filling ability: The ability of SCC to flow into and fill completely all spaces within the formwork, under its own weight, also referred to as deformability or non-restricted flowability.

Filling capacity: The ability of SCC to flow into and fill completely all spaces within intricate formwork containing obstacles such as reinforcement.

Fly ash: The finely divided residue that results from the combustion of ground or powdered coal and that is transported by flue gasses from the combustion zone to the particle removal system. Because of its spherical shape and fineness, fly ash can improve the rheology of SCC.

Ground granulated blast-furnace slag (GGBFS): A fine, granular, mostly latent, hydraulic binding material that can be added to SCC to improve workability of the material. GGBFS is also referred to in some cases as slag cement (a waste product in the manufacture of pig iron and chemically a mixture of lime, silica, and alumina).

Hardened visual stability index (HVSI): A test that involves the visual examination of aggregate distribution in sections made by longitudinal saw cuts of test cylinders.

High-range water-reducing admixture (HRWRA): A water-reducing admixture capable of producing large water reduction (>12%) or greater flowability of a concrete mixture without causing undue set retardation or excessive entrainment of air.

J-ring: An apparatus consisting of a rigid ring supported on 16⅝ in. [16 mm] diameter rods equally spaced on a 12 in. [300 mm] diameter circle 4 in. [100 mm] above a flat surface.

J-ring, ΔD: The difference between the J-ring flow (confined) and slump flow (unconfined) rounded to the nearest ¼ in.

J-ring, ΔH: An indicator of the difference in height of the SCC patty between the inside and the outside of the ring rounded to the nearest ¼ in.

Laitance: A layer of weak material derived from cementitious material and aggregate fines either (1) carried by bleeding to the surface or to internal cavities of freshly placed mixture or (2) separated from the mixture and deposited on the surface or internal cavities during placement of the mixture.

Limestone powder (LSP): Finely crushed limestone with particle sizes passing the No. 100 sieve (0.15 mm) that may be used as a filler to increase the amount of powder in SCC mixes.

Mortar: a mixture of cement paste and fine aggregate; in fresh concrete, the material occupying the interstices among particles of coarse aggregate; in masonry construction, joint mortar may contain masonry cement or may contain hydraulic cement with lime (and possibly other admixtures) to afford greater plasticity and workability than are attainable with standard portland cement mortar.

Nominal maximum size of aggregate (NMSA): The smallest sieve size through which the major portion of the aggregate must pass. The nominal maximum size sieve may retain 5% to 15% of the aggregate, depending on the size number.

Passing ability: The ability of SCC to flow under its own weight (without vibration) and completely fill all spaces within intricate formwork containing obstacles such as reinforcement.

Paste: The fraction of the concrete comprising powder, water and air, plus admixture, if applicable.

Plastic viscosity: The resistance of the plastic material to undergo a given flow. Plastic viscosity is computed as the slope of the shear stress versus shear rate curve measurements. Mixtures with high plastic viscosity are often described as "sticky" or "cohesive." Concrete with higher plastic viscosity takes longer to flow. Plastic viscosity is closely related to T_{50}.

Powder: Includes cement, fly ash, GGBFS, limestone fines, material crushed to less than 0.125 mm (No. 100 sieve), or other non-cementitious filler.

Pozzolan: A siliceous or silico-aluminous material that will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds having cementitious properties (there are both natural and artificial pozzolans).

Pumpability: The ability of an SCC mix to be pumped without significant degradation of its fresh SCC properties.

Rheological properties: Properties dealing with the deformation and flow of the fluid fresh SCC mixture.

Rheology: The science of dealing with flow of materials, including studies of deformation of hardened concrete, the handling and placing of freshly mixed concrete, and the behavior of slurries, pastes, and the like. In the context of SCC, rheology refers to the evaluation of yield stress, plastic viscosity, and thixotropy to achieve desired levels of filling ability, passing ability, and segregation resistance.

Rheometer: An instrument for measuring the rheological properties of a substance.

Segregation: The differential concentration of the components of mixed concrete, aggregate, or the like, resulting in non-uniform proportions in the mass. In the case of SCC, segregation may occur during transport, during flow into the forms, or after placement when the concrete is in a plastic state. This results in non-uniform distribution of in-situ properties of the concrete.

Setting: The process occurring due to chemical reactions after the addition of mixing water, which results in a gradual development of rigidity of a cementitious mixture.

Silica fume: Very fine non-crystalline silica produced in electric arc furnaces as a byproduct of the production of elemental silicon or alloys containing silicon.

Slump flow: The average diameter of the SCC patty after conducting the slump flow test using the slump cone (upright or inverted) to measure mixture filling ability.

Spacing factor: An index related to the maximum distance of any point in a cement paste or in the cement paste fraction of mortar or concrete from the periphery of an air void (also called Powers' spacing factor).

Specific surface: The surface area of particles or of air voids contained in a unit mass or unit volume of a material.

Stability, dynamic: The resistance to segregation when external energy is applied to concrete, namely during placement.

Stability, static: The resistance to segregation when no external energy is applied to concrete, namely from immediately after placement and until setting.

Supplementary cementitious material: An inorganic material such as fly ash, silica fume, metakaolin, or slag cement that reacts pozzolanically or hydraulically.

T_{50}: Also referred to as the T-20 in. time in North America. That is the amount of time for the concrete to reach the 500 mm (20 in.) diameter circle drawn on the slump plate, after starting to raise the slump cone.

Thixotropy: A property of a material to thin upon isothermal agitation and to thicken upon subsequent rest.

Time of initial setting: The amount of time required for a freshly mixed cement paste, mortar, or concrete to achieve initial setting.

Viscosity-modifying admixture (VMA): An admixture used for enhancing the rheological properties of cement-based materials in the plastic state to reduce the risk of segregation.

Visual stability index (VSI): A test that involves the visual examination of the SCC slump flow spread resulting from performing the slump flow test.

Void, air: A space in cement paste, mortar, or concrete filled with air; an entrapped air void is characteristically 1 mm or more in width and irregular in shape; an entrained air void is typically between 10 and 1,000 μm in diameter and spherical or nearly so.

Water-cementitious materials ratio (w/cm): The ratio of the mass of water, exclusive only of that absorbed by the aggregates, to the mass of cementitious material (hydraulic) in concrete, mortar, or grout, stated as a decimal.

Water-to-powder ratio (W/P): The ratio of the mass of free water to the mass of solids composing the paste (material passing the No. 100 [0.15 mm] sieve) in a concrete or mortar mixture.

Workability: That property of freshly mixed concrete or mortar that determines the ease of it being mixed, placed, consolidated, and finished to a homogeneous condition. For SCC, workability encompasses filling ability, passing ability, and segregation resistance. Workability is affected by rheology.

Yield stress: The minimum shear stress required to initiate (static yield stress) or maintain (dynamic yield stress) flow. The yield stress is closely related to slump flow (lower yield stress results in higher slump flow); yield stress is calculated as the intercept of the shear stress versus shear rate plot from rheometer flow curve measurements.

Acronyms

AEA	Air entraining admixture
ANOVA	Analysis of variance
CSC	Concrete surface category
CVC	Conventionally vibrated concrete
DSI	Dynamic segregation index
FA	Filling ability
GGBFS	Ground granulated blast-furnace slag
HRWRA	High-range water-reducing admixture
HVSI	Hardened visual stability index
ICAR	International Center for Aggregates Research
ITZ	Interfacial transition zone
LSP	Limestone powder
LVDT	Linear variable differential transformer
MOE	Modulus of elasticity
MOR	Modulus of rupture
NMSA	Nominal maximum size of aggregate
PA	Passing ability
RCPT	Rapid chloride penetrability
S/A	Sand-to-aggregate
SCC	Self-consolidating concrete
SCM	Supplementary cementitious material
SR	Segregation resistance
VMA	Viscosity-modifying admixture
VSI	Visual stability index
W/P	Water/powder
WRA	Workability retaining mixture

ATTACHMENT A

Proposed Changes to the AASHTO LRFD Bridge Design and Construction Specifications

These proposed changes to the Seventh Edition (2014) of the AASHTO LRFD Bridge Design Specifications and Third Edition (2010) of the AASHTO LRFD Bridge Construction Specifications with 2014 Interim Revisions are the recommendations of the NCHRP Project 18-16 staff at the University of Nebraska-Lincoln. These specifications have not been approved by NCHRP or any AASHTO committee nor formally accepted for the AASHTO specifications.

A.1 Bridge Design Specifications

5.4—MATERIAL PROPERTIES

5.4.2—Normal Weight and Structural Lightweight Concrete

5.4.2.1—Compressive Strength

For each component, the specified compressive strength, *f' c*, or the class of concrete shall be shown in the contract documents.

Design concrete strengths above 10.0 ksi for normal weight concrete shall be used only when allowed by specific Articles or when physical tests are made to establish the relationships between the concrete strength and other properties. Specified concrete with strengths below 2.4 ksi should not be used in structural applications.

The specified compressive strength for prestressed concrete and decks shall not be less than 4.0 ksi. For lightweight structural concrete, air dry unit weight, strength, and any other properties required for the application shall be specified in the contract documents.

C5.4.2.1

The evaluation of the strength of the concrete used in the work should be based on test cylinders produced, tested, and evaluated in accordance with Section 8 of the *AASHTO LRFD Bridge Construction Specifications*.

This Section was originally developed based on an upper limit of 10.0 ksi for the design concrete compressive strength. As research information for concrete compressive strengths greater than 10.0 ksi becomes available, individual Articles are being revised or extended to allow their use with higher strength concretes. Appendix C5 contains a listing of the Articles affected by concrete compressive strength and their current upper limit. It is common practice that the specified strength be attained 28 days after placement. Other maturity ages may be assumed for design and specified for components that will receive loads at times appreciably different than 28 days after placement.

It is recommended that the classes of concrete shown in Table C5.4.2.1-1 and their corresponding specified strengths be used whenever appropriate. The classes of concrete indicated in Table C5.4.2.1-1 have been developed for general use and are included in *AASHTO LRFD Bridge Construction Specifications*, Section 8 “Concrete Structures” from which Table C5.4.2.1-1 was taken. These classes are intended for use as follows:

- Class A concrete is generally used for all elements of structures, except when another class is more appropriate, and specifically for concrete exposed to saltwater.
- Class B concrete is used in footings, pedestals, massive pier shafts, and gravity walls.
- Class C concrete is used in thin sections, such as reinforced railings less than 4.0 in. thick, for filler in steel grid floors, etc.
- Class P concrete is used when strengths in excess of 4.0 ksi are required. For prestressed concrete, consideration should be given to limiting the nominal aggregate size to 0.75 in.
- Class S concrete is used for concrete deposited underwater in cofferdams to seal out water.
- Class SCC is intended for all cast-in-place elements of structures when it is needed/required to eliminate mechanical consolidation.

Strengths above 5.0 ksi should be used only when the availability of materials for such concrete in the locale is verified. Lightweight concrete is generally used only under conditions where weight is critical.

In the evaluation of existing structures, it may be appropriate to modify the *f'c* and other attendant structural properties specified for the original construction to

For concrete Classes A, A(AE), and P used in or over saltwater, the *W/C* ratio shall be specified not to exceed 0.45.

The sum of Portland cement and other cementitious materials shall be specified not to exceed 800 pcy, except for Class P (HPC) concrete where the sum of Portland cement and other cementitious materials shall be specified not to exceed 1000 pcy.

Air-entrained concrete, designated "AE" in Table C5.4.2.1-1, shall be specified where the concrete will be subject to alternate freezing and thawing and exposure to deicing salts, saltwater, or other potentially damaging environments.

recognize the strength gain or any strength loss due to age or deterioration after 28 days. Such modified *f'c* should be determined by core samples of sufficient number and size to represent the concrete in the work, tested in accordance with AASHTO T 24M/T 24 (ASTM C42).

There is considerable evidence that the durability of reinforced concrete exposed to saltwater, deicing salts, or sulfates is appreciably improved if, as recommended by ACI 318, either or both the cover over the reinforcing steel is increased or the *W/C* ratio is limited to 0.40. If materials, with reasonable use of admixtures, will produce a workable concrete at *W/C* ratios lower than those listed in Table C5.4.2.1-1, the contract documents should alter the recommendations in Table C5.4.2.1-1 appropriately.

The specified strengths shown in Table C5.4.2.1-1 are generally consistent with the *W/C* ratios shown. However, it is possible to satisfy one without the other. Both are specified because *W/C* ratio is a dominant factor contributing to both durability and strength; simply obtaining the strength needed to satisfy the design assumptions may not ensure adequate durability.

Table C5.4.2.1-1 Concrete Mix Characteristics by Class

Class of Concrete	Minimum Cement Content	Maximum W/C Ratio	Air Content Range	Coarse Aggregate Per AASHTO M43 (ASTM D448)	28-Day Compressive Strength
	pcy	lbs Per lbs	%	Square Size of Opening (in.)	ksi
A A(AE)	611 611	0.49 0.45	- 6.0 ± 1.5	1.0 to No. 4 1.0 to No. 4	4.0 4.0
B	517	0.58	-	2.0 to No. 3 and No. 3 to No. 4	2.4
B(AE)	517	0.55	5.0 ± 1.5	2.0 to No. 3 and No. 3 to No. 4	2.4
C C(AE)	658 658	0.49 0.45	- 7.0 ± 1.5	0.5 to No. 4 0.5 to No. 4	4.0 4.0
P P(HPC)	564	0.49	As specified elsewhere	1.0 to No. 4 2.0 or 0.75 to No. 4	As specified elsewhere
S	658	0.58		1.0 to No. 4	-
Lightweight	564	As specified in the contract documents			
SCC SCC(AE)	658 658	0.44* 0.44*	- 6.0 ± 1.5	0.75 to No. 4 0.75 to No. 4	4.0 4.0

*Water-to-powder ratio (W/P) is used when limestone powder is added as a filler in SCC mixtures up to 15%.

5.4.2.3—Shrinkage and Creep

5.4.2.3.1—General

Values of shrinkage and creep, specified herein and in Articles 5.9.5.3 and 5.9.5.4, shall be used to determine the effects of shrinkage and creep on the loss of prestressing force in bridges other than segmentally constructed ones. These values in conjunction with the moment of inertia, as specified in Article 5.7.3.6.2, may be used to determine the effects of shrinkage and creep on deflections.

These provisions shall be applicable for specified concrete strengths up to 15.0 ksi. In the absence of more accurate data, the shrinkage coefficients may be assumed to be 0.0002 after 28 days and 0.0005 after one year of drying.

When mix-specific data are not available, estimates of shrinkage and creep may be made using the provisions of:

- Articles 5.4.2.3.2 and 5.4.2.3.3,
- The CEB-FIP model code, or
- ACI 209.

For segmentally constructed bridges, a more precise estimate shall be made, including the effect of:

- Specific materials,
- Structural dimensions,
- Site conditions, and
- Construction methods, and
- Concrete age at various stages of erection.

C5.4.2.3.1

Creep and shrinkage of concrete are variable properties that depend on a number of factors, some of which may not be known at the time of design. Without specific physical tests or prior experience with the materials, the use of the empirical methods referenced in these specifications cannot be expected to yield results with errors less than ±50 percent.

