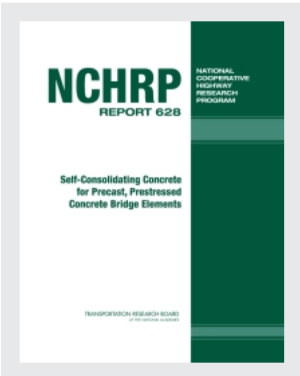

Self-Consolidating Concrete for Precast, Prestressed Concrete Bridge Elements

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N A T I O N A L C O O P E R A T I V E H I G H W A Y R E S E A R C H P R O G R A M

NCHRP REPORT 628

Self-Consolidating Concrete for Precast, Prestressed Concrete Bridge Elements

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Subject Areas
Bridges, Other Structures, and Hydraulics and Hydrology • Materials and Construction

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TRANSPORTATION RESEARCH BOARD

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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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Dr. Kamal Henri Khayat, Professor at the Department of Civil Engineering and Director of the Cement and Concrete Research Group at University of Sherbrooke, was the principal investigator. Professor Denis Mitchell of the Department of Civil Engineering and Structural Mechanics at McGill University served as the subcontractor's principal investigator.

Mr. Wu Jian Long, Ph.D. candidate, Mr. Guillaume Lemieux, master student, Dr. Soo-Duck Hwang, post-doctoral fellow, and Dr. Ammar Yahia, research engineer, all from the University of Sherbrooke, actively participated in all aspects of this project. Dr. William D. Cook, research engineer, and Ms. Lama Baali, master student, at McGill University were involved in the structural performance of the full-scale girders.

Dr. Celik H. Ozyildirim from the Virginia Transport Research Council served as a consultant to the research team.

FOREWORD

By Amir N. Hanna
Staff Officer
Transportation Research Board

This report presents recommended guidelines for the use of self-consolidating concrete (SCC) in precast, prestressed concrete bridge elements. 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 recommended changes to the AASHTO Load and Resistance Factor Design (LRFD) Bridge Design and Construction Specifications, and test protocols for evaluating some of the properties of SCC. The information contained in the report will guide materials and bridge engineers in evaluating, selecting, and specifying SCC mixtures for use in precast, prestressed concrete bridge elements, thereby facilitating fabrication, improving 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.

SCC is a specially proportioned hydraulic cement concrete that enables the fresh concrete to flow easily into forms and around reinforcement and prestressing steel without segregation. Use of this type of concrete for the manufacture of precast, prestressed concrete bridge elements provides the benefits of increased rate of production and safety, reduced labor needs, and lower noise levels at manufacturing plants. In spite of its benefits and widespread use in Japan and Europe, the use of SCC in the United States has been limited because of concerns about certain design and construction 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 precast, prestressed bridge elements 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 recommend related changes to AASHTO LRFD Bridge Design and Construction Specifications. These guidelines and enhanced specifications will provide highway agencies with the information necessary for considering SCC in precast, prestressed concrete bridge elements as a means for expediting construction and reducing cost while increasing safety and reducing noise in manufacturing plants.

Under NCHRP Project 18-12, "Self-Consolidating Concrete for Precast, Prestressed Concrete Bridge Elements," the University of Sherbrooke, Quebec, Canada, worked with the objectives of (1) developing guidelines for the use of SCC in precast, prestressed concrete bridge elements and (2) recommending relevant changes to 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 precast, prestressed concrete bridge elements. 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. Based on this review and analysis of test results, the researchers recommended changes to the AASHTO LRFD Bridge Design and Construction Specifications (included as Attachment A) and guidelines for the use of SCC in precast, prestressed concrete bridge elements (included as Attachment B). In addition, the researchers proposed test protocols for evaluating some of the properties of SCC for which standard test methods are not readily available (included as Attachment C).

The recommended guidelines, changes to LRFD Bridge Design and Construction Specifications, and test protocols 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. Incorporation of these recommendations in the relevant AASHTO documents is therefore recommended.

Attachment D, "Research Description and Findings," provides detailed information on the experimental program and data analysis, and the findings of the literature review. This attachment is not published herein but is available on the TRB website (www.trb.org/news/blurb_detail.asp?id=9627).

C O N T E N T S

SUMMARY

Self-Consolidating Concrete for Precast, Prestressed Concrete Bridge Elements

Research Significance

The use of self-consolidating concrete (SCC) in the United States has been hindered by concerns about certain design and construction issues that are perceived to influence the performance and structural integrity of bridge structures. The lack of standard tests and training has also hampered widespread use of SCC.

Limited and non-systematic information regarding properties of hardened SCC mixtures typically used in precast, prestressed structural applications is available to bridge engineers. There is also uncertainty about key engineering properties of SCC, such as stability, strength development, creep and shrinkage, and durability. Because of the variety of materials employed in the United States in the precast industry (cement type, supplementary cementitious materials, and specialty admixtures), there is a need to better understand the influence of these materials combinations on the properties of fresh and hardened concrete used in prestressed concrete construction and to identify reliable test methods and performance specification for mix design and quality control of SCC. NCHRP Project 18-12 was conducted to address these needs.

Project Objectives and Scope

The objective of this research was to develop guidelines for use of SCC in precast, prestressed bridge elements, including recommended changes to the AASHTO Load and Resistance Factor Design (LRFD) Bridge Design Specifications [2004, 2007] and LRFD Bridge Construction Specifications [1998], hereafter referred to as the AASHTO LRFD Specifications. Such guidelines will provide highway agencies with the information necessary for considering SCC mixtures that are expected to produce a uniform product, expedite construction, and yield economic and other benefits. To accomplish this objective, the research included work to:

- Develop material properties and performance criteria for SCC used for precast, prestressed concrete bridge elements;
- Evaluate key engineering properties, durability characteristics, and structural performance of such concrete; and
- Propose relevant changes to AASHTO LRFD Specifications.

Specifically, this project:

- Developed SCC mixtures that can be produced consistently in the field;
- Identified test methods for use in SCC mix design;

- Identified test methods for use for quality control in precasting plants;
- Developed specifications and criteria for SCC mixtures for precast, prestressed concrete bridge elements;
- Determined the influence of mix parameters, such as raw materials, mixture proportioning, mixing, production, placement, and characteristics of the cast element;
- Compared performance of precast, prestressed concrete elements made with SCC with those made with conventional high-performance concrete;
- Prepared guidelines for testing, proportioning, and casting SCC bridge elements; and
- Investigated applicability of current models recommended by AASHTO LRFD Specifications and suggested revisions whenever applicable.

Overview of the Project

The influence of different variables on the properties of SCC was evaluated in two parts. In the first part, a parametric study was undertaken to evaluate the influence of binder type, water–cementitious material ratio (*w/cm*), and coarse aggregate type and nominal size on key workability characteristics and compressive strength development of SCC mixtures designated for the construction of precast, prestressed AASHTO girders. Non–air-entrained SCC mixtures were prepared to evaluate workability, rheology, workability loss with time, stability, and strength development. The mixtures were prepared using crushed aggregate and gravel of three different nominal maximum sizes [¾, ½, ⅜ in. (19, 12.5, and 9.5 mm)]; two *w/cm* (0.33 and 0.38); and three binder compositions (Type I/II cement, Type III cement with 30% slag replacement, and Type III cement with 20% Class F fly ash replacement). Air-entrained SCC mixtures with low *w/cm* were also prepared to highlight the effect of air entrainment on workability and strength development of SCC.

The effect of fluidity level on key workability responses was also investigated. SCC mixtures were proportioned to have low slump flow values of 23.5 to 25.0 in. (600 to 635 mm) and high slump flow of 28.0 to 30.0 in. (710 to 760 mm) compared with normal slump flow of 26.0 to 27.5 in. (660 to 700 mm). The repeatability of workability tests was also evaluated using SCC mixtures with different slump flow values of 25.0 and 27.5 in. (635 and 700 mm).

Based on results of the parametric study, an experimental fractional factorial design was conducted to evaluate and model the effect of mixture proportioning and material characteristics on properties critical to the performance of precast, prestressed AASHTO girders. The study included 16 non–air-entrained SCC mixtures and enabled the modeling of plastic viscosity, thixotropy, filling ability, passing ability, filling capacity, static stability, formwork pressure, setting time, compressive and flexural strengths, elastic modulus, autogenous shrinkage, drying shrinkage, and creep. The air-void system and frost durability were evaluated for selected mixtures. Relevant modifications to current code provisions for mechanical properties, drying shrinkage, and creep were proposed to allow better prediction of mechanical and visco-elastic properties of SCC designated for precast, prestressed bridge elements.

The effect of SCC static stability and plastic viscosity of SCC on the distribution of pull-out bond strength of horizontally embedded prestressing strands was investigated. Bond strength characteristics and core compressive strength of wall elements cast with SCC were compared with those of similar elements cast with high-performance concrete (HPC) of normal consistency subjected to mechanical vibration. Static stability limits necessary to secure homogenous in-situ properties were recommended.

The structural performance of four full-scale AASHTO-Type II precast, pretensioned girders constructed with SCC was investigated. Two girders were constructed with SCC of 8,000 and 10,000 psi (55 and 69 MPa) compressive strength and two girders with HPC of similar strengths. In particular, the constructability, temperature variations, flexural cracking, shear cracking, shear strength, transfer length, and other design issues of precast, pretensioned girders made with SCC were evaluated.

Based on the results of the material testing and the results of testing the full-scale girders, changes to the AASHTO LRFD Specifications were suggested.

Research Findings

The major findings of this research are summarized as follows:

- The slump flow, J-Ring flow, L-box blocking ratio, and filling capacity tests provide good levels of single-operator and multiple-operator repeatability and are recommended for the design and quality control of SCC.
- A filling capacity test (the caisson filling capacity) is recommended to evaluate the ability of SCC to fill densely reinforced sections. Combinations of filling ability and passing ability tests are also proposed to estimate the filling capacity of SCC.
- A surface settlement test is recommended to evaluate the static stability of SCC. This test reflects the overall consolidation of plastic concrete, which combines segregation, internal and external bleeding, and loss of air. The rate of surface settlement after 15 minutes can be used to estimate the maximum surface settlement that occurs shortly before the initial setting of concrete.
- Concrete mixtures containing high binder content and low *w/cm* have been shown to develop high autogenous shrinkage, which occurs mostly in the first 28 days of age (85% to 95% of its ultimate values). Autogenous shrinkage of SCC for precast, prestressed applications can vary between 100 and 350 μstrain, depending on mixture composition.
- Investigated SCC mixtures have been shown to develop drying shrinkage and creep up to 30% and 20% higher, respectively, after 300 days than those for HPC made with similar *w/cm* but different paste volume (more detailed information on drying shrinkage and creep can be found in Attachment D).
- Based on the comparison of various code provisions, the American Concrete Institute (ACI) 209 and CEB-FIP MC90 models, modified with material coefficients applicable to binder types used in SCC (Type I/II cement and Type III cement with 20% fly ash replacement), are recommended for predicting compressive strength. Similarly, modification to the AASHTO 2007 code equations for predicting elastic modulus and flexural strength is suggested.
- Modifications to the AASHTO 2004 and AASHTO 2007 models for drying shrinkage and creep, respectively, are suggested for SCC. Otherwise, the CEB-FIP MC90 model can be used to estimate drying shrinkage.
- Stable SCC can lead to more homogenous in-situ properties than HPC of normal consistency subjected to mechanical consolidation. A modification factor for bond to prestressing strands of 1.4 can be secured when the static stability of SCC is limited to 0.5%. Use of highly viscous SCC [plastic viscosity greater than 0.0725 psi•s (500 Pa•s) or T-50 close to 6 seconds obtained from upright cone position] may lead to inadequate self-consolidation and reduction in bond between concrete and reinforcement (more detailed information on bond to prestressing strands is presented in Attachment D).
- Tests on four full-scale AASHTO-Type II girders indicated that the greater shrinkage of SCC (compared with that of HPC) can lead to larger prestressing losses and smaller cambers. SCC and HPC girders of similar compressive strengths exhibit similar transfer lengths, flexural cracking moments, and cracking shears. The shear resistances and displacement ductilities of the SCC girders are less than those of similar HPC girders. The lower displacement ductilities of SCC girders are not expected to have a major effect on performance because all of the specimens

were purposely designed to be "shear critical" and the shear levels reached were considerably above the AASHTO predictions.

Based on the findings of this research, some requirements for workability of SCC used in precast, prestressed bridge elements are suggested. Guidelines for material selection and mixture proportioning of SCC for precast, prestressed applications are provided. This information pertains to the effect of *w/cm,* binder type, and maximum size of aggregate (MSA) and type on workability and early-age strength development.

CHAPTER 1

Findings

The major findings of the research study are described in this chapter. Further details of the experimental work, analyses of the data, and conclusions are presented in Attachment D.

1.1 Test Methods and Mixture Requirements

Various test methods are used to assess the workability characteristics of SCC. The most promising test methods that are relevant for the fabrication of precast, prestressed concrete bridge elements (details of test are given in Attachment D) are:

- Filling ability: slump flow and T-50 (ASTM C 1611);
- Passing ability: J-Ring (ASTM C 1621) and L-box;
- Filling capacity: caisson test (filling vessel); and
- Segregation resistance: column segregation (ASTM C 1610), visual stability index (VSI), surface settlement, and rate of settlement.

The use of a combination of test methods is necessary to reduce the time and effort required for quality control in the precasting plant. The caisson filling capacity test (modified from initial value) is found to be promising to evaluate both the filling ability and passing ability of SCC. This test can be especially useful for SCC cast in densely reinforced sections. A mean caisson filling capacity value of 80% (75% to 90%) is considered as a lower limit for precast, prestressed concrete applications. A lower limit of 70% can be tolerated for relatively simple elements. Values greater than 90% can be secured for highly flowable and stable mixtures.

The L-box blocking ratio (h_2/h_1) index, J-Ring flow, or the difference between slump flow and J-Ring flow can be combined with slump flow testing to evaluate the filling capacity of SCC. The recommended combined test methods for evaluating the filling capacity of SCC are (1) slump flow and L-box blocking ratio (h_2/h_1) and (2) slump flow and J-Ring flow.

SCC mixtures suitable for use in precast, prestressed concrete girders should exhibit slump flow of 23.5 to 29 in. (600 to 735 mm), L-box blocking ratio (h_2/h_1) greater than 0.5, J-Ring flow of 21.5 to 26.0 in. (545 to 660 mm), filling capacity greater than 70%, and a difference in slump flow and J-Ring flow values lower than 4 in. (100 mm).

Regardless of the MSA, stable SCC should develop a column segregation index (C.O.V.) less than 5% and percent static segregation lower than 15. The recommended limits for surface settlement depend on the MSA. SCC proportioned with ¾ in. (19 mm) and ½ or ⅜ in. (12.5 or 9.5 mm) MSA should have maximum rates of settlement at 30 minutes of 0.12%/h and 0.27%/h, respectively.

SCC mixtures investigated in this study developed yield stress values varying between 0.00145 and 0.01885 psi (10 and 130 Pa). SCC made with crushed aggregate should develop plastic viscosity of 100 to 225 Pa•s at the time of casting to ensure adequate passing ability and static stability. This range can be 0.0145 to 0.0326 psi•s (100 to 400 Pa•s) for SCC made with gravel having ½ in. (12.5 mm) MSA. The lower limit of plastic viscosity is necessary to secure a maximum rate of settlement of 0.27%/h at 30 minutes of testing and a maximum C.O.V. of 5%. The upper limit of plastic viscosity of 250 and 400 Pa•s is necessary for the SCC with slump flow consistency of 26.0 to 27.5 in. (660 to 700 mm) to achieve adequate passing ability (minimum L-box blocking ratio of 0.5). Based on the properties of SCC made with different viscosity levels cast in experimental wall elements, plastic viscosity higher than 500 Pa•s should be avoided to ensure proper self-consolidating properties and homogeneity distribution of in-situ properties.

1.2 Selection of Concrete Constituents

Effect of Binder Type

The binder content and composition were shown to have direct influence on high-range water-reducing admixture (HRWRA) demand, fluidity retention, temperature rise, early-age strength development, and mechanical properties at 28 and

56 days. Among three binder types used in the parametric study, SCC mixtures made with Type III cement and 20% Class F fly ash exhibited better workability than that for similar mixtures prepared with Type I/II cement or Type III cement and 30% slag. SCC containing 20% Class F fly ash developed high fluidity retention, high passing ability and filling capacity, as well as a high level of static stability. The concrete proportioned with Type III cement and 30% slag exhibited relatively low passing ability [difference between slump flow and J-Ring flow diameters larger than 4 in. (100 mm)].

The evaluated mixtures developed similar compressive strengths after 18 hours of steam curing regardless of binder type. However, concrete made with Type III cement and 20% Class F fly ash developed slightly higher 56-day moist-cured compressive strength than that of concrete made with Type I/II cement.

Based on this evaluation, a mixture of Type III cement and 20% Class F fly ash was selected for the experimental evaluation that was performed to model the performance of SCC for precast and prestressed girder elements.

Effect of Type and Maximum Size of Coarse Aggregate

The maximum size of coarse aggregate and coarse aggregate type had a marked effect on passing ability, filling capacity, and static stability of SCC. The MSA should be selected with consideration of the minimum clear spacing between the reinforcing steel bars and prestressing strands, the cover over the reinforcement, and the geometry of the elements to be cast. The reduction in MSA is required to enhance stability. From a workability point of view, SCC mixture made with crushed aggregate of ⅜ in. (9.5 mm) MSA exhibited greater passing ability [difference between slump flow and J-Ring flow diameters lower than 2 in. (50 mm)] and higher filling capacity (caisson filling capacity higher than 90%). In particular, mixtures containing ¾ in. (19 mm) MSA exhibited a relatively low level of filling capacity (caisson filling capacity less than 70%) and relatively low resistance to segregation (column segregation index higher than 5%). The SCC mixtures made with ⅜ in. (9.5 mm) MSA exhibited surface settlement and column segregation index values similar to those for mixtures made with larger MSA.

As in the case of fresh properties, SCC mixtures made with crushed aggregate of ⅜ in. (9.5 mm) MSA developed similar or higher compressive strengths after 18 hours of steam curing and 56 days of moist curing than those for mixtures made with ½ or ¾ in. (12.5 and 19 mm) MSA. SCC proportioned with gravel developed better passing ability and filling capacity than similar concrete made with crushed aggregate of the same MSA [½ in. (12.5 mm)]. The former had high passing ability [h_2/h_1 greater than 0.7 and difference between slump flow and J-Ring flow diameters less than 2 in. (50 mm)] and high filling capacity (caisson filling capacity greater than 90%). Both SCC types exhibited similar segregation resistance (column segregation index of 2% to 5%). However, mixtures made with gravel developed lower compressive strength and modulus of elasticity (e.g., up to 25% and 16% lower, respectively, under moist curing conditions at 56 days) than those for mixtures made with crushed aggregate of the same MSA. In terms of hardened concrete properties, mixtures made with crushed aggregate exhibited better overall performance than those made with gravel.

Effect of *w/cm* and Air Entrainment

In general, SCC mixtures with 0.38 *w/cm* exhibited better workability than those with 0.33 *w/cm* in terms of passing ability, filling capacity, and fluidity retention. However, SCC mixtures made with 0.33 *w/cm* developed greater static stability and higher 18-hour and 56-day compressive strengths under steam-cured and moist-cured conditions. Also, air-cured SCC mixtures made with 0.33 *w/cm* exhibited lower 18-hour compressive strength than the latter concrete under the same curing regime, possibly due to the relatively higher dosage of HRWRA necessary to achieve the target slump flow. No significant difference was found in the 18-hour modulus of elasticity between the 0.33 and 0.38 *w/cm* mixtures.

SCC with 0.38 *w/cm* will attain a minimum release compressive strength of 5,000 psi (34.5 MPa) and ultimate compressive strength of 8,000 psi (55.2 MPa). Such concrete can be used for casting highly reinforced and restricted sections because of its good filling capacity. Higher strength may require the use of mixtures with lower *w/cm* (e.g., 0.32 to 0.35).

In general, air-entrained SCC exhibited superior passing ability and filling capacity than SCC without air entrainment because of its lower viscosity and greater paste content. However, air-entrained concrete developed lower static stability and lower compressive strength and modulus of elasticity, both under steam-curing and moist-curing conditions.

Effect of Fluidity of SCC

Workability responses and mechanical properties of SCC designed for relatively high, medium, and low slump flow values of 28 to 30 in. (710 to 760 mm), 25 to 28 in. (640 to 710 mm), and 23.5 to 25 in. (600 to 640 mm), respectively, are compared. SCC mixtures with low and medium slump flow had similar levels of passing ability (medium), filling capacity (medium), and resistance to surface settlement (high). Mixtures with high fluidity (slump flow) exhibited high passing ability and filling capacity, but relatively medium to low static stability. As expected, SCC with high fluidity developed lower compressive strengths at 18 hours of steam curing and

56 days of moist curing and lower 18-hour modulus of elasticity than similar concrete having low slump flow and lower HRWRA content. In general, SCC mixtures with medium fluidity level are recommended for casting precast, prestressed concrete girder elements.

Effect of Viscosity-Modifying Admixture

For a given slump flow, SCC designed with low to moderate dosage thickening-type viscosity-modifying admixture (VMA) had greater HRWRA demand. Higher dosage of HRWRA improves retention of workability but reduces early-age development of mechanical properties. The incorporation of thickening-type VMA considerably improves static stability. In general, SCC designed with 0.40 *w/cm* and low HRWRA content exhibited better static stability when the thickening-type VMA was incorporated. SCC containing thickening-type VMA had lower early-age mechanical properties.

In general, the use of VMA is not necessary in SCC proportioned with low *w/cm* and high binder content because such concrete can develop proper stability. On the other hand, SCC made with relatively high *w/cm* and/or low binder content should incorporate a VMA to secure adequate stability and robustness. It is important to note that the incorporation of a low dosage of VMA can enhance robustness, even in SCC made with relatively low *w/cm.*

Guidelines for Materials Selection and Mix Design

Based on the results of the parametric investigation, guidelines for the selection of material constituents, mixture proportioning, and fluidity level necessary to ensure adequate performance of plastic and hardened SCC properties for precast, prestressed concrete bridge elements are recommended. SCC mixtures proportioned with *w/cm* of 0.33, crushed aggregate with ½ in. (12.5 mm) MSA, and Type III cement with 20% Class F fly ash can develop the properties required for this application.

1.3 Factorial Design to Model Fresh and Hardened Concrete Properties

Factorial design was carried out to model the effect of mixture parameters and material properties on workability characteristics, mechanical properties, and visco-elastic properties of SCC. The modeled parameters included binder content (BC), binder type (BT), *w/cm,* dosage of thickening-type VMA, and sand–to–total aggregate volume ratio (S/A). This design enabled the evaluation of the five selected parameters with each evaluated at two distinct levels of −1 and +1 (minimum and maximum levels). In total, 16 SCC mixtures were used in the factorial design.

The derived models that yielded high correlation coefficients (R^2) are summarized in Tables 1 to 3. All factors are expressed in terms of coded values:

- Coded BC = (absolute BC − 793) / 50
- Coded *w/cm* = (absolute *w/cm* − 0.37) / 0.03
- Coded VMA = (absolute VMA − 0.75) / 0.75
- Coded S/A = (absolute S/A − 0.50) / 0.04

The estimated values in the models (e.g., −1.06, −0.33, +0.33, etc. in the HRWRA demand model) reflect the level of significance of each response. A negative estimate signifies that an increase in the modeled parameter can lead to a reduction in the measured response.

Based on the derived statistical models, the following observations can be made for proportioning SCC mixtures for use in precast and prestressed bridge elements:

- Fresh concrete properties
  - Typical *w/cm* for precast, prestressed applications can range between 0.34 and 0.40. The selected value should secure the targeted stability, mechanical properties, visco-elastic properties, and durability requirements.
  - SCC made with Type III cement and 20% Class F fly ash can exhibit better slump flow retention, higher passing ability, and higher filling capacity than that made with Type I/II cement.
  - HRWRA demand decreases with the increase in *w/cm* and binder content. The higher HRWRA demand required for SCC made with Type III cement and 20% Class F fly ash than that required for SCC prepared with Type I/II cement can reduce early-age compressive strength if the concrete is not heat cured. For steam-cured concretes, no difference in 18-hour compressive strength between SCC made with either type of cements should be expected.
  - Better slump flow retention can be obtained with SCC made with a lower *w/cm* because of the higher HRWRA demand.
  - A low S/A value (e.g., 0.46 to 0.50) will result in adequate workability.
  - Coarse aggregate with ½ in. (12.5 mm) MSA is recommended.
  - VMA should be used in SCC made with relatively high *w/cm* and/or low binder content to secure stability and homogenous in-situ hardened properties. The use of thickening-type VMA at low dosage can enhance static stability. VMA can also be used in stable SCC (e.g., low *w/cm*) to enhance robustness.
  - Incorporation of thickening-type VMA can delay setting and the elapsed time to attain peak temperature.

Table 1. Derived statistical models for fresh concrete [slump flow = 26.8 ± 0.8 in. (680 ± 20 mm)].

Modeled response		Derived equations	R^2
$[\text{HRWRA demand}]^{0.5}$ (fl oz/cwt)		4.76 – 1.06 *w/cm* – 0.33 BC + 0.33 BT + 0.11 VMA + 0.13 (*w/cm* · BT)	0.97
Filling ability	Slump flow loss (in.)	0.16 – 0.84 BT – 0.57 BC + 0.42 *w/cm*+ 0.16 S/A – 0.54 (BT · S/A) + 0.49 (BC· *w/cm*) – 0.42 (BC · BT)	0.84
Passing ability	$[\text{L-box blocking ratio}]^{1.4}$	0.69 + 0.13 *w/cm* + 0.12 BC – 0.13 (BC · *w/cm*)	0.93
	$[\text{J-Ring flow}]^{3}$ (in.)	16,329 + 1,344 *w/cm* + 1,324 BC + 814 BT – 729 S/A – 465 VMA – 1,140 (BC · BT) – 1,136 (BC · *w/cm*) + 824 (BT · S/A) – 650 (*w/cm* · BT) – 465 (*w/cm* · S/A) + 351 (VMA · S/A) – 291 (BC · S/A)	0.99
Filling capacity	Caisson filling capacity (%)	92 + 4.38 BC + 3.75 *w/cm* + 3.63 BT – 3.63 (BT · *w/cm*) – 2.63 (*w/cm*· BT) – 2.50 (BC · BT)	0.92
	Slump flow – J-Ring flow (in.)	1.42 – 0.70 BC – 0.63 BT – 0.55 *w/cm* + 0.26 S/A + 0.63 (BC · *w/cm*) + 0.50 (BC · BT) + 0.40 (*w/cm* · BT) – 0.26 (BT · S/A)	0.94
Stability	$[\text{Surface settlement}]^{0.5}$ (%)	0.677 + 0.037 *w/cm* + 0.036 BC – 0.024 BT	0.86
	Column segregation (C.O.V.)	3.25 – 0.30 BC – 0.61 (BC · BT) + 0.44 (BT · S/A) + 0.42 (*w/cm* · BT) – 0.39 (BC · VMA) – 0.36 VMA + 0.30 (*w/cm* · S/A)	0.89
Rheology and formwork pressure	Plastic viscosity (Pa·s)	298 – 133.4 *w/cm*– 105.3 BC + 53.7 S/A + 49.7 (BT · *w/cm*) – 27.6 (*w/cm* · S/A)	0.93
	Thixotropy (A_b) ($J/m^3 \cdot s$)	586 – 323.4 *w/cm* – 181.8 BC + 71.1 (BC · *w/cm*)	0.95
	Initial form pressure at 3.3 ft (1 m) (K_0)	0.90 + 0.027 BC + 0.027 *w/cm* – 0.014 S/A – 0.023 (BC · *w/cm*) – 0.013 (BT · *w/cm*) + 0.11 (S/A · *w/cm*)	0.96

– Use air-entraining admixture where required for frost durability. It is important to note that the use of polycarboxylate-based HRWRA can lead to air entrainment, but it does not necessarily produce an adequate air-void system to secure frost durability.
– Surface settlement of SCC increases with the increase in binder content and *w/cm*.
– Plastic viscosity decreases with the increase in binder content and *w/cm* but increases slightly with the increase in S/A.
– Thixotropy or structural build-up at rest of the SCC decreases with the increase in binder content and *w/cm*. Higher thixotropy can be detrimental to surface finish and advantageous to formwork pressure.

