MOUNTAIN-PLAINS CONSORTIUM

MPC 17-334 | J. Seo, E. Torres, W. Schaffer, and N. Wehbe

Self-Consolidating Concrete for Prestressed Bridge Girders

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October 2017

Acknowledgements

The authors thank the Wisconsin Department of Transportation (Wisconsin DOT) and the Mountain-Plains Consortium (MPC) University Transportation Center for providing the funding for this project. The authors wish to acknowledge the Project Oversight Committee, which put time and effort into this project: Mr. William Oliva, Mr. James Parry, Dr. Michael Oliva, Mr. Steve Doocy, Mr. Ali Soleimanbeigi, Dr. Al Ghorbanpoor, Mr. Tim Holien, and Ms. Rita Lederle. The authors also would like to acknowledge the collaboration of Mr. Forrest Brunette, Mr. Chad Hemenway, Mr. Ziad Sakkal, Mr. Brian Rowekamp, Mr. John Kaiser, and Mr. Brandon Boleen for providing the required material constituents for testing the mixtures of each plant. The authors would like to specifically thank the University of Wisconsin – Madison for its assistance with the creep frames, measurement equipment for camber, and strand readings taken both at the plant and in the field. Finally, the authors would like to thank Mr. Gutzmer for his guidance over the testing of creep and shrinkage and transfer length, and Mr. Phillip Ciha for his effort in collecting the necessary field test data.

ABSTRACT

The ultimate objective of this project was to develop widely accepted recommendations on self-consolidating concrete (SCC) mixture design for its use in WisDOT bridge projects. This project investigated the effects of material constituents on the material properties of trial SCC mixtures made from precasters in Wisconsin. A group of SCC mixtures were identified based on the experimental investigation of results, technical findings from a literature review, and input from a survey to several DOTs. The identified SCC mixtures were tested at plants for the evaluation of their material performance. With a detailed investigation of the results, high quality SCC mixtures were selected and used to build cylinders and prims for the evaluation of their creep and shrinkage. The most appropriate SCC mixture was selected to fabricate a full-scale SCC girder to verify structural performance. The results of the SCC girder were compared with those of a conventional concrete (CC) girder. Then, field monitoring of prestress losses of both girders that were installed in a WisDOT bridge was made from its erection to deck placement. At the end of this project, recommendations for SCC mixture design were established to promote SCC in prestressed bridge girders in Wisconsin.

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EXECUTIVE SUMMARY

Self-consolidating concrete (SCC) is widely used in the concrete industry providing benefits during production due to its superior workability and productivity. SCC can flow through dense reinforcement to fill formwork without additional vibration mechanisms or possible signs of segregation. Along with the particular benefits, various departments of transportation (DOTs) have attempted to use SCC in many precast applications according to their own guidelines regarding SCC mixture development for prestressed concrete (PSC) bridge girders. However, local producers in Wisconsin still struggle to maintain uniformity in terms of material properties with low segregation in the SCC mixture when transporting and placing of SCC for PSC bridge girder production.

For the implementation of prestressed SCC girders across Wisconsin, this project was intended to develop an SCC mixture design guideline that will serve as the basic reference source for local precasters and bridge engineers. To accomplish this objective, the project primarily completed the literature review to understand basic findings from a number of technical documents related to SCC and existing SCC mixture guidelines developed by various DOTs, development of multiple SCC mixtures made of local aggregates, and evaluation of their fresh and hardened properties. Long-term material properties, such as creep and shrinkage, and structural performance of a full-scale SCC girder were also investigated. Further, a survey was sent to several DOTs to refer to existing requirements for the implementation of SCC in PSC bridge girders.

For the fresh and hardened material testing, numerous trials of SCC mixtures that were developed using local materials from three different precasters located in Wisconsin were completed. The precast plants participating in the project were County Materials Janesville, County Materials Roberts, and Spancrete. During the mixture design, trial mixtures were developed to investigate parameters, such as cement content and type, aggregate size and type, sand-to-aggregate ratio (S/Agg) and water-to-cement ratio (w/c). After initial mix design trials, several SCC mixtures were tested in the laboratory to meet criteria established in this project. These mixtures were at first evaluated at fresh state using the following tests: slump flow, Visual Stability Index (VSI), T20, J-ring and column segregation. Then compressive strength per mixture was tested at transfer at 18 hours and at 28 days.

Based on the examination and discussion of the fresh and hardened testing results with the Project Oversight Committee (POC), five SCC mixtures were selected from the mixtures tested in the laboratory. All five mixtures were tested using production practices of each plant in terms of mixing, curing, and quality control. Each mixture was tested for fresh properties and compressive strength at each plant, and corresponding specimens were fabricated to examine their creep and shrinkage for 280 days. Specifically, only the creep cylinders built at the plant were loaded on a creep frame designed to sustain a load of 2000 psi throughout the testing period, and the shrinkage specimens were made at both the plant and laboratory. Any negative effects on the environment during transportation of the specimens and curing conditions between the plant and laboratory on the creep and shrinkage per mixture were investigated.

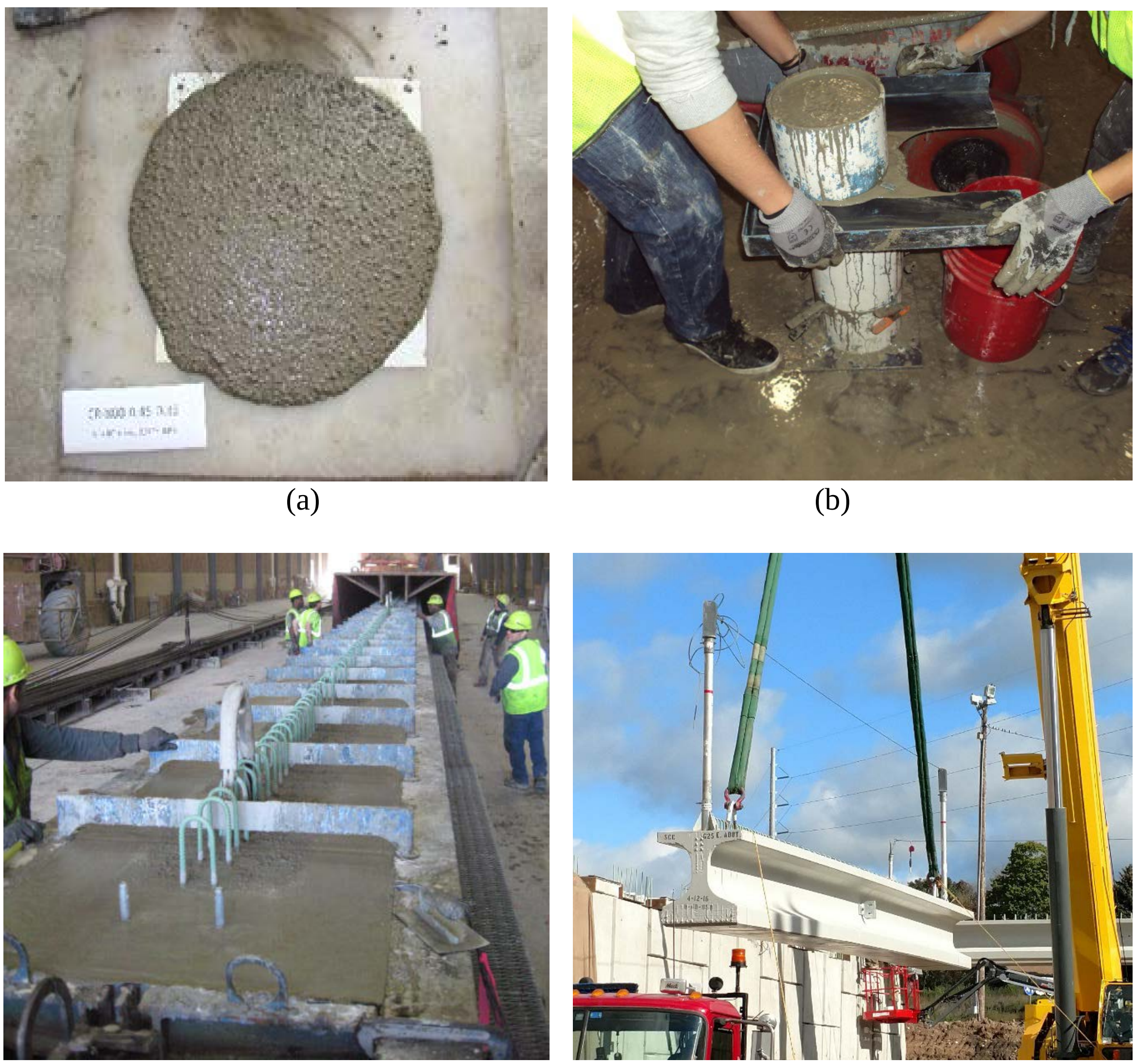
After 28 days of creep and shrinkage monitoring, one mixture was selected to cast a full-scale prestressed SCC girder to monitor structural performance. A conventional concrete (CC) girder with the similar target compressive strength was also fabricated as a control specimen. Afterward, prestress losses and camber for both the SCC and CC girders were monitored in the precast yard for 161 days, and their transfer lengths were measured for 28 days. It was recommended that both the girders be implemented on a bridge, which is a part of ongoing WisDOT Zoo Interchange Bridge projects. Prestress losses were also recorded during construction of the bridge, including the girder erection and deck placement.