5.4.2.3.2—Creep

The creep coefficient may be taken as:

$$\psi(t, t_i) = 1.9\, k_s k_{hc} k_f k_{td} t_i^{-0.118} \qquad (5.4.2.3.2\text{-}1)$$

in which:

$$k_s = 1.45 - 0.13(V/S) \geq 1.0 \qquad (5.4.2.3.2\text{-}2)$$

$$k_{hc} = 1.56 - 0.008H \qquad (5.4.2.3.2\text{-}3)$$

$$k_f = \frac{5}{1 + f'_{ci}} \qquad (5.4.2.3.2\text{-}4)$$

$$k_{td} = \left(\frac{t}{61 - 4f'_{ci} + t}\right) \qquad (5.4.2.3.2\text{-}5)$$

where:

H = relative humidity (%). In the absence of better information, H may be taken from Figure 5.4.2.3.3-1.

k_s = factor for the effect of the volume-to-surface ratio of the component.

k_f = factor for the effect of concrete strength.

k_{hc} = humidity factor for creep.

k_{td} = time development factor.

t = maturity of concrete (day), defined as age of

C5.4.2.3.2

The methods of determining creep and shrinkage, as specified herein and in Article 5.4.2.3.3, are based on Huo et al. (2001), Al-Omaishi (2001), Tadros (2003), and Collins and Mitchell (1991). These methods are based on the recommendation of ACI Committee 209 as modified by additional recently published data. Other applicable references include Rusch et al. (1983), Bazant and Wittman (1982), and Ghali and Favre (1986).

The creep coefficient is applied to the compressive strain caused by permanent loads in order to obtain the strain due to creep.

Creep is influenced by the same factors as shrinkage, and also by:

- Magnitude and duration of the stress,
- Maturity of the concrete at the time of loading, and
- Temperature of concrete.

Creep shortening of concrete under permanent loads is generally in the range of 0.5 to 4.0 times the initial elastic shortening, depending primarily on concrete maturity at the time of loading.

Based on the work by Morcous, et al. (2015), the AASHTO method for determining creep coefficient yields reasonable predictions for normal weight SCC mixtures except those containing 15% limestone powder as a filler. In this case, creep coefficient is expected to be 20% higher than predicted using Eq.

concrete between time of loading for creep calculations, or end of curing for shrinkage calculations, and time being considered for analysis of creep or shrinkage effects.

t_i = age of concrete at time of load application (day).

V/S = volume-to-surface ratio (in.).

f'_{ci} = specified compressive strength of concrete at time of prestressing for pretensioned members and at time of initial loading for nonprestressed members. If concrete age at time of initial loading is unknown at design time, $f'ci$ may be taken as $0.80 f'c$ (ksi).

The surface area used in determining the volume-to-surface ratio should include only the area that is exposed to atmospheric drying. For poorly ventilated enclosed cells, only 50 percent of the interior perimeter should be used in calculating the surface area. For precast members with cast-in-place topping, the total precast surface should be used. For pretensioned stemmed members (I-beams, T-beams, and box beams), with an average web thickness of 6.0 to 8.0 in., the value of k_{vs} may be taken as 1.00.

5.4.2.3.2-1.

The time development of shrinkage, given by Eq. 5.4.2.3.2-5, is proposed to be used for both precast concrete and cast-in-place concrete components of a bridge member, and for both accelerated curing and moist curing conditions. This simplification is based on a parametric study documented in Tadros (2003), on prestress losses in high strength concrete. It was found that various time development prediction methods have virtually no impact on the final creep and shrinkage coefficients, prestress losses, or member deflections.

It was also observed in that study that use of modern concrete mixtures with relatively low water/cement ratios and with high range water reducing admixtures, has caused time development of both creep and shrinkage to have similar patterns. They have a relatively rapid initial development in the first several weeks after concrete placement and a slow further growth thereafter. For calculation of intermediate values of prestress losses and deflections in cast-in-place segmental bridges constructed with the balanced cantilever method, it may be warranted to use actual test results for creep and shrinkage time development using local conditions. Final losses and deflections would be substantially unaffected whether Eq. 5.4.2.3.2-5 or another time-development formula is used.

5.4.2.3.3—Shrinkage

For concretes devoid of shrinkage-prone aggregates, the strain due to shrinkage, ε_{sh}, at time, t, may be taken as:

$$\varepsilon_{sh} = k_p k_s k_{hs} k_f k_{td} 0.48\times10^{-3} \quad (5.4.2.3.3\text{-}1)$$

In which:

$$k_{hs} = (2.00 - 0.014\,H) \quad (5.4.2.3.3\text{-}2)$$

where:

k_{hs} = humidity factor for shrinkage.

k_p = SCC powder composition factor to be determined by physical tests. In the absence of physical tests, k_p shall be taken as 1.6 for cement type I/II with 25% Class C fly ash; 1.4 for cement type I/II with 30% GGBFS; and 1.3 for cement type I/II with 25% Class F fly ash or 20% Class F fly ash and 15% limestone powder. For conventionally vibrated concrete, k_p shall be taken as 1.0.

If the concrete is exposed to drying before 5 days of curing have elapsed, the shrinkage as determined in Eq. 5.4.2.3.3-1 should be increased by 20 percent.

C5.4.2.3.3

Shrinkage of concrete can vary over a wide range from nearly nil if continually immersed in water to in excess of 0.0008 for thin sections made with high shrinkage aggregates and sections that are not properly cured.

Shrinkage is affected by:

- Aggregate characteristics and proportions,
- Average humidity at the bridge site,
- W/C ratio,
- Type of cure,
- Volume to surface area ratio of member, and
- Duration of drying period.

Based on the work by Morcous, et al. (2015), the AASHTO method for determining shrinkage strains of concrete yields low predictions for normal weight SCC mixtures depending on the powder composition. Therefore, a powder composition factor is proposed with recommended values for the compositions being those used in this study.

Large concrete members may undergo substantially less shrinkage than that measured by laboratory testing of small specimens of the same concrete. The constraining effects of reinforcement and composite actions with other elements of the bridge tend to reduce the dimensional changes in some components.

5.4.2.4—Modulus of Elasticity

In the absence of measured data, the modulus of elasticity, E_c, for concretes with unit weights between 0.090 and 0.155 kcf and specified compressive strengths up to 15.0 ksi may be taken as:

$$E_c = 33{,}000\, K_1 K_2 w_c^{1.5} \sqrt{f_c'} \quad (5.4.2.4\text{-}1)$$

where:

K_1 = correction factor for source of aggregate to be taken as 1.0 unless determined by physical test, and as approved by the authority of jurisdiction.

K_2 = correction factor for concrete class to be taken as 0.96 for SCC and 1.0 for other classes of concrete unless determined by physical tests.

w_c = unit weight of concrete (kcf); refer to Table 3.5.1-1 or Article C5.4.2.4.

f'_c = specified compressive strength of concrete (ksi).

C5.4.2.4

See commentary for specified strength in Article 5.4.2.1. For normal weight concrete with w_c = 0.145 kcf, E_c may be taken as:

$$E_c = 1{,}820 \sqrt{f_c'} \quad (\text{C}5.4.2.4\text{-}1)$$

Test data show that the modulus of elasticity of concrete is influenced by the stiffness of the aggregate. The factor K_1 is included to allow the calculated modulus to be adjusted for different types of aggregate and local materials. Unless a value has been determined by physical tests, K_1 should be taken as 1.0. Use of a measured K_1 factor permits a more accurate prediction of modulus of elasticity and other values that utilize it.

The concrete class correction factor K_2 is introduced based on the work by Morcous et al. (2015) to account for the effect of high paste-to-coarse aggregate volume in normal weight SCC mixtures. The research findings also indicate that the correction factor for source of aggregate K_1 is 1.0 and 0.95 for the crushed limestone and natural gravel used in the study, respectively.

5.4.2.6—Modulus of Rupture

Unless determined by physical tests, the modulus of rupture, f_r in ksi, for specified concrete strengths up to 15.0 ksi, may be taken as:

- For normal weight concrete:
  - o Except as specified below .... $0.24\sqrt{f'_c}$
  - o When used to calculate the cracking moment of a member in Article 5.8.3.4.3 ....$0.20\sqrt{f'_c}$

- For lightweight concrete:
  - o For sand-lightweight concrete …....... $0.20\sqrt{f'_c}$
  - o For all-lightweight concrete .... $0.17\sqrt{f'_c}$

When physical tests are used to determine modulus of rupture, the tests shall be performed in accordance with AASHTO T 97 and shall be performed on concrete using the same proportions and materials as specified for the structure.

C5.4.2.6

Most modulus of rupture test data on normal weight concrete are between $0.24\sqrt{f'_c}$ and $0.37\sqrt{f'_c}$ (ACI 1992; Walker and Bloem 1960; Khan, Cook, and Mitchell 1996). A value of $0.37\sqrt{f'_c}$ has been recommended for the prediction of the tensile strength of high-strength concrete (ACI, 1992). However, the modulus of rupture is sensitive to curing method and nearly all of the test units in the dataset mentioned previously were moist cured until testing. Carrasquillio et al. (1981) noted a 26 percent reduction in the 28-day modulus of rupture if high-strength units were allowed to dry after 7 days of moist curing over units that were moist cured until testing.

The flexure cracking stress of concrete members has been shown to significantly reduce with increasing member depth. Shioya et al. (1989) observed that the flexure cracking strength is proportional to H-0.25 where H is the overall depth of the flexural member in inches. Based on this observation, a 36.0 in. deep girder should achieve a flexural cracking stress that is 26 percent lower than that of a 6 in. deep modulus of rupture test.

Since modulus of rupture units were either 4.0 or 6.0 in. deep and moist cured up to the time of testing, the modulus of rupture should be significantly greater than that of an average size bridge member composed of the same concrete. Therefore, $0.24\sqrt{f'_c}$ is appropriate for checking minimum reinforcement in Article 5.7.3.3.2.

The properties of higher strength concretes are particularly sensitive to the constitutive materials. If test results are to be used in design, it is imperative that tests be made using concrete with not only the same mix proportions, but also the same materials as the concrete used in the structure.

The given values may be un-conservative for tensile cracking caused by restrained shrinkage, anchor zone splitting, and other such tensile forces caused by effects other than flexure. The direct tensile strength stress should be used for these cases.

Based on the work by Morcous et al. (2015), the modulus of rupture test data of normal weight SCC are between $0.24\sqrt{f'_c}$ and $0.37\sqrt{f'_c}$, similar to other classes of concrete.

5.4.2.7—Tensile Strength

Direct tensile strength may be determined by either using ASTM C900, or the split tensile strength method in accordance with AASHTO T 198 (ASTM C496).

C5.4.2.7

For normal weight concrete with specified compressive strengths up to 10 ksi, the direct tensile strength may be estimated as $f_r = 0.23\sqrt{f'_c}$.

Based on the work by Morcous et al. (2015), the splitting tensile strength of normal weight SCC may be estimated as $f_r = 0.18\sqrt{f'_c}$.

5.8—SHEAR AND TORSION

5.8.3—Sectional Design Model

5.8.3.3—Nominal Shear Resistance

The nominal shear resistance, V_n, shall be determined as the lesser of:

$$V_n = V_c + V_s + V_p \quad (5.8.3.3\text{-}1)$$

$$V_n = 0.25 f'_c b_v d_v + V_p \quad (5.8.3.3\text{-}2)$$

in which:

$V_c = 0.0316\beta\sqrt{f'_c}\; b_v d_v$, if the procedures of Articles 5.8.3.4.1 or 5.8.3.4.2 are used (5.8.3.3-3)

V_c = the lesser of V_{ci} and V_{cw}, if the procedures of Article 5.8.3.4.3 are used

$$V_s = \frac{A_v f_y d_v (\cot\theta + \cot\alpha)\sin\alpha}{s} \quad (5.8.3.3\text{-}4)$$

Where transverse reinforcement consists of a single longitudinal bar or a single group of parallel longitudinal bars bent up at the same distance from the support, the shear resistance V_s provided by these bars shall be determined as:

$$V_s = A_v f_y \sin\alpha \le 0.095\sqrt{f'_c} b_v d_v \quad (5.8.3.3\text{-}5)$$

where:

C5.8.3.3

The shear resistance of a concrete member may be separated into a component, V_c, that relies on tensile stresses in the concrete, a component, V_s, that relies on tensile stresses in the transverse reinforcement, and a component, V_p, that is the vertical component of the prestressing force.

The expressions for V_c and V_s apply to both prestressed and nonprestressed sections, with the terms β and θ depending on the applied loading and the properties of the section.

Based on the work by Morcous, et al. (2015), the AASHTO method for determining the shear resistance component V_c of normal weight concrete members yields reasonable predictions for normal weight SCC members.

The upper limit of V_n, given by Eq. 5.8.3.3-2, is intended to ensure that the concrete in the web of the beam will not crush prior to yield of the transverse reinforcement.

where α = 90 degrees, Eq. 5.8.3.3-4 reduces to:

$$V_s = \frac{A_v f_y d_v \cot\theta}{s} \quad (C5.8.3.3\text{-}1)$$

As noted in Article 5.8.2.4 for members subjected to flexural shear without torsion, transverse reinforcement with specified minimum yield strengths

b_v = effective web width taken as the minimum web width within the depth d_v as determined in Article 5.8.2.9 (in.).

d_v = effective shear depth as determined in Article 5.8.2.9 (in.).

s = spacing of transverse reinforcement measured in a direction parallel to the longitudinal reinforcement (in.).

β = factor indicating ability of diagonally cracked concrete to transmit tension and shear as specified in Article 5.8.3.4.

θ = angle of inclination of diagonal compressive stresses as determined in Article 5.8.3.4 (degrees); if the procedures of Article 5.8.3.4.3 are used, cot θ is defined therein .

α = angle of inclination of transverse reinforcement to longitudinal axis (degrees).

A_v = area of shear reinforcement within a distance s (in.^{2}).

V_p = component in the direction of the applied shear of the effective prestressing force; positive if resisting the applied shear; V_p = 0 when Article 5.8.3.4.3 is applied (kip).

Where bent longitudinal reinforcement is used, only the center three-fourths of the inclined portion of the bent bar shall be considered effective for transverse reinforcement.

Where more than one type of transverse reinforcement is used to provide shear resistance in the same portion of a member, the shear resistance V_s shall be determined as the sum of V_s values computed from each type.

Where shear resistance is provided by bent longitudinal reinforcement or a combination of bent longitudinal reinforcement and stirrups, the nominal shear resistance shall be determined using the simplified procedure in accordance with Article 5.8.3.4.1.

up to 100 ksi is permitted for elements and connections specified in Article 5.4.3.3.

The angle θ is, therefore, also taken as the angle between a strut and the longitudinal axis of a member.

V_p is part of V_{cw} by the method in Article 5.8.3.4.3 and thus V_p needs be taken as zero in Eq. 5.8.3.3-1.

Requirements for bent bars were added to make the provisions consistent with those in AASHTO (2002).