Table 2. Derived statistical models for mechanical properties.

Property	Age	Derived equations	R^2
Compressive strength (psi)	18 hours	4,752 – 293 *w/cm* – 111 BT – 81 VMA + 153 (*w/cm* · BT) – 128 (VMA · S/A) – 97 (*w/cm* · VMA)	0.96
	56 days	9,176 – 773 *w/cm* + 290 BT + 220 BC – 368 (BC · *w/cm*)	0.87
Modulus of elasticity (ksi)	18 hours	4,419 – 268 *w/cm* – 103 BT – 86 S/A – 78 BC – 158 (BC · *w/cm*) – 96 (BT · S/A)	0.89
	56 days	5,554 – 311 *w/cm* – 166 S/A + 69 BT + 79 (BC · BT)	0.87
Flexural strength (psi)	7 days	1,036 + 123 S/A – 90 BC – 58 *w/cm* – 126 (BC · *w/cm*)	0.76
	56 days	1,128 – 110 *w/cm* + 48 S/A + 35 (BC · BT)	0.83

Table 3. Derived statistical models for visco-elastic properties.

Property	Age	Derived equations	R^2
Autogenous shrinkage (μstrain)	7 days	134 – 42.4 *w/cm* + 37.4 BT – 21.6 (BC · *w/cm*) – 20.1 (*w/cm* · BT) –15.9 (BC · BT)	0.96
	56 days	201 + 67.1 BT – 40.6 *w/cm* – 18.8 (BC · *w/cm*) + 17.8 (BC · S/A)	0.93
Drying shrinkage (μstrain)	28 days	308 – 71.1 *w/cm* + 35 BC + 48.4 (*w/cm* · VMA) + 30.8 (VMA · BT)	0.78
	112 days	554 – 58.1 *w/cm* + 48.4 BC + 37.4 S/A + 46.2 (*w/cm* · VMA) + 41.9 (*w/cm* · BT) – 40.6 (BC · VMA) + 30.8 (VMA · BT)	0.96
Creep (μstrain)	28 days	680 + 79.3 BT – 37.5 *w/cm* + 30.6 (VMA · BT) + 28.8 (*w/cm* · BT)	0.75
	112 days	1,036 + 73.6 BT + 38.8 BC + 40.7 (VMA · BT) + 34.9 (*w/cm* · BT) – 32.9 (BC · S/A)	0.89

  - Initial relative form pressure at 3.3 ft (1 m) in height cast at 13.1 to 16.4 ft/h (4 to 5 m/h) varies between 0.80 and 1.00 of hydrostatic pressure. The relative pressure increases with the increase in binder content and *w/cm* but decreases with the increase in S/A.
- Mechanical properties
  - Mechanical properties, including compressive strength, modulus of elasticity (MOE), and flexural strength, increase with the decrease in *w/cm*.
  - Increase in binder content can lead to higher 56-day compressive strength but lower 18-hour MOE and 7-day flexural strength.
  - The increase in S/A results in lower MOE at 18 hours (steam curing) and 56 days (moist curing), but leads to higher flexural strength.
  - SCC made with Type III cement and 20% Class F fly ash can develop higher compressive strength and MOE at 56 days but lower mechanical properties at 18 hours than those for concrete made with Type I/II cement mainly because of delayed setting resulting from greater HRWRA demand.
- Visco-elastic properties
  - The increase in binder content increases drying shrinkage and creep.
  - Theoretically, for a given binder content, drying shrinkage increases with increase in *w/cm;* however, the derived statistical models show an opposite trend because drying shrinkage also includes autogenous shrinkage that decreases with the increase in *w/cm*.
  - SCC mixtures made with Type I/II cement develop less creep and shrinkage than those prepared with Type III cement and 20% Class F fly ash. However, the latter concrete has better workability and higher mechanical properties than the former SCC. Therefore, use of Type III cement and 20% Class F fly ash will require reduction of binder content to ensure better overall performance.
  - Concrete mixtures containing high binder content and low *w/cm* can exhibit high values of autogenous shrinkage, most of which occurs in the first 28 days and can vary between 100 and 350 μstrain.
  - Autogenous shrinkage is mostly affected by binder type and paste volume. SCC made with Type III cement and 20% Class F fly ash can develop higher autogenous shrinkage and creep than that for concrete with Type I/II cement.
  - For a given *w/cm,* SCC made with high binder content can exhibit high drying shrinkage that can range between 500 and 1000 μstrain after 300 days.
  - SCC exhibits 5% to 30% higher drying shrinkage at 300 days than that of HPC made with similar *w/cm* (more detailed information on drying shrinkage can be found in Attachment D).
  - The increase in S/A can lead to higher long-term drying shrinkage.
  - The binder type does not have significant effect on drying shrinkage but can significantly affect creep. SCC made with Type III cement and 20% Class F fly ash exhibited higher creep compared with similar SCC proportioned with Type I/II cement, regardless of the binder content, *w/cm,* S/A, and use of VMA.
  - The *w/cm* does not have considerable effect on creep because other parameters (binder content, binder type, and S/A) have more predominant influence on creep.
  - SCC exhibited 10% to 20% higher creep after 300 days than that for HPC made with similar *w/cm* (more detailed information on creep can be found in Attachment D).

1.4 Validation of Code Provisions to Estimate Mechanical Properties

Coefficients of prediction models in current codes and procedures were modified to provide better prediction of mechanical properties of SCC for precast, prestressed concrete bridge elements. The following codes and models are recommended:

- ACI 209 and CEB-FIP codes with suggested changes to coefficients for predicting compressive strength

- Current AASHTO 2007 model for predicting elastic modulus
- Current AASHTO 2007 model for estimating flexural strength

The proposed coefficients can be found in Attachment D.

1.5 Validation of Code Provisions to Estimate Visco-Elastic Properties

Creep and shrinkage strains measured in experimental factorial design were compared with values predicted by the AASHTO 2007, AASHTO 2004, ACI 209, CEB-FIP 1990, and GL 2000 (Gardner and Lockman, 2001) models. Coefficients of existing models were modified to provide better prediction of visco-elastic properties for SCC. The following models are recommended:

- AASHTO 2007 model with suggested modifications to estimate creep
- AASHTO 2004 model with suggested modifications to predict drying shrinkage
- Current CEB-FIP MC90 model can be used to predict drying shrinkage

The proposed coefficients can be found in Attachment D.

1.6 Homogeneity of In-Situ Strength and Bond to Reinforcement

Six 60.6 × 84.6 × 7.9 in. (1540 × 2150 × 200 mm) wall elements were cast using a reference HPC concrete of normal consistency and five SCC mixtures of different plastic viscosity and static stability levels. The SCC mixtures were proportioned to yield slump flow consistency of 26.7 ± 0.7 in. (680 ± 15 mm) and minimum caisson filling capacity of 80%. The surface settlement of the SCC mixtures ranged between 0.30% and 0.62% and that of the HPC was 0.23%.

Despite the high fluidity of SCC, stable concrete can lead to more homogenous in-situ properties than HPC of normal consistency subjected to mechanical vibration. Although the SCC mixtures exhibited VSI values of 0.5 to 1 and caisson filling capacity higher than 80%, the tested mixtures developed various levels of uniformity of core compressive strength and pull-out bond strength results. The homogeneity of in-situ properties was shown to vary with plastic viscosity and static stability determined from the surface settlement test.

Recommendations to ensure homogenous in-situ properties are summarized as follows:

- Use highly flowable SCC with adequate static stability, maximum surface settlement of 0.5%, column segregation index of 5%, and percent static segregation of 15%. These limits are especially critical in deep elements. Such SCC can develop at least 90% in-situ relative compressive strength (core results) and modification factor of 1.4 for bond to horizontally embedded prestressing strands.
- Avoid the use of highly viscous SCC (plastic viscosity greater than 0.073 psi•s (500 Pa•s) or T-50 nearing 6 seconds obtained from upright cone position) to ensure adequate self-consolidation.

1.7 Structural Performance

The structural performance of full-scale precast, prestressed bridge girders constructed with SCC and HPC was investigated. Two SCC and two HPC mixtures with target 56-day compressive strengths of 8,000 and 10,000 psi (55 and 69 MPa) were used to cast four full-scale AASHTO-Type II girders. Constructability, temperature variations, transfer length, camber, flexural cracking, shear cracking, and shear strengths of the girders were evaluated. More details on the construction and testing of the girders are given in Attachment D.

The following findings and observations are made based on the results of these tests:

- With the casting from a single location at midspan of the 31-ft (9.44-m) long girders, no visible segregation was observed in any of the girders.
- The maximum temperature rise during the steam-curing operation satisfied the maximum temperature limit of 150°F (65°C).
- There were fewer “bug holes” in the SCC girder than in the HPC girder.
- The target 18-hour compressive strengths, required for prestress release, were met for the two SCC girders.
- The transfer lengths for the four girders were similar and considerably shorter than the transfer length values given in the AASHTO LRFD Specifications [2007] and the ACI 318-05 code.
- At time of prestress release at 18 hours, the coefficients on the square root of the compressive strength used to determine the modulus of elasticity for the two SCC mixtures were about 4% and 11% lower than those for the HPC mixtures.
- The drying shrinkage for the two SCC mixtures was about 20% greater than that for the comparable HPC mixtures.
- In comparison to HPC girders, the SCC girders exhibited smaller cambers because of the greater elastic shortening and long-term losses of prestress due to the lower elastic modulus and greater drying shrinkage.
- The cracking moments for the SCC girders and the companion HPC girders were similar.
- The uncracked and cracked stiffnesses for all four girders were very similar.
- The cracking shears for all four girders were similar.

- All four girders failed in shear after developing a significant number of wide shear cracks; crack widths just before failure were greater than 0.24 in. (6 mm).
- The stirrups developed significant strains beyond strain hardening and ruptured at failure.
- The failure shears exceeded the nominal shear resistances of the girders calculated using the approach given in the AASHTO LRFD Specifications [2007], probably because of the strength and stiffness of the top and bottom flanges of the AASHTO girders.
- The flexural resistances of the HPC girders exceeded the nominal resistances calculated using the AASHTO LRFD Specifications [2007].
- The flexural resistances of the SCC girders were within 1.5% of the theoretical flexural resistance using the approach provided in the AASHTO LRFD Specifications [2007].
- The lower ductilities and lower shear resistance of SCC girders compared with the corresponding HPC girders are due to the lower volume of coarse aggregate that reduces aggregate interlock and results in a lower energy absorption capability on the sliding shear failure plane.

The structural performance tests of two SCC girders and two HPC girders have highlighted a number of differences that could affect design. However, more research is required to support any specific changes to the design specifications.

CHAPTER 2

Background and Research Approach

2.1 Background

Use of SCC in the construction of precast bridge members and bridge substructures and in the repair of bridges has been limited in the United States. Properly designed SCC is expected to provide similar properties as the conventional counterparts except for the high workability. However, changes in mix design and fluidity of SCC can result in SCC with hardened properties and performance that are different from that commonly expected from conventional concrete. Proper selection of material constituents and proper proportioning are necessary for achieving the desired workability and performance of SCC. The factors that significantly influence the design, constructability, and performance of precast, prestressed bridge elements with SCC need to be identified. There is also a need to develop guidelines for the use of SCC in bridge elements and to recommend changes to AASHTO LRFD Specifications. These guidelines will provide highway agencies with the information necessary for considering concrete mixtures that are expected to expedite construction and yield economic and other benefits (e.g., better surface finish, lower labor cost, etc.).

For successful design of SCC, some factors require greater attention than is generally required for conventional concrete, including type and size and grading of coarse aggregate, composition and content of binder materials, and *w/cm*. Proper selection of material constituents is also necessary for workability and performance of the hardened concrete.

A number of test methods have been used to characterize workability of SCC, including filling ability, passing ability, and segregation resistance. However, no single test method has been found to fully characterize all relevant workability aspects of SCC. Selection of proper combined test methods can facilitate workability testing protocol and provide means for quality control of field applications.

Knowledge of the compressive strength, elastic modulus, and flexural strength of concrete is required for estimating camber of prestressed members at the release of the prestressing load, and for determining elastic deflections caused by dead and live loads, axial shortening and elongation, and prestress losses. Literature review showed that the modulus of elasticity of SCC could be as low as 80% of that for HPC of normal consistency because of the lower coarse aggregate volume of SCC [Holschemacher and Klug, 2002]. However, under air-drying conditions, the elastic modulus of SCC can be higher than that of normal concrete at long term. Limited published data are available on relationships between flexural strength and compressive strength of SCC, and applicability of the various code models to SCC need to be validated.

Typically, SCC mixtures are proportioned with higher binder content, lower coarse aggregate volume, and smaller MSA, which increase thermal, autogenous, and drying shrinkage, and creep leading to high loss of prestress and excessive deflections and elastic shortening. Therefore, creep and drying shrinkage characteristics of SCC need to be determined and considered in the design of precast, prestressed bridge elements. According to the literature survey, there seems to be some discrepancy regarding the visco-elastic properties of SCC because of differences in mix design (*w/cm*), type and content of coarse aggregates, type of chemical admixture, and testing exposure. It is reported that the creep potential of SCC appears to be slightly higher than that of conventional concrete made with the same raw materials and having the same 28-day compressive strength [Attiogbe et al., 2002; Pons et al., 2003; Byun et al., 1998]. Depending on the selected binder, *w/cm*, and ambient temperature at the precasting plant, the use of new generation HRWRA may eliminate the need to use radiant heat or steam curing.

SCC used in precast, prestressed applications is typically proportioned with a low *w/cm* (0.32 to 0.36) to enhance stability of the plastic concrete. Relatively low *w/cm* values, coupled with high content of binder, lead to a greater degree of autogenous shrinkage than in conventional concrete. Such type of shrinkage also increases with increased fineness of the binder and fillers in use. Therefore, drying shrinkage, autogeneous shrinkage, and thermal contraction have to be considered in the mix design process and in the structural detailing of the prestressed element.

Studies have shown that the scatter between measured and predicted drying shrinkage values is greater in the case of SCC than that for normal concrete. Experimental shrinkage strains for SCC were found to be larger than those estimated by various prediction models [Byun et al., 1998]. Also, comparison of experimental creep data to those obtained from major creep-prediction models indicated differences. Work is required to compare creep and shrinkage data of SCC mixtures made with representative mix designs and the material constituents available in the United States with those obtained from prediction models.

The stability of SCC is a key property in ensuring uniform mechanical properties and adequate performance of precast, prestressed concrete bridge girders. Properly designed SCC mixtures can exhibit uniform distribution of in-situ compressive strength. Bond strength and its uniformity along the height of the girders can be influenced by flow properties of the SCC, grading of the aggregate, and content of fines. Some studies have found that bond strength of reinforcement to SCC can be lower than that to normal concrete [Koning et al., 2001; Hegger et al., 2003]. Other studies, however, have shown that for a given compressive strength, reinforced concrete members made with SCC can develop higher bond strength than in the case of normal concrete [Dehn et al., 2000; Chan et al., 2003]. Bond strength that can be developed between SCC and prestressed strands and its uniformity along the height of cast wall elements were investigated in this project.

The structural design concerns related to the use of SCC for constructing prestressed girders include the likely lower modulus and greater shrinkage of SCC and the possible larger prestress losses and the reduced shear resistances resulting from the use of a smaller maximum aggregate size or a smaller volume of coarse aggregate.

2.2 Research Approach

Literature Review

As a part of the project, an extensive literature review of factors affecting performance of SCC in structural applications was carried out (details of the literature review are summarized in Attachment D). The literature review pertained to precast, prestressed SCC, including:

- Test methods and acceptance criteria of fresh characteristics of SCC,
- Requirements for constituent materials and mix design considerations,
- Production and placement issues,
- Factors affecting mechanical properties and structural performance,
- Factors affecting visco-elastic properties, and
- Durability characteristics.

Experimental Work Plan

The experimental program was conducted in three phases. Phase I addressed test methods and acceptance criteria; Phase II addressed mixture proportioning and material characteristics; and Phase III addressed structural performance of full-scale girders. Details of this work are discussed below.

Phase 1: Test Methods and Acceptance Criteria for SCC

This work included:

- A parametric study of various concrete mixture parameters and constituent materials to help develop recommendations for mix design of SCC for precast, prestressed applications;
- Evaluations of the effect of MSA, aggregate and binder types, and *w/cm* on workability and compressive strength development of SCC mixtures suitable for precast structural applications;
- Comparison of workability test methods that can be used for mix design and quality control of SCC, and suggestion of performance specifications; and
- Correlation of key workability responses to basic rheological parameters (in particular, plastic viscosity).

The parametric study of 24 non–air-entrained SCC mixtures (No. 1 through 24 in Table 4) was conducted to evaluate the influence of binder type, *w/cm,* and coarse aggregate type and nominal size on workability and compressive strength development of SCC mixtures designated for the construction of precast, prestressed AASHTO girders. These mixtures were prepared using either crushed aggregate or gravel of three different MSA [¾, ½, and ⅜ in. (12, 19.5, and 9.5 mm)], *w/cm* of 0.33 and 0.38, and three binder compositions (Type III cement with 30% slag replacement, Type I/II cement, and Type III cement with 20% Class F fly ash). Three air-entrained SCC mixtures (No. 25 through 27 in Table 4) were prepared with low *w/cm* to obtain an initial air volume of 4% to 7%.

Three SCC mixtures (No. 28 through 30) similar to mixtures No. 1 through 3, having relatively low filling ability (deformability) with slump flow values of 23.5 to 25.0 in. (600 to 640 mm), and three other mixtures (No. 31 through 33) similar to mixtures No. 4 through 6, presenting relatively high slump flow of 28.0 to 30.0 in. (710 to 760 mm), were prepared to evaluate the effect of fluidity level on filling ability, passing ability, filling capacity, stability, and compressive strength development.

Table 4. Parametric experimental program.

Type	Mixture No.	Aggregate type and MSA				Type and content of binder			*w/cm*	
		Crushed ¾ in. (19 mm)	Crushed ⅜ in. (9.5 mm)	Crushed ½ in. (12.5 mm)	Gravel ½ in. (12.5 mm)	Type I/II 809 pcy (480 kg/m^3)	Type III + 30% Slag 775 pcy (460 kg/m^3)	Type III + 20% fly ash 775 pcy (460 kg/m^3)	0.33	0.38
Non–air-entrained (AE) concrete	1	x				x			x	
	2	x					x		x	
	3	x						x	x	
	4	x				x				x
	5	x					x			x
	6	x						x		x
	7		x			x			x	
	8		x				x		x	
	9		x					x	x	
	10		x			x				x
	11		x				x			x
	12		x					x		x
	13			x		x			x	
	14			x			x		x	
	15			x				x	x	
	16			x		x				x
	17			x			x			x
	18			x				x		x
	19				x	x			x	
	20				x		x		x	
	21				x			x	x	
	22				x	x				x
	23				x		x			x
	24				x			x		x
AE concrete	25-27	• Air entrainment of 4%–7% and slump flow of 26.0–27.5 in. (660–700 mm) • *w/cm* of 0.33, Type III + 20% Class F fly ash, crushed aggregate with MSA of ½ in. (12.5 mm)								
Non-AE concrete	28-30	• Low filling ability, slump flow of 23.5–25.0 in. (600–635 mm) • *w/cm* of 0.33, Type III + 30% slag, crushed aggregate with MSA of ¾ in. (19 mm)								
	31-33	• High filling ability, slump flow of 28.0–30.0 in. (710–760 mm) • *w/cm* of 0.38, Type III + 30% slag, crushed aggregate with MSA of ¾ in. (19 mm)								
	34-43	• Two levels of slump flow consistency for evaluation of repeatability: 25.0 and 27.5 in. (635 and 700 mm) • *w/cm* of 0.38, Type I/II, crushed aggregate with MSA of ½ in. (12.5 mm)								

Notes

Sand–to–total aggregate ratio (S/A) is fixed at 0.50, by volume.
PC-based HRWRA (AASHTO M 194, Type F) and air-entraining admixture (AASHTO M 154) are added.
Limestone crushed coarse aggregate.

In addition, 10 SCC mixtures (No. 34 through 43) with proportions similar to those of mixture No. 16 were used to evaluate the repeatability of workability tests. Each concrete mixture was tested for several workability characteristics, compressive strength, and modulus of elasticity as indicated in Table 5. The test methods that were used to evaluate the workability of SCC are described in Attachment D.

Several 4 × 8 in. (100 × 200 mm) concrete cylinders were cast within 10 minutes to evaluate the compressive strength and modulus of elasticity at 18 hours of age. The cylinders were cast in one lift without any mechanical consolidation. The specimens were demolded at 16 hours of age and tested at 18 hours. Some of the specimens were cured in the laboratory at 73 ± 4°F (23 ± 2°C) under wet burlap, while others were steam cured to determine early-age strength and modulus of elasticity. For the determination of strength development beyond 18 hours, the samples were air cured in the molds under wet burlap at 73 ± 4°F (23 ± 2°C) for 1 day before demolding and storing in a moist-curing chamber.

Mixture Proportioning Guidelines. Based on the results of the parametric study, and consideration of the effects of *w/cm*, binder type, and nominal size and type of coarse aggregate on workability characteristics and development of compressive strength, guidelines for the proportioning of SCC for use in precast, prestressed applications were proposed.

Comparison of Responses of Various Test Methods. Correlations among the various test results were used to identify advantages and limitations of these methods. Linear and

Table 5. Experimental program of parametric investigation.

SCC behavior	Property	Test Method	Test age	Number of samples per mixture	Comments
Rheology	Yield stress and plastic viscosity	Modified Tattersall MK III rheometer	10 & 40 minutes	Not applicable	
Filling ability	Slump flow and T-50 (upright cone position)	AASHTO T 119	10 & 40 minutes	Not applicable	
Passing ability, filling capacity	J-Ring, L-box, V-funnel flow, and caisson filling capacity	ASTM C 1621 (for J-Ring)	10 & 40 minutes	Not applicable	
Stability	Surface settlement		Over the first 24 hours	1	
	Column segregation	ASTM C 1610	10 minutes	1	
	Visual stability index	ASTM C 1611		Not applicable	
	Stability of air*	AASHTO T 152	Over 40 minutes	Not applicable	
Mechanical properties	Compressive strength	AASHTO T 22	18 hours	3 air cured 3 steam cured	*Air curing* at 50 ± 4% RH and 73 ± 4°F (23 ± 2°C) *Moist curing* at 100% RH and 73 ± 4°F (23 ± 2°C) *Steam curing* only for 16 hours
			28 days	3 moist cured	
			56 days	3 moist cured	
	Modulus of elasticity	ASTM C 469	18 hours	2 steam cured	

* Agitation of concrete between 10 and 40 minutes at 6 rpm

multiple regression analysis were used to relate the responses of various tests.

Appropriate test methods that can be used to assess the workability of SCC in the laboratory and at the precast plant for quality control were proposed. Ranges of acceptance values for these test methods were established. Non-standard test methods recommended for adoption as standard test methods are provided in Attachment C.

Relationship Between Workability Measurements and Rheological Properties. The various test responses were related to plastic viscosity of the concrete using a concrete rheometer. "Workability boxes" identifying combinations of rheological parameters necessary to secure adequate stability of SCC were established for the SCC mixtures evaluated.

Repeatability of Test Results. One mixture that exhibited good fluidity retention was used at two different slump flow levels (low and high) to establish the repeatability of the workability test methods. Each test was conducted five times, using different batches. Each test was performed by different operators. The data were used to develop precision statements.

Phase 2: Effect of Mixture Proportioning and Material Characteristics on Key Parameters Affecting Fresh and Hardened Properties

Limited information is available on the properties of hardened SCC mixtures typically used in precast, prestressed structural applications. Such properties can vary with the characteristics of constituent materials, including aggregate properties, type and composition of binder, and admixture combinations. Mixture composition and curing conditions necessary to secure the targeted strength for release of the prestressing also have a marked effect on engineering properties and durability of the SCC.

The experimental work included non–air-entrained and air-entrained SCC mixtures. The targeted compressive strength at release of the prestressing strands for structural AASHTO-type girders was set at 5,000 psi (34.5 MPa) after 18 hours of casting.

The targeted 56-day compressive strength of the SCC mixtures that were investigated in this study was 8,000 to 10,000 psi (55.2 to 69 MPa) determined on 4 × 8 in. (100 × 200 mm) cylinders moist cured at 100% relative humidity (RH) and 73 ± 4°F (23 ± 2°C). The specification of 56-day compressive strength is important when fly ash or ground granulated blast-furnace slag is incorporated in the SCC mixture because of the pozzolanic reaction.

Non–Air-Entrained Concrete Mixtures. The experimental factorial design presented in Table 6 was selected to evaluate the influence of mixture proportioning and constituent material characteristics on the properties that are critical to the performance of precast, prestressed concrete girders. The effect of primary ingredients and mix design parameters on key workability and engineering properties of SCC was evaluated. Based on the literature review and findings of the parametric study, four mixture proportioning items and one ingredient type were considered in the experimental design. The factors included binder content, binder type, *w/cm*, S/A, and dosage of VMA. In total, 16 SCC mixtures were selected to form a factorial design with the following five main factors:

- Binder content: 742 and 843 lb/yd³ (440 and 500 kg/m³)
- *w/cm:* 0.34 and 0.40
- Dosage of thickening-type VMA: 0 and moderate dosage
- Binder type: Type I/II and Type III cement with 20% Class F fly ash
- S/A: 0.46 and 0.54, by volume

The magnitude of these variables was selected to cover a wide range of mixture ingredients and designs used in the United States. The *w/cm* and binder type were selected based on the results of the parametric study. A low *w/cm* was included for better mechanical performance and the higher *w/cm* was included for better workability. Type III binder with 20% of Class F fly ash replacement was chosen over Type III binder with 30% slag because of its better overall performance in terms of workability and compressive strength development.

Table 6. Factorial experimental program.