From the results of this project, it can be concluded that precasters in Wisconsin have the ability to develop reliable SCC mixtures, enabling them to meet performance criteria established in other states or specified by WisDOT. A quality control guideline was recommended to WisDOT to assess the performance of SCC mixtures based on the fresh properties material testing. In terms of creep and shrinkage, mixture parameters such as S/Agg and cement type were identified to have more effect on changes in length due to creep and shrinkage effects.

Full-scale girders exhibited similar characteristics between SCC and CC. Transfer length was observed to be higher for the CC girder. Camber results showed that both the SCC and CC girders had the same final values, but the SCC girder started out with a lower camber value than the CC girder. The prestress losses showed interesting results, with a climbing value until day 161 when the girders were placed on site. At this point, the prestress losses began declining until they each reached a final value within 0.3% of each other. It can be concluded that the prestress losses for both girders can be expected to settle at an almost identical final value, despite the CC girder experiencing a 17% higher elastic shortening value than the SCC girder.

1. INTRODUCTION

SCC has a high potential to increase production of PSC girder bridges due to its better workability, quality, and durability compared with CC. With these benefits, several state DOTs have successfully used SCC in PSC girder bridges according to their own guidelines on SCC materials, mixture design, and fresh and hardened properties. However, guidelines specific to SCC, supplied by local precasters to WisDOT, do not exist, resulting in difficulty using SCC in Wisconsin. Therefore, this project aimed to develop an SCC mixture specification for the use of SCC in Wisconsin PSC bridge girders. Figures 1-1(a) through 1-1(d) show sample photographs for the successful laboratory and field testing of SCC mixtures and fabrication and implementation of an SCC bridge girder that were made from this project.



(c) (d)

Figure 1.1 Sample photographs obtained through the SCC project: (a) laboratory slump testing, (b) field column segregation testing, (c) fabrication at plant, and (d) implementation on bridge site

1.1 Background and Problem Statement

SCC was initially developed in the 1980s in Japan (Okamura and Ouchi 1999). SCC is capable of smoothly taking formwork shapes and easily passing through congested reinforcing bars with no vibration efforts. These benefits make it a more practical material when compared with normal concrete, making it a "smart concrete" (Shamsad et al. 2014). SCC is also able to improve workability and economic efficiency under severe environmental conditions. These features are demonstrated by reducing labor, shortening construction time, eliminating vibration and noise hazards, simplifying the placing process, and better finishing (Skarendahl 2003). In particular, SCC has a certain benefit in providing significantly improved surfaces without small holes, referred to as "bug holes," and other defects at a lower fabrication cost. Figure 1.2 presents a visual comparison between SCC and CC girders that were produced by a local plant through this project. It appears that the SCC girder has lesser amounts of exterior bubbled on the surface than the CC girder. Because of these benefits, SCC has been widely utilized through East Asia, Europe, and the United States in numerous cast in-place and precast applications.

Figure 1.2 Visual side-by-side comparison of SCC and CC girders at the precast plant where both girders have been fabricated through this project

Extensive studies (Mata 2004, Burgueno 2007, Erkmen 2008, Trejo et al. 2008, Labonte and Hamilton 2005, Kavanaugh 2009, Wehbe et al. 2009, Mamaghani et al. 2010) on SCC mixture design for PSC bridge girders have been conducted at different U.S. DOTs. An SCC guideline has been established per DOT based on the research findings using the local materials available in each of the states. Although these guidelines have been considered useful when designing SCC PSC bridge girders for certain DOTs, precasters in Wisconsin have had difficulty in maintaining uniformity of the SCC mixture made of local aggregates. Specifically, local precasters in Wisconsin have not been able to consistently mix, deliver, and place SCC in PSC girder construction. Another issue related to excessive segregation of wet batches during placements have been also observed during a previous field trial of SCC in PSC girders in Wisconsin (Torres and Seo 2016).

In addition to these concerns, insufficiently demonstrated data on time-dependent material characteristics for SCC, such as creep and shrinkage, have caused WisDOT to not allow the use of SCC in PSC bridge girders. In fact, the overall structural performance of PSC girders directly relies on creep and shrinkage with fresh and hardened material properties. SCC mixtures have commonly consisted of higher paste volumes, smaller maximum size of aggregate (MSA), lower coarse aggregate volume, and higher ratio of minimum amount of coarse or fine aggregates, S/Agg compared with CC (Kim et al. 2011). Due to the SCC mixture design with different material constituent proportioning, it can develop different values of creep and shrinkage compared with CC, which can substantially affect structural performance of prestressed SCC bridge girders over time.

As mentioned above, the lack of sufficient test data on fresh and hardened material properties, shrinkage, and creep of PSC girders related to time-dependent prestress losses has impeded the use of SCC in PSC girders in Wisconsin. Although the previous projects done by several DOTs have attempted to use SCC in actual PSC girders based on their own state guidelines, there have been no specific recommendations for WisDOT that can be established with substantiated data through the laboratory and field testing with SCC mixtures made of local aggregates. Hence, a widely accepted, uniform guideline for SCC mixture design that achieves the desired performance for use in prestressed girders for WisDOT should be first developed for improving efficiency and safety in its construction. To avoid overestimating or underestimating prestress losses of SCC girders to be made based upon the recommended mixture guideline, an accurate estimation of creep and shrinkage behavior along with understanding its long-term behavior of SCC in terms of prestress losses are needed.

1.2 Objectives

The ultimate objective of this project was to develop a SCC mix design guideline that serves as the basis for the use of SCC in PSC girders on WisDOT bridge projects. Effects of various SCC mixture constituents on the fresh, hardened, and time-dependent material characteristics and long-term structural behavior of a full-scale prestressed SCC girder used on the actual PSC WisDOT bridge project were also examined.

1.3 Project Scope and Organization

To achieve the aforementioned objectives, the following tasks were undertaken in this work:

1) Conduct a comprehensive literature review of the state of the art and practice in development of SCC mixture design and fresh, hardened, and time-dependent material properties.
2) Survey various DOTs to determine practical limits for fresh and hardened properties of SCC.
3) Identify suppliers for prestressed SCC girders in Wisconsin.
4) Conduct laboratory and field examination of SCC material characteristics.
5) Develop SCC design recommendation and guidance.
6) Conduct implementation and field monitoring of SCC bridge girders.
7) Prepare a final report and submission along with a closeout presentation.

This project is divided into nine sections. Section 2 is dedicated to research findings from the literature review in SCC material characteristics necessary for SCC mixture design and material testing. Section 3 deals with a summary of different state DOT survey responses and specifications specific to the SCC mixture. Section 4 provides information for the identified precast concrete plants in Wisconsin. Section 5 details SCC mixture design with local fine and coarse aggregates, and laboratory testing of selected SCC mixtures to determine their fresh and hardened material characteristics. Section 6 presents results and discussion on the creep and shrinkage from the field and/or laboratory testing of the selected SCC mixtures. Section 7 provides an overview and findings from full-scale testing of an SCC girder to capture transfer length and prestress losses and its field extended monitoring after placing the girder on an actual bridge. Section 8 gives SCC mixture design guidance and recommendations on the implementation of SCC girders. Finally, Section 9 contains a summary, conclusions, and future work.

2. COMPREHENSIVE LITERATURE REVIEW

The literature review is presented in four sections: Section 2.1 provides a background for the historical perspectives on SCC; Section 2.2 presents an overview of key SCC constituents and relevant research findings to achieve adequate material performance; Section 2.3 details mixture property testing required for the investigation of fresh and hardened properties, modulus of elasticity, shrinkage, and creep; and Section 2.4 presents the structural performance of SCC and existing codes for the prediction of transfer length, camber, and prestress losses.

2.1 Historical Perspectives on SCC

SCC that was first developed in the 1980s in Japan has broadly expanded through a few decades across Europe and North America (Okamura and Ouchi 1999). SCC has exhibited superior workability compared with CC, creating potential to increase precast production and growth, especially for production of PSC bridge girders (Wehbe et al. 2009). Achieving the SCC desired performance by material testing of SCC is necessary for more efficient SCC construction. Specifically, adequate flowability, good passing and filling abilities, proper segregation resistance, and stability are required to satisfy the fresh property requirements. The required properties can be achieved by properly proportioning the constituent materials and admixtures (Erkmen et al. 2008). Note that flowability and passing ability can be defined as the ability to flow through tight openings, such as spaces between reinforcing bars, under its own weight (Wehbe et al. 2009). If the concrete does not possess adequate passing ability, the result is a non-uniform structure, caused by blockage of coarse aggregate between reinforcing bars.