5.8.4—Interface Shear Transfer—Shear Friction

5.8.4.3—Cohesion and Friction Factors

The following values shall be taken for cohesion, c, and friction factor, μ :

- For a cast-in-place concrete slab on clean concrete girder surfaces, free of laitance with surface roughened to an amplitude of 0.25 in.:
  c = 0.28 ksi
  μ = 1.0
  K_1 = 0.3
  K_2 = 1.8 ksi for normal weight concrete
  = 1.3 ksi for lightweight concrete

- For normal weight concrete placed monolithically:
  c = 0.40 ksi

C5.8.4.3

The values presented provide a lower bound of the substantial body of experimental data available in the literature (Loov and Patnaik, 1994; Patnaik, 1999; Mattock, 2001; Slapkus and Kahn, 2004). Furthermore, the inherent redundancy of girder/slab bridges distinguishes this system from other structural interfaces.

The values presented apply strictly to monolithic concrete. These values are not applicable for situations where a crack may be anticipated to occur at a Service

μ = 1.4
K_1 = 0.25
K_2 = 1.5 ksi

- For lightweight concrete placed monolithically, or nonmonolithically, against a clean concrete surface, free of laitance with surface intentionally roughened to an amplitude of 0.25 in.:
  c = 0.24 ksi
  μ = 1.0
  K_1 = 0.25
  K_2 = 1.0 ksi

- For normal weight concrete placed against a clean concrete surface, free of laitance, with surface intentionally roughened to an amplitude of 0.25 in.:
  c = 0.24 ksi
  μ = 1.0
  K_1 = 0.25
  K_2 = 1.5 ksi

- For concrete anchored to as-rolled structural steel by headed studs or by reinforcing bars where all steel in contact with concrete is clean and free of paint:
  c = 0.025 ksi
  μ = 0.7
  K_1 = 0.2
  K_2 = 0.8 ksi

For brackets, corbels, and ledges, the cohesion factor, c, shall be taken as 0.0. For normal weight SCC with specified compressive strength less than 6 ksi placed monolithically, the cohesion factor, c, shall be taken as 0.0 unless determined by physical tests.

Limit State.

The factors presented provide a lower bound of the experimental data available in the literature (Hofbeck, Ibrahim, and Mattock, 1969; Mattock, Li, and Wang, 1976; Mitchell and Kahn, 2001).

Available experimental data demonstrates that only one modification factor is necessary, when coupled with the resistance factors of Article 5.5.4.2, to accommodate both all-lightweight and sand-lightweight concrete. Note this deviates from earlier specifications that distinguished between all-lightweight and sand-lightweight concrete.

Due to the absence of existing data, the prescribed cohesion and friction factors for nonmonolithic lightweight concrete are accepted as conservative for application to monolithic lightweight concrete.

Tighter constraints have been adopted for roughened interfaces, other than cast-in-place slabs on roughened girders, even though available test data do not indicate more severe restrictions are necessary. This is to account for variability in the geometry, loading, and lack of redundancy at other interfaces.

Since the effectiveness of cohesion and aggregate interlock along a vertical crack interface is unreliable, the cohesion component in Eq. 5.8.4.1-3 is set to 0.0 for brackets, corbels, and ledges.

Based on the work by Morcous et al. (2015), the AASHTO method for determining interface shear resistance of normal weight concrete placed monolithically overestimates the interface shear resistance of normal weight SCC with compressive strength less than 6 ksi. Therefore, the cohesion factor, c, shall be taken as 0.0 in this case.

5.11—DEVELOPMENT AND SPLICES OF REINFORCEMENT

5.11.2—Development of Reinforcement

5.11.2.1—Deformed Bars and Deformed Wire in Tension

The provisions herein may be used for No. 11 bars and smaller in normal weight concrete with specified concrete compressive strengths between 10.0 and 15.0 ksi for design (f'_c). Transverse reinforcement consisting of at least No. 3 bars at 12 in. center shall be provided along the required development length where the

C5.11.2.1

The extension of this article to concrete strengths between 10.0 and 15.0 ksi is limited to No. 11 bars and smaller based on the work presented in *NCHRP Report 602* (Ramirez and Russel, 2008). The requirement of minimum transverse reinforcement along the development length is based on research by specified concrete compressive strength is greater than 10 ksi.

For straight bars having a specified minimum yield strength greater than 75 ksi, transverse reinforcement satisfying the requirements of Article 5.8.2.5 for beams and Article 5.10.6.4 for columns shall be provided over the required development length.

Azizinamini et al. (1999). Transverse reinforcement used to satisfy the shear requirements may simultaneously satisfy this provision.

Confining requirement is not required in bridge slabs or decks.

5.11.2.1.1—Tension Development Length

The tension development length, ℓ_d, shall not be less than the product of the basic tension development length, ℓ_{db}, specified herein and the modification factor or factors specified in Articles 5.11.2.1.2 and 11.2.1.3. The tension development length shall not be less than 12.0 in., except for lap splices specified in Article 5.11.5.3.1 and development of shear reinforcement specified in Article 5.11.2.6.

The basic tension development length, ℓ_{db}, in in. shall be taken as:

- For No. 11 bar and smaller .... $\dfrac{1.25\, A_b f_y}{\sqrt{f'_c}}$

  but not less than .... $0.4\, d_b f_y$

- For No. 14 bars .... $\dfrac{2.70\, f_y}{\sqrt{f'_c}}$

- For No. 18 bars .... $\dfrac{3.5\, f_y}{\sqrt{f'_c}}$

- For deformed wire .... $\dfrac{0.95\, d_b f_y}{\sqrt{f'_c}}$

where:

A_b = area of bar or wire (in.^{2}).
f_y = specified yield strength of reinforcing bars (ksi).
f'_c = specified compressive strength of concrete at 28 days, unless another age is specified (ksi).
d_b = diameter of bar or wire (in.).

5.11.2.1.2—Modification Factors which Increase ℓ_d

The basic development length, ℓ_{db}, shall be multiplied by the following factor or factors, as applicable:

- For top horizontal or nearly horizontal reinforcement, so placed that more than 12.0 in. of fresh concrete is cast below the reinforcement 1.4
- For lightweight aggregate concrete where f_{ct} (ksi) is specified .... $\dfrac{0.22\sqrt{f'_c}}{f_{ct}} \geq 1.0$
- For all-lightweight concrete where f_{ct} is not specified 1.3
- For sand-lightweight concrete where f_{ct} is not specified 1.2

Linear interpolation may be used between all-

Based on the work by Morcous et al. (2015), pull-out test data of No. 6 horizontal bars placed in normal weight SCC walls shows similar bond strength to that of bars placed in conventionally vibrated concrete walls. Also, top-bar effect on bond strength of high-slump flow SCC is lower than that of low-slump flow SCC and conventionally vibrated concrete.

lightweight and sand-lightweight provisions when partial sand replacement is used.

- For vertical or nearly vertical reinforcement placed in fresh SCC …………………………………… 1.3
- For epoxy-coated bars with cover less than $3d_b$ or with clear spacing between bars less than $6d_b$ 1.5
- For epoxy-coated bars not covered above 1.2

The product obtained when combining the factor for top reinforcement with the applicable factor for epoxy-coated bars need not be taken to be greater than 1.7.

Based on the work by Morcous et al. (2015), pull-out test data of No. 6 vertical bars placed in SCC blocks shows lower bond strength than that of bars placed in conventionally vibrated concrete blocks. Therefore, a modification factor of 1.3 is proposed unless determined by physical tests.

A.2 Bridge Construction Specifications

Section 3: Temporary Works

3.2 – FALSEWORK AND FORMS

3.2.3 – Formwork Design and Construction

3.2.3.2 – Design

The structural design of formwork shall conform to the ACI Standard, *Recommended Practice for Concrete Formwork* (ACI 347), or some other generally accepted and permitted standard. In selecting the hydrostatic pressure to be used in the design of forms, consideration shall be given to the maximum rate of concrete placement to be used, the effects of vibration, the temperature of the concrete, and any expected use of set-retarding admixtures or pozzolanic materials in the concrete mix.

When SCC is used, full hydrostatic pressure should be considered in designing the forms unless a mockup form is built and actual formwork pressure is measured in accordance to AASHTO T 352 using the same mixture, placement rate, and temperature.

C3.2.3.2

Formwork design refers to ACI 347-78, *Recommended Practice for Concrete Formwork.*

Based on the work by Morcous et al. (2015), the formwork pressure of SCC could be less than full hydrostatic pressure depending on the placement rate, temperature, and rheological properties of SCC.

Section 8: Concrete Structures

8.2 – CLASSES OF CONCRETE

8.2.2 – Normal Weight (-Density) Concrete

Twelve classes of normal weight (-density) concrete are provided for in these specifications as listed in Table 8.2.2-1, except that for concrete on or over saltwater or exposed to deicing chemicals, the maximum water/cement ratio shall be 0.45.

Coarse aggregate for Class B and Class B(AE) shall be furnished into separate sizes as shown in Table 8.2.2-1.

C8.2.2

With high performance concrete, it is desirable that the specifications be performance-based. Class P(HPC) is intended for use in prestressed concrete members with a specified concrete compressive strength greater than 6.0 ksi and should always be used for specified concrete strengths greater than 10.0 ksi. Class A(HPC) is intended for use in cast-in-place construction where performance criteria in addition to concrete compressive strengths are specified. Other criteria might include shrinkage, chloride permeability, freeze-thaw resistance, deicer scaling resistance, abrasion resistance, or heat of hydration.

For both classes of concrete, a minimum cement content is not included since this should be selected by the producer based on the specified performance criteria. Maximum water-cementitious materials ratios have been included. The value of 0.40 for Class P(HPC) is less than the value of 0.49 for Class P, whereas the value of 0.45 for Class A(HPC) is the same as that for Class A(AE). For Class P(HPC) concrete, a maximum size of coarse aggregate is specified since it is difficult to achieve the higher concrete compressive strengths with aggregates larger than 0.75 in. For Class A(HPC) concrete, the maximum aggregate size should be selected by the producer based on the specified performance criteria. Air content for Class A(HPC) and P(HPC) should be set with trial tests but a minimum of two percent is recommended.

The 28-day specified compression strength may not be appropriate for strengths greater than 6.0 ksi.

Classes SCC and SCC(AE) are intended for all cast-in-place elements of structures where mechanical consolidation is required to be eliminated or is impractical. In addition to strength, other performance criteria, such as filling ability, passing ability, and stability need to be specified.

Table 8.2.2-1 Classification of Normal Weight Concrete

Class of Concrete	Minimum Cement Content	Maximum Water/Cementitious Material Ratio	Air Content Range	Size of Coarse Aggregate Per AASHTO M43 (ASTM D448)	Size Number[a]	Specified Compressive Strength
	lb/yd^3	lb per lb	%	Square Size of Opening (in.)		ksi at days
A	611	0.49	-	1.0 to No. 4	57	4.0 at 28
A(AE)	611	0.45	6.0 ± 1.5	1.0 to No. 4	57	4.0 at 28
B	517	0.58	-	2.0 in. to 1.0 in. and 1.0 in. to No. 4	3 57	2.4 at 28
B(AE)	517	0.55	5.0 ± 1.5	2.0 in. to 1.0 in. and 1.0 in. to No. 4	3 57	2.4 at 28
C	658	0.49	-	0.5 to No. 4	7	4.0 at 28
C(AE)	658	0.45	7.0 ± 1.5	0.5 to No. 4	7	4.0 at 28
P	564	0.49	-[b]	1.0 in. to No. 4 or 0.75 to No. 4	7 67	≤ 6.0 at [b]
S	658	0.58	-	1.0 to No. 4	7	-
P(HPC)	-[c]	0.40	-[b]	≤ 0.75 in.	67	≤ 6.0 at [b]
A(HPC)	-[c]	0.45	-[b]	-[c]	-[c]	≤ 6.0 at [b]
SCC	658	0.44*	-	0.75 to No. 4	67	4.0 at 28
SCC(AE)	658	0.44*	6.0 ± 1.5	0.75 to No. 4	67	4.0 at 28

Notes:

a As noted in AASHTO M 43 (ASTM D448), Table 1–Standard Sizes of Processed Aggregate.

b As specified in the contract documents.

c Minimum cementitious materials content and coarse aggregate size to be selected to meet other performance criteria specified in the contract.

*Water-to-powder ratio (W/P) is used when limestone powder is added as a filler in SCC mixtures for up to 15%.

8.3—MATERIALS

8.3.7—Air-Entraining and Chemical Admixtures

Air-entraining admixtures shall conform to the requirements of AASHTO M 154 (ASTM C260). Chemical admixtures shall conform to the requirements of AASHTO M 194 (ASTM C494/C494M). Unless otherwise specified in the contract documents, only Type A, Type B, Type D, Type F, or Type G shall be used.

Admixtures containing chloride ion (CL) in excess of one percent by weight (mass) of the admixture shall not be used in reinforced concrete. Admixtures in excess of 0.1 percent shall not be used in prestressed concrete.

C8.3.7

The types of chemical admixtures are as follows:

- Type A—Water-reducing
- Type B—Retarding
- Type D—Water-reducing and retarding
- Type F—Water-reducing and high-range
- Type G—Water-reducing, high-range, and retarding

Based on the work by Morcous et al. (2015), the use of polycarboxylate-based high range water-reducing

A Certificate of Compliance signed by the Manufacturer of the admixture shall be furnished to the Engineer for each shipment of admixture used in the work. Said Certificate shall be based upon laboratory test results from an approved testing facility and shall certify that the admixture meets the above specifications.

If more than one admixture is used, documentation demonstrating the compatibility of each admixture with all other proposed admixtures, and the sequence of application to obtain the desired effects, shall be submitted by the Contractor.

Air-entraining and chemical admixtures shall be incorporated into the concrete mix in a water solution. The water so included shall be considered to be a portion of the allowed mixing water.

admixtures (HRWRA) Type F or G conforming to the requirements of ASTM C494 or ASTM C1017 is recommended for Classes SCC and SCC(AE) to achieve the required slump flow of fresh concrete. Also, the use of viscosity modifying admixtures (VMA) may be needed to achieve the required stability of fresh concrete. The dosage of these chemical admixtures varies depending on the powder constituents and content, w/p ratio, aggregate type and gradation, temperature, and mixing conditions.

8.3.8—Mineral Admixtures

Mineral admixtures in concrete shall conform to the following requirements:

- Fly ash pozzolans and calcined natural pozzolans—AASHTO M 295 (ASTM C618)
- Ground granulated blast-furnace slag—AASHTO M 302 (ASTM C989)
- Silica fume—AASHTO M 307 (ASTM C1240)
- Limestone powder—AASHTO M240 (ASTM C595)

Fly ash as produced by plants that utilize the limestone injection process or use compounds of sodium, ammonium, or sulfur, such as soda ash, to control stack emissions shall not be used in concrete.

A Certificate of Compliance, based on test results and signed by the producer of the mineral admixture certifying that the material conforms to the above specifications, shall be furnished for each shipment used in the work.