Type			Mix No.	Coded values: Binder	*w/cm*	VMA[a]	Binder type	S/A[b]	Absolute values: Binder lb/yd³ (kg/m³)	*w/cm*	VMA	Binder type	S/A
Non-AE concrete	SCC (26–27.6 in. [660–700 mm] slump flow)	Fractional factorial points	1	-1	-1	-1	-1	1	742 (440)	0.34	0	I/II	0.54
			2	-1	-1	-1	1	-1	742 (440)	0.34	0	III[c]	0.46
			3	-1	-1	1	-1	-1	742 (440)	0.34	moderate	I/II	0.46
			4	-1	-1	1	1	1	742 (440)	0.34	moderate	III	0.54
			5	-1	1	-1	-1	-1	742 (440)	0.40	0	I/II	0.46
			6	-1	1	-1	1	1	742 (440)	0.40	0	III	0.54
			7	-1	1	1	-1	1	742 (440)	0.40	moderate	I/II	0.54
			8	-1	1	1	1	-1	742 (440)	0.40	moderate	III	0.46
			9	1	-1	-1	-1	-1	843 (500)	0.34	0	I/II	0.46
			10	1	-1	-1	1	1	843 (500)	0.34	0	III	0.54
			11	1	-1	1	-1	1	843 (500)	0.34	moderate	I/II	0.54
			12	1	-1	1	1	-1	843 (500)	0.34	moderate	III	0.46
			13	1	1	-1	-1	1	843 (500)	0.40	0	I/II	0.54
			14	1	1	-1	1	-1	843 (500)	0.40	0	III	0.46
			15	1	1	1	-1	-1	843 (500)	0.40	moderate	I/II	0.46
			16	1	1	1	1	1	843 (500)	0.40	moderate	III	0.54
		Central points		0	0	0	0	0	792 (470)	0.37	moderate	I/II-III	0.50
				0	0	0	0	0	792 (470)	0.37	moderate	I/II-III	0.50
				0	0	0	0	0	792 (470)	0.37	moderate	I/II-III	0.50
	HPC		17	• *w/cm* = 0.34, Type I/II cement, ½ in. (12.5 mm) crushed aggregate • Normal consistency mixtures with 6 in. (150 mm) slump									
			18	• *w/cm* = 0.38, Type III + 20% Class F fly ash, ½ in. (12.5 mm) crushed aggregate • Normal consistency mixtures with 6 in. (150 mm) slump									
AE concrete	SCC		19–22	• Air-entrainment of 4% to7% and slump flow of 26–27.6 in. (660–700 mm) • Mixtures selected based on performance of *non–air-entrained concrete*									

[a] Thickening-type VMA
[b] Crushed aggregate with MSA of ½ in. (12.5 mm) and natural sand
[c] Type III cement + 20% Class F fly ash

The crushed coarse aggregate with a MSA of ½ in. (12.5 mm) was used because it offers better performance in terms of workability and strength development than gravel of similar MSA or crushed aggregate with ⅜ or ¾ in. (9.5 or 19 mm). Three replicate central points were prepared to estimate the degree of experimental error for the modeled responses. In addition to the 16 SCC mixtures, two HPC mixtures of normal consistency were evaluated.

It should be noted that other mixture proportioning and material parameters (e.g., coarse aggregate shape and MSA, combined aggregate gradation, and sand type and fineness modulus) can also influence the performance of SCC. However, only the most relevant factors were considered in the experimental program, as indicated in Table 7.

Air-Entrained Concrete Mixtures. Four SCC mixtures were prepared to evaluate the effect of air-entrainment (4% to 7%) on fresh properties, fluidity retention, strength development, flexural strength, elastic modulus, air-void spacing factor, and frost durability. These mixtures were selected based on results of the non–air-entrained concrete mixtures and were prepared with a selected combination of thickening-type VMA, polycarboxylate-based HRWRA, and a fixed S/A. Two concrete mixtures were prepared using two different binder types.

The initial slump flow of the 16 fractional factorial and three central SCC mixtures was 26.0 to 27.5 in. (660 to 700 mm). The targeted release compressive strength after 18 hours of steam curing and 56-day compressive strength were 5,000 psi (34.5 MPa) and 8,000 to 10,000 psi (55 to 69 MPa), respectively. The compressive strength was determined on 4 × 8 in. (100 × 200 mm) cylinders. For 56-day compressive strength, the specimens were stored at 100% RH and 73 ± 4°F (23 ± 2°C) until the time of testing. The change in temperature in the chamber and in 4 × 8 in. (100 × 200 mm) reference cylinders during steam curing are presented in Attachment D.

Test results were compared with the provisions for elasticity modulus, compressive strength, creep, drying shrinkage, and bond stipulated in several codes (AASHTO LRFD Specifications [2004 and 2007]; Precast/Prestressed Concrete Institute (PCI) Bridge Design Manual 1997; ACI 209, ACI 318, CEB-FIP MC90, etc.).

Formwork Pressure. The initial maximum pressure exerted by SCC and HPC was evaluated by casting concrete in rigid polyvinyl chloride (PVC) column measuring 3.6 ft (1.1 m) in height and 7.9 in. (200 mm) in diameter at a rate of 13 to 16 ft/h (4 to 5 m/h). Pressure sensors were installed at 2, 10, and 18 in. (50, 250, and 450 mm) from the bottom of the pressure decay tube. The sensors were set flush with the inner surface of the PVC column; the drilled holes through the PVC tubing were sealed to avoid leakage. The pressure sensors had a capacity of 25 psi (170 kPa), can operate over a temperature range of −58°F to 212°F (−50°C to 100°C), and were calibrated using a mechanical calibration instrument prior to use. Drop in lateral pressure was monitored until pressure cancellation (results are presented in Attachment D).

Temperature Rise. Temperature rise was measured in a 6 × 12 in. (150 × 300 mm) concrete cylinder that was inserted at the center of a styrofoam box measuring 3.3 × 3.3 × 3.3 ft (1 × 1 × 1 m). Three thermo-couples were installed inside the concrete cylinders—one in the center of the cylinder, one in the middle height of the inner side of the cylinder, and one in the top of the inner side of the cylinder—to determine the temperature rise under semi-adiabatic conditions.

Autogenous Shrinkage. Autogenous shrinkage was measured on 3 × 3 × 11.8 in. (75 × 75 × 285 mm) prisms. The prisms were sealed immediately after removal from the molds at 18 hours of age and kept at 73 ± 4°F (23 ± 2°C) until the end of testing. Autogenous shrinkage was monitored using embedded vibrating wire strain gages until stabilization, which occurred after approximately 3 weeks of age. The autogenous shrinkage was obtained by subtracting the total shrinkage from thermal deformation. A linear thermal expansion coefficient of 6.4 μin./in./°F (11.5 μm/m/°C) was assumed for adjusting vibrating wire gage readings. The thermal expansion coefficient of the concrete was determined from the slope of the total deformation versus temperature curve of concrete prisms subjected to controlled temperature changes. Two prisms were initially immersed in water at the approximate temperature of 122°F (50°C). Once the temperature of the specimens was stabilized, the water was allowed to cool down to approximately 68°F (20°C). The resulting deformations were used to estimate the coefficient of thermal expansion/contraction of the concrete.

Drying Shrinkage and Creep. Six 6 × 12 in. (150 × 300 mm) test specimens were cast to monitor creep and drying shrinkage. The specimens were steam cured until the age of 16 hours and were then demolded. The ends of creep cylinders were ground and external studs were installed for deformation measurements. A digital-type extensometer was used to determine drying shrinkage and creep. Creep and shrinkage testing started at the age of 18 hours. The applied creep loading corresponded to 40% of the 18-hour compressive strength of the steam-cured concrete cylinders. Creep and shrinkage specimens were kept in a temperature-controlled room at 73 ± 4°F (23 ± 2°C) and 50% ± 4% relative humidity. Initial elastic deformations were measured directly after loading; creep and drying shrinkage deformations were monitored for 11 months; the long-term deformations were all stabilized at that time.

Pull-out Bond Strength. Pull-out testing of prestressing strands was conducted for five SCC mixtures and one conventional concrete mixture. The SCC mixtures were proportioned with different viscosity and static stability levels. Tests were

Table 7. Factors considered in the testing program.

SCC behavior	Property	Test method	Test age	Number of samples per mixture	Comments
Rheology	Yield stress and plastic viscosity and thixotropy	Modified Tattersall MK III rheometer	10 & 40 minutes	Not applicable	
Filling ability	Slump flow, T-50 (upright cone position)	ASTM C 1611	10 & 40 minutes	Not applicable	
Passing ability & filling capacity	J-Ring	ASTM C 1621	10 & 40 minutes	Not applicable	
	L-box, caisson filling capacity				
Stability	Surface settlement		Over the first 24 hours	1	
	Column segregation	ASTM C 1610		1	
	Visual stability index	ASTM C 1611		Not applicable	
	Stability of air*	AASHTO T 152	Over 40 minutes	Not applicable	
Mechanical properties	Compressive strength	AASHTO T 22	18 hours	3 air cured 3 steam cured	*Air curing:* 50 ± 4% RH, 73 ± 4°F (23 ± 2°C) *Moist curing:* 100% RH, 73 ± 4°F (23 ± 2°C) *Steam curing:* only for 14 hours (refer to Attachment D)
			7 days	3 moist cured	
			28 days	3 moist cured	
			56 days	3 moist cured	
	Modulus of elasticity	ASTM C 469	18 hours	2 air cured 2 steam cured	
			28 days	2 moist cured	
			56 days	2 moist cured	
	Flexural strength	AASHTO T 97	7 days	3 moist cured	
			28 days	3 moist cured	
			56 days	3 moist cured	
Hydration kinetics	Temperature rise		Over the first 24 hours	1	Semi-adiabatic conditions
	Setting time	AASHTO T 197		1	
Form pressure characteristics	Initial formwork pressure		2 to 4 hours	1	Rate of rise of 13.1 to 16.4 ft/h (4 to 5 m/h)
	Variation of pressure with time		First 24 hours	1	
Visco-elastic properties	Autogenous shrinkage	Embedded vibrating wire gages	Over 10 to 14 days	2	Sealed prisms
	Drying shrinkage	AASHTO T 160	Over 11 months	3	Same curing regime used for release strength
	Creep	ASTM C 512	Over 11 months	3	Loading at release time
Frost durability	Air-void parameters	ASTM C 457	Starting at 56 days	1	
	Freezing and thawing resistance	AASHTO T 161, Method A	Starting at 56 days	2	
Bond strength	Pull-out load-end slip response		56 days	5 SCC & 1 HPC	*Air curing:* at 50 ± 4% RH, 73 ± 4°F (23 ± 2°C)

* Agitation of concrete between 10 and 40 minutes at 6 rpm

conducted to determine the maximum pull-out load versus the end slip response of strands that were horizontally embedded in experimental wall elements. In total, 16 Grade 270, 0.6 in. (15.2 mm) diameter low-relaxation prestressing strands were embedded at four heights in 60.6 H × 84.6 L × 7.9 W in. (1,540 H × 2,150 L × 200 W mm) wall elements. Rigid plastic sheathing was tightly attached to the outer end of each strand near the loaded end as bond breaker to reduce secondary confining stresses along the bonded region.

The formwork was removed 1 day after concrete casting. The concrete wall elements were then maintained under wet curing until 7 days of age before being air-dried. Pull-out tests were conducted at 56 days of age. The pull-out load was applied gradually and recorded using a load cell; the net slip was measured using a linear voltage differential transducer (LVDT) connected to the unloaded end of the strand.

Phase 3: Structural Performance of Full-Scale AASHTO-Type II Girders

The structural performance of full-scale AASHTO precast, prestressed bridge girders constructed with selected SCC mixtures was investigated to evaluate the applicability of current design provisions (AASHTO and PCI) and to recommend appropriate modifications to the AASHTO LRFD Specifications. The aspects studied were constructability, temperature variations, transfer lengths, cambers, flexural cracking, shear cracking, and shear strengths. More details on the construction and testing of these girders are given in Attachment D.

Two non–air-entrained SCC mixtures of different compressive strength levels were used to cast two full-scale AASHTO-Type II girders. One mixture had target 56-day compressive strength of 8,000 (55 MPa) and release strength of 5,000 psi (34.5 MPa) and the other had target compressive and release strengths of 10,000 psi (69 MPa) and 6,250 psi (43 MPa), respectively. Two additional girders were cast using HPC mixtures with target 56-day compressive strengths of 8,000 and 10,000 psi (55 and 69 MPa). The HRWRA dosages for the HPC and SCC mixtures were adjusted to obtain a slump of 6.3 ± 0.8 in. (160 ± 20 mm) and a slump flow of 26.8 ± 0.8 in. (680 ± 20 mm), respectively.

The AASHTO-Type II girders have overall lengths of 31 ft (9.4 m) with center-to-center spans of 29 ft (8.8 m). The girders were prestressed with eight 0.6 in. (15.2 mm) diameter Grade 270 low-relaxation prestressing strands of six straight strands and two strands harped at double harping points located 4 ft 11 in. (1.5 m) from mid-span as shown in Figure 1. The pretensioning jacking system was calibrated to ensure accurate application of the force to each strand.

The four mixes were proportioned with Type III cement and 20% Class F fly ash and crushed aggregate with MSA of ½ in. (12.5 mm), as presented in Table 8.

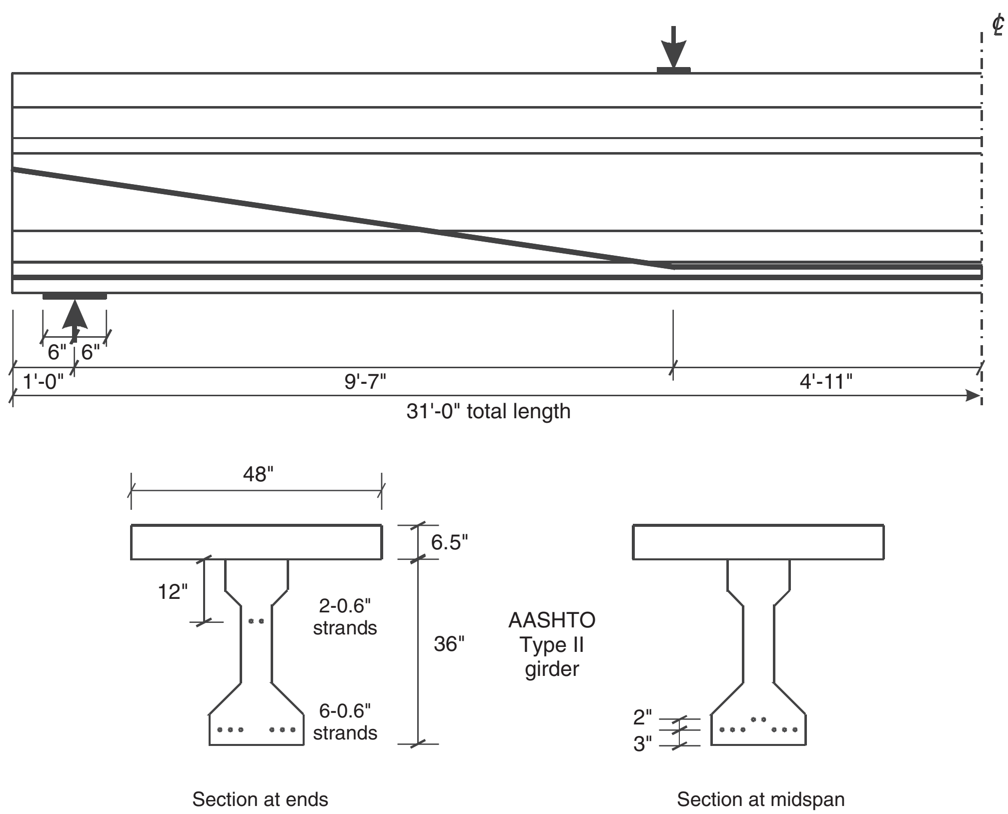

Figure 1. Details of precast pretensioned AASHTO-Type II girders.

Table 8. Mixtures used for full-scale girders.

Concrete	Targeted 56-day compressive strength	Codification* (*w/cm*–binder content–binder type–S/A–VMA)
HPC	8,000 psi (55 MPa)	38-797-III20%FA (*w/cm* = 0.38, Type III cement + 20% Class F fly ash)
	10,000 psi (69 MPa)	33-793-III20%FA (*w/cm* = 0.33, Type III cement + 20% Class F fly ash)
SCC	8,000 psi (55 MPa)	38-742-III20%FA-S/A54 (*w/cm* = 0.38, Type III cement + 20% Class F fly ash, S/A = 0.54)
	10,000 psi (69 MPa)	32-843-III20%FA-S/A46-VMA (*w/cm* = 0.32, Type III cement + 20% Class F fly ash, S/A = 0.46)

* ½ in. (12.5 mm) crushed aggregate for all mixtures

The testing program of the concrete used in the girders is presented in Table 9. For each girder, a minimum of fifty 4 × 8 in. (100 × 200 mm) cylinders and eighteen 3.9 × 3.9 × 15.7 in. (100 × 100 × 400 mm) beams were prepared. In total, 28 cylinders and nine flexural beams were match cured with the concrete girders. The rest of the cylinders and flexural beam specimens were demolded after 18 hours of air curing, then moist cured at 100% RH and 73.4°F (23°C) until testing. At the time of prestress release, three steam-cured and three air-cured cylinders were tested to determine the compressive strength.

Four cylinders, two for each curing method, were used to determine the modulus of elasticity. The remaining steam-cured cylinders were stored near the girders and tested to

Table 9. Concrete testing program for the girders.

SCC behavior	Property	Test method	Test age	Number of samples per mixture	Size/volume of specimen	Comments
Rheology	Yield stress, plastic viscosity	Modified Tattersall MK III rheometer	At arrival & after casting	Not applicable	0.89 ft^3 (25 *l*)	
Filling ability	Slump flow[a], T-50 (upright cone position)	ASTM C 1611	At arrival & just after casting	Not applicable	0.11 ft^3 (3.14 *l*)	
Passing ability, filling capacity	J-Ring	ASTM C 1621	At arrival & after casting	Not applicable	2.54 ft^3 (72 *l*)	
	L-box, caisson filling capacity	See Attachment D				
Stability	Surface settlement	See Attachment D	Over 24 hours	1	7.9 × 23.6 in. (200 × 600 mm) cylindrical specimens	
	Column segregation	ASTM C 1610		1	7.9 × 26 in. (200 × 660 mm) cylindrical specimens	
	Visual stability index	ASTM C 1621		Not applicable	0.11 ft^3 (3.14 *l*)	
	Stability of air	AASHTO T 152	At arrival & after casting	Not applicable	0.25 ft^3 (7 *l*)	
Visco-elastic properties	Autogenous shrinkage	Embedded vibrating wire gages	Over 1 month	2	3 × 3 × 11.2 in. (75 × 75 × 285 mm) prism[b]	
	Drying shrinkage	AASHTO T 160	Over 6 months	3	6 × 12 in. (150 × 300 mm) cylinder[c]	

[a] Slump for HPC mixtures
[b] Sealed prisms after demolding at release time
[c] Same curing regime used for release strength

Table 9. (Continued).

SCC behavior	Property	Test method	Test age	Number of samples per mixture	Size/volume of specimen
Mechanical properties	Compressive strength	AASHTO T 22	At release	3 steam cured 3 air cured	4 × 8 in. (100 × 200 mm) cylinders
			7 days	3 moist cured[d] 3 air cured[e]	
			28 days	3 moist cured[d] 3 air cured[e]	
			56 days	3 moist cured[d] 3 air cured[e]	
			At shear testing	3 moist cured[d] 3 air cured[e]	
	Modulus of elasticity	ASTM C 469	At release	2 steam cured 2 air cured	4 × 8 in. (100 × 200 mm) cylinders
			7 days	2 moist cured[d] 2 air cured[e]	
			28 days	2 moist cured[d] 2 air cured[e]	
			56 days	2 moist cured[d] 2 air cured[e]	
			At shear testing	2 moist cured[d] 2 air cured[e]	
	Flexural strength	AASHTO T 97	At release	3 steam cured 3 air cured	3.9 × 3.9 × 15.7 in. (100 × 100 × 400 mm) prisms
			28 days	3 moist cured[d] 3 air cured[e]	
			56 days	3 moist cured[d] 3 air cured[e]	
Hydration kinetics	Temperature rise (semi-adiabatic conditions)			1	6 × 12 in. (150 × 300 mm) cylinders
	Setting time	AASHTO T 197		1	Sieved mortar
Structural performance	Transfer length, flexural cracking, and shear capacity	3-point flexural & shear testing		2 SCC girders 2 HPC girders	Full-scale AASHTO-Type II girder with 31 ft (9.4 m) in length
	Camber growth			2 SCC girders 2 HPC girders	

[d] 18 hours of air curing followed by moist curing at 100% RH and 73°F (23°C)
[e] 18 hours of steam curing followed by air curing near the corresponding girderat 50 ± 4% RH and 73 ± 4°F (23 ± 2°C)

determine the compressive strength and modulus of elasticity at 7, 28, and 56 days, and also at the age corresponding to the time of testing the girders. The tests on beam specimens provided data on the modulus of rupture at the time of prestress release and at 28 and 56 days.

2.3 Approach for Relevant Changes to AASHTO LRFD Bridge Design and Construction Specifications

To recommend relevant changes to AASHTO LRFD Bridge Design and Construction Specifications, the specification sections that relate to the proposed research were examined. Relevant changes are integrated in Attachment A.

2.4 Guidelines for Use of SCC in Precast, Prestressed Concrete Bridge Elements

Based on the results of the literature survey and the laboratory evaluation, guidelines were developed for the use of SCC in precast, prestressed concrete bridge elements. The guidelines, provided in Attachment B, include information on the selection of material constituents, mixture proportioning, and testing of SCC. Performance-based specifications of fresh and hardened concrete properties are provided, and special placement and construction issues are discussed. The guidelines deal with the early-age properties, mechanical properties, durability, and structural performance of SCC.

CHAPTER 3

Interpretation, Appraisal, and Application

This chapter provides an interpretation of the findings in terms of highway engineering practice. Recommendations for revisions to the AASHTO LRFD Specifications are presented in Attachment A. Suggested methods for testing SCC are described in Attachment C. Guidelines for quality control testing, acceptance specifications, and proportioning of SCC for precast, prestressed concrete bridge elements are provided in Attachment C. These guidelines can be of particular interest to bridge engineers and specifiers, concrete producers, testing laboratories, and manufacturers; will facilitate successful use of SCC; and will contribute to its acceptance.

Adopting quality control measures for producing SCC leads to enhanced durability and longer life expectancy of bridge structures. Eliminating the need for vibration in precast bridge elements also provides a potential for enhancing the manufacturer's environmental, health, and safety conditions.

The standard test methods and others (e.g., slump flow and T-50, J-Ring flow, column segregation, and VSI) can be used to assess workability characteristics of SCC. Based on this project's findings, filling capacity and surface settlement test methods are recommended for use in evaluating the filling capacity and static stability of SCC.

CHAPTER 4

Conclusions and Suggested Research

This chapter presents the major conclusions of the research effort and provides suggestions for future research.

4.1 Test Methods and Material Requirements

The use of proven combinations of test methods is necessary to reduce time and effort required for quality control of SCC used in precast, prestressed bridge elements. These methods include the components required for evaluating the deformability, passing ability, and resistance to segregation of the concrete. The most promising SCC test methods for these evaluations are:

- Filling ability (slump flow and T-50);
- Passing ability (J-Ring and L-box);
- Filling capacity [caisson test (filling vessel)]; and
- Segregation resistance (VSI, surface settlement and rate of settlement, and column segregation).

Recommended acceptance values for these tests are summarized in Table 10. These tests are appropriate for material selection and mix design as well as for quality control (QC) testing.

4.2 Material Constituents and Mix Design

Based on the results derived from the factorial design, the relative influence of various mixture parameters on the modeled properties of SCC are summarized in Table 11. Table 12 gives recommendations for proportioning of SCC mixtures for use in precast, prestressed applications.

Regarding the fresh SCC properties, the following recommendations and observations are made:

- A *w/cm* should be selected to obtain the targeted stability, mechanical properties, visco-elastic properties, and durability (typical *w/cm* for precast, prestressed applications can range between 0.34 and 0.40).
- Low S/A values (e.g., 0.46 to 0.50) should be used to obtain adequate workability.
- Coarse aggregate with ½ in. (12.5 mm) MSA is recommended to achieve adequate workability and mechanical properties.
- Use of thickening-type VMA is required for SCC made with moderate and relatively high *w/cm* and low binder content to enhance stability and obtain homogenous in-situ properties. The use of thickening-type VMA at a low level can enhance static stability (lower column segregation index). VMA can also be used in highly stable SCC (e.g., with low *w/cm*) to enhance robustness.
- Use of air entrainment is required for frost durability (use of air-entraining admixture will help stabilize small air bubbles).
- SCC made with Type III cement and 20% Class F fly ash can exhibit better slump flow retention, higher passing ability, and higher filling capacity than SCC made with Type I/II cement.
- The HRWRA demand decreases with the increase in *w/cm* and binder content. The use of Type III cement and 20% Class F fly ash necessitates higher HRWRA demand than that required for SCC prepared with Type I/II cement (thus resulting in lower early-age compressive strength).
- Better slump flow retention can be obtained with SCC made with low *w/cm* because of the higher HRWRA demand required to achieve 26.0 to 27.5 in. (660 to 700 mm) slump flow.
- Surface settlement of SCC increases with the increase in binder content and *w/cm*.
- Plastic viscosity decreases with the increase in binder content and *w/cm* but increases slightly with the increase in S/A.
- Thixotropy or structural build-up at rest of the SCC decreases with the increase in binder content and *w/cm*.

Table 10. Recommended test methods and target values.

Property	Test method	Target value	Design	QC
Filling ability	Slump flow T-50 (ASTM C 1611)	23.5–29 in. (600–735 mm) 1.5–6 sec (upright cone position)	√	√
Passing ability	J-Ring flow (ASTM C 1621) Slump flow – J-Ring flow	21.5–26 in. (545–660 mm) 0–3 in. (0–75 mm)	√	√
	L-box blocking ratio (h_2/h_1)	0.5–1.0	√	√
Filling capacity	Filling capacity	70%–100%	√	
	Slump flow and J-Ring flow			√
	Slump flow and L-box tests			√
Static stability	Surface settlement	Rate of settlement, 25–30 min (value can decrease to 10–15 min) – MSA of ⅜ and ½ in. (9.5 and 12.5 mm) ≤ 0.27%/h (Max. settlement ≤ 0.5%) – MSA of ¾ in. (19 mm) ≤ 0.12%/h (Max. settlement of 0.3%)	√	
	Column segregation (ASTM C 1610)	Column segregation index (C.O.V.) ≤ 5% Percent static segregation (S) ≤ 15%	√	
	VSI (ASTM C 1611)	0–1 (0 for deep elements)	√	√
Air volume	AASHTO T 152	4%–7% depending on exposure conditions, MSA, and type of HRWRA. Ensure stable and uniform distribution of small air voids.	√	√

Table 11. Relative significance of modeled SCC parameters.