SCC, compared with high strength concrete and ordinary concrete, is much more prone to segregation (Bonen and Shah 2004). It is worthwhile to note that segregation resistance is defined as the distribution of aggregate particles in the concrete that is relatively equivalent at all locations (Turkel and Kandemir 2010). A lack of segregation resistance might be caused by internal and external bleeding of water associated with differential accumulation of light ingredients and air voids. Segregation can also result in settling of the aggregates on the bottom of the paste. The segregation resistance varies depending on three main factors: 1) the viscosity of the cement, 2) the difference in the specific densities of cement and aggregate, and 3) the particle size of the aggregates (Bonen and Shah 2004). Desired segregation resistance is achieved by using high powder (cement and fillers) content, viscosity modifying admixtures (VMA), or a combination of the two admixtures (Bonen and Shah 2004, and Berke et al. 2003). SCC is susceptible to segregation at higher w/c ratios due to the decrease in viscosity on the mix.

Stability is of high importance in SCC, for which fresh and hardened methods are used for quality control of the mix. There are two types of stability characteristics: dynamic and static stability. Dynamic stability describes the resistance of the concrete to the separation of the constituents during transport, placement, and spread into the formwork. Static stability refers to the resistance of the concrete to bleeding, segregation, and surface settlement after casting until the beginning of setting (Long et al. 2014). The stability of SCC can be enhanced by incorporating fine materials such as limestone powder, slag cement, fly ash, and micro silica fume. The use of such powders can enhance the grain-size distribution and the particle packing, ensuring greater cohesiveness (Sonebi et al. 2007).

2.2 Overview of Key SCC Constituents

SCC constituents are proportioned according to the type of SCC needed. Three types of SCC can be produced: powder-type, VMA-type, and combination-type (Wehbe et al. 2009). The powder type SCC is characterized by the large amounts of powder, which is usually in the range of 925 to 1095 lb/yrd^3. In the VMA-type, the powder content is in a lower range of 590 to 760 lb/yrd^3. In the combination type of SCC, the powder content is between the previous two ranges at 760 to 925 lb/yrd^3 (Burgueno and Bendert 2007). The key constituents of SCC include coarse aggregate, fine aggregate, cement, and water, along with admixtures. This section is devoted to a description of characteristics on each constituent and relevant research findings for prestressed SCC bridge girders.

2.2.1 Cement

Cement types that are in use for SCC vary for each state and precaster. According to the American Society of Testing Materials (ASTM) C150 (ASTM 2016), Portland cement can be classified into five types: Type I, Type II, Type III, Type IV, and Type V. Types I, II, and III are employed to produce SCC for the casting of PSC girders across regions in the United States (Wehbe et al. 2007). Type I is used when special properties of other cements are not necessary. Type II is utilized when moderate sulfate resistance or adequate heat of hydration are desired. Type III is used when high early strength is desired (ASTM C150).

2.2.2 Fillers

Fillers may be added to enhance a certain concrete property or reduce the amount of cement required (Wehbe et al. 2009); thus, fillers are used as additional components or to be replaced with some of the cement in a concrete mix. Most common fillers used for SCC mix include fly ash, ground granulated blast-furnace slag, silica fume, and limestone powder. The technical benefits of using fillers are an increase in early strength and bleeding control, improvement of the concrete workability, deformability, viscosity, and reduction of porosity (Shamsad et al. 2014). Workability improves as a result of the reduction of internal friction between the particles (Sonebi et al. 2007). Reduction in friction is achieved by increasing the distance between particles and the amount of paste (Khayat et al. 2009). Khayat and Mitchell (2009) studied the effect of different fillers on the performance of SCC. Their conclusion was to maintain the replacement percentage values within the ranges shown in Table 2.1.

Table 2.1 Suggested cement replacement percent

Filler	% Replacement
Fly Ash*	20-40%
Limestone	20-30%
Slag Furnace	30-60%
Fly Ash/Slag Furnace	Max 50%

Note: the presence of "" indicate classes of fly ashes of C, D, and F*

2.2.3 Coarse Aggregate

Coarse aggregate has 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 space over the reinforcement, and the geometry of the elements to be cast (Khayat and Mitchell 2009)**.** The maximum aggregate size must be selected to avoid blockage. Khayat et al. (2009) developed a model for SCC to study the effect of MSA in terms of workability and strength development. Results showed that MSA of ½" showed better performance in comparison with ⅜" and ¾". Khayat et al. (2009) recommended that the coarse aggregate size for SCC be between ⅜" and ½", but not to exceed ¾".

2.2.4 Admixtures

Admixtures are ingredients in a concrete mixture other than Portland cement, water, and aggregates that are added to the mixture immediately before or during mixing (Pellerin et al. 2005). Admixtures can be classified by function as indicated below:

1. Air-entraining admixtures
2. Water-reducing admixtures
3. Plasticizers
4. Accelerating admixtures
5. Retarding admixtures
6. Hydration-control admixtures
7. Corrosion inhibitors
8. Shrinkage reducers
9. Alkali-silica reactivity inhibitors
10. Coloring admixtures

Air entraining admixtures are added to freshly mixed SCC to raise the air content. The main goal of increasing the air content in a concrete mixture is to improve durability. The amount of air in the fresh mix can increase in the short term, but decrease gradually over longer periods of time. The addition of air entraining admixtures can improve workability, cohesiveness, segregation, and bleeding resistance and decrease strength by 10% to 20% (Mindess et al. 2003).

High Range Water Reducing (HRWR) admixtures, also called plasticizers, are used to achieve high flowability. HRWR admixtures are added in small amounts to freshly mixed SCC to improve the workability for a short period of time. HRWR admixtures typically have a workability window of 30 to 60 minutes. These admixtures are added to decrease the water demand of concrete and create fluidity in the mix (Kosmatka et al. 2002). Fluidity in the mix is achieved by neutralizing the surface charge of the cement particles. Once the particles have the same charge, the particles are able to repel each other throughout the water. As particles are more evenly dispersed, more water is used to hydrate the cement. As a result of the particle dispersion, HRWR admixtures can make mixes with lower w/c ratio to have acceptable flowability and higher strength (EFNARC 2006). Some relevant studies conducted by Erkmen et al. (2008) and Wehbe et al. (2009) have shown that plasticizers can increase the compressive strength of concrete by 10% to 25%.

VMAs are high molecular weight polymers, which increase the viscosity of the mix, to the extent where there is no need to reduce the water content. Consequently, the VMAs are able to reduce segregation and bleeding. However, VMAs are not auxiliary for poor quality constituents or mixture design. According to European Federation of National Associations Representing for Concrete (EFNARC 2006), potential benefits of using VMA are the following:

- Less sensitivity to variations in the moisture content of the aggregate
- Lower powder content
- Reduction in the level of production control
- Allowance of more fluid mixes to be used without the risk of segregation

- Improved placing rate
- Better surface appearance

2.3 SCC Mixture Properties

With an increase in demand of SCC in various structures, SCC test methods were established to determine workability of freshly mixed SCC and its hardened properties along with time-dependent material characteristics. The majority of the test methods, such as slump flow and column segregation testing, were provided by ASTM. The Precast/Prestressed Concrete Institute (PCI) has also developed guidelines for SCC test methods and mixing procedures (PCI 2003). Detailed information on each method with relevant findings gained from the literature review is presented in the following subsections.

2.3.1 Fresh Properties

As mentioned previously, there are three key characteristics of SCC in the fresh state: filling ability, passing ability, and resistance to segregation or stability. Filling ability is the ability of concrete to fill the form with its own weight, while passing ability is the ability of fresh concrete to flow through congested spaces between strands or reinforcement without segregation or blocking. Resistance to segregation or stability is the ability to maintain a homogeneous composition without bleeding in the fresh state (Trejo et al. 2008). Fresh tests used to determine these characteristics include slump flow, Visual Stability Index (VSI), J-Ring, L-Box and column segregation. Table 2.2 shows what fresh tests are used for each fresh property. All the tests have standard test guidelines from the ASTM (Mata 2004) with the exception of L-Box, which is included in the Interim Guidelines written by PCI (PCI 2003).

Table 2.2 Test methods for SCC fresh properties

Test Methods	Fresh Properties
Slump Flow (ASTM C 1611)	Filling Ability
L-Box (PCI), J-Ring (ASTM C 1621)	Passing Ability
VSI (ASTM C 1611) **Column Segregation (ASTM C 1610)**	Segregation Resistance

(a) (b)

Figure 2.1 Slump comparison between SCC and normal concrete (Wehbe et al. 2007): (a) SCC slump flow test and (b) slump test for normal concrete

The slump flow test (see Figure 2.1) is the most widespread method for determining the free flowability of the mixtures (ASTM 2011). The slump flow is best correlated with the yield stress of the concrete and is a useful tool for evaluation of the consistency of successive batches (Saak et al. 2004). The ASTM C1611 specifies a required diameter between 20 and 30 inches.