Where special materials other than those identified above are included in a concrete mix design, the properties of those materials shall be determined by methods specified in the contract documents.

Ground limestone, sometimes referred to as limestone powder, can be used in Classes SCC and SCC(AE) with up to 15% replacement of the total powder content. Ground limestone shall comply with all the physical and chemical requirements specified in the contract documents. The fineness of ground limestone has a significant impact on both fresh and hardened concrete properties.

C8.3.8

Pozzolans (fly ash, silica fume) and slag are used in the production of Class P(HPC) and Class A(HPC) concretes to extend the service life. Fly ash, GGBFS and limestone powder are commonly used in the production of Classes SCC and SCC(AE) to enhance the performance of the fresh and hardened concrete.

Occasionally, it may be appropriate to use other materials; for example, when concretes are modified to obtain very high strengths through the introduction of special materials, such as:

- Silica fume,
- Cements other than portland or blended hydraulic cements,
- Proprietary high early strength cements,
- Ground granulated blast-furnace slag, and
- Other types of cementitious and/or pozzolanic materials.

8.4—PROPORTIONING OF CONCRETE

8.4.1—Mix Design

8.4.1.1—Responsibility and Criteria

The Contractor shall design and be responsible for the performance of all concrete mixes used in structures. The mix proportions selected shall produce concrete that is sufficiently workable and finishable for all uses intended and shall conform to the requirements in Table 8.2.2-1 and all other requirements of this Section.

For normal weight (-density) concrete, the absolute volume method, such as described in American Concrete Institute Publication 211.1, shall be used in selecting mix proportions. For Class P(HPC) with fly ash, the method given in American Concrete Institute Publication 211.4 shall be permitted. For lightweight (low-density) concrete, the mix proportions shall be selected on the basis of trial mixes, with the cement factor rather than the water/cement ratio being determined by the specified strength, using methods such as those described in American Concrete Institute Publication 211.2.

For classes SCC and SCC(AE), the methods given in the American Concrete Institute Publication 237R-07 and International Center for Aggregates Research (ICAR) Report 108-1 may be used for proportioning SCC mixtures.

The mix design shall be based on the specified properties. When strength is specified, select an average concrete strength sufficiently above the specified strength so that, considering the expected variability of the concrete and test procedures, no more than one in ten strength tests will be expected to fall below the specified strength. For classes SCC and SCC(AE), the specified properties shall include workability properties such as filling ability, passing ability, and stability. Mix designs shall be modified during the course of the work when necessary to ensure compliance with the specified fresh and hardened concrete properties. For Class P(HPC) and Class A(HPC), such modifications shall only be permitted after trial batches to demonstrate that the modified mix design will result in concrete that complies with the specified concrete properties.

C 8.4.1.1

Normal weight (-density) mix design refers to the American Concrete Institute (ACI), Publication 211.1, 1991. Lightweight (low-density) mix design refers to the ACI Publication 211.2, 1998.

For Class P(HPC) with fly ash, the method given in ACI Publication 211.4, 1993, is permitted.

In Class P(HPC) and Class A(HPC) concretes, properties other than compressive strength are also important, and the mix design should be based on specified properties rather than only compressive strength.

In classes SCC and SCC(AE), properties other than compressive strength, such as filling ability, passing ability, and stability, shall be specified based on the geometric characteristics of the component as well as production and placement methods. Refer to Morcous et al. (2015) for proposed workability targets for examples of cast-in-place bridge components.

8.4.1.2—Trial Batch Tests

For classes A, A(AE), P, P(HPC), SCC, SCC(AE) and A(HPC) concrete; for lightweight (low-density) concrete; and for other classes of concrete when specified in the contract documents or ordered by the Engineer; satisfactory performance of the proposed mix design shall be verified by laboratory tests on trial batches. The results of such tests shall be furnished to the Engineer by the Contractor or the Manufacturer of precast elements at the time the proposed mix design is submitted.

If materials and a mix design identical to those proposed for use have been used on other work within the previous year, certified copies of concrete test results from this work that indicate full compliance with these specifications may be substituted for such laboratory tests.

The average values obtained from trial batches for the specified properties, such as strength, shall exceed design values by a certain amount based on variability. For compressive strength, the required average strength used as a basis for selection of concrete proportions shall be determined in accordance with AASHTO M 241 (ASTM C685/C685M). For classes SCC and SCC(AE), workability properties shall be verified by laboratory tests on trial batches.

C8.4.1.2

In Class P(HPC) and Class A(HPC) concretes, properties other than compressive strength are also important. However, if only compressive strength is specified, AASHTO M 241 (ASTM C685/C685M) provides the method to determine the required average strength.

8.4.2—Water Content

For calculating the water/cement ratio of the mix, the weight (mass) of the water shall be that of the total free water in the mix, which includes the mixing water, the water in any admixture solutions, and any water in the aggregates in excess of that needed to reach a saturated-surface-dry condition.

The amount of water used shall not exceed the limits listed in Table 8.2.2-1 and shall be further reduced as necessary to produce concrete of the consistencies listed in Table 8.4.2-1 at the time of placement.

When Type F or G high-range, water-reducing admixtures are used, Table 8.4.2-1 slump limits may be exceeded as permitted by the Engineer.

When the consistency of the concrete is found to exceed the nominal slump, the mixture of subsequent batches shall be adjusted to reduce the slump to a value within the nominal range. Batches of concrete with a slump exceeding the maximum specified shall not be used in the work.

If concrete of adequate workability cannot be obtained by the use of the minimum cement content allowed, the cement and water content shall be increased without exceeding the specified water/cement ratio, or an approved admixture shall be used.

For classes SCC and SCC(AE), the amount of water used shall not exceed the limits listed in Table

8.2.2-1 and shall be further reduced as necessary to achieve the specified workability targets at the time of placement as well as durability and strength requirements.

Table 8.4.2.1 – Normal-Weight Concrete Slump Test Limits

Type of Work	Nominal Slump, in.	Maximum Slump, in.
Formed Elements: Sections over 12.0 in. Thick Sections 12.0 in. Thick or Less	 1-3 1-4	 5 5
Cast-in-Place Piles and Drilled Shafts Not Vibrated	5-8	9
Concrete Placed under Water	5-8	9
Filling for Riprap	3-7	8

8.4.4—Mineral Admixtures

Mineral admixtures shall be used in the amounts specified in the contract documents. For all classes of concrete except Classes P(HPC) and A(HPC), when Types I, II, IV, or V AASHTO M 85 (ASTM C150) cements are used and mineral admixtures are neither specified in the contract documents nor prohibited, the Contractor will be permitted to replace:

- up to 25 percent of the required portland cement with fly ash or other pozzolan conforming to AASHTO M 295 (ASTM C618),
- up to 50 percent of the required portland cement with slag conforming to AASHTO M 302 (ASTM C989), or
- up to ten percent of the required Portland cement with silica fume conforming to AASHTO M 307 (ASTM C1240).

When any combination of fly ash, slag, and silica fume are used, the Contractor will be permitted to replace up to 50 percent of the required portland cement. However, no more than 25 percent shall be fly ash and no more than ten percent shall be silica fume. The weight (mass) of the mineral admixture used shall be equal to or greater than the weight (mass) of the portland cement replaced.

In calculating the water-cementitious materials ratio of the mix, the weight (mass) of the cementitious materials shall be considered to be the sum of the weight (mass) of the portland cement and the mineral admixtures.

For Class P(HPC) and Class A(HPC) concrete, mineral admixtures (pozzolans or slag) shall be permitted to be used as cementitious materials with portland cement in blended cements or as a separate addition at the mixer. The amount of mineral admixture shall be determined by trial batches. The water-cementitious materials ratio shall be the ratio of the weight (mass) of water to the total cementitious materials, including the mineral admixtures. The

C8.4.4

Mineral admixtures are widely used in concrete in the percentages given. For Class P(HPC) and Class A(HPC) concretes, different percentages may be used if trial batches substantiate that such amounts provide the specified properties. A 25-percent maximum of portland cement replacement is permitted for all classes, except for Classes P(HPC) and A(HPC), which have a 50-percent maximum portland cement replacement.

properties of the freshly mixed and hardened concrete shall comply with specified values.

For classes SCC and SCC(AE), mineral admixtures shall be permitted to be used in blended cements or as a separate addition at the mixer. The amount of mineral admixture shall be determined by trial batches. The water-cementitious materials ratio shall be the ratio of the weight (mass) of water to the total powder materials, including the mineral admixtures. The properties of the freshly mixed and hardened concrete shall comply with specified values.

Limestone powder used in classes SCC and SCC(AE) for up to 15% should be considered in the total powder content. Several studies have indicated that there is a synergistic effect of ground limestone that is reacting with the C3A in the system to enhance the reactivity of the remaining constituents, such as cement and fly ash (Cost et al., 2012; Beeralingegowda and Gundakalle, 2013; and Bucher, 2009).

8.5—MANUFACTURE OF CONCRETE

The production of ready-mixed concrete and concrete produced by stationary mixers shall conform to the requirements of AASHTO M 157 and the requirements of this Article.

8.5.4—Batching and Mixing Concrete

8.5.4.1—Batching

The size of the batch shall not exceed the capacity of the mixer as guaranteed by the Manufacturer or as determined by the Standard Requirements of the Associated General Contractors of America. For classes SCC and SCC(AE), the maximum size of the batch shall not exceed 80% of the mixer capacity due to the relatively high fluidity of the concrete. The measured materials shall be batched and charged into the mixer by means that will prevent loss of any materials due to effects of wind or other causes.

8.5.4.2—Mixing

The concrete shall be mixed only in the quantity required for immediate use. Mixing shall be sufficient to thoroughly intermingle all mix ingredients into a uniform mixture. Concrete that has developed an initial set shall not be used. Retempering concrete shall not be permitted.

For other than transit-mixed concrete, the first batch of concrete materials placed in the mixer shall contain a sufficient excess of cement, sand, and water to coat the inside of the drum without reducing the required mortar content of the mix.

When mixer performance tests as described in AASHTO M 157 are not made, the required mixing time for stationary mixers shall be not less than 90 s nor more than 5 min. The minimum drum revolutions for transit mixers at the mixing speed recommended by the Manufacturer shall not be less than 70 and not less than that recommended by the Manufacturer.

The timing device on stationary mixers shall be equipped with a bell or another suitable warning device adjusted to give a clearly audible signal each time the lock is released. In case of failure of the timing device,

C8.5.4.2

For classes SCC and SCC(AE), adjustments to the mixing time and/or energy may be necessary to ensure sufficiency and uniformity of the mixtures. Trial batches might be needed to determine these adjustments.

the Contractor shall be permitted to operate the mixer while the timing device is being repaired, provided he furnishes an approved timepiece equipped with minute and second hands. If the timing device is not placed in good working order within 24 h, further use of the mixer shall be prohibited until repairs are made.

For small quantities of concrete needed in emergencies or for small noncritical elements of the work, concrete may be hand-mixed using methods approved by the Engineer.

Between uses, any mortar coating inside of mixing equipment which sets or dries shall be cleaned from the mixer before use is resumed.

8.7—HANDLING AND PLACING CONCRETE

8.7.1—General

Concrete shall be handled, placed, and consolidated by methods that will not cause segregation of the mix and will result in a dense homogeneous concrete that is free of voids and rock pockets. The methods used shall not cause displacement of reinforcing steel or other materials to be embedded in the concrete. Concrete shall be placed and consolidated prior to initial set and in no case more than 1.5 h after the cement was added to the mix. Concrete shall not be retempered. For Class SCC and Class SCC(AE), concrete shall not be consolidated by any mechanical means.

Concrete shall not be placed until the forms, all materials to be embedded, and, for spread footings, the adequacy of the foundation material, have been inspected and approved by the Engineer. All mortar from previous placements, debris, and foreign material shall be removed from the forms and steel prior to commencing placement. The forms and subgrade shall be thoroughly moistened with water immediately before concrete is placed against them. Temporary form spreader devices may be left in place until concrete placement precludes their need, after which they shall be removed.

Placement of concrete for each section of the structure shall be done continuously without interruption between planned construction or expansion joints. The delivery rate, placing sequence, and methods shall be such that fresh concrete is always placed and consolidated against previously placed concrete before initial set has occurred in the previously placed concrete.

During and after placement of concrete, care shall be taken not to injure the concrete or break the bond with reinforcing steel. Workers shall not walk in fresh concrete. Platforms for workers and equipment shall not be supported directly on any reinforcing steel. Once the concrete is set, forces shall not be applied to the forms or to reinforcing bars which project from the

C8.7.1

For classes SCC and SCC(AE), limited mechanical consolidated (e.g., vibration) may be applied to the surface of a placed batch immediately before placing the next batch when concrete placement is interrupted for an extended period of time (e.g., 20 minutes) to avoid formation of joints or pour lines (lift lines) within monolithic pours.

concrete until the concrete is of sufficient strength to resist damage.

8.7.2—Sequence of Placement

8.7.2.2—Superstructures

Unless otherwise permitted, no concrete shall be placed in the superstructure until substructure forms have been stripped sufficiently to determine the character of the supporting substructure concrete.

Concrete for T-beam or deck girder spans whose depth is less than 4.0 ft may be placed in one continuous operation or may be placed in two separate operations; first, to the top of the girder stems, and second, to completion. For T-beam or deck girder spans whose depth is 4.0 ft or more, and unless the falsework is non-yielding, such concrete shall be placed in two operations, and at least five days shall elapse after placement of stems before the top deck slab is placed.

Concrete for box girders may be placed in two or three separate operations consisting of bottom slab, girder stems, and top slab. In either case, the bottom slab shall be placed first and, unless otherwise permitted by the Engineer, the top slab shall not be placed until the girder stems have been in place for at least five days

C8.7.2.2

<u>For classes SCC and SCC(AE) used in tub or box girders, concrete may be placed in one continuous operation by placing it from one location and allowing it to flow and fill the bottom slab and stems of the girder.</u>

8.7.3—Placing Methods

8.7.3.1—General

Concrete shall be placed as nearly as possible in its final position, and the use of vibrators for extensive shifting of the weight (mass) of fresh concrete will not be permitted.

Concrete shall be placed in horizontal layers of a thickness not exceeding the capacity of the vibrator to consolidate the concrete and merge it with the previous lift. In no case shall the depth of a lift exceed 2.0 ft. <u>This requirement does not apply to self-consolidating concrete (SCC).</u> The rate of concrete placement shall not exceed that assumed for the design of the forms as corrected for the actual temperature of the concrete being placed.

When placing operations would involve dropping the concrete more than 5.0 ft, the concrete shall be dropped through a tube fitted with a hopper head or through other approved devices, as necessary to prevent segregation of the mix and spattering of mortar on steel and forms above the elevation of the lift being placed. This requirement shall not apply to cast-in-place piling when concrete placement is completed before initial set occurs in the first placed concrete.