	Binder content			*w/cm*			VMA content			Binder type			S/A		
	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
HRWRA demand		■				■	■				■		■		
Slump flow retention			■			■	■					■		■	
J-Ring			■			■		■			■			■	
Slump flow – J-Ring flow			■			■	■					■		■	
L-box blocking ratio (h_2/h_1)			■			■	■			■			■		
Caisson filling capacity			■			■	■					■	■		
Maximum surface settlement			■			■	■				■		■		
Column segregation index			■	■					■	■			■		
Plastic viscosity			■			■	■			■				■	
Thixotropy (A_b)			■			■	■			■			■		
Form pressure			■			■	■			■				■	
18-hour f_c'	■					■		■			■		■		
56-day f_c'		■				■	■				■		■		
18-hour MOE		■				■	■				■			■	
56-day MOE	■					■	■				■				■
7-day flexural strength		■			■		■			■					■
56-day flexural strength	■					■	■			■				■	
Autogenous shrinkage at 7 days	■					■	■					■	■		
Autogenous shrinkage at 56 days	■					■	■					■	■		
Drying shrinkage after 28 days of exposure		■				■	■			■			■		
Drying shrinkage after 112 days of exposure			■			■	■				■			■	
Creep after 28 days of loading	■				■		■					■	■		
Creep after 112 days of loading		■		■			■					■	■		

Darkened areas indicate high degree of influence for the modeled mixture parameter.

Table 12. Recommendations for proportioning SCC mixtures.

	w/cm		Binder type		Binder content		S/A		VMA	
	0.34	0.40	I/II	III + 20% fly ash	742 lb/yd³ (440 kg/m³)	843 lb/yd³ (500 kg/m³)	0.46	0.54	0	Moderate
Filling ability retention	■			■		■	■			
Passing ability		■		■		■	■			
Filling capacity		■		■		■				
Static stability	■			■						■
18-hour f_c'	■		■							
56-day f_c'	■			■		■				
18-hour MOE	■		■		■		■			
56-day MOE	■			■			■			
Flexural strength	■				■			■		
Autogenous shrinkage		■	■							
Drying shrinkage		■	■		■		■			
Creep	■		■		■					

Darkened areas indicate better performance for each property.

Higher thixotropy can be detrimental to surface finish and advantageous to formwork pressure.

- Initial relative form pressure at 3.3 ft (1 m) in height cast at 13.1 to 16.4 ft/h (4 to 5 m/h) varies between 0.80 and 1.00 of hydrostatic pressure; it increases with the increase in binder content and *w/cm* but decreases with the increase in S/A.
- Incorporation of thickening-type VMA in the mixture could delay setting and increase the time to attain peak temperature, thus leading to some delay in early-age strength development. In that case, steam curing could be used to accelerate the strength development.

Regarding the mechanical properties, the following recommendations and observations are made:

- Mechanical properties increase with the decrease in *w/cm.*
- Increase in binder content can lead to higher 56-day compressive strength but to lower 18-hour MOE and 7-day flexural strength.
- The increase in S/A results in lower MOE at 18 hours (steam curing) and 56 days (moist curing) and higher flexural strength.
- SCC made with Type III cement and 20% Class F fly ash exhibits lower early-age compressive strength than that made with Type I/II cement (due to higher HRWRA demand).
- SCC made with Type III cement and 20% Class F fly ash can develop higher compressive strength and MOE at 56 days but lower mechanical properties at 18 hours than for concrete made with Type I/II cement (mainly because of delayed setting resulting from greater HRWRA demand).

Regarding the visco-elastic properties, the following recommendations and observations are made:

- The increase in binder content increases drying shrinkage and creep.
- Although for a given binder content drying shrinkage is expected to increase with increased *w/cm,* for the derived statistical models an opposite trend appears because the drying shrinkage also includes autogenous shrinkage that decreases with the increase in *w/cm.*
- SCC mixtures made with Type I/II cement develop less creep and shrinkage than those prepared with Type III cement and 20% Class F fly ash. However, the latter concrete has better workability and higher mechanical properties than the former SCC. Therefore, use of Type III cement and 20% Class F fly ash will require reduction of binder content to ensure better overall performance.
- Concrete mixtures containing high binder content and low *w/cm* can exhibit high autogenous shrinkage; the majority (85% to 95%) of which occurs in the first 28 days (values after 56 days can vary between 100 and 350 µstrain depending on mixture composition).
- Autogenous shrinkage is mostly affected by binder type and paste volume. SCC made with Type III cement and 20% Class F fly ash can develop higher autogenous shrinkage and creep than SCC made with Type I/II cement.
- For a given *w/cm,* increasing binder content can result in higher drying shrinkage (500 and 1000 µstrain after 300 days is possible).
- SCC exhibits up to 30% higher drying shrinkage at 300 days than HPC made with similar *w/cm* but different paste

volume. More detailed information on drying shrinkage can be found in Attachment D.

- Increase in S/A can lead to higher long-term drying shrinkage.
- The binder type does not have significant effect on drying shrinkage but can significantly affect creep (e.g., SCC made with Type III cement and 20% fly ash exhibited higher creep than similar SCC proportioned with Type I/II cement regardless of the binder content, *w/cm*, S/A, and use of thickening-type VMA).
- The *w/cm* does not have considerable effect on creep because of the more predominant influence of other parameters such as binder content, binder type, and S/A.
- SCC exhibits up to 20% higher creep after 300 days than HPC made with similar *w/cm* but different paste volume. More detailed information on creep can be found in Attachment D.

4.3 Code Provisions for Estimating Mechanical and Visco-Elastic Properties

Mechanical Properties

Material coefficients of existing prediction models were modified to provide better prediction of mechanical properties of SCC for precast, prestressed concrete bridge elements. The following codes are recommended:

- ACI 209 and CEB-FIP codes with modified coefficients for predicting compressive strength
- Current AASHTO 2007 model for predicting elastic modulus
- Current AASHTO 2007 model for estimating flexural strength

Visco-Elastic Properties

Creep and shrinkage strains measured in experimental factorial design were compared with values predicted by the AASHTO 2007, AASHTO 2004, ACI 209, CEB-FIP MC90, and GL 2000 (Gardner and Lockman, 2001) models. Coefficients of the following models were modified to provide better prediction of visco-elastic properties for SCC:

- AASHTO 2004 model for estimating drying shrinkage
- AASHTO 2007 model for estimating creep

4.4 Homogeneity of In-Situ Strength and Bond to Reinforcement

- Highly flowable SCC should have adequate static stability with maximum surface settlement, column segregation index, and percent static segregation of 0.5%, 5%, and 15%, respectively, particularity for deep elements.
- Highly flowable SCC can develop at least 90% in-situ relative compressive strength (core results) and modification factor of 1.4 for bond to horizontally embedded prestressing strands. More detailed information on bond to prestressing strands is presented in Attachment D.
- Use of highly viscous SCC [plastic viscosity greater than 0.073 psi•s (500 Pa•s) or T-50 nearing 6 seconds (obtained from upright cone position)] should be avoided to ensure adequate self-consolidation.

4.5 Structural Performance of AASHTO-Type II Girders

The following conclusions and observations are based on the construction and testing of the full-scale precast, pretensioned girders:

- With the casting from only a single location at midspan of the 31 ft (9.44 m) long girders, no visible segregation was observed and fewer “bug holes” were observed in the SCC concrete than in the HPC.
- The transfer lengths were similar for the four concrete mixtures and were considerably shorter than the values given in the 2007 AASHTO LRFD Specifications and the ACI 318-05 code.
- At time of prestress release at 18 hours, the coefficients on the square root of the compressive strength used to determine the modulus of elasticity for the SCC mixtures were about 4% and 11% lower than those for the HPC mixtures.
- Due to the low elastic modulus and greater drying shrinkage, greater elastic shortening losses and greater long-term losses of prestress occurred, resulting in smaller cambers for the SCC girders.
- The cracking moments for the SCC girders and the companion HPC girders were similar, and the uncracked and cracked stiffnesses for all four girders were very similar.
- The cracking shears for all four girders were similar.
- The four girders failed in shear after developing a significant number of wide shear cracks; shear crack widths just before failure were greater than 0.24 in. (6 mm). The failure shears exceeded the nominal shear resistances predicted using the approach given in 2007 AASHTO LRFD Specifications, probably because of the strength and stiffness of the top and bottom flanges of the girders.
- The flexural resistances of the HPC girders exceeded that predicted using the 2007 AASHTO LRFD Specifications.
- The flexural resistances of the SCC girders were within 1.5% of the flexural resistance calculated using the approach provided in the 2007 AASHTO LRFD Specifications.
- The HPC girders exhibited higher ductilities than the corresponding SCC girders.
- The lower shear resistance and lower ductility experienced by the SCC girders are probably due to the lower volume

of coarse aggregate that reduces aggregate interlock and results in lower energy absorption capability on the sliding shear failure plane.

4.6 Recommendations for Future Research

The following recommendations are made for future research related to SCC used in precast, prestressed applications.

Constructability

- **Short term**
  - Validation of the recommended workability characteristics proposed in Table 13 using full-scale prestressed girders.
  - Evaluation of the effect of horizontal flow distance and free-fall distance of concrete in the formwork on segregation potential and in-situ properties of the hardened concrete.
  - Evaluation of the effect of concrete workability, placement techniques, casting rate, and form release material on surface finish of SCC.
  - Evaluation of the effect of rheological properties of SCC, delivery period, and delay between successive placement on cold joint formation and surface defects.

Test Methods

- **Short term**
  - Development of a reliable test method to determine bond-strength and modification factor to prestressing strands.
- **Medium term**
  - Development of a QC test method to evaluate plastic viscosity of SCC.

Table 13. Workability values of SCC used in precast/prestressed applications.

			Slump flow (ASTM C 1611/C 1611 M-05)			J-Ring (Slump flow– J-Ring flow) (ASTM C 1621)			L-box blocking ratio (h_2/h_1)			Caisson filling capacity		
Relative values			23.5-25 in.	25-27.5 in.	27.5-29 in.	3- 4 in.	2-3 in.	≤ 2 in.	0.5-0.6	0.6-0.7	≥ 0.7	70%-75%	75%-90%	≥ 90%
Element characteristics	Low	Reinforcement density	■				■			■			■	
Element characteristics	Medium	Reinforcement density		■			■			■			■	
Element characteristics	High	Reinforcement density			■			■			■			■
Element characteristics	Small	Shape intricacy	■				■			■			■	
Element characteristics	Moderate	Shape intricacy		■			■			■			■	
Element characteristics	Congested	Shape intricacy			■			■			■			■
Element characteristics	Shallow	Depth	■			■				■		■		
Element characteristics	Moderate	Depth		■			■				■		■	
Element characteristics	Deep	Depth		■				■			■			■
Element characteristics	Short	Length	■				■			■			■	
Element characteristics	Moderate	Length		■			■			■			■	
Element characteristics	Long	Length		■				■			■			■
Element characteristics	Thin	Thickness		■				■			■			■
Element characteristics	Moderate	Thickness		■			■			■			■	
Element characteristics	Thick	Thickness	■				■			■			■	
	Low	Coarse aggregate content			■			■		■			■	
	Medium	Coarse aggregate content			■		■			■			■	
	High	Coarse aggregate content	■			■					■			■

1 in. = 25.4 mm
Shaded zones indicate suggested workability characteristics. All SCC mixtures must meet requirements for static stability.

– Development of a QC test method to determine structural build-up and evaluate its effect on consolidation level, surface quality, and cold joint formation.
– Development of a dynamic stability test to assess segregation resistance of SCC subjected to horizontal flow and free-fall into the formwork.

Material Selection and Mix Design

- **Short term**
  - Evaluation of the effect of shrinkage-reducing admixtures on shrinkage and creep of SCC used in precast, prestressed applications (relevant because of the higher drying shrinkage and creep of SCC).
  - Investigation of the compatibility issues between chemical admixtures (in particular HRWRA, VMA, shrinkage-reducing admixtures, and air-entraining admixtures) on flow properties and strength development of SCC.
  - Determination of key factors affecting robustness of SCC and ways to enhance it in order to ensure consistent concrete quality and productivity.
- **Medium term**
  - Extension of the modeled region of the factorial design beyond the range of −1 to +1 as well as incorporating other parameters in order to take into consideration the quadratic effect of various parameters in the derived models, in particular those of the visco-elastic properties and formwork pressure.
  - Investigation of the influence of mixture proportioning and material characteristics that were not considered in this research {e.g., MSA [⅜ and ½ in. (9.5 and 12.5 mm)], combined sand and coarse aggregation content and gradation, sand type [crushed vs. natural], and paste volume} on workability, mechanical properties, and visco-elastic properties of SCC.
  - Investigation of the effect of finely ground limestone fillers on fresh and hardened concrete properties of SCC, in particular stability, temperature rise, strength development, and visco-elastic properties.

Structural Performance

- **Short term**
  - Determination of modification factor (top-bar effect) of reinforcing bars in structural elements cast with SCC of different workability characteristics (especially static stability) and element depth.
  - Evaluation of the effect of SCC on transfer length with simple transfer length specimens.
  - Evaluation of the influence of coarse aggregate content and MSA on aggregate interlock (direct shear "push-off" specimens) and companion tests to investigate the shear behavior of simple SCC elements (non-prestressed rectangular beam specimens).
- **Medium term**
  - Evaluation of key engineering properties, durability characteristics, and structural performance of SCC with high-release strength [e.g., 7,000 psi (48 MPa)] and design compressive strength greater than 12,000 psi (83 MPa).
  - Evaluation of the use of steel and synthetic fibers in SCC mixtures.
  - Extensive testing and evaluation of full-scale specimens to provide definitive information on structural performance, including the contribution of the presence of top and bottom flanges to the shear resistance.

Glossary

Some of the following definitions are general and apply to conventional concrete, while others are specific to self-consolidating concrete. Some of these definitions are based on definitions given in American Concrete Institute (ACI) and Precast/Prestressed Concrete Institute (PCI) technical documents.

Admixture—A material, other than water, aggregates, hydraulic cement, and fiber reinforcement, 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 (ACI 116).

Autogenous shrinkage—The shrinkage occurring in the absence of moisture exchange due to the hydration reactions taking place inside the cement matrix (ACI 209).

Binder—A cementing material, either a hydrated cement or reaction products of cement or lime and reactive siliceous material; also, materials such asphalt, resins, and other materials forming the matrix of concretes, mortars, and sanded grouts.

Bingham fluid—A fluid characterized by a yield stress and a constant plastic viscosity, regardless of flow rate (PCI 2003).

Bleed water—The water that rises to the surface subsequent to the placing of the concrete. The rise of mixing water within, or its emergence from, newly placed concrete, caused by settlement and consolidation of the plastic concrete (PCI 2003).

Bleeding test—The standard test for determining the relative quantity of mixing water that will bleed from a sample of freshly mixed concrete (ASTM C 232).

Blocking—The condition in which coarse aggregate particles combine to form elements large enough to obstruct the flow of the fresh concrete between the reinforcing steel or other obstructions in the concrete formwork (PCI 2003).

Cohesiveness—The tendency of the SCC constituent materials to stick together, resulting in resistance to segregation, settlement, and bleeding (PCI 2003).

Consistency—The relative mobility or ability of freshly mixed concrete or mortar to flow (ACI 116).

Consolidation—The process of inducing a closer arrangement of the solid particles in freshly mixed concrete or mortar during placement by the reduction of entrapped voids (ACI 116). In SCC, consolidation is achieved by gravity flow of the material without the need of vibration, rodding, or tamping.

Creep—Time-dependent deformation due to sustained load (ACI 209).

Deformability—The ability of SCC to flow under its own mass and fill completely the formwork.

Drying shrinkage—Shrinkage occurring in a specimen that is exposed to the environment and allowed to dry (ACI 209).

Fillers—Finely divided inert material, such as pulverized limestone, silica, or colloidal substances, sometimes added to portland cement paint or other materials to reduce shrinkage, improve workability, or act as an extender or material used to fill an opening in a form (ACI 116).

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 deformability (ACI 237).

Filling capacity—The ability of SCC to flow into and fill completely all spaces within the formwork.

Flowability—The ability of fresh concrete to flow in confined or unconfined form of any shape, reinforced or not, under gravity and/or external forces, assuming the shape of its container (PCI 2003).

Fluidity—The ease by which fresh concrete flows under gravity (PCI 2003). Fluidity is the reciprocal of dynamic viscosity.

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 (ACI 116). Because of its spherical shape and fineness, fly ash can improve the rheology of SCC.

Formwork pressure—Lateral pressure acting on vertical or inclined formed surfaces, resulting from the fluid-like behavior of the unhardened concrete confined by the forms (ACI 116).

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 (PCI 2003). 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).

High-range water-reducing admixture (HRWRA)—A water-reducing admixture capable of producing large water reduction or greater flowability without causing undue set retardation or entrainment of air in mortar or concrete (ACI 116).

J-Ring flow—The distance of lateral flow of concrete using the J-Ring in combination with a slump cone (ASTM C 1621).

J-Ring test—Test used to determine the passing ability of SCC, or the degree to which the passage of concrete through the bars of the J-Ring apparatus is restricted (ASTM C 1621).

L-box test—Test used to assess the confined flow of SCC and the extent to which it is subject to blocking by reinforcement (ACI 237).

Metakaolin—Mineral admixture used as binding material (supplementary cementitious material) in concrete (PCI 2003).

Mixture robustness—The characteristic of a mixture that encompasses its tolerance to variations in constituent characteristics and quantities, as well as its tolerance to the effects of transportation and placement activities (PCI 2003).

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 (ASTM C 1621).

Paste volume—Proportional volume of cement paste in concrete, mortar, or the like, expressed as volume percent of the entire mixture (ACI 116).

Plastic viscosity—The resistance of the plastic material to undergo a given flow. It 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. It is closely related to T-50 and V-funnel time (higher plastic viscosity: higher T-50 and V-funnel time).

Powder (also referred to as graded powder)—Includes cement, fly ash, GGBFS, limestone fines, material crushed to less than 0.125 mm (No. 100 sieve), or other non-cementitious filler (ACI 237).

Powder-type SCC—SCC mixtures that rely extensively on the amount and character of the fines and powder included in the mixture for meeting workability performance requirements (stability) (PCI 2003).

Pumpability—The ability of an SCC mixture to be pumped without significant degradation of workability (PCI 2003).

Rheological properties—Properties dealing with the deformation and flow of matter (PCI 2003).

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 (ACI 116). 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.

Segregation—The differential concentration of the components of mixed concrete, aggregate, or the like, resulting in non-uniform proportions in the mass (ACI 116). 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.

Segregation resistance—The ability of concrete to remain uniform in terms of composition during placement and until setting (PCI 2003). Segregation resistance encompasses both dynamic and static stability.

Self-consolidating concrete (SCC) (also self-compacting concrete)—A highly flowable, non-segregating concrete that can spread into place, fill the formwork, and encapsulate the reinforcement without any mechanical consolidation (ACI 237).

Service life—The time during which the structure performs its design functions without unforeseen maintenance or repair.

Settlement—The condition in which the aggregates in SCC tend to sink to the bottom of the form resulting in non-homogeneous concrete (PCI 2003). Surface settlement can also be caused by bleeding of free water and loss of air as well as movement of aggregate particles within fresh concrete (consolidation).

Shear stress—The stress component acting tangentially to a plane (ACI 116).

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 (ACI 116). Silica fume can be added to SCC to improve the rheological properties.

Slump flow—Test method used (upright or inverted) to measure mixture filling ability (ASTM C 1611).

Slump flow retention—The ability of concrete to maintain its slump flow over a given period of time.

Slump flow spread—The distance of lateral flow of concrete during the slump-flow test (ASTM C 1611). Slump flow spread is the numerical value in inches (mm) of flow determined as the average diameter of the circular deposit of SCC at the conclusion of the slump flow test.

Stability—The ability of a concrete mixture to resist segregation of the paste from the aggregates (ASTM C 1611).

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.

T-50 measurement (also referred to as the T-20 in. time in North America)—The 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 (ASTM C 1611).

Texture—The pattern or configuration apparent in an exposed surface, as in concrete and mortar, including roughness, streaking, striation, or departure from flatness (ACI 116).

Thixotropy—The property of a material that enables it to stiffen in a short period while at rest, but to acquire a lower viscosity when mechanically agitated, the process being reversible, a material having this property is termed thixotropic or shear thinning (ACI 116). Thixotropy indicates formwork pressure and segregation resistance of SCC.

Transportability—The ability of concrete to be transported from the mixer to the placement site while remaining in a homogeneous condition (PCI 2003).

V-funnel—Device used to determine the time for a given volume of concrete to flow out through a funnel opening (PCI 2003).

Viscosity—The resistance of a material to flow under an applied shearing stress (ASTM C 1611).

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 and washout (ACI 237).

Visual Stability Index (VSI)—A test that involves the visual examination of the SCC slump flow spread resulting from performing the slump flow test (ACI 237).

Water-cementitious material ratio (*w/cm*)—The ratio of the mass of water, exclusive only of that absorbed by the aggregate, to the mass of cementitious material (hydraulic) in concrete, mortar, or grout, stated as a decimal (ACI 116).

Workability—That property of freshly mixed concrete or mortar that determines the ease with which it can be mixed, placed, consolidated, and finished to a homogenous condition (ACI 116). For SCC, workability encompasses filling ability, passing ability, and segregation resistance, and it is affected by rheology.

Yield stress—The minimum shear stress required to initiate (static yield stress) or maintain (dynamic yield stress) flow (ACI 237). The yield stress is closely related to slump flow (lower yield stress results in higher slump flow); it is calculated as the intercept of the shear stress versus shear rate plot from rheometer flow curve measurements.

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ATTACHMENT A

Recommended Changes to AASHTO LRFD Bridge Design and Construction Specifications

These proposed changes to AASHTO LRFD Bridge Design and Construction Specifications are the recommendations of the NCHRP Project 18-12 staff at the University of Sherbrooke. These specifications have not been approved by NCHRP or any AASHTO committee nor formally accepted for the AASHTO specifications.

CONTENTS

This attachment presents the recommended modifications to AASHTO LRFD Bridge Design and Construction Specifications. These modifications are shown in underlined format. P(SCC) refers to self-consolidating concrete for use in precast, prestressed applications; SCC refers to self-consolidating concrete for use in general cast-in-place and/or precast applications.

Specifications

Commentary

A.1 Bridge Design Specifications

A.1.1 Mixture Characteristics

Clause 5.4.2 Normal and Structural Lightweight Concrete

Clause 5.4.2.1 Compressive Strength

Clause C5.4.2.1

Suggest the addition of a new Class of concrete to Table C5.4.2.1-1, as indicated below.

Table C5.4.2.1-1. Concrete mix characteristics by class.

Class of Concrete	Minimum Cement Content	Maximum ~~W/C~~ *w/cm* Ratio	Air Content Range	Coarse Aggregate Per AASHTO M 43 (ASTM D 448)	28-day Compressive Strength	56-day Compressive Strength
	pcy	lbs. Per lbs.	%	Square Size of Openings (in.)	ksi	ksi
P(SCC)	700*	0.45	As specified elsewhere (5.5 ± 1.5% for severe freezing and thawing conditions). Higher air content may be required when using small MSA and/or HRWRA that can lead to relatively large air bubbles)	½ in. – No. 4 or ¾ in. – No. 4 (maximum)	6.0 to 8.0	8.0 to 10.0

* total cementitious materials

A.1.2 Code Provisions for Mechanical and Visco-Elastic Properties

Clause 5.4.2.3 Shrinkage and Creep

Clause 5.4.2.3.2 Creep

The creep coefficient may be taken as:

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

in which: $k_{vs} = 1.45 - 0.0051(V/S) \geq 0.0$

$$k_{hc} = 1.56 - 0.08H$$

$$k_f \frac{35}{7 + f'_{ci}}, \; k_{td} = \left(\frac{t}{61 - 0.58 f'_{ci} + t} \right)$$

where:

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

k_{vs} = factor for the effect of the volume-to-surface ratio of the component

Specifications | **Commentary**

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 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 when load is initially applied (day)
V/S = volume-to-surface ratio (mm)
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'_{ci} (MPa)
$\underline{A}$ = factor for the effect of cement type: 1.19 for Type I/II cement and 1.35 for Type III + 20% FA binder which may be used for P(SCC)

Clause 5.4.2.3.3 Drying Shrinkage

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

$$\varepsilon_{sh} = -k_s k_h \left(\frac{t}{55+t}\right) 0.56\times10^{-3} \underline{\times A} \left(\underline{\text{steam-cured}}\right) \quad (5.4.2.3.3\text{-}1)$$

$$k_s = \left[\frac{\dfrac{t}{26e^{0.0142(V/S)}+t}}{\dfrac{t}{45+t}}\right]\left[\frac{1064-3.70(V/S)}{923}\right]$$

where:

t = drying time (day)
k_s = size factor
k_h = humidity factor
V/S = volume-to-surface ratio, and
$\underline{A}$ = cement factor: 0.918 for Type I/II cement and 1.065 for Type III + 20% FA binder which may be used for P(SCC)

Clause C5.4.2.3.3

The CEB-FIP MC90 model[A1] for drying shrinkage can also be used for P(SCC). The model takes into consideration relative humidity, cement factor, compressive strength at 28 days, cross-sectional area, and perimeter, as well as age of concrete at testing and duration of curing before drying.

P(SCC) proportioned with high binder content and low *w/cm* can exhibit autogenous shrinkage of 100 and 350 μstrain. Autogenous shrinkage is mostly affected by binder type and paste volume.

A.2 Construction Specifications

A.2.1 Classification

Clause 8.2 CLASS OF CONCRETE

Clause 8.2.2 Normal-Weight (-Density) Concrete

Eleven classes of normal-weight (-density) concrete are provided for in these specifications as listed in Table 8.2.2-1. A new Class of concrete, P(SCC), is added to Table 8.2.2-1.

[A1] CEB-FIP Model Code, *Design Code 1990*, Comité Euro-International du Béton (1990).

Specifications **Commentary**

Table 8.2.2-1. Classification of normal-weight concrete.

Class of Concrete	Minimum Cement Content	Maximum *w/cm* Ratio	Air Content Range	Size of Coarse Aggregate Per AASHTO M 43 (ASTM D 448)	Size Number	Specified Compressive Strength
	lb/yd³	lb per lb	%	Nominal Size		Ksi at days
P(SCC)	700*	0.45	As specified elsewhere (5.5 ± 1.5% for severe freezing and thawing conditions). Higher air content may be required when using small MSA and/or HRWRA that can lead to relatively large air bubbles)	½ in. – No. 4 or ¾ in. – No. 4 (maximum)	7 or 67	6.0 to 8.0 at 28D or 8.0 to 10.0 at 56D

* total cementitious materials

A.2.2 Material Constituents

Clause 8.3.1 Cements

For Class P(HPC), P(SCC), and Class A (HPC), trial batches using all intended constituent materials shall be made prior to concrete placement to ensure that cement and admixtures are compatible. Changes in the mill, brand, or type of cement shall not be permitted without additional trial batches.

Clause C8.3.1

Selection of cement type depends on the overall requirements for the concrete, such as compressive strength at release and ultimate age, visco-elastic properties, and durability characteristics. Type I/II or Type III cement can be used for P(SCC) designated for precast, prestressed bridge elements. Supplementary cementitious materials can be incorporated to replace part of the cement; for example, 20 percent Class F fly ash or 30 percent slag can be used as part of the total mass of binder for P(SCC) made with Type III cement.

Clause 8.3.3 Fine Aggregate

Fine aggregate for concrete shall conform to the requirements of AASHTO M 6. Fine aggregate should be well-graded concrete sand. It may be beneficial to blend natural and manufactured sands to improve workability and stability, which is critical for P(SCC). Particle size fractions less than 0.005 in. (0.125 mm) should be considered as powder materials in proportioning P(SCC). Such fine content can have marked effect on water and admixture demand, as well as workability of P(SCC).