VSI is typically used to evaluate the dynamic stability of a batch. VSI ratings range from 0 to 3, indicating a stable mix to poor segregation, respectively. VSI entails visual inspection of the fresh batch after a slump flow test. To determine a VSI rating for the fresh mixture, an operator inspects it to ensure uniform distribution of coarse aggregate and bleeding in the perimeter of the spread and surface of the mortar (ASTM 2011). According to the ACI regulations (ACI 2007), VSI is a subjective test that can be used by precasters in quality control of the SCC mix. VSI provides a visual image of the distribution of aggregates and the presence of bleeding throughout the mix (PCI 2003).

Figure 2.2 J-Ring test

The passing ability of freshly mixed SCC can be evaluated by the J-Ring test (see Figure 2.2) in accordance with ASTM C 1621. The test is similar to the slump spread, but the J-Ring is placed around the slump cone and the SCC is forced to pass through the legs of the J-Ring (Wehbe et al. 2007).

Aggregate size is the most influential factor on the results of this test as it can cause blockage between the bars of the metal ring.

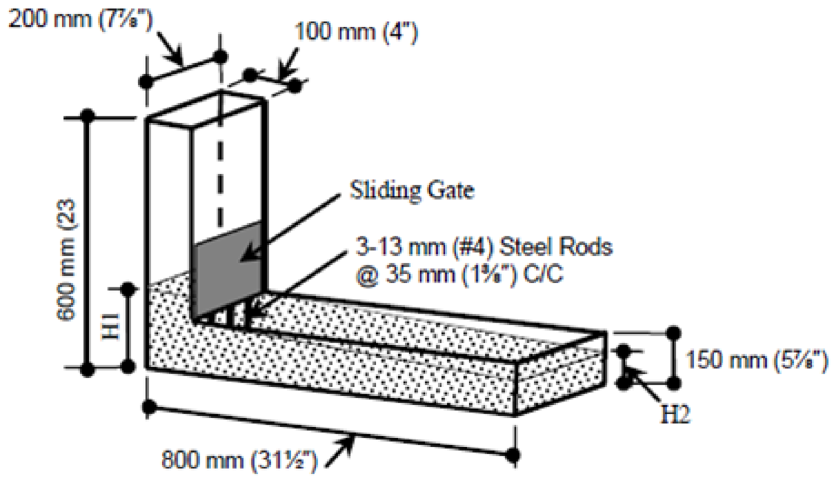


Figure 2.3 L-box test (Wehbe et al. 2009)

The L-Box test is not an ASTM standard test, but is used to evaluate passing ability. Figure 2.3 shows the setup of an L-Box test. The test can be performed in accordance with the PCI interim guidelines 2003 (PCI 2003). The measured L-Box results are expressed in terms of the ratio H2/H1, which are the heights at the horizontal ends as seen in Figure 2.3 (Wehbe et al. 2007 and PCI 2003). Acceptable values of H2/H1 are between 0.80 and 1.00 inches (JSCE 1998 and PCI 2003).

The ASTM C1610 test method covers the determination of static segregation of self-consolidating concrete by measuring the coarse aggregate content in the top and bottom portions of a cylindrical specimen. Column segregation test results are expressed as the percentage ratio of the difference of aggregate mass between the bottom and the top segments of the column to the total aggregate mass in the two segments (Wehbe et al. 2009). Figure 2.4 shows a sample picture of a column segregation test.

Figure 2.4 Column segregation test

2.3.2 Hardened Properties

Determining hardened properties of SCC (i.e., compressive strength and modulus of elasticity) is important to estimate the structural performance of SCC in prestressed girders. The following subsections will detail technical findings obtained through the literature review for each hardened property.

2.3.2.1 Compressive Strength

SCC has shown positive results with respect to final compressive strength, in some cases better than normal concrete. PSC girders require a higher strength in comparison with other applications such as columns and box culverts. Cement content, water cement, and coarse aggregate ratios are the constituents that have more influence on the compressive strength (Vilanova et al. 2012).

Attiogbe et al. (2006), Collepardi et al. (2005) and Wehbe et al. (2007) concluded that the compressive strength of SCC is comparable or higher than that of normal concrete with the same w/c ratio. Burgueno et al. (2007) tested three different types of SCC: powder type, VMA type and combination type I/II. From the compressive strength test, powder type and VMA type showed higher strength than normal concrete. However, combination type I/II showed slower strain gains compared with the rest of SCC types. Another parameter that has been studied is the replacement of cement for respective fillers. Turkel et al. (2010) studied how different fillers affect properties of the mix. Results showed that SCC mixtures using limestone have substantial higher strength than mixtures with other mineral admixtures or fillers (Turkel et al. 2010). Compressive strength is tested according to the ASTM C36 (ASTM 2011). Readings are recorded at intervals of 18 hours, three, seven, 14, 28, and 56 days of curing. Curing conditions have shown to have an impact on the early strength of concrete. Heat curing conditions significantly improve strength gains at early age relative to moist curing (Wehbe et al 2009).

2.3.2.2 Modulus of Elasticity

Modulus of elasticity is known as the resistance to deform elastically when a force is applied. The modulus of elasticity in the SCC mixtures is affected by the use of mineral admixtures, paste volume, and size of coarse aggregate. Modulus of elasticity increases in the following order for the different mineral admixture types: fly ash, limestone filler, and ground-granulated blast-furnace slag (Vilanova et al. 2012). SCC girders may exhibit lower modulus of elasticity than CC girders due to greater prestress losses in SCC (Shamsad et al. 2014).

2.3.3 Time Dependent Material Characteristics

Time-dependent material characteristics for SCC PSC girders have been studied by the quantification of its creep and shrinkage. The following subsections summarize test methods for creep and shrinkage and its relevant findings from the literature review.

2.3.3.1 Shrinkage

Shrinkage is a phenomenon that is the result of moisture loss in concrete. Volume change occurs as concrete loses excess water. Concrete can lose water to its surroundings through evaporation or through the hydration process. When the internal water evaporates, negative capillary pressures are formed that cause the paste to contract (Wehbe et al. 2009). A volume-to-surface area ratio is used in shrinkage prediction equations; thus, higher volume-to-surface area ratio ratios lead to less shrinkage. For SCC concrete, there are three cases of shrinkage that need special consideration as follows: 1) plastic shrinkage occurs as the surface of fresh concrete rapidly loses moisture; 2) autogeneous shrinkage occurs when concrete begins to dry internally, and a volume reduction of paste occurs due to the hydration process; and 3) drying shrinkage is the strain caused by water loss from hardened concrete when it is exposed to the environment (Kosmatka 2002).

Lower autogeneous and higher drying shrinkage have been reported to have a higher effect on SCC (ACI 237 2007). The aggregate content is one of the main factors affecting the shrinkage strains of concrete. The main function of the aggregate is to restrain the shrinkage deformations. SCC with a low aggregate content is associated with a higher shrinkage strain (Gomez et al. 2007). SCC made with higher binder content can exhibit higher drying shrinkage varying between 500 and 1000 micro strain after 300 days. However, substituting Portland cement by non-pozzolanic filler, such as limestone, substantially decreases the drying shrinkage.

Many studies (Mata 2004, Wehbe et al. 2009, and Khayat et al. 2009) have focused on the effect of the shrinkage on SCC performance used for prestressed bridge girders. Shrinkage values of SCC are compared to those for CC with the similar characteristics and curing conditions and to those from the AASHTO prediction models. Shrinkage can be measured following the approach stipulated by ASTM C157 (ASTM 2011). This approach can determine the changes in length that are produced by causes other than externally applied forces and temperature changes in hardened concrete specimens. These specimens are exposed to controlled conditions of temperature (73° ± 2°) and relative humidity (50% ± 4%) recommended by ASTM C157. Shrinkage test setup is seen in Figure 2.5.

(a) (b)

Figure 2.5 Shrinkage test setup: (a) HM-250D length comparator and (b) SCC prism specimen

2.3.3.2 Creep

Creep is a volumetric change due to external loads. In concrete, long-term creep deformations are generally larger than the initial elastic deformation due to applied loads (Trejo 2008). The creep shortening of concrete under permanent loading ranges from 0.5 to 4 times the initial elastic shortening. The magnitude of creep depends on concrete maturity at the time of loading (Trejo 2008).

Previous research (Khayat and Mitchell 2009) on creep comparing high performance concrete (HPC) to SCC shows that SCC may experience 10% to 20% more strain than HPC. SCC with high paste volumes may result in increased creep and prestress losses and deflections, along with reduced capacities of PSC elements made with this high paste volume (Kim et al. 2011).

In addition to the effect of high paste volume, aggregates used in SCC mix have an influence on the creep. For example, river gravel exhibits lower creep in comparison with limestone due to the higher stiffness of the river gravel (Kim et al. 2011). It was also found that the w/c ratio did not appear to have considerable effect on creep. This can be attributed to the fact that other mixture parameters, such as binder content and type, had a more predominant influence on creep (Long and Khayat 2011).