C8.7.3.1

<u>Based on the work by Morcous et al. (2015), the free-flow distance of SCC shall not exceed 33 ft in simple sections (i.e., thick elements with one directional flow) and 20 ft in complex sections (i.e., intricate shape or thin elements).</u>

<u>Based on the work by Morcous, et al. (2015), the free-fall height of SCC proportioned with high segregation resistance shall not exceed 15 ft, otherwise, the free-fall height shall not exceed 5 ft.</u>

8.7.3.2—Equipment

All equipment used to place concrete shall be of adequate capacity and designed and operated so as to prevent segregation of the mix or loss of mortar. Such equipment shall not cause vibrations that might damage the freshly placed concrete. No equipment shall have aluminum parts which come in contact with the concrete. Between uses, the mortar coating inside of placing equipment which sets or dries out shall be cleaned from the equipment before use is resumed.

Chutes shall be lined with smooth watertight material and, when steep slopes are involved, shall be equipped with baffles or reverses.

Concrete pumps shall be operated such that a continuous stream of concrete without air pockets is produced. When pumping is completed, the concrete remaining in the pipeline, if it is to be used, shall be ejected in such a manner that there will be no contamination of the concrete or separation of the ingredients.

Conveyor belt systems shall not exceed a total length of 550.0 linear ft, measured from end to end of the total assembly. The belt assembly shall be so arranged that each section discharges into a vertical hopper arrangement to the next section. To keep segregation to a minimum, scrapers shall be situated over the hopper of each section so as to remove mortar adhering to the belt and to deposit it into the hopper. The discharge end of the conveyor belt system shall be equipped with a hopper and a chute or suitable deflectors to cause the concrete to drop vertically to the deposit area.

C8.7.3.2

Despite its high fluidity, SCC flow is fundamentally different from that of conventionally vibrated concrete (sheared layers versus large plug flow), which may require adjustments to minimize the risk of blockage in the pump line. SCC may require the use of a larger pump line diameter (depending on its viscosity) than that required for high slump conventionally vibrated concrete containing the same aggregate type and size.

8.7.4—Consolidation

All concrete, except concrete placed under water, SCC, and concrete otherwise exempt, shall be consolidated by mechanical vibration immediately after placement. Except as noted herein, vibration shall be internal. External form vibrators may be used for thin sections when the forms have been designed for external vibration.

Vibrators shall be of approved type and design and of a size appropriate for the work. They shall be capable of transmitting vibration to the concrete at frequencies of not less than 75 Hz.

The Contractor shall provide a sufficient number of vibrators to properly compact each batch of concrete immediately after it is placed in the forms. The Contractor shall also have at least one spare vibrator immediately available in case of breakdown.

Vibrators shall be manipulated so as to thoroughly work the concrete around the reinforcement and embedded fixtures and into the corners and angles of the forms. Vibration shall be applied at the point of deposit and in the area of freshly deposited concrete. The vibrators shall be inserted and withdrawn out of

C8.7.4

Limited mechanical consolidated (e.g., vibration) may be applied to the surface of a placed batch immediately before placing the next batch when concrete placement is interrupted for an extended period of time (e.g., 20 minutes) to avoid formation of joints or pour lines (lift lines) within monolithic pours.

the concrete slowly. The vibration shall be of sufficient duration and intensity to thoroughly consolidate the concrete but shall not be continued so as to cause segregation. Vibration shall not be continued at any one point to the extent that localized areas of grout are formed. Application of vibrators shall be at points uniformly spaced and not farther apart than 1.5 times the radius over which the vibration is visibly effective.

Vibration shall not be applied either directly to, or through the reinforcement to, sections or layers of concrete which have hardened to the degree that the concrete ceases to be plastic under vibration. Vibrators shall not be used to transport concrete in the forms. Where immersion-type vibrators are used to consolidate concrete around epoxy-coated reinforcing steel, the vibrators shall be equipped with rubber or other nonmetallic coating.

Vibration shall be supplemented by such spading as is necessary to ensure smooth surfaces and dense concrete along form surfaces and in corners and locations impossible to reach with the vibrators. When approved by the Engineer, concrete for small noncritical elements may be consolidated by the use of suitable rods and spades.

ATTACHMENT B

Proposed Guidelines for Use of Self-Consolidating Concrete in Cast-in-Place Bridge Components

These proposed guidelines are the recommendations of the NCHRP Project 18-16 staff at the University of Nebraska-Lincoln. These guidelines have not been approved by NCHRP or any AASHTO committee nor formally accepted for adoption by AASHTO.

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Introduction

Self-consolidating concrete (SCC) is highly flowable, non-segregating concrete that can spread into place, fill the formwork, and encapsulate the reinforcement without any mechanical consolidation (ACI 237R-07). The use of SCC in cast-in-place bridge construction is limited due to the lack of design and construction guidelines and concerns about certain design and construction issues that are perceived to influence the structural integrity of the bridge system. Therefore, these guidelines were developed to address the factors that significantly influence the design, constructability, and performance of cast-in-place concrete bridge components using SCC. These guidelines provide highway agencies with the information necessary for considering cast-in-place SCC to expedite construction and yield economic and other benefits.

B.1 Guidelines for Selection of Constituent Materials

B.1.1 General

The proper and uniform selection of constituent materials is essential to ensure the satisfactory performance of SCC in both fresh and hardened conditions. All constituent materials shall follow the requirements of AASHTO LRFD design specifications (2014) and construction specifications (2010). When requirements are not available, engineering authorization is needed for incorporating any constituent materials. Changes in materials or their proportions shall be monitored continually to avoid any adverse effects on the performance of SCC.

B.1.2 Cement, Supplementary Cementitious Materials, and Fillers

All portland cements that conform to the requirements of AASHTO M 85 can be used for the production of SCC for cast-in-place bridge components. Blended hydraulic cements that conform to the requirements of AASHTO M 240 can be also used. Types IP (portland-pozzolan cement), IS (portland blast-furnace slag cement), and PLC (portland-limestone cement) can be used. When types I, II or III cements are used, replacements with supplementary cementitious materials (SCMs) and fillers are recommended as they enhance the fresh and hardened SCC properties.

Fly ash shall conform to the requirements of AASHTO M 295, ground granulated blast-furnace slag (GGBFS) shall conform to the requirements of AASHTO M 302, and silica fume shall conform to the requirements of AASHTO M 307. Limestone powder approved for use in concrete with average particle size of 11 μm or less can be also used as a filler. For cast-in-place bridge components with specified compressive strength from 4 ksi–6 ksi, SCC with total cementitious materials ranging from 658 lb/yd^3–797 lb/yd^3 is recommended. Cement replacements of 25% with Class C fly ash, 25% Class F fly ash, 30% GGBFS, or combination of 20% Class F fly ash in addition to 15% limestone powder are recommended.

B.1.3 Fine Aggregates and Coarse Aggregates

Fine aggregates shall conform to the requirements of AASHTO M 6 and coarse aggregates shall conform to the requirements of AASHTO M 80. Well-graded combined aggregates are recommended for the production of SCC for cast-in-place bridge components. Natural gravel or crushed stone can be used as coarse aggregate, while natural or manufactured sand can be used as fine aggregate. Coarse aggregate with nominal maximum size of aggregate (NMSA) greater than ¾ in. is not recommended for use in SCC. NMSA of coarse aggregate shall be determined based on the geometric characteristics of the component and its reinforcement spacing. The moisture content, water absorption, and gradation of the aggregate shall be continually monitored to ensure the consistency of SCC production and performance. If any changes in aggregate source or properties are observed, a field trial should be mandatory for determining the suitability of that aggregate for the project.

B.1.4 Chemical Admixtures

Chemical admixtures are mainly used in SCC for cast-in-place bridge components to reduce water content, provide air entrainment, improve viscosity, and enhance workability retention. In special circumstances, other chemical admixtures are used to accelerate strength development, retard setting time, reduce drying shrinkage, and protect against reinforcement corrosion. The performance of chemical admixtures depends on the types and proportions of constituent materials, temperature, and compatibility among different admixtures. Trial batches using the plant conditions and materials utilized in production are needed to evaluate the performance of chemical admixtures. Also, when no standard specifications exist, admixtures supplier should be consulted to ensure an admixture's suitability for the application.

B.1.4.1 High-Range Water-Reducing Admixtures

The use of high-range water-reducing admixtures (HRWRAs) Type F (water reducing, high range) or G (water reducing, high range, and retarding) that conform to the requirements of ASTM C 494 or ASTM C 1017 is necessary to achieve the required flowability of fresh SCC for cast-in-place bridge construction. An HRWRA can be combined with Type A (water reducing), D (water reducing and retarding), or E (water reducing and accelerating) in different dosages to achieve the target flowability.

B.1.4.2 Air-Entraining Admixtures

Air-entraining admixtures that conform to the requirements of AASHTO M 154 are commonly used in cast-in-place bridge construction to generate an air void system that enhances the durability of bridge components especially with respect to their freeze and thaw resistance

B.1.4.3 Viscosity-Modifying Admixtures

Viscosity-modifying admixtures (VMAs) can be used in SCC to improve its stability especially when a large aggregate (size ¾ in.) and/or a high water/cementitious material ratio (more than 0.4) is used. A VMA should be used only to enhance the stability of SCC and not to correct the performance of a poorly designed SCC that is already segregating. Also, large dosages of a VMA may negatively affect the flowability of SCC, which may result in a higher demand for an HRWRA to achieve the required flowability.

B.1.4.4 Workability Retaining Admixtures

Workability retaining admixtures (WRAs) are used in SCC to maintain its fresh characteristics throughout the transporting, placing and finishing operations without adversely affecting its time of setting and hardened properties. A WRA should be added to the mixture at the plant and may reduce the demand for an HRWRA.

B.2 Guidelines for Mix Proportioning

B.2.1 General

For proportioning SCC, the target values/ranges for SCC properties in both fresh and hardened conditions need to be identified. Workability target values/ranges are identified based on the geometric characteristics of the cast-in-place bridge component as well as the production and placement conditions. Target values/ranges of hardened properties, including mechanical, visco-elastic, and durability properties, are usually identified by the bridge/materials engineer in the project specifications. The properties of the available and approved constituent materials also play an important role in proportioning SCC. Figure B-1 shows the general steps of proportioning SCC mix. In the following sections, the common target values/ranges are summarized and the approach used for mix proportioning is discussed.

B.2.2 Workability Targets

The workability targets are presented in terms of the three main performance properties of fresh SCC: filling ability (i.e., fluidity or deformability), passing ability, and stability (i.e., segregation resistance). Two classes are defined for each property as shown in Table B-1 for simplification. These definitions are based on the literature (EFNARC, 2005; ACI, 2007, and Daczko, 2012).

To determine which workability target value/range applies to a specific bridge component, the decision tree shown in Figure B-2 is used. This decision tree provides

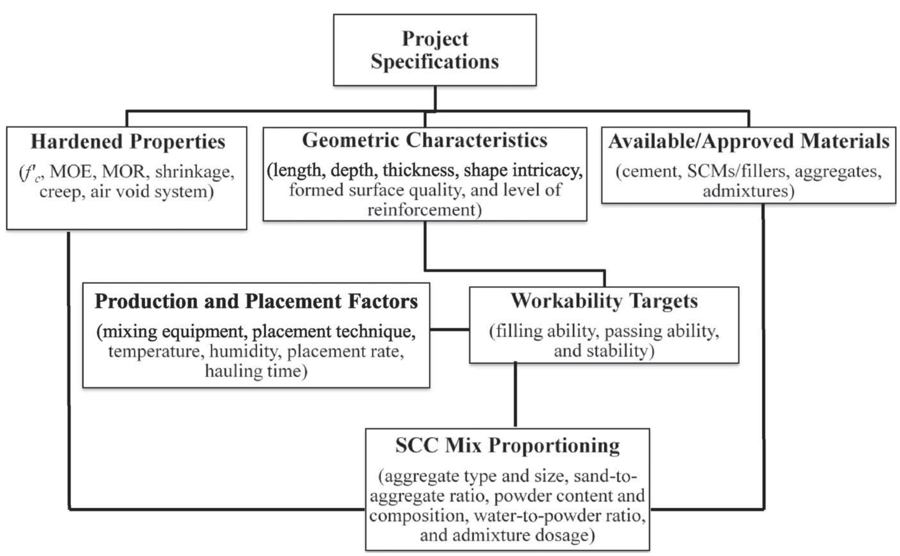

Figure B-1. General steps of proportioning SCC mix for cast-in-place bridge components.

Table B-1. Classes of SCC workability properties and their definitions for cast-in-place bridge components.

Workability Property	Class	Value/Range	Application
Filling Ability (FA)	FA1	22 in. ≤ Slump Flow < 26 in.	Simple Sections
	FA2	26 in. ≤ Slump Flow ≤ 30 in.	Complex Sections or high formed surface quality
Segregation Resistance (SR)	SR1	10% < Column Segregation ≤ 15% 0.5 in. < Penetration ≤ 1 in. VSI = 1	Short or shallow components
	SR2	Column Segregation ≤ 10% Penetration ≤ 0.5 in. VSI = 0	Long or deep components
Passing Ability (PA)	PA1	80% > Filling Capacity ≥ 70% 2 in. < J-Ring ΔD ≤ 4 in. 0.6 in. < J-Ring ΔH ≤ 0.8 in.	Wide spacing between reinforcing bars
	PA2	Filling Capacity ≥ 80% J-Ring ΔD ≤ 2 in. J-Ring ΔH ≤ 0.6 in.	Narrow spacing between reinforcing bars

guidelines on workability targets based on the geometric characteristics of the bridge component. The three-digit identification shown at the bottom of the tree represents the target workability with respect to filling ability (FA), segregation resistance (SR), and passing ability (PA) classes respectively. For example, 111 means FA1, SR1, and PA1. Table B-2 shows examples of common substructure and superstructure bridge components, their geometric characteristics, and the corresponding target workability determined using these guidelines. Also, Table B-3 shows quantitative guidelines for defining the "low" and "high" values of each of the geometric characteristics (EFNARC, 2005; and Daczko, 2012). The selected target workability classes should be revised to consider production and placement conditions. For example, lower FA and high SR are needed when high energy mixing and placement methods are used. The final target workability is used in proportioning SCC mix as presented in the next section.

B.2.3 Proportioning Approach

Several approaches can be used in proportioning SCC mixes (Okamura and Ozawa, 1995; EFNARC, 2002; Bui, Akkaya, and Shah, 2002; PCI 2003; GRACE, 2005; ACI 237, 2007; Koehler and Fowler, 2007; Domone, 2009; Kheder and Jadiri, 2010). The International Center for Aggregates Research (ICAR) mixture proportioning procedure developed by Koehler and Fowler (2007) is recommended for cast-in-place SCC as this procedure considers the effect of aggregate gradation, shape, and angularity in mix proportioning. In addition, this procedure only requires conducting simple and standard tests to identify necessary

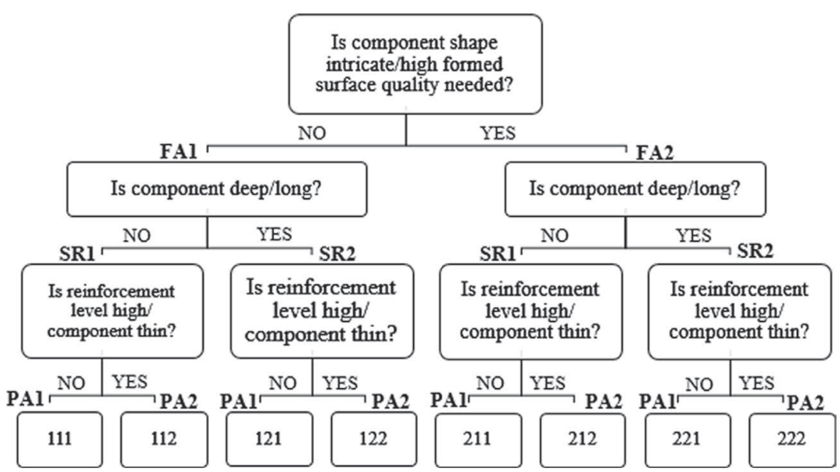

Figure B-2. Decision tree used to determine workability targets.