Clause 8.3.4 Coarse Aggregate

Coarse aggregate for concrete shall conform to the requirements of AASHTO M 80.

Clause C8.3.4

In the design of P(SCC), MSA values are typically smaller than those of conventional vibrated concrete. The MSA depends on the particular application, including reinforcement density, clear spacing between reinforcement and cover, and section minimum dimension. In general, MSA of ½ in. (12.5 mm) is recommended for P(SCC) designated for precast, prestressed bridge elements.

Specifications

Clause 8.3.7 Air-Entraining and Chemical Admixtures

Air-entraining admixtures shall conform to the requirements of AASHTO M 154 (ASTM C 260). In the case of P(SCC), air-entraining admixtures may be used to increase the workability of the concrete and facilitate handling and finishing.

The use of Type F or G HRWRA is essential to achieve P(SCC) fluidity. The HRWRA can be used in combination with water-reducing admixtures or mid-range water-reducing admixtures. Some mid-range water-reducing admixtures may be classified under ASTM C 494 as Type A or F, depending on the applied dosage rate.

Viscosity-modifying admixture (VMA) can be used in P(SCC) to increase stability and robustness. In mixtures with low *w/cm* with sufficient stability, VMA may be incorporated at low concentration to enhance robustness. This can result in concrete less sensitive to small variations in mixture proportioning and material characteristics, including moisture content of sand, as well as mixing conditions and fresh concrete temperature.

If a shrinkage-reducing admixture is specified in the contract documents, verification of the air-void system in the hardened concrete is recommended.

Commentary

Clause C8.3.7

In some cases, high dosage rate of high-range water-reducing admixture (HRWRA), coupled with high fluidity, can make it difficult to ensure fine air-void system in the hardened concrete. Highly flowable concrete of marginal stability can result in loss of entrained air voids and foaming at the surface. Air-entraining admixture that can stabilize small air bubbles should be used, especially in the case of P(SCC), whenever the concrete requires protection from frost action.

Clause 8.3.8 Mineral Admixture

Clause C8.3.8

Pozzolans (fly ash, silica fume) and slag can be used in the production of Class P(HPC), Class A(HPC), and Class P(SCC) concretes for improved durability and to extend the service life.

Fly ash 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. The carbon content in fly ash can affect air entrainment as it absorbs some of the air-entraining admixture and adversely affects the ability to entrain air. Care should be exercised, and frequent tests should be conducted, to verify the presence of sufficient air voids in the concrete.

A.2.3 Mix Design and Proportioning

Clause 8.4.1.1 Responsibility and Criteria

For Class P(HPC), Class A(HPC), and Class P(SCC), 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.

Clause C8.4.1.1

Mix design of P(SCC) is vital for the performance of the material, both in the plastic and hardened stages. In designing P(SCC), a number of factors should be taken into consideration to a greater degree than when designing conventional vibrated concrete:

- Properties of locally available raw materials, including mineral, geometric, and physical properties of aggregates and cementitious materials

Specifications

Commentary

- Need for higher level of quality control, greater awareness of aggregate gradation, and better control of mix water and aggregate moisture
- Choice of chemical admixtures and their compatibilities with the selected binder
- Consideration of placement technique, configuration of cast element, and environmental conditions

Clause 8.4.2 Water Content

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 (a) at the time of placement.

Clause C8.4.2

For P(SCC) member, workability characteristics shown in Table 8.4.2-1 (a) are recommended.

Table 8.4.2-1 (a). Workability characteristics for P(SCC).

Relative values		Slump flow, in.			Slump flow – J-Ring flow, in.		
		23.5–25	25–27.5	27.5–29	3–4	2–3	≤ 2
Low	Reinforcement density	■				■	
Medium	Reinforcement density		■			■	
High	Reinforcement density			■			■
Small	Shape intricacy	■				■	
Moderate	Shape intricacy		■			■	
Congested	Shape intricacy			■			■
Shallow	Depth	■			■		
Moderate	Depth		■			■	
Deep	Depth		■				■
Short	Length	■				■	
Moderate	Length		■			■	
Long	Length		■				■
Thin	Thickness		■				■
Moderate	Thickness		■			■	
Thick	Thickness	■				■	
Low	Coarse aggregate content			■			■
Medium	Coarse aggregate content			■		■	
High	Coarse aggregate content	■			■		

1 in. = 25.4 mm
Shaded areas refer to recommended workability values.

Clause 8.4.3 Cement Content

The minimum cement content shall be as listed in Table 8.2.2-1 or otherwise specified in the contract documents. For Class P(HPC) and P(SCC), the total cementitious materials content shall be specified not to exceed 1000 lb/yd^3 (593 kg/m^3) of concrete.

Clause 8.4.4 Mineral Admixtures

Clause C8.4.4

Mineral admixtures are widely used in concrete in the percentages given. For Class P(HPC), Class P(SCC), and Class A(HPC) concretes, different percentages may be used if trial bathes 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), P(SCC), and A(HPC), which have a 50-percent maximum portland cement replacement.

Specifications

For Class P(HPC), P(SCC), 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. In some cases, limestone filler may be used to replace part of the portland cement or to increase the powder content of SCC. Selected fillers should be uniform in chemical composition and physical characteristics and should not hinder the targeted performance of SCC (workability, strength development, and durability). 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 admixture. The properties of the freshly mixed and hardened concrete shall comply with specified values.

A.2.4 Production, Handling, and Placement

Clause 8.5.4 Batching and Mixing Concrete

Clause 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. The batch size should be determined in consideration of the type of concrete, mixing efficiency of the mixer, volume of concrete to be transported, and shipping rate. The batch volume should be limited to 80 percent of the maximum capacity of the mixer for SCC. This value can be increased for concrete of relatively low fluidity, and final adjustments to concrete deformability are made on site prior to casting.

Clause 8.5.4.2 Mixing

Mixing equipment and mixing sequence should be validated during mix qualification testing of SCC. Necessary adjustments, such as time and energy of mixing, should be carried out until consistent and compliant results are obtained. Insufficient mixing could result in lower fluidity and could hinder the generation of adequate air-void system.

Clause C8.5.5 Delivery

Commentary

Clause C8.5.5

It is essential to ensure that the delivery and placement of SCC be within the workability-retention period of the mixture. SCC can be transported by mixer trucks, tuckerbilts, sidewinders, clam buckets, pumping, or overhead cranes. Mixer trucks are suitable when transporting SCC over rough terrain or long transport distance. During transport, the loads in trucks may be limited to avoid spillage, or mixtures with lower flow can be shipped by holding back the mix water and the admixtures, which then can be added at the job site.

Specifications

Clause 8.5.7 Evaluation of Concrete Strength

Clause 8.5.7.3 For Acceptance of Concrete

Except for Class P(HPC), Class A(HPC), and Class P(SCC) concrete, any concrete represented by a test that indicates a strength that is less than the specified compressive strength at the specified age by more than 0.500 ksi (3.5 MPa) will be rejected and shall be removed and replaced with acceptable concrete. Such rejection shall prevail unless either:

For Class P(HPC), Class A(HPC), and Class P(SCC) concrete, any concrete represented by a test that indicates a strength that is less than the specified compressive strength at the specified age will be rejected and shall be removed and replaced with acceptable concrete.

Clause 8.7 HANDLING AND PLACING CONCRETE

Clause 8.7.3 Placing Methods

Clause 8.7.3.1 General

Because SCC is based on concrete placement without vibratory consolidation, an adequate construction plan should be formulated in consideration of the properties specific to SCC so that the proportioned concrete could be transported and placed while the required self-consolidation is retained. Under normal conditions, P(SCC) has an open time of 35 to 45 minutes (time after the end of mixing where the concrete still satisfies the stipulated flowability, passing ability, and stability requirements). Delays in concrete deliveries between successive lifts may lead to surface crusting, formation of cold joints, and other surface defects given the lack of surface bleeding that is typically encountered in P(SCC).

Commentary

Clause C8.5.7.3

In the case of Class P(SCC) concrete, fresh concrete needs to be tested for its self-consolidating properties. It is recommended that the producer conduct workability tests and make necessary adjustments until consistent and compliant results are obtained. Given that in a precast concrete plant the manufacturing conditions are rather constant, the first three mixtures of a day can be subjected to more complete inspection and routine testing. Subsequent mixtures of similar composition may be subjected to limited and less frequent quality control testing. Nonetheless, every batch should still be visually checked before transportation, then tested for slump flow consistency and T-20 (T-50), and visually checked prior to casting. The Contractor may also elect to verify the passing ability on site by conducting a J-Ring test. In the case that the P(SCC) is air entrained, air volume should be evaluated as per Contract documents.

Clause C8.7.3.1

Placement techniques of SCC can have a significant impact on the required fluidity level and flowing performance. For example, whenever a relatively high energy is available during SCC placement, a lower fluidity level could be possible to achieve the desired consolidation and filling capacity of the cast element. In the case of placement technique involving higher energy, extra care should be taken with regard to stability characteristics.

Some guidelines to the relative level of energy provided during different placement techniques are summarized in Table C8.7.3-1.

Specifications | **Commentary**

Table C8.7.3-1. Relative placement energy associated with different placement techniques for SCC (Daczko and Constantiner, 2001).[A2]

Placement Technique	Discharge Rate	Discharge Type	Single Discharge Volume	Flow Momentum Rating
Truck Chute	High	Continuous	High	High
Pump	Medium/High	Continuous	Medium	High/Medium
Conveyor	Medium	Continuous	High	High
Buggy	Medium	Continuous	Low	Low
Crane and Bucket	High	Discontinuous	Low	Low/Medium
Auger	Low	Continuous	Medium	Medium
Drop Tube	High	Discontinuous	High	High

Placement of SCC in horizontal elements can be done by starting at one end of the mold, with the discharge point close to the form surface. It is recommended to discharge the SCC in the direction of desired flow to maximize the travel distance. To minimize segregation, the free-flow distance of the SCC should be limited to 10 and 33 ft (3 and 10 m), depending on section geometry and level of reinforcement.

Clause 8.7.4 Consolidation

All concrete, except concrete placed under water, Class P(SCC), and concrete otherwise exempt, shall be consolidated by mechanical vibration immediately after placement.

Clause C8.7.4

Mechanical vibration shall not be applied for the consolidation of Class P(SCC) except when delays occur between successive lifts. In this case, extreme care must be taken to minimize any risk of segregation during mechanical consolidation.

Clause 8.11 CURING CONCRETE

Clause 8.11.3 Methods

Clause 8.11.3.5 Steam or Radiant-Heat Curing Method

Clause C8.11.3.5

For Classes P(HPC) and P(SCC) concrete, temperature-sensing devices should be placed within the concrete to verify that temperatures are uniform throughout the concrete and within the limits specified.

[A2]Daczko, J. A., and Constantiner, D., "Rheodynamic Concrete." *Proceedings,* 3rd Congresso Brasileiro do Concreto (IBRACON), paper IV-003, August, Brazil (2001), 15 p.

ATTACHMENT B

Recommended Guidelines for Use of Self-Consolidating Concrete in Precast, Prestressed Concrete Bridge Elements

These proposed guidelines are the recommendations of the NCHRP Project 18-12 staff at the University of Sherbrooke. These guidelines have not been approved by NCHRP or any AASHTO committee nor formally accepted for adoption by AASHTO.

CONTENTS

Introduction

The competitive situation in the precast concrete construction market is significantly affected by price and cost factors as well as by productivity and quality. This environment is characterized by ever-shorter construction times, rising labor costs, as well as greater demand for high workability, strength, and durability. Technological developments and methods of production that can lead to improved concrete quality and savings are therefore becoming increasingly important. Self-consolidating concrete (SCC) represents a significant advancement in concrete technology that provides great potential for efficiency and economy in concrete construction.

SCC is a highly workable concrete that can flow through densely reinforced or geometrically complex structural elements under its own weight without mechanical consolidation and adequately fill the formwork with minimum risk of segregation. The flowability of SCC is higher than that of normal high-performance concrete typically used in precast, prestressed concrete plants. This characteristic of SCC, coupled with the absence of the noise associated with vibration, make SCC a desirable material for fabricating prestressed bridge elements. More specifically, SCC offers the following advantages:

- Simplification of the concreting procedure and ability to produce heavily reinforced precast elements with virtually any cross-sectional shape
- Greater flexibility to produce a wide variety of architectural finishes
- Increased assembly rates and reduced labor for placement, vibration and finishing
- Improved working environment and safety
- Lower capital investment costs and higher service life of the formwork elements
- Improved surface quality with greater uniformity and fewer surface imperfections

Use of SCC in the precast, prestressed applications can result in specific advantages. Complex precast concrete members can be prefabricated with greater ease, speed, economy, and higher surface quality. This can be achieved even in tightly spaced areas or congested reinforcement—such as columns, cap beams, and superstructure elements—and lead to providing uniform and aesthetically pleasing surfaces. The quality control and quality assurance measures used for producing SCC will help achieve structures with the desired durability and service life.

These guidelines provide the information necessary for considering use of SCC in precast, prestressed bridge girders. The guidelines include information on the selection of concrete constituents and proportioning of concrete mixtures, workability characteristics, testing methods, mechanical properties, visco-elastic properties, production and control issues, and durability of SCC.

Glossary

The following definitions may be referred to in these guidelines. Some of them are general and apply to conventional concrete while others are specific to SCC. Some of these definitions are based on definitions given in ACI and PCI technical documents.

Admixture—A material, other than water, aggregates, hydraulic cement, and fiber reinforcement, 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 (ACI 116).

Autogenous shrinkage—The shrinkage occurring in the absence of moisture exchange due to the hydration reactions taking place inside the cement matrix (ACI 209).

Binder—A cementing material, either a hydrated cement or reaction products of cement or lime and reactive siliceous material; also materials such asphalt, resins, and other materials forming the matrix of concretes, mortars, and sanded grouts.

Bingham fluid—A fluid characterized by a yield stress and a constant plastic viscosity, regardless of flow rate (PCI 2003).

Bleed water—The water that rises to the surface subsequent to the placing of the concrete. The rise of mixing water within, or its emergence from, newly placed concrete, caused by settlement and consolidation of the plastic concrete (PCI 2003).

Bleeding test—The standard test for determining the relative quantity of mixing water that will bleed from a sample of freshly mixed concrete (ASTM C 232).

Blocking—The condition in which coarse aggregate particles combine to form elements large enough to obstruct the flow of the fresh concrete between the reinforcing steel or other obstructions in the concrete formwork (PCI 2003).

Cohesiveness—The tendency of the SCC constituent materials to stick together, resulting in resistance to segregation, settlement, and bleeding (PCI 2003).

Consistency—The relative mobility or ability of freshly mixed concrete or mortar to flow (ACI 116).

Consolidation—The process of inducing a closer arrangement of the solid particles in freshly mixed concrete or mortar during placement by the reduction of entrapped voids (ACI 116). In SCC, consolidation is achieved by gravity flow of the material without the need of vibration, rodding, or tamping.

Creep—Time-dependent deformation due to sustained load (ACI 209).

Deformability—The ability of SCC to flow under its own mass and fill completely the formwork.

Drying shrinkage—Shrinkage occurring in a specimen that is exposed to the environment and allowed to dry (ACI 209).

Fillers—Finely divided inert material, such as pulverized limestone, silica, or colloidal substances, sometimes added to portland cement paint or other materials to reduce shrinkage, improve workability, or act as an extender or material used to fill an opening in a form (ACI 116).

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 deformability (ACI 237).

Filling capacity—The ability of SCC to flow into and fill completely all spaces within the formwork.

Flowability—The ability of fresh concrete to flow in confined or unconfined form of any shape, reinforced or not, under gravity and/or external forces, assuming the shape of its container (PCI 2003).

Fluidity—The ease by which fresh concrete flows under gravity (PCI 2003). Fluidity is the reciprocal of dynamic viscosity.

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 (ACI 116). Because of its spherical shape and fineness, fly ash can improve the rheology of SCC.

Formwork pressure—Lateral pressure acting on vertical or inclined formed surfaces, resulting from the fluid-like behavior of the unhardened concrete confined by the forms (ACI 116).

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 (PCI 2003). 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).

High-range water-reducing admixture (HRWRA)—A water-reducing admixture capable of producing large water reduction or greater flowability without causing undue set retardation or entrainment of air in mortar or concrete (ACI 116).

J-Ring test—Test used to determine the passing ability of SCC, or the degree to which the passage of concrete through the bars of the J-Ring apparatus is restricted (ASTM C 1621).

J-Ring flow—The distance of lateral flow of concrete using the J-Ring in combination with a slump cone (ASTM C 1621).

L-box test—Test used to assess the confined flow of SCC and the extent to which it is subject to blocking by reinforcement (ACI 237).

Metakaolin—Mineral admixture used as binding material (supplementary cementitious material) in concrete (PCI 2003).

Mixture robustness—The characteristic of a mixture that encompasses its tolerance to variations in constituent characteristics and quantities, as well as its tolerance to the effects of transportation and placement activities (PCI 2003).

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 (ASTM C 1621).

Paste volume—Proportional volume of cement paste in concrete, mortar, or the like, expressed as volume percent of the entire mixture (ACI 116).

Plastic viscosity—The resistance of the plastic material to undergo a given flow. It 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. It is closely related to T-50 and V-funnel time (higher plastic viscosity: higher T-50 and V-funnel time).

Powder (also referred to as graded powder)—Includes cement, fly ash, GGBFS, limestone fines, material crushed to less than 0.125 mm (No. 100 sieve), or other non-cementitious filler (ACI 237).

Powder-type SCC—SCC mixtures that rely extensively on the amount and character of the fines and powder included in the mixture for meeting workability performance requirements (stability) (PCI 2003).

Pumpability—The ability of an SCC mixture to be pumped without significant degradation of workability (PCI 2003).

Rheological properties—Properties dealing with the deformation and flow of matter (PCI 2003).

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 (ACI 116). 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.

Segregation—The differential concentration of the components of mixed concrete, aggregate, or the like, resulting in non-uniform proportions in the mass (ACI 116). 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.

Segregation resistance—The ability of concrete to remain uniform in terms of composition during placement and until setting (PCI 2003). Segregation resistance encompasses both dynamic and static stability.

Self-consolidating concrete (SCC) (also self-compacting concrete)—A highly flowable, non-segregating concrete that can spread into place, fill the formwork, and encapsulate the reinforcement without any mechanical consolidation (ACI 237).

Service life—The time during which the structure performs its design functions without unforeseen maintenance or repair.

Settlement—The condition in which the aggregates in SCC tend to sink to the bottom of the form resulting in non-homogeneous concrete (PCI 2003). Surface settlement can also be caused by bleeding of free water and loss of air as well as movement of aggregate particles within fresh concrete (consolidation).

Shear stress—The stress component acting tangentially to a plane (ACI 116).

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 (ACI 116). Silica fume can be added to SCC to improve the rheological properties.

Slump flow—Test method used (upright or inverted) to measure mixture filling ability (ASTM C 1611).

Slump flow retention—The ability of concrete to maintain its slump flow over a given period of time.

Slump flow spread—The distance of lateral flow of concrete during the slump-flow test (ASTM C 1611). Slump flow spread is the numerical value in inches (mm) of flow determined as the average diameter of the circular deposit of SCC at the conclusion of the slump flow test.

Stability—The ability of a concrete mixture to resist segregation of the paste from the aggregates (ASTM C 1611).

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.

T-50 measurement (also referred to as the T-20 in. time in North America)—The 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 (ASTM C 1611).

Texture—The pattern or configuration apparent in an exposed surface, as in concrete and mortar, including roughness, streaking, striation, or departure from flatness (ACI 116).

Thixotropy—The property of a material that enables it to stiffen in a short period while at rest, but to acquire a lower viscosity when mechanically agitated, the process being reversible, a material having this property is termed thixotropic or shear thinning (ACI 116). Thixotropy indicates formwork pressure and segregation resistance of SCC.

Transportability—The ability of concrete to be transported from the mixer to the placement site while remaining in a homogeneous condition (PCI 2003).

V-funnel—Device used to determine the time for a given volume of concrete to flow out through a funnel opening (PCI 2003).

Viscosity—The resistance of a material to flow under an applied shearing stress (ASTM 1611).

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 and washout (ACI 237).

Visual Stability Index (VSI)—A test that involves the visual examination of the SCC slump flow spread resulting from performing the slump flow test (ACI 237).

Water-cementitious material ratio (*w/cm*)—The ratio of the mass of water, exclusive only of that absorbed by the aggregate, to the mass of cementitious material (hydraulic) in concrete, mortar, or grout, stated as a decimal (ACI 116).

Workability—That property of freshly mixed concrete or mortar that determines the ease with which it can be mixed, placed, consolidated, and finished to a homogenous condition (ACI 116). For SCC, workability encompasses filling ability, passing ability, and segregation resistance, and it is affected by rheology.

Yield stress—The minimum shear stress required to initiate (static yield stress) or maintain (dynamic yield stress) flow (ACI 237). The yield stress is closely related to slump flow (lower yield stress results in higher slump flow); it is calculated as the intercept of the shear stress versus shear rate plot from rheometer flow curve measurements.

Guidelines | Commentary

B.1 Guidelines for Selection of Constituent Materials

B.1.1 General

The production of SCC requires uniform quality of all constituent materials, and it is therefore necessary that these materials meet standard specifications. A choice of suitable constituent materials is vital to the optimization of SCC mix design for different applications.

Constituent material qualification for SCC designated for precast, prestressed concrete bridge elements generally follows the requirements of AASHTO LRFD Bridge Design [2007] and Construction [1998] Specifications. Except mixing water and materials mentioned in the following Sections B.2.2 to B.2.4, no materials may be incorporated into the concrete without the authorization of the Engineer. It is important to continually check for any change in materials or proportions that will affect surface appearance, strength, or other characteristics of SCC that may affect its overall performance.

B.1.2 Cement and Cementitious Materials

One must ensure that material additions do not adversely affect the desired architectural appearance, where appearance is a design requirement.

B.1.2.1 Cement and Blended Cement

All cements that conform to the AASHTO M 85 or ASTM C 150 standard specifications can be used for the production of SCC. The correct choice of cement type is normally dictated by the specific requirements of each application or by the availability.

For SCC applications where visual appearance is important, adequate cement content and uniform *w/cm* should be adopted to minimize the color variation. Therefore, the cement should be from the same mill and of the same type, brand, and color.

Selection of the type of cement will depend on the overall requirements for the concrete, such as compressive strength at early and ultimate ages, mechanical properties, durability, and color considerations in architectural applications where color and color uniformity are important.

Blended hydraulic cements that conform to the AASHTO M 240 or ASTM C 595M can also be used. Unless otherwise specified, Types I, II, or III cement; Types IA, IIA, or IIIA air-entrained cement; or Types IP (portland-pozzolan cement) or IS (portland blast-furnace slag cement) blended hydraulic cements can be used for the construction of precast, prestressed concrete elements. Types I, II or III cements can be used with some replacements by supplementary cementitious materials and other hydraulic binders. In general, fly ash and slag replacement values shall not exceed 20% and 40%, respectively, to ensure high-early strength for satisfactory release of strands.

The total content of cementitious materials used in prestressed concrete for a 28-day design compressive strength of 4,000 to 8,000 psi (28 to 55 MPa) can vary from 600 to 1,000 lb/yd^3 (356 to 593 kg/m^3) [PCI, 1997]. The AASHTO LRFD Bridge Design Specifications [2007] suggest that the sum of portland cement and other cementitious materials should

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not exceed 800 lb/yd^3 (475 kg/m^3), except for Class P concrete where the total cementitious materials should not exceed 1,000 lb/yd^3 (593 kg/m^3). These values for SCC designated for precast, prestressed applications shall range between 650 and 800 lb/yd^3 (386 and 475 kg/m^3) [ACI Committee 237, 2007 (237R-07)].

B.1.2.2 Fly Ash

Pozzolans and slag meeting ASTM C 618, C 989, or C 1240 are supplementary cementitious material and may be added to portland cements during mixing to produce SCC with improved workability, increased strength, reduced permeability and efflorescence, and improved durability. In general, Class F fly ash has been shown to be effective in SCC providing increased cohesion and robustness to changes in water content [European Guidelines, 2005].

Fly ash should conform to the AASHTO M 295 or ASTM C 618 [AASHTO, 1998, 2007]. In general, the content of cement replaced with fly ash is 18% to 22% by mass [Florida DOT, 2004].

B.1.2.3 Silica Fume

Silica fume conforming to AASHTO M 307 or ASTM C 1240 can be used as supplementary cementitious material in the proportioning of SCC for improved strength and durability. Silica fume also improves resistance to segregation and bleeding. Special care should be taken to select the proper silica fume content.

B.1.2.4 Ground Granulated Blast-Furnace Slag

Ground granulated blast-furnace slag (GGFBS) meeting AASHTO M 302 or ASTM C 989 may be used as supplementary cementitious materials. GGBFS provides reactive fines and due to large replacement rate usually about 40% enables a low heat of hydration.

Cement replacement by GGBFS is based on the severity of the environment to which the concrete is exposed. The level of GGBFS addition is 25% to 70% for slightly and moderately aggressive environments, and 50% to 70% by mass when used in extremely aggressive environments.

When used in combination with silica fume and/or metakaolin, GGBFS content should be limited to 50% to 55% of the total cementitious content, by mass of binder [Florida DOT, 2004]. However, in precast, prestressed members, the amount of slag is usually 40%. GGBFS shall not be used with Type IP or Type IS cements.

Commentary

In some cases, higher level of fly ash replacement may reduce the ability of SCC to flow. The replacement rate of fly ash also affects strength and durability. Contribution of fly ash delays the hydration process and strength development. Fly ash can also affect air entrainment since the carbon present in fly ash can absorb air-entraining admixture and adversely affect the ability to entrain air. Therefore, specific limits on LOI which is indicative of the carbon content need to be stated. Fly ash shall not be used with Type IP or IS cements.

In some cases, a high level of silica fume addition can cause rapid surface crusting that leads to cold joints or surface defects if delays occur in concrete delivery or surface finish (and also increases cost). According to Florida DOT [2004], the quantity of cement replacement with silica fume should be 7% to 9% by mass of cementitious materials.

A high proportion of GGBFS (e.g., exceeding 40%) may however affect stability of SCC resulting in reduced robustness with problems of consistency control while delayed setting can increase the risk of static segregation.

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B.1.2.5 Fillers

The particle-size distribution, shape, and water absorption of fillers may affect the water demand/sensitivity and suitability for use in the production of SCC. Calcium carbonate-based mineral fillers can enhance workability and surface finish. The fraction below 0.005 in. (0.125 mm) shall be of most benefit to SCC flow properties. Contents of fillers should be evaluated to ensure adequate performance of concrete, including strength development and durability.

B.1.2.6 Other Supplementary Cementitious Additions

Metakaolin, natural pozzolan, ground glass, air-cooled slag and other fine fillers have also been used or considered as additions for SCC, but their effects need to be carefully evaluated for both short- and long-term effects on the fresh and hardened concrete.

B.1.3 Aggregate Characteristics

A well-graded combined aggregate with sufficient intermediate sizes is highly desirable for improved stability. Also, if the proper particle shape and texture are selected, combined aggregate grading can lead to large reductions in water, paste, and cement contents leading to improved hardened concrete properties.