A test method used to determine creep is the ASTM C512 (ASTM 2011). This test method measures the load-induced time dependent compressive strain at selected ages for concrete under an arbitrary set of controlled environmental conditions. According to the ASTM C512, the load applied to the samples must be less than 40% of the compressive strength. Creep frame setup can be seen in Figure 2.6.


(a)


(b)

Figure 2.6 Creep frame setup (Oliva and Cramer 2008): (a) creep frame and (b) chucks location at one end

2.4 Structural Performance

A lack of prediction models for the structural performance for different SCC mixture designs has made the implementation of SCC for PSC girders difficult (Bassem 2013). This section presents existing code requirements (i.e., transfer length, prestress loss, and camber) necessary for the implementation of PSC girders.

2.4.1 Transfer Length

The ACI code (ACI 2008) defines transfer length as the length of the embedded pretensioned strand, required to transfer the effective prestress to the concrete. A number of past studies (Labonte and Hamilton 2005, Wehbe et al. 2009, and Trejo et al. 2014) have determined the transfer length of both SCC and CC girders. Wehbe et al. (2009) utilized two methods to determine transfer length. The first method consisted of installing demec points on the surface of the girder flange, while the second method used strain gages attached to the strands near each end of the girder. After release of the strands, the second method exhibited similar results between the CC and SCC girders. Labonte and Hamilton (2005) placed vibrating wire gages along the bottom flange in both ends of the SCC girder. Different transfer length was observed at each end of the girder due to sudden release of the strands; however, resulting transfer length remained similar for both SCC and CC girders. Hence, Wehbe et al. (2009) and Labonte and Hamilton (2005) concluded that there was not significant differences in transfer length between SCC and CC girders.

On the other hand, Trejo et al. (2014) found similar transfer length after release of the strands for both SCC and CC girders, but also observed that the transfer length almost doubled after 128 days of monitoring for both the girders. Similarly, the other studies (Barnes et al. 2003, Kaar et al. 1963) showed that transfer length increases over time due to time-dependent properties. Barnes et al. (2003) and Kaar et al. (1963) found that creep, shrinkage, and strand relaxation around the transfer region increased the transfer length for PSC girders. Details for the determination of transfer length are provided in the next subsections.

2.4.1.1 Codified Equations

Transfer length can be determined following the ACI (2008) and AASHTO LRFD Bridge Design Specifications (2014). The ACI code provides Eq. 2.1 to simply determine the transfer length of prestressing strands. Note that this equation assumes strand Grade 270 being prestressed to 75% of ultimate strength, and approximately 25% of prestress losses.

$$L_t = 50d_b \qquad \textbf{(Eq. 2.1)}$$

where L_t is the transfer length and d_b is the strand bar diameter.

The AASHTO LRFD specifications have developed a more conservative equation for transfer length as shown below:

$$L_t = 60d_b \qquad \textbf{(Eq. 2.2)}$$

where L_t is the transfer length and d_b is the strand bar diameter.

2.4.1.2 Test Interpretation

The 95% average maximum strain (AMS) procedure proposed by Russell and Burns (1997) have been frequently used by several researchers to determine the transfer length of PSC girders. Note that the concrete samples used for the study had a compressive strength of 4000 psi at release and 6000 psi after 28 days, and the induced force in the strands was 75% the tensile strength of the prestressing strands. This procedure can be applied to prestress strands with a diameter of 0.6 in, Grade 270 seven-wire, low relaxation strands.

Transfer length can be determined using the 95% AMS method (see Figure 2-7) as follows:

- Plot the strain profile against the potential transfer length of the strand;
- Determine the AMS for the specimen by computing the numerical average of all the strains contained within the strain plateau of the fully effective prestress force;
- Scale the AMS value by 0.95 and construct a line on the plot corresponding to 0.95 AMS;

• Determine the transfer length as the length between zero strain and the intersection of the strain profile with the 0.95 AMS line.

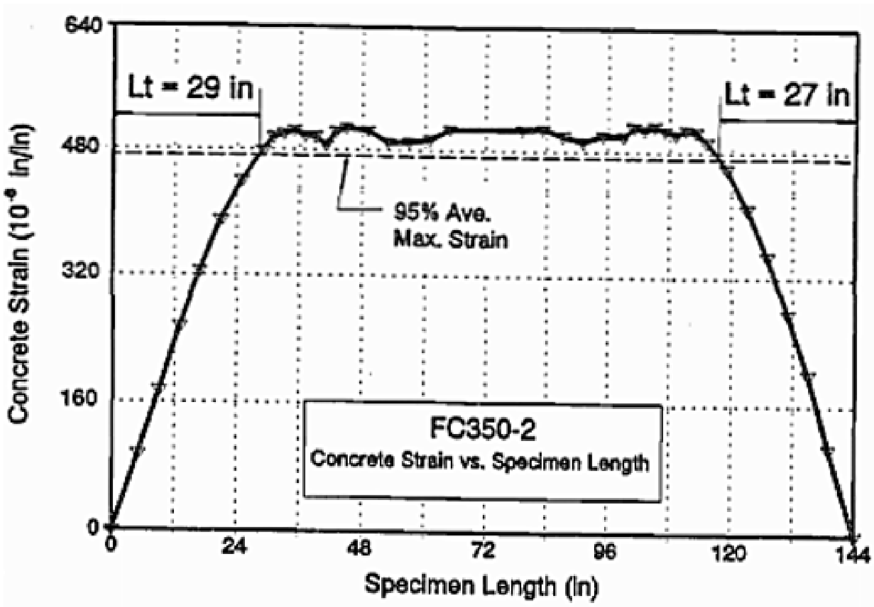


Figure 2.7 Sample AMS method (Russell and Burns 1993)

2.4.2 Prestress Losses

Codified approaches to predict prestress losses are available in the AASHTO LRFD Specifications (2014) and PCI Design Handbook (2004). Overview for prestress loss and details for each approach are presented in the following subsections.

2.4.2.1 Overview

Prestress losses tend to decrease after release of the strands as a product of material properties, environmental conditions, and construction processes. As shown in Figure 2.8**,** prestress losses occur due to elastic shortening of concrete, creep, shrinkage, and relaxation of prestressing strands. However, deck placement and superimposed dead and live loads can produce an increase of stress in the prestress strands (Trejo et al. 2008).

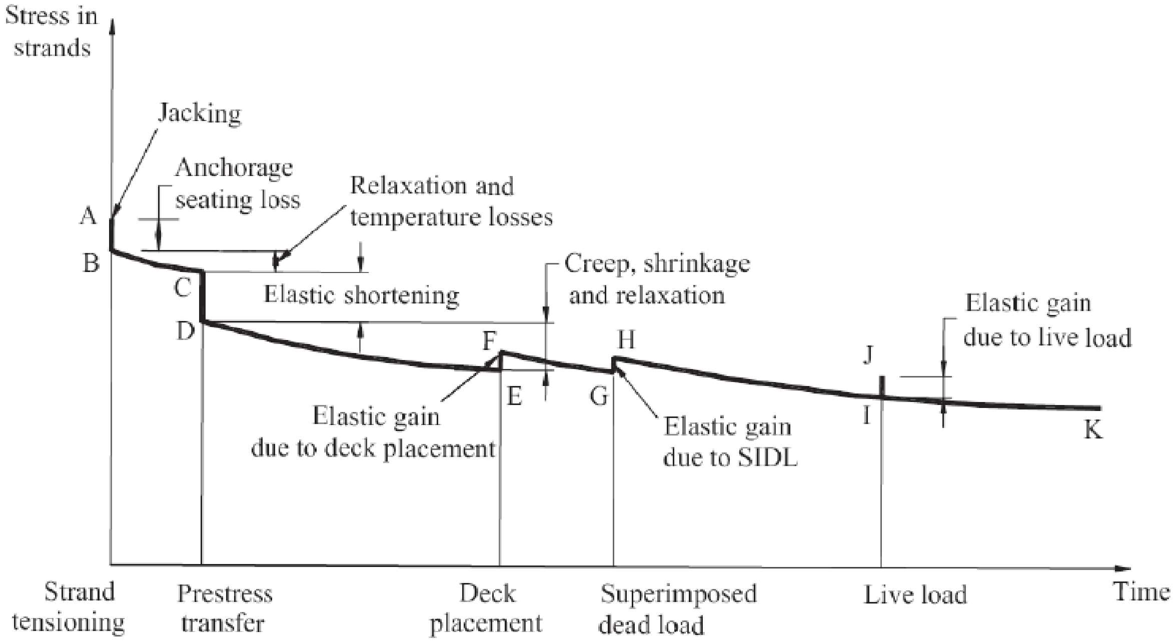


Figure 2.8 Stress in strands over time (Tadros et al. 2003)

Several past studies (Erkmen et al. 2007, Burgueno and Bendert 2007, and Wehbe et al. 2009) have compared the prestress losses of both CC and SCC girders where contradictory results have been reported. Specifically, Burgueno and Bendert (2007) and Erkmen et al. (2007) concluded that both SCC and CC girders tend to develop similar losses. It was also reported that the AASHTO and PCI prediction models are likely to overestimate long-term prestress losses of SCC and CC girders. In contrast, Wehbe et al. (2009) reported higher losses for SCC girders during the elastic shortening stage, but lower long-term losses compared with CC girders.