Table B-2. Workability targets for example of cast-in-place bridge components.

Component Category	Bridge Component	Component Geometric Characteristics						SCC Workability Targets	
		Length	Depth	Thickness	Shape Intricacy	Formed Surface Quality	Level of Reinforcement	Proposed Property Classes*	ID
Substructure	Footing	Low	Low	High	Low	Low	Low	FA1, SR1, PA1	111
	Pile Cap	Low	Low	High	Low	Low	High	FA1, SR1, PA2	112
	Wing Wall	Low	Low	High	Low	Low	Low	FA1, SR1, PA1	111
	Abutment Wall	High	High	High	Low	Low	Low	FA1, SR2, PA1	121
	Pier Wall	Low	High	High	High	High	Low	FA2, SR2, PA1	221
	Pier Column	Low	High	High	Low	High	High	FA2, SR2, PA2	222
	Strut or Tie	Low	Low	High	Low	High	Low	FA2, SR1, PA1	211
	Pier Cap	Low	Low	High	Low	High	High	FA2,SR1, PA2	212
Superstructure	Box Girder	High	Low	Low	High	High	High	FA2, SR2, PA2	222
	Stringer	Low	Low	High	Low	Low	High	FA1, SR1, PA2	112
	Floor Beam	Low	Low	High	Low	Low	Low	FA1, SR1, PA1	111
	Girder	High	Low	Low	Low	High	High	FA2,SR2, PA2	222
	Arch	High	High	High	Low	High	Low	FA2, SR2, PA1	221

* For deep/long components, SR1 could be acceptable if free-fall height/free-travel distance are controlled (e.g., tremie pipe).

parameters. This method can be used in combination with ACI 211.1-91 Table 6.3.3 to estimate mixing water requirements for different NMSA; and ACI 237R-07 Tables 4.1 and 4.2 to verify that the powder content, powder volume, and aggregate volume are within the recommended ranges for SCC. Below are the steps followed to proportion an SCC mix for a given workability class (e.g., 212) using the recommended procedure.

1. Select the NMSA based on the PA and SR classes as follows:
   a. NMSA is ¾ in. for PA1 and SR1
   b. NMSA is ½ in. for PA2 and SR1 or PA1 and SR2
   c. NMSA is ⅜ in. for PA2 and SR2

   In addition, NMSA should not exceed ⅓ of the narrowest component dimension and ½ of the smallest clear spacing between bars.

Table B-3. Definitions of the geometric characteristics of cast-in-place bridge components.

Component Geometric Characteristic	Class	Value/Definition
Length	Low	≤ 33 ft
	High	> 33 ft
Depth	Low	≤ 16 ft
	High	> 16 ft
Thickness	Low	≤ 8 in.
	High	> 8 in.
Shape Intricacy	Low	Concrete flows in a single direction
	High	Concrete flow around corners and cutouts
Formed Surface Quality	Low	Unexposed to the traveling public
	High	Exposed to the traveling public
Level of Reinforcement	Low	Large spacing between bars (≥ 3 in.)
	High	Small spacing between bars (< 3 in.)

2. Determine the optimal gradation of the combined coarse and fine aggregates that results in the highest density. The ratio of sand to aggregate (S/A) can be changed to achieve optimal gradation using the 0.45 power curve. As a starting point, use S/A = 0.45 and change in the range from 0.4 to 0.5 until the optimal gradation is achieved. In the case of gap grading aggregate, more than two types of coarse aggregates can be used. Another method to determine the optimal S/A ratio is the use of predefined limits for the minimum and maximum percent retained on each sieve.
3. Determine the shape and angularity rating ($R_{S\text{-}A}$) of the blended aggregate using the guidelines published in Table 6 of the ICAR 108-1 report (Koehler and Fowler, 2007).
4. Calculate the minimum percentage of paste that achieves the flowability of the mixture made of the blended aggregate. This is calculated as follows: Min $V_{paste} = 1 - (1 - \%voids)(1 - \%spacing)$, where, %voids is the percentage of voids calculated using the dry-rodded unit weight of the blended aggregate, S/A ratio, and specific gravity of fine and coarse aggregates. The %spacing is calculated based on the shape and angularity rating as follows: $8 + 2(R_{S\text{-}A} - 1)$. Selected paste volume percentage shall be within the range (34% to 40%) recommended by ACI 237R-07.
5. Subtract the target air content (e.g., 6%) to get the volume of powder and water. Powder content can be estimated based on the target FA class (650–750 lb/cy for FA1, and >750 lb/cy for FA2). Strength requirements do not usually control the design of SCC mixes for cast-in-place applications. To determine powder content more precisely, water content for SCC mixtures is estimated using Table 6.3.3 of ACI 211.1-91 for different NMSA and assuming a 1 to 2 in. slump in air entrained concrete (305 lb/cy for ⅜ in. NMSA; 295 lb/cy for ½ in. NMSA; and 280 lb/cy for ¾ in. NMSA). Water-to-powder ratio (w/p) shall be between 0.37 and 0.44 for cast-in-place SCC.
6. Select the type and amount of SCMs and mineral fillers based on availability and project requirements. Recommended SCM and filler percentages are 25% Class F fly ash, 25% Class C fly ash, 30% slag, and 20% Class F fly ash + 15% limestone powder. Limestone powder should be included in the total powder content and W/P ratio calculations. This is because several earlier studies have indicated that there is a synergistic effect of ground limestone that is reacting with the C3A in the system to enhance the reactivity of the remaining constituents, such as cement and fly ash (Cost et al., 2012; Beeralingegowda and Gundakalle, 2013; and Bucher, 2009).
7. Using the absolute volume method, determine the quantities of fine and coarse aggregate. According to ACI 237, the absolute volume of coarse aggregate should be 28% to 38%.

B.2.4 Quality Assurance

Once the SCC mix proportioning is completed, at least three trial batches are needed to verify the properties of the fresh and hardened SCC. For cast-in-place bridge components, the target 28-day compressive strength usually ranges from 4 ksi to 6 ksi, and the target air content usually ranges from 4.5% to 7.5%. These targets, in addition to any other requirements in the project specifications, shall be checked for each trial batch prior to concrete production in the plant setting. Necessary adjustments shall be made to ensure that all requirements are fulfilled.

Trial batches are also used to determine the dosage of HRWRA (typically polycarboxylate based), VMA (if needed), and WRA (if needed) that achieve the workability targets. Guidelines for adjustments that might be needed when workability targets are not met can be found in Table 5 of the ICAR 108-1 report (Koehler and Fowler, 2007). In addition, the robustness of SCC mixes shall be evaluated by investigating the effect of minor variations in the water content (8–16 lb/cy) on the workability properties of the designed SCC mix.

B.3 Guidelines for Testing Fresh Concrete

B.3.1 General

Properly designed SCC should have adequate workability in its fresh state to allow placement without mechanical consolidation while maintaining its stability to ensure satisfactory performance in the hardened state. Workability requirements for successful casting of SCC include good deformability (FA), PA, and adequate SR. In terms of fundamental rheology, SCC is characterized by a low yield stress to ensure high deformability and a moderate plastic viscosity to maintain homogeneous suspension of coarse aggregate, hence avoiding segregation and blockage during flow and ensuring good passing and filling abilities. Several empirical test methods have been developed and used to evaluate the workability properties of SCC. Other fresh and early-age concrete properties, such as air content, heat of hydration, and formwork pressure, also need to be checked to ensure the constructability, durability, and strength of SCC.

B.3.2 Rheology

Rheology is the science of deformation and flow of matter. The two key parameters used to describe the rheology of SCC are: yield stress (τ_0), which represents the amount of shear stress required to cause concrete to deform (flow); and plastic viscosity (μ_p), which describes the ease/resistance of flow at a certain shear stress. A high yield stress results in low FA, while a high plastic viscosity results in difficult placement and slow flow of SCC. Slump flow and T_{50} are good indicators of yield stress and plastic viscosity, respectively. A properly designed SCC should have lower yield stress than conventional concrete to achieve the target FA, and adequate viscosity to ensure SR. Concrete/mortar rheometers are used to determine yield stress and plastic viscosity by plotting the relationship between shear stress and shear rate for a given mixture assuming the Bingham model (ACI 237R, 2007). This test should be conducted in the lab as it requires qualified personnel to operate the rheometer and interpret the data (not suitable for site use).

Another rheological property that is important to describe the behavior of SCC is thixotropy, which is the reversible time-dependent increase in viscosity when concrete is at rest (i.e., stiffening or build-up) and decrease in viscosity (i.e., break-down) when subjected to adequate shearing force (agitated). A high thixotropic SCC has several advantages, such as high static stability and reduced lateral pressure on forms. On the other hand, it is not favorable for multi-lift castings as it could result in pour lines (lift lines) when the time between successive castings is relatively long. Thixotropy can be evaluated in the lab using the rheometer or on the site using the portable vane test (Omran, Naji, and Khayat, 2011).

The yield stress, viscosity, and thixotropy of SCC have a significant effect on several fresh concrete properties, such as FA, PA, stability, pumpability, formwork pressure, and workability retention.

B.3.3 Filling Ability

FA (deformability or flowability) describes the ability of the SCC to flow into and completely fill all spaces within the formwork under its own weight without any mechanical consolidation. Different levels of flowability might be needed based on the geometry of the component, the required quality of the formed surface, and the method of placement (placement energy, location of placement point, and spacing between placement points).

The slump flow test is a common procedure used to determine the horizontal free-flow characteristics of SCC in the absence of obstructions (AASHTO T 347). The procedure is based on AASHTO T 119 standards for determining the slump of conventional concrete. The test is easy to perform either at a concrete plant or on a job site, repeatable, reproducible, and can be performed by single operator. This test evaluates the capability of the concrete to deform under its own weight and the time needed for the concrete to spread 20 in. (T_{50}). It should be noted that the results of two slump flow tests on the same batch properly conducted by the same operator should not differ by more than 3 in. (ASTM C1611). Other non-standard test methods for evaluating the FA of SCC include the V-funnel test and Orimet test (EFNARC, 2002).

Two levels of FA are recommended for cast-in-place bridge components: moderate FA (22–26 in.), and high FA (26–30 in.). T_{50} of 1 to 6 sec is generally acceptable for civil engineering applications (EFNARC, 2002). Examples of the required level of FA for different bridge components are shown in Table B-2.

B.3.4 Passing Ability

PA describes the ability of SCC to pass among obstacles (e.g., reinforcements) and narrow spacing in the formwork without segregation and blockage. Different levels of PA might be needed based on the geometry of the component, level of reinforcement intensity and spacing, and method of placement.

The J-ring test can be used to characterize the passing ability of fresh SCC with NMSA of up to 1 in. (AASHTO T 345). When SCC is placed in forms containing steel reinforcement, the mixture should remain cohesive, and the aggregates should not separate from the paste fraction of the mixture when it flows between obstacles. This is a critical characteristic of the mixture when it is used in highly congested reinforced structures. The difference between the J-ring slump flow and the unconfined slump flow is an indication of the degree to which the passage of SCC through reinforcing bars is restricted. Another measurement of the J-ring test is the height difference of concrete inside and outside of the J-ring. The greater the difference in height inside and outside of the J-ring, the less the PA. Two levels of PA are recommended for cast-in-place bridge components: moderate PA (2–4 in. diameter difference and 0.6–0.8 in. height difference; and high PA (<2 in. diameter different and 0.6 in. height difference). The NMSA is determined based on the required level of PA. Examples of the required level of PA for different bridge components are shown in Table B-2.

The J-ring test is easy to perform either at a concrete plant or on a job site. The test is repeatable, reproducible, and can be performed by one operator. Other test methods for evaluating the PA of SCC include the caisson test (AASHTO T 349). The caisson test evaluates the filling capacity of SCC, which describes the FA and PA of SCC with up to ¾ in. NMSA. The test is designed specifically for sections with reinforcement bars/strands that are at 2 in. spacing vertically and horizontally. The test is difficult to perform with one operator and requires calculation to determine the filling capacity of SCC; therefore, it is not recommended for on-site use. Filling capacity of 80% or more is recommended for components that require high PA, while filling capacity of 70% to 80% is acceptable for components that require moderate PA. Other non-standard test methods include the L-box test and U-box test (EFNARC, 2002).

B.3.5 Static Stability

Static stability describes the ability of SCC to maintain homogeneous distribution of its various constituents while being in the forms (at rest). Static stability refers to the resistance of SCC to bleeding, segregation, and surface settlement from the end of casting until setting. Different levels of stability might be required based on the geometry of the component and placement method.

The visual stability index (VSI) is commonly used to visually determine the apparent stability of the slump flow patty (AASHTO T 351). This test method is simple and can be performed by a single operator at the same time the slump flow test is performed. The VSI is a qualitative rating that is used to compare batches of the same or similar SCC mixtures with respect to the tendency to bleeding and uniformity of aggregate distribution. A similar test can be performed on hardened SCC, known as the hardened visual stability index (HVSI) (AASHTO PP 058), to determine the relative stability of SCC batches by comparing the cut planes of hardened concrete cylinders. A quantitative rating is assigned based on the uniformity of aggregate distribution and the thickness of the top mortar layer.

Two levels of static stability are recommended for cast-in-place bridge components: moderate stability (VSI = 1 and HVSI = 2) and high stability (VSI = 0 and HVSI = 0).

Other test methods for the quantitative assessment of SCC static stability include the column segregation test (ASTM C1610) and rapid penetration test (ASTM C1712). The column segregation test is suitable for laboratory use to determine the potential static segregation of a SCC mixture by measuring the difference in coarse aggregate content in the top and bottom portions of a vertical cylindrical specimen that simulates SCC in a vertical form. The test is difficult for a single operator to perform, time consuming, and requires a special apparatus. The rapid penetration test provides a simple and quick method to evaluate static stability indirectly by measuring the penetration of a specific cylinder into the SCC placed in the slump cone before conducting the slump test. Guidelines for classifying SCC static stability using these test methods are that penetration less than 0.5 in. and column segregation less than 10% indicates high stability, while penetration from 0.5 to 1.0 in. and column segregation from 10% to 15% indicates moderate stability. Other non-standard tests include the sieve segregation test (De Schutter, 2005) and surface settlement test (Khayat and Mitchell, 2009)

B.3.6 Dynamic Stability

Dynamic stability describes the ability of SCC to maintain homogeneous distribution of its various constituents during mixing and placement (free fall and flow). Adequate dynamic stability is required when SCC has to travel a long distance in a horizontal and/or vertical direction before reaching its final position and filling the form. Example applications include girders, walls, and arches.