The moisture content, water absorption, grading and variations in fines content of all aggregates should be closely and continuously monitored and must be taken into account in order to produce SCC of constant quality. Changing the source of supply for aggregates is likely to make a significant change to the concrete properties and should be carefully and fully evaluated [European Guidelines, 2005].

B.1.3.1 Coarse Aggregate

Unless otherwise specified in the contract documents, the recommendation is to use normal-density coarse aggregate meeting the requirements of AASHTO M 80 or ASTM C 33. The use of continuously graded aggregates is recommended. The nominal maximum-size of coarse aggregate (MSA) should be selected based on mix requirements and minimum clear spacing between the reinforcing steel and prestressing strands, cover of the reinforcement steel, and thickness of the member. The recommendations given in the PCI Bridge Design Manual [1997] apply.

Commentary

Gravel, crushed stone, or combinations can be used as coarse aggregate. In the case of fine aggregate, natural sand or manufactured sand can be used. Coarse and fine aggregates should conform to the grain-size distribution recommendations of the project specifications.

Slightly gap-graded aggregates may lead to greater flowability than continuously graded aggregate. Gap-graded aggregate can, however, increase the risk of bleeding and segregation, and proper measures are needed to ensure adequate static stability of the concrete.

In the design of SCC, typically the MSA values are smaller than those of conventional vibrated concrete. The MSA is generally limited to 1/2 to 3/4 in. (12.5 to 19 mm). In the placement of SCC in highly congested and restricted section, MSA value of 3/8 in. (9.5 mm) can be used.

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Commentary

If aggregates susceptible to alkali-aggregate reactivity are used, special precautions must be observed. These include the use of low-alkali cement, blended cements, or pozzolans and GGBFS.

B.1.3.2 Fine Aggregate

For normal weight concrete, fine aggregates conforming to AASHTO M 6 are appropriate for the production of SCC. The fine aggregate component should be well-graded concrete sand.

Fine aggregates for SCC should conform to the gradation requirements of AASHTO M 6 or ASTM C 33, as presented in Table B.1.

It may be beneficial to blend natural and manufactured sand to improve plastic properties of SCC. Common concrete sand, including crushed or rounded sand and siliceous or calcareous sand, can be used in SCC.

Table B.1. Grading requirements for fine aggregates.

Sieve	Percent passing (AASHTO M 6)	Percent passing (ASTM C 33)
⅜ in. (9.5 mm)	100	100
No. 4 (4.75 mm)	95 to 100	95 to 100
No. 8 (2.36 mm)	80 to 100	80 to 100
No. 16 (1.18 mm)	50 to 85	50 to 85
No. 30 (600 µm)	25 to 60	25 to 60
No. 50 (300 µm)	10 to 30	5 to 30
No. 100 (150 µm)	2 to 10	0 to 10

Particle size fractions of less than 0.005 in. (0.125 mm) should be considered as powder material in proportioning SCC. Such fine content can have marked effect on rheology.

B.1.4 Chemical Admixtures

Chemical admixtures are used in precast, prestressed concrete to reduce water content, improve filling ability and stability, provide air entrainment, accelerate strength development, enhance workability retention, and retard setting time.

Because chemical admixtures can produce different results with different binders, and at different temperatures, the selection of the admixtures should be based on the plant materials and conditions that will be utilized in production.

For prestressed concrete, chloride-ion content in chemical admixtures should be limited to 0.1%, by mass of the admixture [AASHTO, 2004].

Incompatibility of admixtures with binders can lead to improper air void system and delayed or accelerated setting time. Therefore, before the start of the project, concrete with the job materials, including the admixtures, should be tested to ensure compatibility. Such testing should be repeated whenever there is a change in the binder and admixtures.

B.1.4.1 High-Range Water-Reducing Admixtures

High-range water-reducing admixtures (HRWRA) shall conform to the requirements of ASTM C 494 Type F (water-reducing, high range) or G (water-reducing, high range, and retarding) or ASTM C 1017. The admixture should enable the required water reduction and fluidity during transport and placement.

The use of Type F or G HRWRA is essential to achieve SCC fluidity. Such HRWRA can be used in combination with reg-

The required consistency retention will depend on the application. Precast concrete is likely to require a shorter retention time than cast-in-place concrete.

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ular water-reducing admixtures or mid-range water-reducing admixtures. There are mid-range water-reducing admixtures that may be classified under ASTM C 494 as Type A or F depending on dosage rate.

B.1.4.2 Viscosity-Modifying Admixtures

Use of a viscosity-modifying admixture (VMA) for SCC proportioned with *w/cm* higher than 0.40 is recommended to ensure stability of the fresh concrete. Starting with a low dosage rate of VMA, the rate should be gradually increased to establish the dosage rate that provides the desired level of stability.

VMA should not be added to SCC as a means for improving a poor mix design or poor selection of materials. High dosage of VMA may lead to increased HRWRA demand and in some cases, some delay in setting, and development of early-age mechanical properties.

VMAs are used in SCC to enhance segregation resistance and to enhance robustness by minimizing the effect of variations in aggregate moisture content, temperature, etc. This can make the SCC less sensitive to small variations in the proportioning and characteristics of material constituents.

There are currently no ASTM specifications for VMA. Producers should confirm by trial mixtures that VMA does not adversely affect the hardened concrete properties.

B.1.4.3 Air-Entraining Admixtures

Air-entraining admixtures shall conform to the requirements of AASHTO M 154 or ASTM C 260. Air-entraining admixtures are used in concrete primarily to increase the resistance of the concrete to freeze-thaw damage. Proper selection of air-entraining admixture that can stabilize small bubbles and properly formulated HRWRA that does not cause a large number of coarse air bubbles are needed to design the SCC with an adequate air-void system.

In some cases, high dosage of HRWRA coupled with the high fluidity of the mixture can make it difficult to ensure the entrainment of a fine, stable air-void system in the concrete. HRWRA can also entrain coarse air bubbles. Compatibility evaluation between the air-entraining admixture and HRWRA is therefore needed to achieve the targeted air-void characteristics.

B.1.4.4 Set-Retarding and Set-Accelerating Admixtures

An ASTM C 494 Type D set-retarding admixture may be used during hot weather concreting or when a delay in setting is required, subject to acceptance by the Engineer. Some water-reducing admixtures at high dosage rates can act as retarding admixtures. They should be used with caution. Set-accelerating admixture (Type C) shall be used to decrease setting time and increase the development of early-age mechanical properties. The admixture is particularly beneficial in precast concrete construction to facilitate early form removal and release of prestressing [PCI, 1997].

In the absence of accelerated radiant heat or steam curing, the use of set-accelerating admixture in SCC may be beneficial in precast applications when using HRWRA, especially the polynaphthalene- or melamine-based products.

B.1.4.5 Shrinkage-Reducing Admixtures

If a shrinkage-reducing admixture is specified in the contract documents, verification of the air-void system, including air content in hardened concrete, spacing factor, and specific surface, is recommended. It could be difficult to entrain

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air and large dosages of air-entraining admixture are needed when a shrinkage-reducing admixture is used.

B.1.4.6 Other Admixtures

Corrosion-inhibiting admixtures can be incorporated to protect the reinforcement from corrosion. Producers should confirm by trial mixtures that the addition of any admixture does not adversely affect the hardened concrete properties.

Coloring pigments used in SCC shall conform to the requirements of ASTM C 979. All coloring admixtures required for a project shall be ordered in one lot and shall be finely ground natural or synthetic mineral oxide or an organic phthalocyanine dye with a history of satisfactory color stability in concrete [European Guidelines, 2005].

The use of corrosion-inhibiting admixtures may hinder the efficiency of other admixtures and cause non-uniformity in color of the concrete surface (darkening and mottling). There are currently no AASHTO or ASTM specifications for corrosion-inhibiting admixtures.

B.1.5 Fibers

Synthetic and steel fibers (hybrid fiber) can be used. The dosage rates of the fiber in SCC ranges between 0.25% and 0.50%, by volume, depending on the type of applications. The dosage of fibers should be determined given the workability requirements of the mixtures, which should take into consideration element characteristics and placement conditions. Changes in mixture proportioning may be needed to secure good passing ability and filling capacity of the fiber-reinforced SCC.

The incorporation of synthetic fiber is recommended to reduce the risk of cracking due to restrained or plastic shrinkage. The dosage of synthetic fiber should not exceed the 0.50%, by volume, when casting complex and narrow sections or densely reinforced structures.

B.2 Guidelines for Selection of Workability Test Methods

B.2.1 General

Workability describes the ease with which concrete can be mixed, placed, consolidated, and finished. It describes the filling properties of fresh concrete in relation to the behavior of concrete in the production process. Workability of SCC is described in terms of filling ability, passing ability, and stability (resistance to segregation) and is characterized by data that relates to specific testing methods [ACI Committee 237, 2007]. Various test methods have been used to assess the workability characteristics of SCC. In general, test methods include the components required for evaluating simultaneously the filling ability, passing ability, and static stability. Table B.2 summarizes some of the main test methods proposed for the evaluation of workability of SCC.

B.2.2 Filling Ability

B.2.2.1 Significance

The ability of SCC to flow into and fill completely all spaces within the formwork, under its own weight, is of great

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Table B.2. Key workability characteristics of SCC.

	Test methods	Applicable standard
Filling ability	Slump flow and T-50	ASTM C 1611
Passing ability	L-box	
	J-Ring	ASTM C 1621
	V-funnel	
Filling capacity	Combining filling and passing abilities	
Static stability	Surface settlement	
	Column segregation	ASTM C 1610
	Visual stability index	ASTM C 1611

importance to SCC casting, distance between filling points, etc. [ACI Committee 237, 2007].

B.2.2.2 Test Methods to Assess Filling Ability

Slump flow test [ASTM C 1611] is used to assess the horizontal free flow of SCC in the absence of obstruction. The test method is based on the test method for determining the slump of a normal concrete. The diameter of the concrete circle is a measure of the flowability of the SCC.

B.2.2.3 Special Issues

Advantages and precautions of slump flow and T-50 flow test methods are presented in Table B.3.

Commentary

The filling capacity combines the filling and passing abilities of SCC and can be tested using the caisson filling capacity [Yurugi et al., 1993].

In general, slump flow varies from 23.5 to 29 in. (600 to 735 mm) for SCC used in precast, prestressed applications [Khayat et al., 2007]. When slump flow test is performed, the time needed for the concrete to spread 20 in. (500 mm) is also noted. This test is called T-50 flow time.

Table B.3. Advantages and precautions of slump flow test and T-50.

Slump flow	
Advantages	**Precautions**
o Simple o Reproducible o Results correlate to yield stress o Low sensitivity to water content o Can be performed by a single operator	o Roughness and moisture of base plate affect results o Large base plate is required to perform test o Must be performed on level surfaces
T-50	
o Results correlate to plastic viscosity o Can be performed simultaneously with slump flow using a second operator	o Sensitive to roughness and moisture of base plate o Poor single- and multi-operator repeatability o High error for low-viscosity mixtures

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B.2.3 Passing Ability

B.2.3.1 Significance

The passing ability tests evaluate the ability of concrete to pass among various obstacles and narrow spacing in the formwork without local aggregate segregation in the vicinity of the obstacles that give rise to interlocking and blockage of the flow in the absence of any mechanical vibration [ACI Committee 237, 2007].

B.2.3.2 Test Methods to Assess Passing Ability

The J-Ring test [ASTM C 1621] can be used to assess the restricted deformability of SCC through closely spaced obstacles [Bartos, 1998].

In general, the maximum difference between slump flow and J-Ring flow varies from 2 to 3 in. (50 to 75 mm) depending on the filling ability (slump flow) of the mixture. A difference between slump flow and J-Ring flow less than 1 in. (25 mm) indicates good passing ability and no visible blocking of the concrete. A difference greater than 2 or 3 in. (50 or 75 mm), depending on the slump flow value, reflects blocking of the concrete.

In the L-box test, the vertical part of the box is filled with concrete and left at rest for 1 minute. The gate separating the vertical and horizontal compartments is then lifted, and the concrete flows out through closely spaced reinforcing bars at the bottom. The time for the leading edge of the concrete to reach the end of the long horizontal section is noted. The heights of concrete remaining in the vertical section and at the leading edge are determined. The blocking ratio (h_2/h_1) is calculated to evaluate the self-leveling characteristic of the concrete.

A blocking ratio of 0.5 and higher is indicative of adequate passing ability. Higher values are necessary in densely reinforced and thin sections.

The V-funnel apparatus consists of a V-shaped funnel with an opening of 2.55 × 3.0 in. (65 × 75 mm) at its bottom. The funnel is filled with concrete, then after 1 minute, the gate is opened and the time taken for concrete to flow through the apparatus is measured. In the case of structural applications, the V-funnel flow time lower than 8 seconds indicates good passing ability [Hwang et al., 2006].

B.2.3.3 Special Issues

Advantages and precautions of the slump flow and J-Ring flow test, L-box, and V-funnel methods are presented in Table B.4.

B.2.4 Filling Capacity

B.2.4.1 Significance

The property to completely fill intricate formwork or formwork containing closely spaced obstacles is critical for SCC to achieve adequate in-situ performance. SCC with high

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Commentary

Table B.4. Advantages and precautions of J-Ring, L-box, and V-funnel flow test.

J-Ring	
Advantages	**Precautions**
o Simple o Good repeatability o Can be performed by a single operator o Material segregation can be visually detected	o Roughness and moisture of base plate affect results o Large base plate is required to perform the test o Must be performed on level surfaces
L-box	
o Good repeatability o Can be performed by a single operator o Flow time correlates to plastic viscosity	o Must be performed on level surfaces
V-funnel	
o Can be performed by a single operator o Flow time correlates to plastic viscosity	o Poor repeatability o Risk of flow interruption in high-viscosity mixtures

filling and passing abilities can achieve good filling capacity and spread into a predetermined section to fill the formwork under the sole action of gravity without segregation and blockage [ACI Committee 237, 2007].

B.2.4.2 Test Method to Assess Filling Capacity

The filling capacity test provides a small-scale model of a highly congested section and is suitable to evaluate the filling capacity and its self-consolidating characteristics [Ozawa et al., 1992; Yurugi et al., 1993].

For the caisson test, the maximum size aggregate (MSA) is limited to 3/4 in. (19 mm). In general, a filling capacity higher than 70% is recommended for SCC used in precast, prestressed applications.

B.2.4.3 Special Issues

Advantages and precautions of the caisson filling capacity test are presented in Table B.5.

Table B.5. Advantages and precautions of filling capacity test.

Filling capacity	
Advantages	**Precautions**
o Good repeatability o Good indicator of filling capacity, which combines filling ability and passing ability of SCC o Visual appreciation of filling capacity through congested sections	o Difficult to perform by single operator o Requires some calculation to evaluate filling capacity

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B.2.5 Static Stability

B.2.5.1 Significance

Static stability refers to the resistance of concrete to bleeding, segregation, and surface settlement after casting while the concrete is still in a plastic state [ACI Committee 237, 2007].

B.2.5.2 Test Methods to Assess Static Stability

The surface settlement test method can be used to evaluate the surface settlement of SCC from a plastic state until the time of hardening [Manai, 1995]. In general, a maximum surface settlement lower than 0.5% or a rate of settlement after 30 minutes lower than 0.27% per hour is recommended for SCC used in precast, prestressed bridge elements.

The static stability of SCC can also be determined using the column segregation test [ASTM C 1610]. The coefficient of variation of the aggregate among the column sections can be taken as a segregation index (I_{seg}) [Assaad et al., 2004]. Another index consisting of the percent static segregation (S) can be obtained by measuring the difference between aggregate mass at the top and bottom sections of the column.

The visual stability index (VSI) involves visual examination of SCC prior to placement and after performance of the slump flow test. It is used to evaluate the relative stability of batches of the same or similar SCC mixtures. The VSI procedure assigns a numerical rating of 0 to 3, in 0.5 increments. The VSI test is most applicable to SCC mixtures that tend to bleed [Daczko and Kurtz, 2001].

Commentary:

The surface settlement test enables the quantification of the effect of mixture proportioning on static stability. The settlement is monitored until a constant value is achieved.

The column segregation test consists of casting concrete in a column divided into four sections along the concrete sample. From each section, the concrete is weighed and washed out. Then, the coarse aggregate content is determined for each section.

In general, a segregation index (I_{seg}) lower than 5% or a percent of static segregation (S) lower than 15% is recommended for SCC used in precast, prestressed bridge elements.

The test can be considered as a static stability index when it is observed in a wheelbarrow or mixer following some period of rest time (static condition). VSI value of 0 to 1 is recommended for SCC for precast, prestressed concrete bridge elements.

B.2.5.3 Special Issues

Advantages and precautions of surface settlement and column segregation tests are presented in Table B.6.

B.2.6 Dynamic Stability

B.2.6.1 Significance

Adequate resistance of concrete to separation of constituents upon placement and spread into the formwork is required for SCC when flowing through closely spaced obstacles and narrow spaces to avoid segregation, aggregate interlock, and blockage [ACI Committee 237, 2007].

B.2.6.2 Test Methods to Assess Dynamic Stability

The caisson test measures the filling capacity indicative of the filling and passing abilities; therefore, it is a good indicator of the dynamic stability.

Commentary:

Concrete with high filling ability (deformability) and good passing ability can achieve adequate filling capacity in restricted and congested sections that are typical precast, prestressed applications. An adequate combination of filling and passing ability tests can be used to evaluate the filling capacity of the concrete, which is indicative of the dynamic stability.

Table B.6. Advantages and precautions of surface settlement and column segregation tests.

Advantages	Precautions
Surface settlement test	
o Easy to perform in laboratory o Good repeatability o Maximum settlement can be estimated from rate of settlement between 25 and 30 min	o Requires a dial gage o Difficult to perform by a single operator o Requires large amount of concrete
Column segregation test	
o Good correlations between column I_{seg} and S	o Requires electronic balance o Requires large amount of concrete o Difficult to perform by a single operator o Repeatability lower than surface settlement
Visual stability index	
o Simple o Can be performed by a single operator	o Depends on operator experience o SCC with low VSI may exhibit some lack of stability

B.2.7 Rheology

B.2.7.1 Significance

Generally, two key parameters are determined when a rheology measurement test is performed: the yield stress, τ_0, and plastic viscosity, μ_p.

Below the yield stress value, the mixture does not undergo any deformation and behaves as an elastic material. In SCC, the yield stress should be maintained low enough to ensure good deformability.

The plastic viscosity of concrete affects its ease of placement and speed of flow. In practice, good balance between yield stress and plastic viscosity should be achieved to ensure both good deformability, ease of placement, and flow rate of SCC.

B.2.7.2 Test Methods to Assess Rheological Parameters

Rheological parameters of concrete can be determined using a concrete rheometer. In general, the test involves recording the shear stress response to maintain a given rate of shear at different shear rate values.

A linear regression of the data is usually used to determine the rheological parameters (τ_0 and μ_p) according to the Bingham model.

B.2.7.3 Special Issues

Advantages and limitations of rheometer testing are presented in Table B.7.

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Commentary

Table B.7. Advantages and limitations of rheometer testing.

Rheometer	
Advantages	**Limitations**
o Easy to perform in laboratory o Good repeatability, especially for plastic viscosity o Provides fundamental flow properties of SCC o Enables evaluation of structural build-up of SCC at rest	o Expensive apparatus, though portable and more affordable models are available o Requires qualified personnel to operate and interpret data

B.3 Guidelines for Mix Design

B.3.1 General

The mix design is chosen to satisfy all performance criteria for the concrete in both the fresh and hardened states. As in the case of conventional vibrated concrete, the *w/cm* is one of the fundamental keys governing strength and durability of SCC. The *w/cm* of the concrete shall not exceed 0.45 by weight [AASHTO, 2004]. Satisfactory performance of the proposed mix design shall be verified by laboratory tests on trial batches. For mix design approval, a minimum of three test cylinders are taken from a trial batch. The average compressive strength shall be at least 1,200 psi (8.3 MPa) greater than the specified compressive strength when the specified strength is equal to or less than 5,000 psi (34.5 MPa). The average strength shall be at least 700 psi (4.8 MPa) greater than 110% of the specified strengths over 5,000 psi (34.5 MPa) [ACI Committee 318, 2005 (318R-05)].

B.3.2 Mix Design Principles

Mix design of SCC is vital for the performance of the material, both in the plastic and hardened states. In designing SCC, a number of factors should be taken into consideration to a greater degree than when designing conventional vibrated concrete:

- Properties of raw materials, including mineral, geometric, and physical properties of aggregates and cementitious materials
- Need for a higher level of quality control, greater awareness of aggregate gradation, and better control of mix water and aggregate moisture
- Choice of chemical admixtures and their compatibilities with the selected binder
- Placement technique, configuration of cast element, and environmental conditions

Any mix design approach should consider both the fresh and hardened properties of the SCC, and include the characteristics of cementitious materials and fillers, the water content or *w/cm,* the volume of coarse aggregate, the sand-to-aggregate ratio (S/A), as well as the air content. The selection of the type and combinations of chemical admixtures is part of the mix design process and depends closely on the flow characteristics that are required.

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As illustrated in Figure B.1, the fresh properties of SCC are dictated by the required flow characteristics of the fresh concrete in addition to engineering properties and durability requirements.

Commentary

For the production of SCC for precast, prestressed concrete bridge elements, the most relevant hardened properties that affect material selection and mix design include early and ultimate compressive strengths, flexural strength, elastic modulus, bond-to-reinforcement, creep, shrinkage, frost durability, impermeability, and resistance to corrosion.

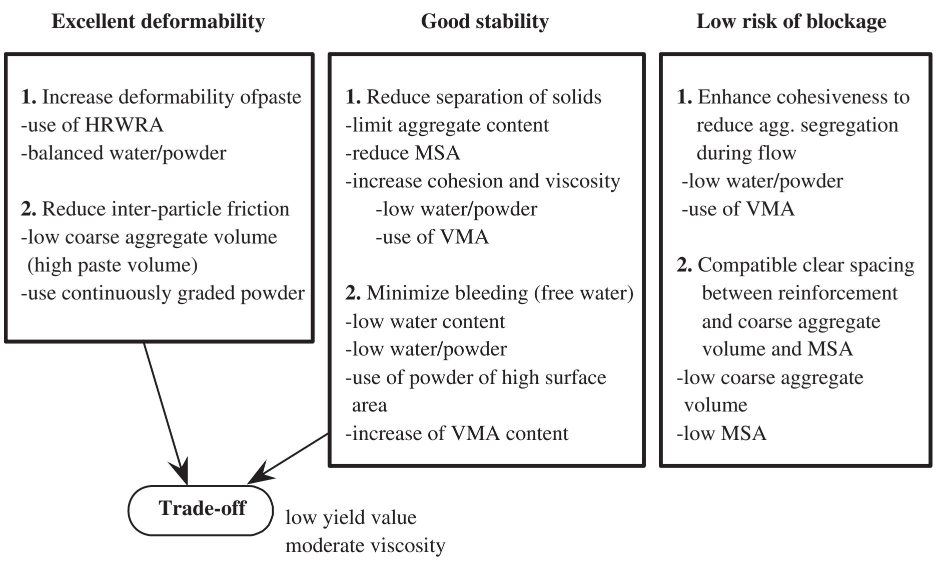

Figure B.1. Principles of SCC mix design [Khayat, 1999].

SCC used for structural precast, prestressed applications is typically characterized by relatively low water content, high concentration of ultra-fine particles (i.e. ≤ 80 μm), and use of an efficient HRWRA (typically polycarboxylate based, although other types are also used). SCC made with polycarboxylate-based HRWRA can usually exhibit short setting time, high early-strength development, and reduced tendency to segregation.

In principle, three approaches can be used for the production of SCC:

- Increase of the ultra-fines content by using fly ash, blast-furnace slag, limestone filler (powder type), and in some cases low content of silica fume
- Use of suitable viscosity-modifying admixture (VMA) (viscosity agent type)
- A combination of the above approaches (combination type) where low concentration of VMA is used in SCC of high fines/powder content

These approaches are highlighted below.

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B.3.2.1 Minimum Free Water Content

This approach entails the use of high content of ultra-fine materials and low water content to enhance the filling ability, passing ability, and stability of the SCC. Such concrete typically has a *w/cm* of 0.30 to 0.35 with a content of ultra-fines ≤ 80 μm (approximately No. 200 sieve) of 845 to 1,110 lb/yd³ (500 to 600 kg/m³) [Okamura, 1997; Ozawa et al., 1992].

The replacement of part of the cement with a less reactive powder is necessary to limit the heat of hydration, and minimize volumetric changes. In general, this approach can result in SCC mixtures with low yield value and moderate-to-high viscosity. The concrete requires a relatively high dosage of HRWRA.

B.3.2.2 Moderate Water Content and Medium Concentration of VMA

In this approach, the *w/cm* can be maintained at the level necessary to satisfy strength and durability requirements (for example *w/cm* of 0.40). A moderate dosage of VMA is then incorporated to secure the required stability.

When incorporated in mixtures with relatively high paste content (exceeding 35% and sand-to-cement ratio of 0.60 to 0.66, by volume), the use of suitable VMA-HRWRA combination can ensure high deformability and adequate stability also leading to greater filling capacity and better in-situ homogeneity than mixtures made with low *w/cm* and no VMA [Khayat, 1998].

The incorporation of VMA becomes imperative when the powder content is reduced to levels comparable with those of conventional concrete or high-performance concrete.

B.3.2.3 Low Water Content and Low Concentration of VMA

This approach involves the combination of a high content of powder materials and low dosage of VMA. Such mixtures are typically more robust than those proportioned with high powder content and low *w/cm.*

A robust mixture can react less sensitively to fluctuations in the mixture composition, characteristics of the raw materials, water content, and concrete temperature.

B.3.3 Cementitious Materials Content and Water-Cementitious Material Ratio

The concrete supplier shall determine the cementitious materials content and *w/cm* required to satisfy the specified concrete category. In general, the cementitious materials content recommended for SCC ranges between 650 and 800 lb/yd³ (386 and 475 kg/m³) [ACI Committee 237, 2007 (237R-07)]. The *w/cm* ranges from 0.32 to 0.45.

Special care should be taken to select the binder composition of the SCC made with low *w/cm* to limit the compressive strength to the target value. Otherwise, high strength and stiffness could lead to cracking given the high degree of restrained shrinkage that can take place.

B.3.4 Nominal Size of Coarse Aggregate

Select MSA based on mix requirements and minimum clear spacing between the reinforcing steel, cover to reinforcement, and thickness of the member. Use coarse aggregate with MSA of ½ to ¾ in. (12.5 to 19 mm), unless otherwise specified in the contract documents. Coarse aggregate of ⅜ in. (9.5 mm) MSA shall be used for casting highly reinforced and restricted sections.

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B.3.5 Air-Entrainment and Air-Void Stability

Generally, SCC made with polynaphthalene sulfonate (PNS)-based HRWRA can exhibit a relatively stable air-void system. The use of polycarboxylate ether (PCE)-based HRWRA can lead in some cases to entrapment of large air bubbles, especially if the SCC is subjected to prolonged mixing or agitation after the introduction of such HRWRA. The introduction of shrinkage-reducing admixture (SRA) may also have significant effect on the air-void system since it makes proper air-entrainment of the concrete more difficult.

B.3.6 Mixture Robustness

During the mixture qualification process, an investigation is recommended into the robustness of the particular design of SCC to fluctuations in the characteristics of concrete constituents. In addition, it is desirable to investigate the effect of slump flow variation on stability for a particular mix design and set of materials.