Varying material characteristics make it difficult to predict whether SCC will have higher losses than CC. For example, Trejo et al. (2008) compared the effect of limestone and river gravel on long-term losses. It was found that SCC mixtures with limestone exhibited higher long-term losses than those with river gravel, and SCC and CC mixtures had similar losses when they were made of the same type of aggregate.

2.4.2.2 AASHTO LRFD Specifications

The prestress losses are divided into the initial losses due to elastic shortening and long-term losses as shown in Eq. 2.3:

$$\Delta f_{pT} = \Delta f_{pES} + \Delta f_{pLT} \qquad \textbf{(Eq. 2.3)}$$

where Δf_{pT} is the total loss (ksi), Δf_{pES} are losses due to elastic shortening (ksi), and Δf_{pLT} is the sum of the long-term losses.

The losses due to elastic shortening are computed as follows:

$$\Delta f_{pES} = \frac{E_p}{E_{ct}} f_{cgp} \qquad \textbf{(Eq. 2.4)}$$

where E_p is the modulus of elasticity of the prestressing strands (ksi), E_{ct} is the modulus of elasticity of concrete at transfer (ksi), and f_{cgp} is the concrete stress of the prestressing tendons due to the prestressing force immediately after transfer.

Long-term losses (Δf_{pLT}) are determined by the following equations:

$$\Delta f_{pLT} = 10.0 \frac{f_{pi}A_{ps}}{A_g} \gamma_h \gamma_{st} + \Delta f_{pr} \quad \textbf{(Eq. 2.5)}$$

$$\gamma_h = 1.7 - 0.01\, H \quad \textbf{(Eq. 2.6)}$$

$$\gamma_s = \frac{5}{(1.7-0.01H)} \quad \textbf{(Eq. 2.7)}$$

where f_{pi} is the prestress steel prior to transfer (ksi), A_{ps} is the area of the prestressing strand (in^2), A_g is the gross area of concrete section (in^2), γ_h is the correction factor for relative humidity, γ_{st} is the correction factor for specified concrete strength at time of prestress transfer, H is the relative humidity (%), and Δf_{pR} is an estimate of the relaxation loss assumed to be 2.5 ksi for low relaxation strands.

2.4.2.3 PCI Design Handbook Method

This method was developed with the joint participation of both ACI and ASCE. Total prestress losses (TL) are computed as follows:

$$TL = ES + CR + SH + RE \quad \textbf{(Eq. 2.8)}$$

where ES is the loss due to elastic shortening (psi), CR are the creep losses (psi), SH are the shrinkage losses (psi) and RE are the losses due to the relaxation of tendons (psi).

Elastic shortening losses are determined as follows:

$$ES = K_{es} f_{cir} \left(\frac{E_{ps}}{E_{ci}}\right) \quad \textbf{(Eq. 2.9)}$$

where K_{es} is 1.0 for pretensioned members, E_{ps} is the modulus of elasticity of prestressing tendons (psi), E_{ci} is the modulus of elasticity of concrete (psi), and f_{cir} is the net compressive stress in concrete at the center of gravity of prestressing force immediately after the prestress has been applied to the concrete (psi).

$$f_{cir} = K_{cir} \left(\frac{P_i}{A_g}\right) - \frac{M_g e}{I_g} \quad \textbf{(Eq. 2.10)}$$

where K_{cir} is 0.9 for pretensioned members, P_i is the initial prestress force before release (lb), e is the eccentricity of center of gravity of tendons with respect to the center of gravity of the concrete section (in), A_g is the gross concrete section (in^2), I_g is the moment of inertia of the concrete section (in^4), and M_g is the bending moment due to self-weight (lb-in).

Losses due to creep (CR) are estimated with the following equation:

$$CR = K_{cr} \left(\frac{E_{ps}}{E_c}\right) (f_{cir} - f_{cds}) \quad \textbf{(Eq. 2.11)}$$

where K_{cr} is 2.0 for CC and SCC for this study, E_{ps} is the modulus of elasticity of concrete at release (psi), E_c is the modulus of elasticity of concrete at 28 days (psi), and f_{cds} is the compressive stress in concrete at the center of gravity of the prestressing steel due to all dead loads applied to the member after it has been prestressed (psi).

$$f_{cds} = \frac{M_{sd}.e}{I_g} \qquad \textbf{(Eq. 2.12)}$$

where M_{sd} is the moment due to superimposed dead loads after prestress force is applied (lb-in).

Shrinkage losses (SH) are determined as follows:

$$SH = (8.2 \times 10^{-6})K_{sh}E_{ps}(1 - 0.06\frac{V}{S})(100 - RH) \qquad \textbf{(Eq. 2.13)}$$

where K_{sh} is 1.0 for pretensioned members, V/S is the volume to surface area ratio (in), and RH is the relative humidity (%).

Relaxation in the strands is computed using the following equation:

$$RE = [K_{re} - J(SH + CR + ES)]C \qquad \textbf{(Eq. 2.14)}$$

where K_{re} and J are given in Table 2.3 depending on the type of the strand, and C is a factor based on the ratio of f_{pi} and f_{pu} as shown in Table 2.4. These tables show values for 270 grade strands for other types of strands, referring to the PCI handbook.

Table 2.3 Factors to calculate relaxation of strand

Type of Tendon	**K_{re}**	**J**
270 Grade stress-relieved strand or wire	20,000	0.15
270 Grade low-relaxation strand	5,000	0.040

Table 2.4 C factor for strand or wire

f_{pi}/f_{pu}	Stress-Relieved Strand or Wire	Stress-Relieved Bar or Low-Relaxation Strand or Wire
0.80	-	1.28
0.79	-	1.22
0.78	-	1.16
0.77	-	1.11
0.76	-	1.05
0.75	1.45	1.00
0.74	1.36	0.95
0.73	1.27	0.90
0.72	1.18	0.85
0.71	1.09	0.80
0.70	1.00	0.75
0.69	0.94	0.70
0.68	0.89	0.66
0.67	0.83	0.61
0.66	0.78	0.57
0.65	0.73	0.53
0.64	0.68	0.49
0.63	0.63	0.45
0.62	0.58	0.41
0.61	0.53	0.37
0.60	0.49	0.33

Note: "-" means data are not available for given conditions

2.4.3 Camber

Camber is defined as an upward deflection that is typically used as a measure of in-service performance of PSC girders. Factors associated with a change in camber include prestress losses, compressive strength, modulus of elasticity, and bond strength. According to several past findings from Trejo et al. (2008), Erkmen et al. (2008), and Labonte and Hamilton (2005), SCC girders have shown similar camber behavior compared to those with CC. In fact, Labonte and Hamilton (2005) concluded that the prediction equations provide a good estimate of camber for both SCC and CC. However, Wehbe et al. (2009) found that camber of SCC girders was substantially higher compared with the CC girders. This was attributed to the prestress losses caused by elastic shortening.

To predict camber, the PCI Design Handbook (2010) provides equations for initial and long-term camber as shown below:

$$\Delta = \frac{P_0 e l^2}{8E_{ci}I} - \frac{5wl^4}{384E_{ci}I} \quad \textbf{(Eq. 2.15)}$$

where Δ is the initial deflection at the mid-span (in), P_o is the prestress force at transfer (kips), e is the eccentricity of the prestress force (in), l is the span length (in), E_{ci} is the modulus of elasticity of the concrete at transfer, I is the moment of inertia of the beam section (in^4), and w is the self-weight of the member (kip/in). To estimate long-term camber, the initial camber has to be multiplied by factors provided by PCI (2012) as shown in Table 2.5.

Table 2.5 PCI (2010) recommended factors for long-term camber

Cause of Deflection	**Type of Deflection**	**Without Composite Topping**	**With Composite Topping**
Deflection due to member weight at release	Downward	2.70	2.40
Camber due to prestress release	Upward	2.45	2.20
Deflection due to superimposed dead load	Downward	3.00	3.00
Deflection due to composite topping	Downward	-	2.30

Note: "-" means data are not available for given conditions

3. RESULTS AND DISCUSSION ON DOT SURVEY

A brief survey to get a better understanding of SCC specifications to determine desired fresh and hardened properties of SCC PSC girders was conducted online across the United States. Through the online survey, the effect of SCC mixture parameters on fresh and hardened properties and their fresh property requirements for the use of SCC PSC girders were discussed. The survey form was distributed to each DOT, requesting information about individual current practices regarding the use of SCC. It is worthwhile to note that survey responses were not obtained from every DOT, and in some cases they solely provided their state specifications instead of answering the particular questions. Table 3.1 lists the DOTs that responded and how they provided information to the project.