Some of the FA and PA test methods can be used to indicate the dynamic stability of SCC. No standard test method is currently available to specifically evaluate the dynamic stability of SCC. The flow trough test was developed to determine the dynamic segregation index (DSI) of SCC by measuring the difference in the weight of coarse aggregate in two samples taken before and after flowing in a 6 ft long apparatus (Lange et al., 2008). Modifications to the flow trough were made and indicated a better performance in evaluated dynamic stability of SCC. The higher the DSI, the lower the resistance to dynamic segregation. Few experiments have indicated acceptable performance when DSI is less than 20%. Other test methods include the tilting box, in which the penetration depth in SCC is compared before and after traveling several cycles in a tilting box (Esmaeilkhanian et al., 2014).

B.3.7 Heat of Hydration

Any action that promotes the hydration process would increase heat liberation, such as increasing the portland cement quantity or using finer cement. There are no unique effects of using SCC with respect to heat liberation, especially when common ranges of paste content are used in mix design and a significant portion of the cement is replaced using SCMs and/or fillers. Calorimeters used to assess the heat of hydration of concrete mixtures are semi-adiabatic calorimeters (RILEM 119-TCE) and isothermal calorimeters (ASTM C 1749). Using both semi-adiabatic and isothermal calorimeters to measure the heat generation indicated that there was no significant difference in temperature rise/heat generation between SCC and CVC mixtures. However, there was a significant delay in reaching the peak temperature in SCC mixtures. It should be noted that the rate of reaching the peak temperature is also dependent on the type of SCM/filler used. In mass concrete, special attention should be given to the release of heat of hydration to avoid cracking.

B.3.8 Pumpability

Pumping is the most common method of placing SCC because it provides the highest placing rate (EFNARC, 2002). Pump lines should be lubricated with cement mortar for the first part of the load (25–40 gallons) before pumping SCC. When SCC is pumped from the top, it is recommended that it be placed with a submerged hose in order to minimize the trapped air and segregation that could occur from free fall. Pumping SCC from the bottom minimizes the entrapped air and risk of segregation, which results in higher quality formed surfaces.

Despite the fact that SCC is more fluid than CVC, the higher pressure loss of SCC is attributed to the difference in the rheological properties of SCC and CVC (lower yield stress and higher viscosity and thixotropy) resulting in a different shear rate distribution and, consequently, a different velocity profile inside pipes (Feys, Verhoeven, and De Schutter, 2008). Using a slightly larger hose diameter for SCC than the corresponding hose diameter for high slump CVC with similar aggregate type and size can significantly reduce the pressure loss and reduce the risk of blockages in the pump line.

B.3.9 Time of Setting

Time of initial setting is the elapsed time after initial contact of cement and water required for sieved mortar to reach a penetration resistance of 500 psi according to AASHTO T 197. In general, there was no evidence that the time of initial set of SCC mixtures with low slump flow was different from that of CVC mixtures (4 to 6 hr). However, the time of setting is highly dependent on the type of SCM/filler, dosage of HRWRA, and temperature. Mixtures with Class C fly ash have the longest time of setting, while mixtures with Class F fly ash have the shortest time of setting. Also, mixtures with high slump flow are expected to have a longer time of setting (6 to 10 hr) than those with low slump flow due to the retarding effects of HRWRA. The ambient temperature also has a significant effect on the time of setting. The higher the temperature, the shorter the time of setting.

B.3.10 Workability Retention

In some cast-in-place applications, retaining concrete workability for extended periods (90 minutes or more) is vital. Workability retention of SCC mixtures is dependent on the temperature, initial slump flow, type and dosage of admixtures used, and type and replacement percentage of SCM/filler used. This property was investigated by conducting the slump flow test (AASHTO T 347) at different times (15, 30, 60, and 90 minutes) to evaluate the loss of slump flow with time. Results indicated that the type of SCM/filler had a slight effect on workability retention; however, initial slump flow had a significant effect on the rate of losing workability. For example, SCC mixtures with an initial slump flow of 30 in. lose flowability at an average rate of 7 in. per hr, while mixtures with an initial slump flow of 24 in. lose flowability at an average rate of 4 in. per hr. The use of workability retaining admixtures early in the mixing phase has shown satisfactory results in reducing the rate of workability loss. Also, adding limited dosages of HRWRA later on, after observing slump flow loss at the job site, can be effective in recovering the initial slump flow. However, the additional dosages of HRWRA may have a negative effect on the entrained air content and, therefore, should be carefully observed.

B.3.11 Formwork Pressure

For cast-in-place bridge components, formwork pressure plays a significant role in the construction cost and duration. Formwork pressure development is significantly influenced by casting rate, casting method, ambient environmental conditions, and mixture composition. Comparing the formwork pressure of several SCC and CVC mixtures has shown that the ratio of maximum exerted lateral pressure to hydrostatic pressure ($P_{maximum}/P_{hydrostatic}$) was higher in SCC than CVC. This comparison has also shown that low slump flow SCC mixtures (22–26 in.) exert less lateral pressure than high slump flow mixtures (26–30 in.). The correlations between $P_{maximum}/P_{hydrostatic}$ and the rheological properties (i.e., thixotropy and yield stress) of SCC mixtures indicated that $P_{maximum}/P_{hydrostatic}$ exhibited a linear relationship with thixotropy and yield stress as reported by Assaad et al. (2003) and Khayat and Assaad (2012). The higher the thixotropy and yield stress, the lower the lateral pressure. Therefore, the rheological properties of SCC need to be evaluated in order to allow for lower formwork pressure than the hydrostatic pressure in formwork design when SCC is used. Alternatively, a pressure test (according to the AASHTO TP 094) can be performed to determine the pressure distributed in a mockup form.

B.4 Guidelines for Hardened Properties

B.4.1 General

The hardened properties of SCC need to be accurately predicted to allow bridge engineers to properly design cast-in-place bridge components using current design specifications and ensure their satisfactory performance and durability.

B.4.2 Compressive Strength

For cast-in-place bridge construction, the minimum specified 28-day compressive strength commonly ranges from 4.0 ksi to 6.0 ksi. In several situations, 7-day, 14-day, and 56-day compressive strength are specified for construction and structural purposes. Studying the relationships between the average 28-day compressive strength and that at 7, 14, and 56 days for SCC mixtures with different SCMs/fillers and aggregate types indicated that there was no significant difference between SCC and CVC with respect to compressive strength development. The ACI 209R-92 model can be used to accurately predict the ratio of compressive strength in ksi at a given time (t) in days $(f_c)_t$ to the 28-day compressive strength as follows:

$$(f_c)_t/(f_c)_{28d} = \frac{t}{\alpha+\beta t}$$

The values of the constants α and β for cement type I and moist cured concrete are 4.0 and 0.85, respectively, according to Table 2.2.1 of ACI 209R-92. The average ratio of 7-day, 14-day, and 56-day compressive strength to 28-day compressive strength were found to be 0.77, 0.88, and 1.12, respectively, for SCC mixtures. Also, mixtures with limestone aggregate have shown higher compressive strength than those with gravel aggregate, which is attributed to the effect of the interfacial transition zone (ITZ) between aggregate particles and paste. Additionally, all mixtures with limestone powder have experienced low compressive strength, which is attributed to the powder particle size. Limestone powder with finer particle size results in higher compressive strength.

B.4.3 Modulus of Elasticity

Modulus of elasticity (MOE) is an important design parameter for deflection, deformation, and prestress loss calculations. In the design phase, MOE is predicted, according to AASHTO LRFD Equation 5.4.2.4-1, as a function of specified compressive strength and the unit weight of concrete. The measured MOE of SCC mixtures, according to ASTM C469, was found to be slightly lower than predicted by AASHTO LRFD, as reported by Pineaud et al. (2005). Therefore, it is recommended to introduce a modification factor to the AASHTO LRFD equation as follows:

$$E_c = 33{,}000 K_1 \, K_2 w_c^{1.5} \sqrt{f_c'} \qquad (5.4.2.4\text{-}1)$$

where

K_2 = modification factor to be taken as 0.96 for SCC and 1.0 for CVC.

Comparing the predicted MOE using the revised equation with the measured MOE for SCC mixtures with different aggregate types indicated that the aggregate source factor (K_1) should be taken as 1.0 for crushed limestone and 0.95 for natural gravel. This is because SCC mixtures with gravel aggregate demonstrated slightly lower MOE than those with limestone aggregate as reported by Mokhtarzadeh and French (2000).

B.4.4 Splitting Tensile Strength

The splitting (direct) tensile strength of concrete is used in the design of bridge components subjected to tension force caused by means other than flexure, such as in anchorage zones. The direct tensile strength of SCC obtained from testing, according to AASHTO T198, was found to be 20% less than that predicted by AASHTO LRFD 5.4.2.7 as $0.23\sqrt{f_c'}$. Therefore, a modification factor of 0.8 is recommended for all SCC mixtures with compressive strength less than 8 ksi and regardless of the aggregate type.

B.4.5 Modulus of Rupture

The modulus of rupture (MOR) of concrete is used primarily in calculating the cracking moment of bridge components for serviceability limit states. AASHTO LRFD Section 5.4.2.6 provides a range for the MOR of normal weight concrete from $0.24\sqrt{f_c'}$ to $0.37\sqrt{f_c'}$. The measured MOR of SCC mixtures according to AASHTO T97 was found to be within the predicted range (mostly closer to the upper limit) and very comparable to that of CVC, a finding that is in agreement with findings reported in *NCHRP Report 628* (Khayat and Mitchell, 2009). Therefore, no changes are recommended to the current AASHTO LRFD with respect to MOR.

B.4.6 Bond to Deformed Reinforcing Steel Bars

The bond strength of concrete to reinforcing steel is an important parameter for determining the development length of bars. Results of pull-out testing of #6 deformed bars embedded vertically in concrete blocks made of SCC and CVC mixtures, according to Moustafa (1974), indicated that the bond strength of SCC was significantly lower than that of CVC. Therefore, a development length modification factor of 1.3 is recommended to AASHTO LRFD 5.11.2.1.2 for bars in tension placed vertically in SCC. This factor is close to the 1.4 factor recommended in *NCHRP Report 628* for bond with prestressing strands (Khayat and Mitchell, 2009). Results of pull-out testing of #6 deformed bars embedded horizontally at different elevations in concrete walls made of SCC and CVC mixtures indicated that the bond strength of SCC is not significantly different from that of CVC. This testing also indicated that the top-bar effect in SCC mixtures with high slump flow is lower than that in CVC mixtures and SCC mixtures with low slump flow. However, no development length modification factor is recommended for top horizontal tension bars in high slump flow SCC, and the 1.4 factor used for top horizontal tension bars in CVC according to AASHTO LRFD 5.11.2.1.2 will be used for SCC regardless of the slump flow as the slump flow may change with time in the same component.

B.4.7 Shear Resistance

The interface shear resistance of SCC and CVC mixtures was evaluated using push-off testing for a wide range of concrete strengths (4.0–8.0 ksi). The results indicated that the average interface shear resistance of SCC was similar to that of CVC. Comparing the measured interface shear resistance versus that predicted according to AASHTO LRFD 5.8.4.1 indicated that the AASHTO LRFD over estimates the interface shear resistance for mixtures with compressive strength less than 6 ksi. Therefore, it is recommended to take the cohesion factor, *c*, as 0.0 for predicting the interface shear resistance when concrete compressive strength is less than 6 ksi. It should be noted that AASHTO LRFD doesn't consider the concrete compressive strength in estimating interface shear resistance, but does consider both cohesion and friction factors.

The nominal shear resistance of SCC and CVC mixtures was evaluated using beams with different levels of transverse reinforcement tested under point loads. Results indicated that there was no significant difference in the shear resistance of SCC and CVC regardless of the level of shear reinforcement. Results also showed that the nominal shear resistance of SCC can be conservatively predicted using AASHTO LRFD Section 5.8.3.3 (sectional design method) when different levels of transverse reinforcement are used.

B.4.8 Drying Shrinkage

Predicting drying shrinkage of concrete is important to minimizing cracking and estimating long-term losses in post-tensioned components. The drying shrinkage of SCC and CVC mixtures was measured using AASHTO T160 for 56 days and compared against predicted shrinkage according to AASHTO LRFD 5.4.2.3. Results indicated that measured shrinkage was significantly higher than predicted, as reported in the findings of *NCHRP Report 628* (Khayat and Mitchell, 2009). Results also indicated that the type of SCM has a significant effect on the drying shrinkage. Therefore, in the absence of a physical test, the following modification factors are proposed to better estimate drying shrinkage for each type of SCM/filler: 1.6 for Class C fly ash, 1.4 for GGBFS, and 1.3 for Class F fly ash with/without limestone powder.

B.4.9 Restrained Shrinkage

Most cast-in-place concrete components experience shrinkage while they are restrained, which results in tensile stresses that cause cracking. Therefore, measuring the restrained shrinkage of SCC and CVC mixtures according to ASTM C1581 is important in order to compare their cracking potential in conditions similar to the site conditions. Under NCHRP Project 18-16, the time to cracking and average stress rate of SCC and CVC mixtures were measured for up to 28 days. Results indicated that there was no significant difference in the cracking potential of SCC and CVC mixtures containing the same SCM/filler and aggregate size. Mixtures with Class C fly ash and/or ⅜ in. NMSA had a higher cracking potential than those with Class F fly ash and ¾ in. NMSA.

B.4.10 Creep

Predicting creep of concrete is important for determining long-term deformation and prestress losses in bridge components. Creep of SCC and CVC mixtures was measured according to ASTM C512 over a 1-year period and used to calculate the creep coefficient. Results indicated no significant difference between the creep of SCC and CVC mixtures containing the same type of SCM/filler. Also, comparing measured and predicted creep coefficients using AASHTO LRFD 5.4.2.3.2-1 indicated that the creep coefficient can be accurately predicted using AASHTO LRFD for all SCC mixtures except those with limestone powder that exhibit higher creep strains. Therefore, a modification factor of 1.2 is proposed only for predicting the creep of SCC mixtures containing limestone powder as reported by Heirman et al. (2008).

B.4.11 Durability Properties

The durability of a concrete element is highly dependent on its permeability. As an alternative to the rapid chloride ion penetrability test of concrete mixtures, a surface resistivity test was conducted (according to AASHTO TP 95) on SCC and CVC mixtures to evaluate their penetrability. Results indicated that the surface resistivity of SCC and CVC was not significantly different. Results also indicated that the surface resistivity was highly dependent on the type of SCM/filler: mixtures with Class C fly ash had the lowest surface resistivity, while mixtures with GGBFS had the highest surface resistivity. Comparing the surface resistivity results to the chloride ion penetration classes (according to ASTM C1202) indicated that all SCC mixtures developed for cast-in-place bridge components had low-moderate penetrability.