A well-designed and robust SCC can typically accept a change of 8.5 to 17 lb/yd^3 (5 to 10 L/m^3) in water content without falling outside the specified classes of performance [European Guidelines, 2005].

B.3.7 Trial Batches

SCC mix design shall require a minimum of four trial batches for varying cementitious materials or *w/cm* to establish the proportions that can achieve workability ranges and robustness: two water contents above and two below the target value. The following information shall be included in the trial batch data:

- Source of all materials
- Specific gravity and gradation results for sand and coarse aggregate
- Design slump flow range
- Target air content and design strength
- Details of mixture proportioning, including admixture dosage rates for design slump flow range
- SCC trial mixture test results for QC testing
- Mixer used for the mix design, mixing sequence, charging sequence, and mixing time

B.3.8 Recommended Range of Workability Characteristics

The use of proven combinations of test methods and performance-based specifications is necessary to reduce time

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SCC mixtures are more sensitive to the variations in the properties and conditions of constituent materials and quantity fluctuations during production. Fluctuations in raw materials, such as gradations and moisture contents of aggregates, and batching fluctuation can have dramatic influence on the flowability and the stability of the concrete.

Well-designed SCC can give acceptable tolerance to daily fluctuations in ingredients characteristics and environmental changes, such as temperature. This tolerance is usually termed "robustness" and is controlled by good practice in the selection and proportioning of ingredients and the storage and handling of basic constituents, by appropriate content of the fine powders, and/or by use of VMA [European Guidelines, 2005].

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and effort required for the development and quality control of high-performance SCC. A set of performance-based specifications of SCC is summarized in Table B.8. Such specifications also include test methods recommended for material selection and mix design that can be performed when developing the concrete mixture as well as quality control (QC) test methods that can be performed for concrete acceptance at the precasting plant.

Table B.8. Recommended workability characteristics for mix design and QC testing at precasting plant.

Property	Test method	Target values	Design	QC
Filling ability	Slump flow T-50 (ASTM C 1611)	23.5–29 in. (600–735 mm) 1.5–6 s	√	√
Passing ability	J-Ring flow (ASTM C 1621)	21.5–26 in. (545–660 mm)	√	√
	L-Box blocking ratio (h_2/h_1)	0.5–1.0	√	√
Filling capacity	Filling capacity	70%–100%	√	
	Slump flow and J-Ring flow tests			√
	Slump flow and L-Box tests			√
Static stability	Surface settlement	Rate of settlement, 25–30 min (value can decrease to 10–15 min) - MSA of ⅜ and ½ in. (9.5 and 12.5 mm) ≤ 0.27%/h (Max. settlement ≤ 0.5%) - MSA of ¾ in. (19 mm) ≤ 0.12%/h (Max. settlement of 0.3%)	√	
	Column segregation (ASTM C 1610)	Column segregation index (C.O.V.) ≤ 5% Percent static segregation (S) ≤ 15%	√	
	VSI (ASTM C 1611)	0–1 (0 for deep elements)	√	√
Air volume	AASHTO T 152	4%–7% depending on exposure conditions, MSA, and type of HRWRA. Ensure stable and uniform distribution of small air voids.	√	√

Specific requirements for SCC in the fresh state may change depending on the type of application and especially on:

- Confinement conditions related to the element geometry, congestion level of reinforcement, inserts, cover, etc.
- Placing equipment (e.g., bucket, pump, direct from truck-mixer, skip, tremie)
- Placing method (e.g., number and position of delivery points)
- Finishing method

As indicated in Table B.9, the performance-based specifications for the workability of SCC should take into consideration the cast element characteristics and coarse aggregate content.

B.3.9 Quality Confirmation of SCC

Regardless of the mix design approach, laboratory trials should be used to verify properties of the initial mixture

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Table B.9. Workability values of SCC used in precast/prestressed applications.

			Slump flow (ASTM C1611/C1611 M-05)			J-Ring (Slump flow– J-Ring flow) (ASTM C1621)			L-box blocking ratio (h_2/h_1)			Caisson filling capacity		
Relative values			23.5-25 in.	25-27.5 in.	27.5-29 in.	3-4 in.	2-3 in.	≤ 2 in.	0.5-0.6	0.6-0.7	≥ 0.7	70%-75%	75%-90%	≥ 90%
Element characteristics	Low	Reinforcement density	■				■			■			■	
	Medium			■			■			■			■	
	High				■			■			■			■
	Small	Shape intricacy	■				■			■			■	
	Moderate			■			■			■			■	
	Congested				■			■			■			■
	Shallow	Depth	■			■				■		■		
	Moderate			■			■				■		■	
	Deep			■				■			■			■
	Short	Length	■				■			■			■	
	Moderate			■			■			■			■	
	Long			■				■			■			■
	Thin	Thickness		■				■			■			■
	Moderate			■			■			■			■	
	Thick		■				■			■			■	
	Low	Coarse aggregate content			■			■		■			■	
	Medium				■		■			■			■	
	High		■			■					■			■

1 in. = 25.4 mm

Shaded zones indicate suggested workability characteristics. All SCC mixtures must meet requirements for static stability.

composition with respect to the specified characteristics and classes. If necessary, adjustments to the mixture composition should be made. Once all requirements are fulfilled, the mixture should be tested at full scale in the concrete plant to verify fresh and hardened concrete properties.

In case that satisfactory performance is not obtained, consideration should be given to a fundamental redesign of the mixture. Depending on the apparent problem, the following courses of action might be appropriate [European Guidelines, 2005]:

- Adjust the cement to powder ratio and the water to powder ratio and test the flow and other properties of the mixture.
- Try different types of cementitious materials (if available).

Given the same raw material sources and the same 28-day compressive design strength, the engineering properties of SCC should be similar to those of conventional high-performance concrete. For mix design qualification of hardened properties,

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- Adjust the proportions of the fine aggregate and the dosage of HRWRA.
- Adjust the proportion or grading of the coarse aggregate.
- Consider using a VMA to enhance the robustness of the mixture.

Mock-ups are recommended to confirm the production methods and to test the resulting mixture characteristics. If there is any sign of deficiency that impairs the concrete performance, such as segregation, sedimentation, cold joints, or any other visual defects, perform the saw-cut of the mock up products to verify the aggregate distribution along the saw-cut area.

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modulus of elasticity, shrinkage, and creep testing should be performed.

The lower *w/cm* of SCC will normally provide a higher 28-day compressive strength than conventional concrete with normal consistency used in similar applications. The actual strength attained should be used as the basis for the engineering properties.

B.4 Guidelines for Early-Age and Hardened Properties

B.4.1 General

The quality of SCC in terms of strength and durability is expected to be equal to or better than that of a similar specified conventional concrete mixture.

B.4.2 Setting

Typically, SCC used in precast, prestressed applications proportioned with low *w/cm* requires a high dosage of HRWRA. The setting time increases with the increase in HRWRA dosage. Set-accelerating admixtures or heat (steam or radiant) curing may be needed to decrease the setting time and increase the early strength development.

SCC made with Type I/II cement is shown to have lower HRWRA demand than that with Type III cement with 20% Class F fly ash. The latter concrete can then exhibit longer setting time. The use of VMA increases the HRWRA demand and may lead to some set retardation.

The initial and final setting times can be as low as 4 to 6 hours and 5 to 7 hours, respectively. These values depend on the materials in use, including HRWRA type and dosage, binder composition, as well as temperature. Greater setting times can be obtained when using naphthalene- or melamine-based HRWRA. The difference between initial and final setting time (ASTM 403–05) can range between 1 and 3 hours for SCC used in precast, prestressed applications proportioned with w/cm of 0.34 and 0.40, and Type I/II cement or Type III cement with 20% of fly ash replacement [Khayat et al., 2007]. Setting time of SCC can be determined by using AASHTO T 197.

B.4.3 Temperature Development

In general, SCC proportioned with high cement content or with Type III cement can lead to considerable temperature rise.

SCC made with Type III cement with 20% Class F fly ash can develop comparable heat rise as that of SCC made with Type I/II cement. SCC proportioned with 0.34 *w/cm* has longer time to attain maximum temperature than SCC made with 0.40 *w/cm*. This is mainly due to higher HRWRA concentration of the former concretes. For a given *w/cm,* the use of VMA delays cement hydration, thus extending time to attain peak temperature.

Typical temperature development of SCC proportioned with *w/cm* of 0.34 and 0.40, cement content of 742 and 843 lb/yd^3 (440 to 500 kg/m^3), and Type I/II and Type III cement with 20% of fly ash lie in the range of 115 to 125°F (46 to 52°C)

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after 48 hours under semi-adiabatic condition. The maximum temperature can range from 126 to 145°F (52.2 to 62.8°C). The time to reach maximum temperature is in the range of 17 to 28 hours [Khayat et al., 2007].

B.4.4 Release Compressive Strength

For precast applications, SCC mixtures are typically proportioned with 0.32 to 0.36 *w/cm* [ACI Committee 237, 2007]. The upper range may be increased to 0.40 depending on the concrete temperature and mixture compositions. Relatively low *w/cm* can lead to higher compressive strength compared with conventional slump concrete.

The minimum specified compressive strength for prestressed concrete bridge elements and decks is 4,000 psi (27.6 MPa) [AASHTO, 1998]. Typically, compressive strength at release of the prestressing strands of structural AASHTO type girders is on the order of 5,000 psi (34.5 MPa) after 18 hours of casting. The typical 56-day compressive strength is set at 8,000 to 10,000 psi (55 to 69 MPa).

Release strength should be achieved within 18 hours after the concrete is cast into place. The targeted release strength is selected so that the strength of the concrete in the prestressed beam does not exceed 60% of the design concrete compressive strength at the time of release (before any losses due to creep and shrinkage) [PCI, 1997]. This value is limited to 55% in the case of post-tensioned members. Maturity testing can be considered as an effective way to monitor strength development at early age whether accelerated heating is used or not.

ACI 209 and CEB-FIP MC90 models can be used to estimate f'_c:

ACI 209

$$(f'_c)_t = \frac{t}{A + Bt}(f'_c)_{28d}$$

$(f'_c)_t$ = compressive strength of concrete at a given time t (in psi);
$(f'_c)_{28d}$ = 28-day compressive strength of concrete;
t = age of concrete (in days);

16 non-AEA SCC + 4 AEA SCC + 2 HPC:
Type I/II cement (moist-cured):
A = 1.52; B = 0.92; R^2 = 0.95

Type III + 20% FA (moist-cured):
A = 1.64; B = 0.91; R^2 = 0.90

16 non–air-entrained SCC:
Type I/II cement (moist-cured):
A = 1.70; B = 0.90; R^2 = 0.97

SCC made with polycarboxylate-based HRWRA can develop higher early compressive strength and ultimate strength than similar SCC made with naphthalene- or melamine-based HRWRA. The use of VMA can increase the HRWRA demand and could lead to reduction in early strength development.

Type III cement with supplementary cementitious materials (for example 20% of fly ash or 30% slag) is shown to attain greater release strength than SCC made with Type I/II cement. Initial curing with heat (steam or radiant) may then be necessary, especially for SCC proportioned with relatively low *w/cm* by reason of high dosage of HRWRA demand causing retardation. The use of finely ground limestone filler can also enhance compressive strength development at early age. Finely ground fillers and supplementary cementitious materials can lead to a denser hardened cement matrix and a denser interfacial transition zone with aggregate and embedded reinforcement. This can lead to greater strength and durability.

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Type III + 20% FA (moist-cured):
A = 2.15; B = 0.89; $R^2 = 0.95$

CEB-FIP MC90

$$f_{cm}(t) = \exp\left[s\left(1-\left(\frac{28}{t/t_1}\right)^{1/2}\right)\right]f_{cm}$$

$f_{cm}(t)$ = mean compressive strength at t days (in psi);
f_{cm} = mean 28-day compressive strength;
s = coefficient depending on cement type (0.20 for high early-strength cement, 0.25 for normal-hardening cement, and 0.38 for slow-hardening cement);
t_1 = 1 day.

16 non-AEA SCC + 4 AEA SCC + 2 HPC:
$s = 0.19$ Type I/II cement; $R^2 = 0.95$

$s = 0.20$ Type III + 20% FA; $R^2 = 0.92$

16 non–air-entrained SCC:
$s = 0.20$ Type I/II cement; $R^2 = 0.95$

$s = 0.23$ Type III + 20% FA; $R^2 = 0.93$

B.4.5 Flexural Strength

For precast and structural civil engineering applications, SCC mixtures are typically proportioned with relatively low *w/cm* of 0.32 to 0.36 and with supplementary cementitious materials and fillers and are expected to achieve higher flexural strength and flexural-to-compressive ratio than conventional slump concrete [ACI Committee 237, 2007].

The flexural strength can be determined by testing in accordance with ASTM C 293 and C 78-02 or can be estimated from the compressive strength. For SCC used for precast, prestressed applications, the flexural strength can be estimated with the AASHTO 2007 model, given by:

$$f_r = 0.97\sqrt{f_c'}$$

f_c' = specified compressive strength of concrete (MPa)

The flexural strength of SCC depends on the *w/cm,* coarse aggregate volume, and quality of the interface between the aggregate and cement paste. The curing method of SCC can significantly influence the flexural strength. Moist-cured specimens can exhibit higher flexural strength because the samples do not develop surface drying that could lead to premature microcracking development.

B.4.6 Modulus of Elasticity

In applications where the modulus of elasticity (MOE) is an important design parameter, the MOE should be determined and considered in the design of the prestressed concrete member. In the absence of measured data, the equation proposed by the AASHTO LRFD Bridge Design Specifications [2007] is recommended to estimate the elastic modulus

The MOE is used to calculate camber of prestressed members at the release of the prestressing load, elastic deflections, axial shortening and elongation, and prestress losses.

The MOE is related to the compressive strength of the concrete, type and content of aggregate, as well as unit weight of the concrete. The modulus of elasticity is related to compressive

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of concrete having a unit weight of 2,427 to 4,214 lb/yd^3 (1,440 and 2,500 kg/m^3) and specified compressive strength of up to 15,230 psi (105 MPa). For an accurate prediction, determine the MOE in conformance with ASTM C 469 using the job-specific materials.

The modulus of elasticity for SCC used for precast, prestressed applications can be estimated using the AASHTO 2007 equation:

$$E_c = 0.043\gamma_c^{1.5}\sqrt{f_c'}$$

γ_c = unit weight of concrete (kg/m^3);
f_c' = specified compressive strength of concrete (MPa)

strength and unit weight of the concrete, aggregate type and content, and testing parameter, including loading rate, moisture and temperature conditions of the test specimen, as well as specimen size and shape. The content and MOE of the aggregate have the largest influence on the MOE of the concrete.

Selecting an aggregate with high modulus of elasticity will increase the modulus of elasticity of the concrete. Increase in sand-to-coarse aggregate ratio can decrease the modulus of elasticity of the concrete.

In some cases, SCC mixtures can develop modulus of elasticity that can be up to 20% lower than typical values found in high-performance concrete of normal consistency, which is mainly due to the lower coarse aggregate volume, increase in paste content, and higher content of ultra-fine materials. At equivalent strength, SCC made with different cement types should develop similar modulus of elasticity when cured and tested under identical conditions.

B.4.7 Creep

Incorrect or inaccurate design for creep and shrinkage may have important undesirable consequence on stability and performance of the structure.

In applications where creep characteristics are important design parameters, this aspect should be considered in the design and confirmed for the mixture used in the production of precast members.

Perform creep testing in accordance with ASTM C 512 using the job-specific materials. The age when the load is applied affects creep values. For SCC used in precast, prestressed elements load should be applied at an early age corresponding to prestress release time.

In the absence of measured data, the modified AASHTO 2007 prediction model can be used to predict the creep of SCC.

AASHTO 2007

$$\psi(t,t_i) = 1.9k_{vs}k_{hc}k_f k_{td}t_i^{-0.118} \times A$$

in which: $k_{vs} = 1.45 - 0.0051(V/S) \geq 0.0$
$k_{hc} = 1.56 - 0.008H$

$$k_f = \frac{35}{7+f_{ci}'}, k_{td} = \left(\frac{t}{61-0.58f_{ci}'+t}\right)$$

where:

H = relative humidity (%). In the absence of better information, H may be taken from Figure 5.4.2.3.3-1 of AASHTO Bridge Design Specifications [2007].
k_{vs} = factor for the effect of the volume-to-surface ratio of the component
k_f = factor for the effect of concrete strength

Length changes of prestressed members due to time-dependent deformation, creep, and shrinkage play a crucial role in the design of concrete structures and on structural behavior, especially at long term.

Creep behavior is related to the compressive strength of the matrix, coarse aggregate type, relative content of aggregate, as well as magnitude of applied load and age of loading. Creep takes place in the cement paste and is influenced by the capillary porosity of the paste. Cement type and *w/cm* can affect creep. High early-strength cement can lead to lower creep. The presence of aggregate restrains creep deformation in the paste. Therefore, an increase in the volume and elastic modulus of the aggregate can lower creep.

Due to the higher volume of cement paste and fines and smaller MSA of SCC, creep potential of SCC can be higher than conventional concrete made with the same raw materials and having the same 28-day design compression strength.

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k_{hc} = humidity factor for creep
k_{td} = time development factor
t = maturity of concrete (day). Defined as age of 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 when load is initially applied (day)
V / S = volume-to-surface ratio (mm)
f'_{ci} = specified compressive strength of concrete at time of prestressing for pretensioned members and at time of initial loading for non-prestressed members. If concrete age at time of initial loading is unknown at design time, f'_{ci} may be taken as 0.80 f'_{ci} (MPa)
A = factor for the effect of cement type: 1.19 for Type I/II cement and 1.35 for Type III + 20% FA binder which may be used for P(SCC)

B.4.8 Autogenous Shrinkage

SCC and conventional concrete used in precast applications proportioned with relatively low *w/cm* (0.32 to 0.36) and high content of cement and supplementary cementitious materials could exhibit high autogenous shrinkage. This is especially the case when capillary porosity is refined when using silica fume. Cement type has a considerable effect in the development of autogenous shrinkage. Higher surface area of the cement can activate the reactivity of the binder, hence increasing the degree of autogenous shrinkage.

Autogenous shrinkage corresponds to the macroscopic volume reduction due to cement hydration (chemical shrinkage) as well as self-desiccation of the cement paste. The volume of the hydration products is less than the original volume of unhydrated cement and water. Such reduction in volume can lead to tensile stresses in the cement paste and microcracking. The reduction of relative humidity in capillary pores due to cement hydration can also result in negative pressure in the capillary pores, leading to the formation of meniscus and the development of tensile stresses in the cement paste.

In the case of concrete proportioned with high *w/cm* (higher than 0.40), autogenous shrinkage is low given the ample presence of water in capillary pores.

B.4.9 Drying Shrinkage

In prestressed applications, shrinkage should be considered in the mix design and taken into consideration in the structural design of the member. Proportion SCC with relatively low binder content and *w/cm* to reduce drying shrinkage.

Drying shrinkage can be evaluated in accordance with ASTM C 157 (AASHTO T 160). In the absence of measured data, the modified AASHTO 2004 or CEB-FIP MC90 shrinkage models can be used to estimate drying shrinkage of SCC, as indicated below. For steam cured concretes devoid of shrinkage-prone aggregates, the strain due to shrinkage, ε_{sh}, at time, t, may be taken as:

Drying shrinkage must be taken into consideration to avoid cracking and excessive deflection resulting from time-dependent concrete deformation and loss of prestress. Drying shrinkage is caused by the loss of water from the concrete to the atmosphere. The increased volume of paste in SCC and reduction in aggregate content and size can increase the potential for drying shrinkage. The presence of aggregate restrains shrinkage of the cement paste; therefore, the increase in aggregate volume reduces drying shrinkage. A decrease in the MSA can necessitate higher paste volume, thus leading to higher shrinkage. Drying shrinkage increases with the increase in powder material content, which is particularly high in SCB.

The use of fly ash in normal proportions does not significantly influence drying shrinkage of concrete. The use of limestone powder with Blaine fineness greater than that of

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AASHTO 2004

$$\varepsilon_{sh} = -k_s k_h \left(\frac{t}{55+t}\right) \times 0.56 \times 10^{-3} \times A(\text{steam-cured})$$

$$k_s = \left[\frac{\dfrac{t}{26e^{0.0142(V/S)}+t}}{\dfrac{t}{45+t}}\right]\left[\frac{1064-3.70(V/S)}{923}\right]$$

t = drying time (day)
k_s = size factor
k_h = humidity factor
V/S = volume-to-surface ratio
A = cement factor: 0.918 for Type I/II cement and 1.065 for Type III + 20% FA binder which may be used for P(SCC)

CEB-FIP MC90

$$\varepsilon_{cso} = \varepsilon_s(f_{cm})(\beta_{RH})\sqrt{\frac{(t-t_c)}{\left(350\left(\dfrac{2A_c}{100\mu}\right)^2+(t-t_c)\right)}}$$

$\varepsilon_s(f_{cm}) = [160 + 10\beta_{sc}(9 - 0.1 f_{cm})] \times 10^{-6}$
$\beta_{RH} = -1.55\beta_{ARH}$; $\beta_{ARH} = 1 - (RH/100)^3$
ε_{cso} = drying shrinkage (mm/mm)
ε_s = drying shrinkage obtained from RH-shrinkage chart
β_{sc} = cement type factor
β_{RH} = relative humidity factor
f_{cm} = mean 28-day compressive strength (MPa)
A_c = cross-sectional area (mm^2)
μ = perimeter (mm)
t_c = age at which drying commenced (day)
t = age of concrete (day).

portland cement can reduce drying shrinkage of SCC. This can be explained by the denser matrix obtained when fine limestone powder is used [Holschemacher and Klug, 2002].

The effect of HRWRA and VMA on shrinkage of SCC is reported to be beneficial. Indeed, the use of HRWRA reduces the surface tension of the water, thus decreasing the capillary tension of pore water [Ulm et al., 1999; Acker, 1988; Acker and Bazant, 1998; Neville, 1981; Wittman, 1976; Neville and Meyers, 1964]. However, the air content may increase when using polycarboxylate-based HRWRA, which could lead to greater shrinkage.

B.4.10 Durability and Air-Void System

It is essential to proportion SCC with adequate stability to ensure high performance, including durability, of the hardened concrete. The durability of a concrete structure is closely associated to the permeability of the surface layer and curing. The most significant durability characteristics affecting the durability of SCC used in precast, prestressed elements production include: *w/cm*, cement content, degree of consolidation, curing, cover over the reinforcement, and reactivity of aggregate-cement combinations.

Bridge structures constructed in environments prone to freezing and thawing may become critically saturated, thus necessitating air entrainment when exposed to cycles of freezing and thawing. In some cases, the bridge deck can shelter

Segregation and bleeding have significant negative effect on permeability and quality of the interfacial zone between cement paste and aggregate, embedded reinforcement, and existing surface, and hence on durability of the concrete.

Higher air content (6% to 9%) may be necessary in most severe frost environments, especially when using polycarboxylate-based HRWRA, which could result in some entrapment of relatively large air voids. Coalescence of small air bubbles during agitation can occur when high air contents are obtained and when concrete is retempered with water.

The dosage of AEA in SCC prepared with polycarboxylate-based HRWRA can be quite low compared with values used for conventional concrete of normal consistency. Still, it is

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some of the precast beam elements, thus reducing the rate of saturation and exposure to any deicing salt applied on the bridge deck. In most cases, bridge girders can be considered to be subjected to moderate exposure conditions that correspond to situations where deicing salts are not used or where the concrete is only occasionally exposed to moisture prior to freezing and do not get critically saturated. Therefore, under these conditions, prestressed bridge girders require sufficient air content for moderate exposure conditions. For example, under these conditions, SCC proportioned with 1/2 in. (12.5 mm) nominal MSA would then require 4% to 7% air volume in the fresh concrete to provide adequate frost resistance.

ASTM C 457 can be used to test the air-void parameters of the concrete, and ASTM C 666, Procedure A (AASHTO T 161, Method A), is used to test resistance to freezing and thawing.

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critical to incorporate an AEA in concrete subjected to moderate frost exposure conditions to secure stable and closely spaced air bubbles (adequate spacing factor). In general, for mixtures made with a relatively low content of cementitious materials and a high *w/cm,* the air-void stability increases when a VMA is incorporated [Khayat, 1995].

Air entrainment is necessary to stabilize small, closely spaced, and well-distributed voids in concrete. Such voids can be obtained when the SCC is proportioned with an effective AEA that is compatible with the HRWRA and other chemical admixtures in use.

B.4.11 Bond to Prestressing Strands

Ensuring proper stability of SCC is essential to ensure homogenous in-situ properties, including bond to embedded reinforcement, which is critical for structural performance of precast, prestressed applications [Moustafa, 1974; Logan, 1997].

In general, adequate concrete cover is necessary to properly transfer bond between prestressed tendons and concrete.

Despite the high fluidity of SCC, high static stability of the SCC after placement can lead to more homogenous in-situ properties and denser matrix at the interface between the cement paste and reinforcement, thus enhancing bond strength compared with normal conventional concrete subjected to mechanical vibration. On the other hand, bond can be significantly affected by excessive segregation found in poorly designed SCC. As indicated in Table B.10, in order to secure adequate static stability, the SCC should have maximum surface settlement of 0.5%, column segregation index of 5%, or percent static segregation of 15%.

Bond between the strand and concrete is affected by the position of the embedded reinforcements and quality of the cast concrete. Bond to prestressed tendons can be influenced by the flow properties of the SCC, grading of the aggregate and content of fines in the matrix [Holschemacher and Klug, 2002].

A surface settlement of 0.5% corresponds to 1.4 modification factor of prestressing strands [Khayat et al., 1997; Petrov et al., 2001]. It is important to note that selection of highly viscous SCC can result in some lack of consolidation of the concrete, which can in turn affect bond stresses between the concrete and prestressing strand.

Table B.10. Recommendations to secure homogenous in-situ properties of SCC.

Material properties	Recommended values
Static stability	Maximum surface settlement ≤ 0.5% Column segregation index (I_{seg}) ≤ 5% Percent static segregation (S) ≤ 15%
Viscosity	Plastic viscosity ≤ 0.0725 psi·s (500 Pa·s) *(Modified Tattersall two-point rheometer with vane device)*
Mechanical properties	Core-to-cylinder compressive strength ≥ 90% (similar curing conditions) Bond strength modification factor ≤ 1.4

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B.5 Guidelines for Production and Control

B.5.1 General

The need for adequate quality control is much more critical with SCC than in the case of conventional concrete. In order to maintain a given workability, it is essential to maintain constant quality of all concrete constituent during SCC production. Successful production of SCC requires greater competence and proper control of materials and equipments used for production.

SCC intended for use in precast plants should meet the technical requirements of the fresh concrete. The mixture needs to be tested to ensure that required properties are achieved given the performance specifications, casting conditions, and geometry of the cast element. Before selecting the raw material and finalizing the mix design, several factors should be known, including the size and shape of elements to be cast.

Laboratory trials should be used to validate the material selection and verify the properties of the mix design to achieve the targeted properties. Once the optimum properties are achieved, proper quality control for material properties should be observed to eliminate fluctuations in fresh and hardened properties of the concrete. Any changes in raw materials properties should be immediately identified to allow necessary adjustments of the mix to meet the specified properties.