Table 3.1 Information provided by state DOTs

State DOTs	Survey Form	SCC Specifications	Research Report
Alabama	O	O	
Florida		O	O
Georgia		O	O
Illinois		O	O
Iowa	O		
Kentucky		O	
Louisiana		O	
Michigan		O	O
Minnesota	O	O	O
Nebraska	O	O	O
New York		O	
North Carolina	O	O	O
Ohio	O		
Pennsylvania	O	O	
Rhode Island	O	O	
South Carolina	O	O	O
South Dakota	O	O	O
Texas	O	O	O
Utah	O	O	
Washington	O	O	

Note: the presence of "o" indicates that the DOT officials have provided the information such as the survey form they filled out, SCC specifications, or relevant research reports

The survey was designed to cover three aspects of SCC. The first aspect was directed at the practices and future planning for the use of SCC. The second aspect was to investigate the materials used in a state and specific parameters for its mixture. This aspect was of high importance because of the lack of specific guidelines for SCC in PSC girders. The third aspect was to gather data on each of the state-level requirements and test methods to approve an SCC mixture. The first two aspects, which related to the acceptance and applications of SCC to prestressed bridge girders in use in individual DOTs, were covered by performing the survey. Summaries of the survey results are presented in the following subsections. Note that the details for the survey form and its results can be found in Appendix A.

3.1 SCC Mixture Parameters

Several parameters in the survey form were considered highly important for the SCC mixture design for PSC girders. The most significant parameter that should be considered for the SCC mixture design is the cement content. Determining the minimum amount of total cement content required is the initial step to adjust the appropriate proportions of the SCC mixtures. To obtain minimum compressive strengths for a specific DOT, each DOT has established a minimum amount of cement content. For example, some DOTs (e.g., Utah, South Dakota, Nebraska, and Alabama) require the minimum cement content to be over 22.0 lb/ft^3. Some other states may require higher cement content, such as the Florida DOT, which requires a minimum of 27.8 lb/ft^3. On the other hand, a few DOTs, such as in Illinois, have established an upper limit of 26.1 lb/ft^3. Once the cement content is determined, w/c ratio has to be determined. Figure 3.1 shows a range of maximum w/c ratios used by the participating DOTs. It appears that the most common range of maximum w/c ratios is within 0.41 to 0.45.

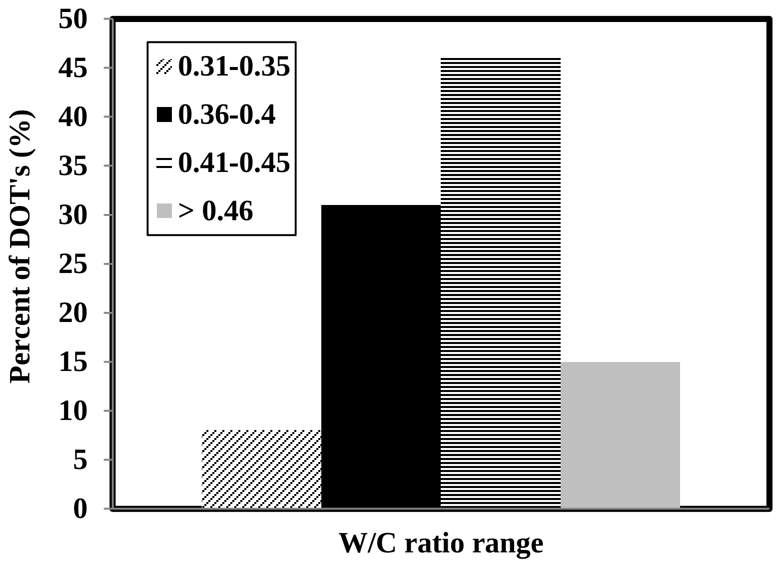


Figure 3.1 Percent of DOTs that approve the range of maximum w/c ratio

Another important parameter to be considered for designing an SCC mixture is the replacement of cement by fillers. Figure 3.2 illustrates that around 30% of DOTs approve the replacement of cement by fillers. As described before, the most common fillers widely used across the DOTs are fly ash, ground granulated blast furnace slag, silica fume, limestone, metakaolin, and micro silica. For example, Florida DOT has used fly ash and ground granulated blast furnace slag, especially since it has been allowed to replace up to 70% of total cement content. Other DOTs, such as Georgia DOT, have used the same fillers as the Florida DOT with the inclusion of metakaolin and micro silica. However, the Georgia DOT approves the combination of filler to replace up to 40% of the total cement content. Once total cementitious materials within the designated w/c ratio are determined, determining appropriate aggregate size is vital for properly designing SCC mixtures.

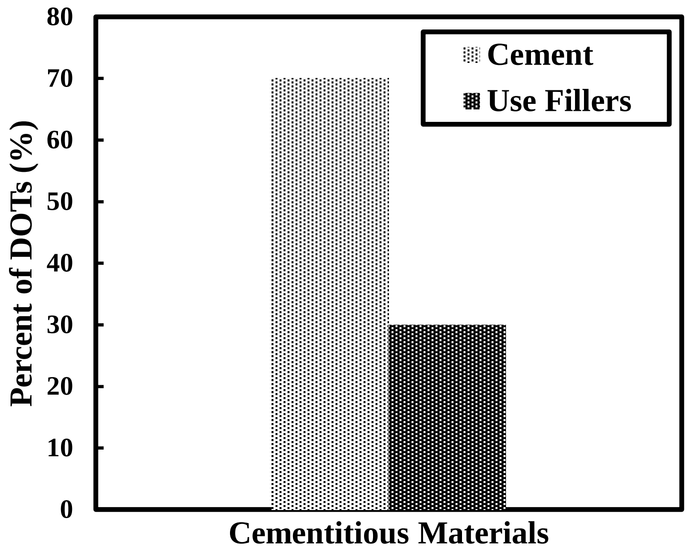


Figure 3.2 Percent of DOTs that approve the use of fillers for a SCC mixture used in prestressed bridge girders

The DOTs suggest either minimum amount of coarse or fine aggregates. This parameter is denominated as S/Agg. Values specified by the majority of DOTs for S/Agg range between 0.4 and 0.5. Specifically, Illinois DOT stipulates that fine aggregates should not exceed 50% of total aggregates. Meanwhile, South Dakota DOT specifies a minimum of 40% coarse aggregate.

MSA is another important parameter often specified by the DOTs. Most DOTs state that 0.5 in. and 0.75 in. should be used as MSA. However, some DOTs, such as in North Carolina and Florida, provide a wide range of MSA of 1 in., 0.75 in., 0.5 in., and 0.375 in. corresponding to stone #57, #67, #78, and #89, respectively. Virginia DOT was the only one to specify the minimum MSA, which should not be less than 1/5 of the narrowest dimension between the sides of the forms, and not less than 0.75 in. of minimum clear spacing between bars and tendons.

3.2 Fresh Property Requirements

The survey collected information on what each of the DOTs consider a requirement for SCC fresh performance directly related to the mixture proportioning. It is important to recognize what fresh property requirements are frequently used in different states across DOTs to construct reliable SCC girders.

Table 3.2 summarizes the requirements of participating DOTs of all test methods for the fresh property evaluation. For instance, Illinois DOT has parameters for all fresh property methods explained herein. For the slump flow, Illinois DOT has a lower and upper limit of 20 in. and 28 in., respectively. VSI shall be a maximum of 1. The J-Ring value should be a maximum of 4 in., meaning that the value is the height of the concrete in the inner diameter of the ring. L-Box must be a minimum of 60%. Column segregation index shall be a maximum of 15%. Additionally, Illinois DOT allows contractors to establish stricter guidelines based on their own SCC mixture design. New York State and Washington DOTs allow the contractors to select a “target” value, and report results within ±2” from the target value.