For bridge components subjected to freezing and thawing, the air void system is vital to their durability. Air void system parameters (i.e., air content, space factor, and specific surface) are measured for SCC and CVC mixtures according to ASTM C 457. Results indicated that there was no significant difference between SCC and CVC with respect to air void system parameters. All mixtures had a space factor less than 0.2 mm and specific surface higher than 24 mm^2/mm^3, which are the recommended thresholds for good freeze-thaw resistance (PCA, 2009). The air content in hardened concrete varied from 3% to 8%, which might be accepted by several transportation agencies depending on the application and environment. However, comparing the air content in fresh SCC at the plant to that at the job site showed significant differences, which may be due to the effect of the additional dosages of HRWRA (to increase slump flow) on the entrained air content.

B.5 Guidelines for Production and Construction

B.5.1 General

Successful production and construction of cast-in-place bridge components using SCC requires more attention to the selection of materials, mixing and testing procedures, and placement and finishing methods than using conventional vibrated concrete. Trial batches are necessary to verify that SCC properties meet the target values/ranges and to make necessary adjustments to mixture proportions and/or production and construction procedures.

B.5.2 Quality Control of Constituent Materials

SCC is more sensitive to variations in constituent materials than CVC; therefore, proper control of the properties and quantity of all constituent materials should be ensured. Special consideration should be given to water content as it is a key factor in the stability of the mixture. RILEM (2006) recommends the use of at least two different methods for measuring the moisture content of aggregates. Also, only production equipment that has a tolerance of 1 to 2 gallons per cubic yard in water content can be used. It is highly recommended that best practices on maintaining material stockpiles be used, such as moisture control, free drainage, cleanliness, and prevention of segregation. The use of overhead bins for material storage is also recommended. Concrete plants should have additional silo capacity to store various filler materials and extra high volume tanks and dispersing systems for liquid admixtures (i.e., HRWRA and VMA). Combining admixtures is not recommended due to the different dosage rate requirements of each admixture. Since small variations in the physical properties of the aggregates (i.e., gradation, particle shape, absorption, moisture content, and percentage of fines) can have a significant effect on workability, frequent inspections of the aggregate storage places are necessary.

B.5.3 Mixing Procedures

According to AFGC (2002), a concrete plant with the following characteristics is recommended for the production of SCC: a mixer with a high shear rate, entirely automatic production control, wattmeter or equivalent; moisture probes for sand, and storage of aggregates in a dry place and/or use of a reliable moisture content evaluation system for each aggregate size. The EFNARC (2002) does not recommend any specific mixer type. Forced action mixers (e.g., paddle mixers), and free-fall mixers (e.g., truck mixer) can be used. RILEM (2006) indicates that force type mixers are more efficient in mixing SCC and large mixers are recommended because small mixers tend to require a longer mixing time. Generally, the mixing time of SCC is expected to be longer than that of CVC (an additional 30 to 90 sec) (ACI Committee 237). Below are concrete mixing guidelines according to AFGC (2002)

- Use stationary equipment during the time required to obtain complete stabilization of the wattmeter, or set up a reliable procedure to measure mixing efficiency.
- Whatever the case is, the mixing time must not be fewer than 35 sec for strengths less than or equal to 4.5 ksi and 55 sec for other strengths.
- In the case of on-site production of concrete that is not to be kept at least 5 minutes in a receptacle that keeps the concrete moving (truck mixer or receiving bin), the mixing time in a concrete plant must be at least 55 sec.

B.5.4 Plant Quality Assurance

EFNARC (2002) suggests that additional resources may be needed for supervision of all aspects of the initial production of SCC. According to ACI Committee 237 (2007), the employees associated with the production, testing, or use of SCC should be trained and qualified appropriately for day-to-day quality control, have appropriate certification, understand the engineering properties and placement techniques of fresh SCC, and learn the proper corrective actions when performance requirements are not met. The slump flow test and VSI should be checked for each truck load in addition to air content and unit weight of fresh SCC. The rapid penetration and J-ring tests could be conducted if specified by the material engineer. Records should be kept for future adjustments if necessary.

B.5.5 Transportation Procedures

According to ACI Committee 237 (2007), SCC can be transported using all of the conventional concrete devices, but some precautions should be considered as follows:

1. Transit mixer: Deliver SCC to a job site by a concrete truck.
   - Place the volume of SCC into a truck without exceeding 80% capacity of the drum to ensure that SCC does not spill out of a concrete truck whenever the truck goes up or down a steep incline.
   - Keep the revolving drum turning in the mixing mode direction while in transport. Alternatively, deliver the mixtures to the project at a lower slump flow than required and add an HRWRA to bring the mixture to the required slump flow.
   - When SCC is delivered and placed by a concrete truck where the speed of discharge and volume of concrete delivered is high and continuous, the mixture may experience further flowing distances and improved filling capacities.

   - A concrete truck is an effective method of placing SCC mixtures with all slump flow levels.
2. Hopper or bucket: SCC can also be transported to forms by hopper or bucket transporters or other specialized devices.
   - When hopper-type vehicles are used, SCC mixtures should be very stable and able to resist segregation from vibratory forces without receiving any additional mixing.
   - SCC transported by bucket from an overhead lift receives minimal or no vibration and does not require the same level of stability as SCC transported in a hopper-type vehicle.
   - Bolting rubber strips or pads to the clam shell discharge point of buckets is an effective method to prevent leakage of low viscosity SCC mixtures during transport to forms.
   - A chute attached below the bucket opening can direct the flow of SCC toward specific areas of the form to be filled.
   - When a hopper or bucket placement method is used, a limited volume of SCC can be placed at any one time, thus reducing the rate of concrete placement and resulting in a discontinuous discharge rate of flow of concrete compared with placement by truck chute, where a large volume of concrete can be continuously cast.
   - The use of larger volume transport vehicles, such as concrete trucks, rather than hopper or bucket transporters, is advantageous in rapidly filling forms and avoids the production of multiple batches of concrete in the case of a relatively large section.
   - SCC placement by bucket has a high discharge rate and is discontinuous. SCC transported to a form by bucket should have a slump flow of 24 to 28 in. to help facilitate placement by increasing flow distance and permitting consolidation with consecutive loads.

B.5.6 Site Quality Assurance

Inspection of SCC should be conducted on site to confirm that workability requirements are satisfied. According to JSCE (1999), for on-site quality control:

- SCC should be tested at the time of concrete placing/unloading, and the slump flow test and VSI shall be carried out for each batch unless additional workability requirements are specified.
- When SCC is rejected due to low slump flow, HRWRA may be added at a predetermined dosage. But, when SCC is rejected due to segregation, SCC must not be used. Causes of rejection should be identified and documented to improve subsequent production and transportation practices. Caution should be given to the effect of added HRWRA at the job site on the entrained air content.

RILEM (2006) recommends tighter quality assurance in the start-up phase of casting SCC. This is because of large workability fluctuations caused by the starting up of mixer, truck, pumps, etc. Sampling of every batch or truckload is recommended until the stability and consistent quality of the delivered concrete is achieved. AFGC (2002) recommends that on-site acceptance of concrete involves checking whether SCC is suitable for placement without consolidation. It is recommended to carry out an acceptance test on at least the first batch of the day and systematically whenever there is any doubt. The acceptance procedure includes sampling of a representative specimen of concrete (if the concrete is delivered by truck, it should be mixed at high speed for at least one minute); conducting a slump flow test using the traditional slump cone; and checking that the results lie within the specified range.

B.5.7 Placement Methods

Before placing SCC, reinforcement and formwork should be inspected as it is for vibrated concrete to ensure that they are arranged as planned, and the formwork is in good condition (EFNARC, 2002). When placing SCC in the forms, the free-fall heights and horizontal flow distance defined for the different SCC classes must be respected unless the SCC has been tested and no segregation was found (AFGC, 2002). The following rules are advised by EFNARC (2002) to minimize the risk of segregation:

- Limit the vertical free-fall distance to 16.5 ft.
- Limit the permissible distance of horizontal flow from point of discharge to 33 ft.

For low viscosity SCC (T_{50} < 2 sec), the maximum period of time between layers is about 90 minutes. However, for high viscosity SCC, the maximum period of time between layers should be studied for specific viscosity and layer thickness (AFGC, 2002). For horizontal applications, SCC can be placed by pouring it directly from the chute of the truck mixer or the concrete skip or by pumping. For vertical applications, AFGC (2002) recommends several SCC placement methods including the following:

1. Concrete skip with flexible pipe:
   - Unsatisfactory results in terms of formed surface quality (bugholes) may be obtained in placing SCC by pouring it into the forms from above even if the free-fall height is respected.
   - Use a concrete skip with a flexible pipe and limit the free-fall height of the concrete into the forms, along with possibly reducing the pipe diameter (3 to 4 in. maximum).
   - Attention should be paid to the closure of the gate when concrete is placed by skip.

2. Skip with tremie pipe:
   - Insert a tremie pipe into the concrete in order to avoid the fall of fresh concrete into the forms.
   - The diameter of the tremie pipe must be adjusted to suit both the geometry of the forms (height and thickness) and the density of the reinforcement (passages must be left for the pipes to go through).
   - The diameter of the tremie pipe must reduce the risk of plugging the tube (usual pumping rules).
   - A funnel should be placed on top of the tremie pipe to make it easier to pour the concrete.
   - The advantages of this method are that all the placement precautions are systematically respected, and keeping the pipe in the concrete during pouring prevents entrapped air during placement.
3. Pump (with tremie pipe):
   - Using a pump allows high placement rates of SCC as no interruptions are needed to consolidate concrete. The rate of discharge is dependent on the availability of concrete and formwork design (no upper/lower bounds for the rate of discharge).
   - Pumping pressure depends on the rheological properties of the SCC mixture in addition to the external factors. Also, the rheology of SCC may be changed due to pumping.
   - Pumping SCC follows the same procedures as pumping CVC.
4. Pumping from the bottom of the form (with injection pipe):
   - Pumping SCC from the bottom of the forms via injection pipes prevents the concrete free falling and reduces the number of site workers.
   - Pumping SCC from the bottom of the form reduces the entrapped air and, consequently, the formation of bugholes, which results in a better concrete surface quality.
   - The concrete injection system at the bottom of the form must be designed to prevent the concrete from bouncing off the opposite side of the form and facilitate closing of the box-out at the end of placement (sliding hatch).

According to the JSCE (1999), pumping SCC tends to reduce the slump flow, and increasing the pumping rates leads to greater pumping pressure loss than with CVC. Therefore, the pump type and the diameter and length of the pipeline should be examined before consideration. In general, pumping through 4 to 5 in. diameter pipes that are not longer than 1,000 ft is common with SCC. High placement rates of SCC can entrap air if the mixture is not proportioned adequately for the given geometry and reinforcement condition.

B.5.8 Formwork Considerations

According to AFGC (2002) and ACI Committee 237 (2007), the following guidelines are provided to attain a good formed surface quality of the SCC component:

- Special attention must be paid to the condition of the forms, which should be free of grease, grout, and rust when metal forms are used.
- High quality release oil in spray form should be used to produce a uniform film with no drips.
- Any excess oil, which results in bugholes and concrete build-up on the surface, can be removed.
- SCC's very fluid consistency (especially with low viscosity SCC) requires that the formwork used for SCC be designed with more attention to water tightness and grout tightness, particularly at the bottom, than conventional formwork in order to avoid honeycombs, surface defects, and leakage.
- Due to the good cohesion of SCC, the formed surface quality is not altered by slight tightness defects (typically less than 0.1 in.).
- When placing SCC in closed spaces, vent holes shall be provided in an appropriate position in the top forms to allow entrapped air to escape.

Despite the fact that SCC has thixotropic properties resulting in lower formwork pressure than hydrostatic pressure, the high fluidity of SCC promotes a high placement rate, which offsets the benefit from SCC thixotropic effects and leads to higher formwork pressure than CVC (AFGC, 2002). Therefore, it is highly recommended to dimension the forms to withstand the full hydrostatic pressure, especially for high form filling speed (greater than or equal to 40 ft/hr), unless a mockup form has been tested to prove otherwise (AFGC, 2002; JSCE, 1999; ACI Committee 237, 2007). Below are other recommendations from AFGC (2002) regarding the formwork pressure of SCC:

- It is essential to design forms, falsework, and bracing to withstand the pressure at the bottom of the formwork (i.e., where it is highest).
- When SCC is pumped or injected from the bottom, the local dynamic effects due to injection must be considered in addition to the pressure exerted by the concrete.
- Thixotropic properties of SCC depend on the temperature of the fresh concrete and can be altered by vibration after placement (e.g., site traffic).

ACI Committee 237 (2007) states that the maximum initial formwork pressure and its rate of drop with time are affected by the rheology, thixotropy, initial consistency of the concrete, casting rate, and ambient temperatures. Mixture proportions affecting formwork pressure of SCC include coarse aggregate volume, binder type and content, and the type and dosage of

HRWRA (Assaad and Khayat, 2005). Formwork designs that accommodate the expected liquid head formwork pressures can allow unrestricted placement rates and permit the contractor to take full advantage of the fast casting rate of the SCC.

B.5.9 Finishing Techniques

Due to the absence of bleeding water and the possible thixotropic stiffening of SCC, the surface finish of horizontal concrete surfaces could be problematic. To obtain an acceptable finish on a horizontal surface, a float should be used immediately after placing concrete (AFGC 2002; JSCE 1999). Otherwise, measures to prevent surface drying until the time of finishing should be considered. EFNARC (2002) advises that surfaces of SCC should be roughly leveled to the specified dimensions, and the finishing should then be applied at an appropriate time before the concrete stiffens.

The small amount of bleeding water in SCC forms less laitance on the surface of the joint, which improves the performance of the joint surface even with little surface roughening (JSCE, 1999). According to ACI Committee 237 (2007), applying a roughened finish too soon may result in the SCC mixture flowing back to a smooth, level surface. Performing a setting-time test on the SCC mixture before placement can provide the information necessary to establish the correct timing of the final finish operation (ASTM C 403/C 403M).

B.5.10 Curing Methods

According to ACI Committee 237 (2007), SCC is no different than CVC in terms of outside factors that affect performance. Other factors, such as cement type, aggregate gradations, water content, mixture proportions, and air content, can affect SCC in a manner similar to CVC. Therefore, the established guidelines for curing in ACI 308R and AASHTO LRFD 8.11 should be followed with SCC.

EFNARC (2002) advises that initial curing should be commenced as soon as practicable after placing and finishing SCC in order to minimize the risk of shrinkage cracking. AFGC (2002) recommends that particular care should be taken in choosing the curing methods to be used after placement in order to prevent too much evaporation during the first hours of hardening depending on the type and amount of SCM and filler used. For horizontal applications, curing should be applied immediately after concrete placement in order to prevent too much evaporation, which causes early cracking and loss of durability in concrete cover. The used curing agent should be compatible with the subsequent addition of a sealing coat. Membrane curing or similar methods for curing cast-in-place components should stay for at least 4 days (Swedish Concrete Association, 2002).

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation

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