B.5.2 Control of Raw Materials

Depending on the mix design, SCC may be less robust than conventional concrete. SCC may therefore undergo greater changes in workability given small variations in the physical properties of its constituents, especially in the moisture content of the sand, fine particle content in sand, as well as grading and shape of the sand and coarse aggregate. This would necessitate frequent controls to check for any changes in material properties that could affect the performance of SCC.

The maximum deviation of the sand moisture should not exceed ± 0.2% in order to minimize the variations in fresh properties of SCC. The water content of sand should be determined just before production of SCC.

Changes in coarse aggregate physical characteristics (shape, texture, gradation) can affect workability. Inspection at the storage location should be conducted on coarse aggregate to characterize their physical characteristics for every aggregate delivery.

The moisture content, water absorption, aggregate gradation, and variations in fines content of the aggregate should be continuously monitored and must be taken into account to produce SCC with constant characteristics. Changing the source of supply for aggregate is likely to significant change the concrete properties and should be carefully and fully evaluated [European Guidelines, 2005].

It is preferable to control the moisture of sand before every batch of SCB. The moisture content in coarse aggregate must be also taken into account and should be determined at least twice a day, at the beginning of the first and second production shifts.

When designing SCC, some factors should be taken into consideration to a greater degree than when designing conventional concrete to ensure good filling capacity, such as the geometry configuration of cast elements and placement conditions. Indeed, the nominal maximum size of coarse aggregate should be selected based on mix requirements and the minimum clear spacing between the reinforcing steel, cover to reinforcing steel, and thickness of the member. The thickness of the cast element and the congestion level of the reinforcement are key factors affecting workability of SCC.

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B.5.3 Mixing Process and Sequence

The mixing process should be properly determined given the conditions at hand. For example, the batch volume should be determined in consideration of the type of SCC (consistency level), efficiency of the mixer to produce a well-dispersed and homogeneous mix, and transportation rate from the plant to the casting site.

Just prior to mixing of the first batch, the mixer should be pre-wetted or "buttered" with SCC of approximately similar consistency.

Suitable mixing sequence should be determined given the mixing and storage equipments available at the plant. Cement particles should be wetted before contact with HRWRA. Dry mixing before water introduction is not recommended, because it may lead to build-up of fine materials in the mixer. All batching water should be added at the same time. For example, it has been shown that the introduction of VMA at the end of the mixing sequence and of air-entraining admixture at the beginning can provide good performance [Khayat 1995; Khayat and Assaad, 2002]. The addition sequence of VMA should be evaluated given the mix design and admixture in use.

The batch volume is typically limited to 80% to 90% of the maximum capacity of the mixer to allow efficient mixing energy [JSCE, 1999]. When the mixer is alternatively used for mixing normal concrete and SCC, testing should be performed to verify that this does not result in any adverse effect on SCC properties.

Mixing equipment and mixing sequence should be validated by testing consistency and self-consolidation properties for a given mix design. Necessary adjustments to time and speed of mixing should be carried out until consistent and compliant results are obtained.

B.5.4 Transport

SCC should be delivered in a continuous and timely manner to ensure continuous placement of precast members with the workability-retention period of the mixture. This is necessary to avoid lift lines and other surface defects.

Transport method shall be confirmed in order to provide SCC at the casting location that is sufficiently homogeneous to allow successful placement in the precast element and to achieve the targeted properties. Mixer trucks have proven to be the best method of delivery of SCC when transporting over rough terrain or long transport distance [PCI, 2003].

B.5.5 Site Acceptance of Plastic Concrete

The producer should determine the frequency of performing quality control testing based on available experience mixtures [PCI, 2003].

The quality control tests should include visual inspection of every batch of the concrete and any specific tests and compliance parameters. For example, the slump flow and VSI tests can be adopted. The T-50 can also be run at least once on new mixtures and used to check the performance in the event of mix performance problems.

Quality control for frequently used SCC is less critical than in the case of SCC that is occasionally produced.

B.5.6 Placement Techniques and Casting Considerations

Prior to the production process, full-size mock-ups should be cast for final approval. Placement method should be selected

In a placement case that will require multiple batches, mixing facilities are required to ensure that concrete will be

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given the production capacity and transport rate to the casting point.

Placement techniques should be selected based on the total volume of the concrete to be discharged, the transportation rate, and whether the placement process is continuous or discontinuous.

In the case of placement technique involving higher energy, extra care should be taken with regard to stability characteristics. Relative energy involved during each placement technique is summarized in Table B.11 [PCI, 2003].

available within a short time frame with proper workability characteristics as specified in performance specifications.

Placement techniques of SCC can have a significant impact on the required fluidity level and flowing performance of the concrete. For example, in the case of higher energy involved during placement, lower fluidity level for the SCC will be required to achieve a given flow and filling performances.

Table B.11. Summary of different placement techniques for SCC [Bury and Bühler, 2002].

Placement technique	Discharge rate	Discharge type	Single discharge volume	Relative energy delivered
Truck discharge	High	Continuous	High	High
Pumping	Medium/High	Continuous	Medium	High/Medium
Crane and bucket	High	Discontinuous	Low	Medium
Auger (Tuckerbuilt) discharge	Low/Medium	Continuous	Medium	Low/Medium

Placement of SCC in horizontal elements can be done by starting at one end of the mold, with the discharge as close to the form surfaces as possible. It is recommended to discharge the SCC in the direction of desired flow to maximize the travel distance. The recommended maximum flowing distance should be between 10 and 33 ft (3 and 10 m), depending on the geometry of the element [RILEM, 2000].

As in the case of conventional concrete, the free-fall distance should be controlled to avoid concrete segregation. For example, based on the Norwegian experience, the free-fall distance should be limited to 6.5 ft (2 m) when casting wall and beam elements.

Free-fall distance should be fixed given the element depth to be cast and static and dynamic stability of the concrete.

B.5.7 Temperature Control

The mix design should be tailored to achieve the targeted properties specified in the performance specifications. When the use of steam curing is required to achieve the targeted early-age strength, the temperature of the concrete should not exceed 160°F (71°C) [AASHTO, 1998]. Furthermore, according to the AASHTO LRFD Bridge Construction Specifications [1998], the temperature within the curing chamber shall increase at a rate not exceeding 72°F (22°C) per hour.

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B.5.8 Formwork Considerations and Lateral Pressure

Formwork for SCC can be constructed of different materials, including wood, steel, plastic, fiberglass, or combination of these materials. Formwork made with wood often leads to less pores and bubble formation than smooth formwork. Because of the high fluidity of SCC compared with conventional concrete, formwork should be rigid enough with accommodate variations in product dimensions and form, and to withstand lateral form pressure exerted by the plastic concrete.

Given the high fluidity of SCC compared with conventional concrete, extra care should be taken to avoid any leakage. Formwork joints should be adequately sealed. Vegetable oil has been shown to be a good release agent as it reduces the amount of pores on the concrete surface [Brite-EuRam, 1998].

Before applying the release agent, the wood of the formwork should be dry to ensure good release performance and avoid appearance of air-bubbles at the formed surface of the cast element.

Depending on the casting rate and thixotropy of SCC, lateral pressure can be lower than the theoretical hydrostatic pressure. This is especially the case when the casting rate exceeds 10 ft/h (3 m/h).

Lateral pressure can be 50% to 80% of the calculated pressure for conventional vibrated bridge concrete with a slump consistency of 4 in. (100 mm) [RILEM, 2000].

Experience has shown that for a given casting rate, concrete with a higher level of thixotropy can develop lower lateral pressure, faster decay in lateral pressure, and shorter time to pressure cancellation [Assaad et al., 2004]. SCC cast at 16 ft/h (5m/h) is shown to develop maximum initial lateral pressure of 90% of hydrostatic pressure. In general, sections measuring up to 10 ft (3 m) in height should be designed for full hydrostatic pressure.

Lateral pressure developed by SCC cast from the top of the formwork is lower than in the case when the concrete is pumped from the bottom. SCC pumped from the bottom should be designed for full hydrostatic pressure.

B.5.9 Finishing

Finishing of SCC is easier and faster than for conventional concrete. Finishing practices employed with conventional concrete can be employed with SCC. However, finishing operations should be delayed slightly more than for conventional superplasticized concrete [PCI, 2003].

Given the concrete properties and ambient conditions, some surfaces may require only nominal screeding and floating, while other surfaces may require mild vibratory screeding [ACI Committee 237, 2007; PCI, 2003].

Surface drying during finishing should be prevented. Fog misting to increase the relative humidity would minimize rate of evaporation and reduce the risk of plastic shrinkage.

SCC exposed surfaces may dry faster than those of normal superplasticized concrete. This can happen when casting at hot temperature or windy conditions. Also, depending on the SCC mixture proportioning, stiffening can increase rapidly in the period 10 to 40 minutes after casting. Setting time of the SCC mixture should be adjusted to allow necessary time to carry out the placement process.

Because of the relatively higher content of fines and eventual presence of VMA, SCC mixtures develop little or no bleed water compared with conventional concrete.

It is important to begin the finishing of the surface with light vibrating screeds, or other manual equipment, as soon as the correct level of the concrete in the formwork has been reached.

B.5.10 Curing

Membrane curing, matting, foils, or appropriate materials should be left in place for at least 4 days for cast-in-place

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concrete elements [Swedish Concrete Association, 2002]. This measure should be applied to SCC with low *w/cm* and SCC made with high fines content or VMA. During hot or windy weather conditions, moisture should be added by watering or by protecting the surface with wetted membranes for proper curing.

AASHTO LRFD Bridge Construction Specifications [1998] recommend that for concrete cured by other than steam or radiant heat methods, whenever there is a probability of air temperature below 36°F (2°C) during the curing period, the concrete shall be maintained at a temperature of not less than 45°F (7°C) for the first 6 days after placement. This period must be extended if pozzolans are used as partial replacement of cement. If the compressive strength of 65% of the specified 28-day design strength is achieved in 6 days, an extended period of controlled temperature may be waived [AASHTO, 1998].

Due to the specification in terms of early-age compressive strength, steam curing or radiant heat curing can be used for precast concrete members. The initial application of steam or heat shall be from 2 to 4 hours after the initial placement of concrete to allow the initial set of the concrete to take place [AASHTO, 1998]. In the case of concrete incorporating a set retarder, the waiting period shall be increased to between 4 and 6 hours after casting.

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During the waiting period, the temperature within the curing chamber shall not be less than 10°C. During the application of steam, the ambient temperature within the curing chamber shall not increase at an average rate greater than 22°C/h until the targeted temperature value is reached.

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ATTACHMENT C

Recommended Standard Test Methods

These proposed test methods are the recommendations of the NCHRP Project 18-12 staff at the University of Sherbrooke. These test methods have not been approved by NCHRP or any AASHTO committee nor formally accepted for the AASHTO Specifications.

CONTENTS

Recommended Standard Method of Test for

Filling Capacity of Self-Consolidating Concrete Using the Caisson Test

AASHTO Designation: T XXX

1. SCOPE

1.1 This test method covers the determination of filling capacity of self-consolidating concrete.

1.2 The test method is limited to self-consolidating concrete having a nominal size aggregate of 1 in. [25 mm].

1.3 The values stated in either inch-pounds or SI units are to be regarded separately as standard. Within the text, the SI units are shown in brackets. The values stated in each system are not exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance with the standard.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations to use.*

Warning—Fresh hydraulic cementitious mixtures are caustic and may cause chemical burns to skin and tissue upon prolonged exposure (Note 1).

Note 1—The safety precautions given in the *Manual of Aggregate and Concrete Testing*, located in the related section of Volume 04.02 of the *Annual Book of ASTM Standards*, are recommended.

1.5 The text of these standard reference notes provides explanatory material. These notes (excluding those in tables and figures) shall not be considered as requirements of the standard.

2. REFERENCED DOCUMENTS

2.1 *AASHTO Standards*
- R 39, Making and Curing Concrete Test Specimens in the Laboratory
- T 141, Sampling Freshly Mixed Concrete

2.2 *ASTM Standards*
- C 125, Terminology Relating to Concrete and Concrete Aggregates
- C 1621, Standard Test Method for Passing Ability of Self-Consolidating Concrete by J-Ring

3. TERMINOLOGY

3.1 *Definitions*
- For definitions of terms used in this test method, refer to Terminology C 125

3.2 *Definitions of Terms Specific to This Standard*
- Filling ability–The ability of self-consolidating concrete to flow under its own mass and completely fill formwork (ACI 237).
- Passing ability–The ability of self-consolidating concrete to flow under its own weight (without vibration) and fill completely all spaces within intricate formwork containing obstacles, such as reinforcement (ASTM C 1621).
- Filling capacity–The ability of self-consolidating concrete to flow and completely fill all spaces within the formwork.

4. SUMMARY OF THE TEST METHOD

4.1 The caisson filling capacity test is used to assess the filling capacity of the self-consolidating concrete. Self-consolidating concrete is introduced from tremie pipe equipped with hopper at a constant rate in a container with obstacles until the concrete rises in the caisson to a height of 9 in. [225 mm]. The area occupied by the concrete in the restricted section is used to calculate the filing capacity.

5. SIGNIFICANCE AND USE

5.1 This test method provides users with a laboratory procedure to determine the potential filling capacity of self-consolidating concrete.

5.2 This test method shall be used to develop self-consolidating concrete mixtures with a high level of workability. Self-consolidating concrete is a fluid concrete that can be prone to segregation if not proportioned to be cohesive. A cohesive self-consolidating concrete is important for all applications but is especially critical for deep and highly reinforced sections.

6. APPARATUS

6.1 *Caisson*—The caisson measuring 19.7 × 11.8 × 5.9 in. [500 × 300 × 150 mm] L × H × W in dimension shall have a flat and smooth surface. In the container are 35 obstacles made of copper with a diameter of 0.6 in. [16 mm] and a distance center to center of 2 in. [50 mm], as shown in Fig. 1.

6.2 *Measuring Device*—Ruler, metal roll-up measuring tape, or similar rigid or semi-rigid length-measuring instrument marked in increments of 0.25 in. [5 mm] or less.

6.3 *Sample Receptacle*—The receptacle shall be a heavy gage metal pan, wheelbarrow, or flat, clean non-absorbent board of sufficient capacity to allow easy remixing of the entire sample with a shovel, trowel, or scoop.

6.4 *Tremie Pipe*—The tremie pipe shall have a minimum diameter of 3.94 in. [100 mm].

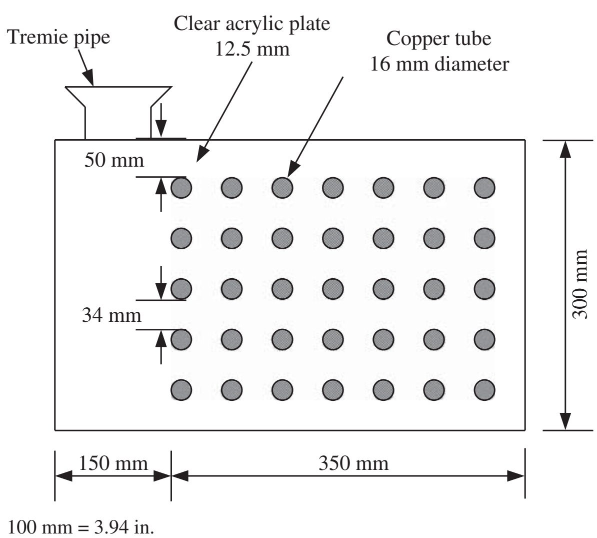

Figure 1. Details of caisson.

7. SAMPLE

7.1 Obtain a sample of freshly mixed self-consolidating concrete in accordance with Test Method T 141 and place it in the sample receptacle in accordance with Practice R39.

8. PROCEDURE

8.1 Perform the filling capacity test on a flat, level surface. Do not subject the testing surface to any vibration or disturbance.

8.2 *Remixing of Sample*—Remix the sample obtained in accordance with Section 7.1 in the sample receptacle using a shovel or scoop so that the concrete is homogeneous.

8.3 *Filling the Mold*—Using a bucket, fill the caisson with concrete at a constant rate of approximately 0.7 ft^3/min [20 L/min] until the concrete rises in the caisson to a height of 9 in. [225 mm].

8.4 Wait for the concrete to stop flowing and then measure the height of concrete from h_1 to h_8, as shown in Fig. 2. Determine the filling capacity in accordance with Section 9 of this test method.

9. CALCULATION

9.1 Calculate the filling capacity using the following equation:

$$FC(\%) = \left(\frac{\sum_{i=1}^{7} (h_i + h_{i+1})}{h_1 \times 14} \right) \times 100$$

where:

FC = Filling capacity
h_i = Height of concrete at i position

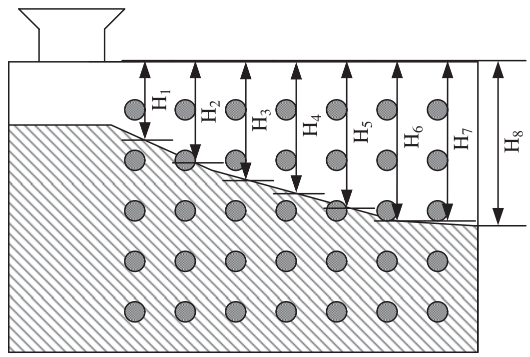

Figure 2. Details on calculation of filling capacity.

10. REPORT

10.1 Mixture designation.

10.2 The h values at different positions.

10.3 The filling capacity to the nearest 2%.

11. PRECISION AND BIAS

11.1 *Precision*—The estimate of the precision of this test method is provisional. A repeatability standard deviation of 1.2% was obtained from a study (*1*) involving five replicate batches of a concrete mixture with a mean filling capacity of 94%.

11.2 The procedure used in this test method has no bias since filling capacity of self-consolidating concrete is defined only in terms of this method.

12. KEYWORDS

12.1 coarse aggregate; self-consolidating concrete; stability; filling capacity; passing ability

Recommended Standard Method of Test for

Surface Settlement Test to Evaluate Static Stability of Concrete

AASHTO Designation: T XXX

1. SCOPE

1.1 This test method is used to evaluate the static stability of concrete, including self-consolidating concrete, from a plastic state after placement until the time of hardening by measuring the total surface settlement and rate of surface settlement at early age of concrete cast in a cylindrical specimen (or column).

1.2 The test method can be used for self-consolidating concrete and conventional concrete.

1.3 The values stated in either inch-pounds or SI units are to be regarded separately as standard. Within the text, the SI units are shown in brackets. The values stated in each system are not exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance with the standard.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations to use.*

Warning—Fresh hydraulic cementitious mixtures are caustic and may cause chemical burns to skin and tissue upon prolonged exposure (Note 1).

Note 1–The safety precautions given in the *Manual of Aggregate and Concrete Testing*, located in the related section of Volume 04.02 of the *Annual Book of ASTM Standards*, are recommended.

1.5 The text of these standard reference notes provides explanatory material. These notes (excluding those in tables and figures) shall not be considered as requirements of the standard.

2. REFERENCED DOCUMENTS

2.1 *AASHTO Standards*
- R 39, Making and Curing Concrete Test Specimens in the Laboratory
- T 141, Sampling Freshly Mixed Concrete

2.2 *ASTM Standards*
- C 125, Terminology Relating to Concrete and Concrete Aggregates
- D 1785, Specifications for Poly(Vinyl Chloride) (PVC) Plastic Pipe, Schedules 40, 80, and 120

3. TERMINOLOGY

3.1 *Definitions*
- For definitions of terms used in this test method, refer to Terminology C 125.

3.2 *Definitions of Terms Specific to This Standard*
- Static Segregation, n—Resistance to segregation when no external energy is applied to concrete, namely from immediately after placement and until setting (ACI 237).

4. SUMMARY OF THE TEST METHOD

4.1 A sample of freshly mixed self-consolidating concrete is placed in a cylindrical mold without tamping or vibration. A dial gage or a linear variable differential transformer (LVDT) is placed on top of a thin acrylic plate placed at the upper surface of the concrete. The initial reading is taken after the installation of the monitoring set-up. Changes in height are monitored until reaching steady state condition. The difference in height indicates the settlement of the concrete.

5. SIGNIFICANCE AND USE

5.1 This test method provides users with a laboratory procedure to determine the potential static segregation of concrete, including self-consolidating concrete.

5.2 This test method shall be used to develop concrete, including self-consolidating concrete mixtures with segregation not exceeding specified limits. Self-consolidating concrete is a fluid concrete that can be prone to bleeding and segregation if not proportioned to be cohesive. A stable self-consolidating concrete is important for all applications but is especially critical for deep sections, such as walls or columns. Therefore, the surface settlement can indicate if a mixture is suitable for the application. Surface settlement shall affect the development of homogeneous distribution of in-situ properties of the hardened concrete, including bond to reinforcement.

6. APPARATUS

6.1 *Column mold*—The column shall be PVC plastic pipe, Schedule 40, meeting the requirements of Specifications D 1785. The column shall be 8 in. [200 mm] in diameter × 26 in. [660 mm] in height. The column shall be securely attached to a non-absorbent, rigid base plate measuring at least 12 in. [300 mm] × 12 in. [300 mm] square, as shown in Fig. 1.

6.2 *Dial gage or LVDT*—The dial gage with a 0.0004 in. [0.01 mm] precision or a LVDT with a minimum travel range of 2 in. [50 mm].

6.3 *Acrylic plate*—The plate shall be 6 in. [150 mm] in diameter and 0.15 in. [4 mm] in thickness with four holes measuring ½ in. [0.4 mm] for the escape of bleed water, as shown in Fig. 1.

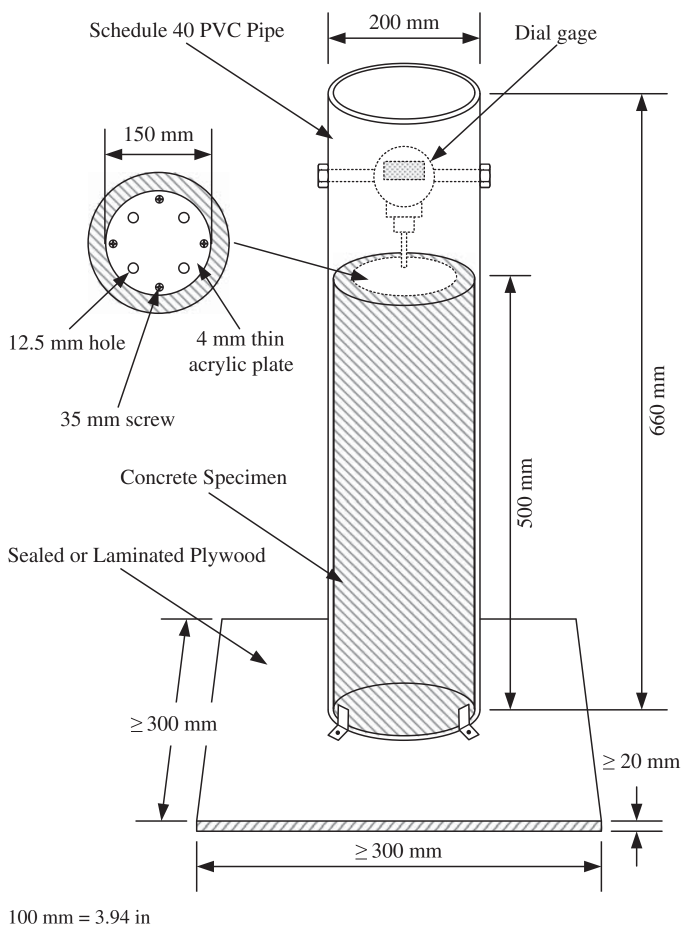

Figure 1. Details of surface settlement test.

6.4 *Screw*—Four 1.4 in. [35 mm] screws for the positioning of the acrylic plate, as shown in Fig. 1.

6.5 *Sample receptacle*—The receptacle shall be a heavy gage metal pan, wheelbarrow, or flat, clean non-absorbent board of sufficient capacity to allow easy remixing of the entire sample with a shovel, trowel, or scoop.

6.6 *Small tools*—Tools and items such as shovels, plastic pails, trowels, scoops, and rubber gloves shall be provided.

7. SAMPLE

7.1 Obtain a sample of freshly mixed self-consolidating concrete in accordance with Test Method T 141 and place it in the sample receptacle in accordance with Practice R39.

8. PROCEDURE

8.1 Perform the surface settlement test on a flat, level surface. Do not subject the testing surface and the column mold to any vibration or disturbance.

8.2 Remixing of Sample: Remix the sample obtained in accordance with Section 7.1 in the sample receptacle using a shovel or scoop so that the concrete is homogeneous.

8.3 Filling Procedure: Using a shovel, scoop, or plastic pail, immediately fill the column mold with concrete up to 19.7 in. [500 mm] height, within 2 min.

8.4 Carefully install the acrylic plate with the screws in the center of the column.

8.5 Install the dial gage or LVDT in the center of the acrylic plate. The initial reading of the dial gage or LVDT is taken 60 seconds after the installation of the monitoring set-up. Settlement values are taken at 5-minute intervals for the first 30 minutes and then every 2 hours until hardening of the concrete.

9. CALCULATION

9.1 Calculate the Surface Settlement* using the following equation:

$$S(\%) = \frac{H_I - H_F}{H_C} \times 100\%$$

where:

S = Surface settlement (%)
H_I = Initial reading of the dial gage or LVDT
H_F = Final reading of the dial gage or LVDT
H_C = Height of the concrete in the column

*The maximum surface settlement shall be obtained using the settlement value at the time of concrete hardening.

9.2 Calculate the rate of surface settlement between 10 and 15 minutes using the following equation:

$$\text{Rate of Settlement}(\%/hr) = \left(\frac{S_{15} - S_{10}}{60}\right) \times 100\%$$

where:

Rate of Settlement = Rate of surface settlement between 25 and 30 minutes
S_{15} = Surface settlement at 15 minutes (%)
S_{10} = Surface settlement at 10 minutes (%)

10. REPORT

10.1 Mixture designation.

10.2 The variation height obtained from the dial gage or LVDT at different time.

10.3 The maximum surface settlement to the nearest 0.01%.

10.4 The rate of settlement between 10 and 15 minutes to the nearest 0.01%.

11. PRECISION AND BIAS

11.1 *Precision*—The estimate of the precision of this test method is provisional. A repeatability standard deviation of 0.02% was obtained from a study (*1*) involving five replicate batches of a concrete mixture with a mean maximum surface settlement of 0.16%. Settlement rates of concrete determined at 15, 30, and 60 minutes after the beginning of surface settlement testing can be correlated to the maximum settlement values. The 15-minute rate of settlement can be used to estimate the maximum surface settlement.

11.2 *Bias*—The procedure used in this test method has no bias since surface settlement of self-consolidating concrete is defined only in terms of this method.

12. KEYWORDS

12.1 coarse aggregate; self-consolidating concrete; stability; static stability; surface settlement

Reference

(1) J., Assaad, K. H., Khayat, and J., Daczko, "Evaluation of Static Stability of Self-Consolidating Concrete," *ACI Materials Journal,* Vol. 101, No. 3, May–June 2004, pp. 207–215.

ATTACHMENT D

Research Description and Findings

This attachment is not published herein, but is available on the TRB website (www.trb.org/news/blurb_detail.asp?id=9627).

Abbreviations and acronyms used without definitions in TRB publications:

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	Air Transport Association
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
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
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
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
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