Table 3.2 SCC fresh property requirements for surveyed state DOTs

State	Slump Flow (in.)	J-Ring (in.)	VSI	L-Box	Column Segregation
Alabama	25 - 29	±3	0-1	N/A	N/A
Florida	27 ± 2.5	±2	0-1	N/A	Max 15%
Georgia*	Min 20	N/A	N/A	Min 0.8	N/A
Illinois*	20 - 28	Max 4	0-1	Min 0.6	Max 15%
Iowa	Max 27	N/A	N/A	N/A	N/A
Kentucky*	Provide Spread Limits, Production Records and Quality Control Procedures.				
Louisiana	20 - 28	Provide Aggregate Gradations			
Michigan	27 ± 1	±0.6	0-1	Min 0.8	N/A
Minnesota	Max 28	±2	0-1	N/A	N/A
Nebraska	ASTM C1611	N/A	ASTM C1611	N/A	N/A
Nevada*	No specific guidelines.				
New York*	±2 Target	±2	0-1	N/A	Max 15%
North Carolina	24 - 30	±2	N/A	Min 0.8	N/A
Ohio	27 ± 2	N/A	N/A	N/A	N/A
Pennsylvania*	20 - 30	±2	0-1	N/A	N/A
Rhode Island	20 - 26	±2	N/A	N/	N/A
South Carolina	Precasters in the state are hesitant in using SCC.				
South Dakota	20 – 28	±2	0-1	N/A	N/A
Texas*	22 – 27	±2	0-1	N/A	Max 10%
Utah	18 – 32	±1	0-1	N/A	Max 10%
Virginia	26 ± 3	±2	0-1	N/A	Max 15%
Washington	± 2 Target	±1.5	0-1	N/A	Max 10%

*Note: the existence of * indicates that required values were obtained from each of the following state-DOT specifications: 1) Georgia: Special Provisions Section 500 Concrete Structures (Georgia DOT 2006); 2) Illinois: Specifications for Precast Products Section II.3.1 SCC (Illinois DOT 2012); 3) Kentucky: II.4.1 Method for Approval of Using SCC (Kentucky TC 2006); 4) Nevada: Section 501 Portland Cement Concrete (RTCSNV 2014); 5) Nebraska: Section 1002 in the Standard Specification (Nebraska DOR 2008); 6) New York: Self Consolidating Concrete Mix Design Qualification Procedure For Precast Work Performed Under the QC/QA Program (New York DOT 2014); 7) Pennsylvania: Section 714—precast concrete products (Pennsylvania DOT 2014); and 8) Texas: Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges Section 4.2.8.(Texas DOT 2015)*

4. WISCONSIN PRECAST CONCRETE PLANT IDENTIFICATION

SCC mixture design has many difficulties with determining the constituent proportions due to the lack of specific requirements and guidelines in producing consistent and high quality SCC mixtures. To produce good quality SCC mixtures, several trial batches are required to identify material properties, admixture dosages, and long-term properties. Due to the possibility of creating several high quality mixtures with different parameters and materials, a large test matrix was developed.

In this project, three different precasters in different regions of Wisconsin were selected to produce SCC mixtures with their available materials. SCC mixtures of each precaster were evaluated and refined in a laboratory setting using trial batch procedures to achieve satisfactory workability properties. The three prestressed plants were County Materials Roberts, County Materials Janesville, and Spancrete. Throughout this report, county material plants will be referred to as Roberts and Janesville, respectively. Each plant was contacted in a preliminary stage of the project to determine expectations and concerns. All three plants were eager to collaborate to achieve the production of SCC girder in Wisconsin. Along with the survey sent to the DOTs, each precaster was also asked to provide input to develop a mixture design. Some parameters, such as cement content, w/c ratio, and S/Agg, were chosen based on the survey responses, precasters input, and WisDOT recommendations. Description of the materials and construction techniques used by each plant will be discussed in subsequent sections.

5. SCC MIXTURE DESIGN AND LABORATORY MATERIAL TESTING

Due to the lack of information on SCC mixtures using materials from Wisconsin, the initial number of parameters to consider was substantial; thus, a refinement process was introduced to identify the key parameters having a direct influence on the workability and strength of SCC. Note that this process was initiated at the SDSU Structures Laboratory. The subsequent sections provide detailed descriptions of materials, SCC performance criteria, SCC mixture designs, and testing for workability and strength for each plant.

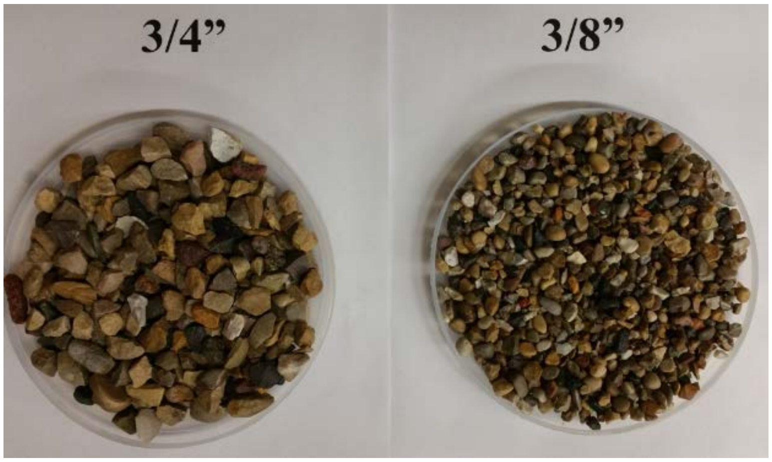
5.1 Material Properties

Materials used for the refinement process were obtained directly from the respective precast plants and shipped to the SDSU Structures Laboratory. Each plant provided detailed information regarding their material constitutions, including cement type, coarse and fine aggregate, and admixture provider. Note that the admixture provider recommended a specific product and dosages for SCC mixtures based on their specific product. Table 5.1 summarizes the respective materials used at each plant for the production of prestressed SCC girders. It should be noted that the coarse aggregate consisted of limestone No 67 (3/4") and No 78 (3/8"), conforming to the AASHTO M43 (AASHTO 2009) for county materials and river gravel No 67 (3/4") and No 78 (3/8") for Spancrete. Aggregate characteristics were obtained from the respective distributors to be used for the SCC mixture design.

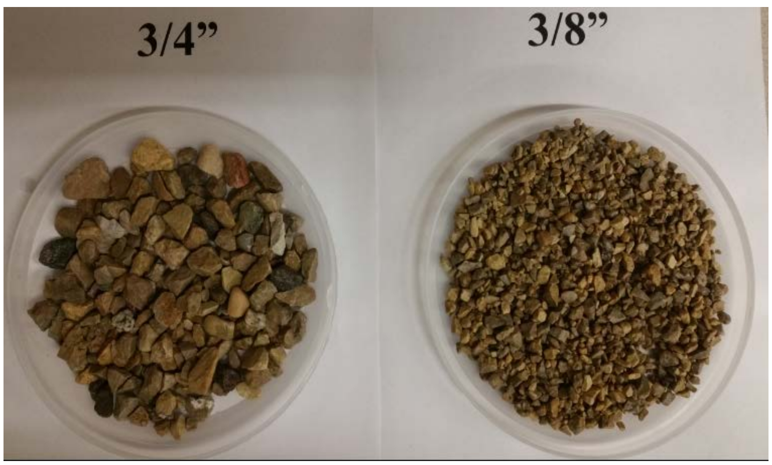
Table 5.1 Materials used for the production of prestressed SCC girders for all the plants

Material	Roberts	Janesville	Spancrete
Cement Type	Type I/II	Type III	Type III
Coarse Aggregate	Crushed Limestone	Crushed Limestone	River Gravel
Fine Aggregate	River Sand	River Sand	Silty Sand
Admixture Provider	Grace	Grace	SIKA

As shown in Table 5.1, the Janesville plant uses Cement Type III with its specific gravity of 3.15. The 3/4'' and 3/8'' crushed limestones used in the Janesville plant are shown in Figure 5.1(a) with a coarse aggregate specific gravity of 2.66 and a percentage absorption of 1.52%. Fine aggregates had a specific gravity of 2.65 and percentage absorption of 0.5%. The Roberts plant used Portland Cement Type I/II (see Table 5.1) with a specific gravity of 3.14. Coarse aggregate consisted of crushed limestone; however, the Roberts plant used a different pit than Janesville. The 3/4'' and 3/8'' crushed limestones used in the Roberts plant can be seen in Figure 5.1(b), and visually compared with those used in Janesville in Figure 5.1(a). The Roberts plant coarse aggregate had a specific gravity of 2.59 and percentage absorption of 2.64%. The fine aggregate had a specific gravity of 2.65 and percentage absorption of 0.69%. Finally, the Spancrete plant (see Table 5.1) used Cement Type III with a specific gravity of 3.15. The coarse aggregate was river gravel, as shown in Figure 5.1(c), which had a specific gravity of 2.76 with 0.94% absorption.



(a)



(b)

(c)

Figure 5.1 Types of aggregate: (a) Janesville crushed limestone, (b) Roberts crushed limestone, and (c) Spancrete river gravel

5.2 Workability and Strength Performance Criteria

Workability performance criteria were established using information collected in the literature review section from past studies and current practices of state DOTs as shown in Table 5.2. The compressive strength required by the WisDOT for the successful fabrication of SCC girders is needed at both 18 hours and 28 days, in addition to the workability criteria. As shown in Table 5.2, the required strength for SCC mixes was 6800 psi at time of release and 8000 psi at 28 days. These criteria were used as a requirement for all SCC mixtures throughout the investigation.

Table 5.2 Workability and compressive strength criteria for SCC mixtures

Evaluation Table for Fresh Properties		
Fresh Properties Tests	**Acceptable Range**	**Target Value**
Slump Flow	22” – 28”	25”
J-Ring	Max 2”	Max 2”
Column Segregation	≤ 15%	Close to 10%
T20	3-10 sec	< 6 sec
VSI	≤ 1	≤ 1
Compressive Tests	**Target strength**	
Strength	6800 psi (18 hours) 8000 psi (28 days)	

5.3 Laboratory SCC Mixtures

The trial batch process was divided into two stages: 1) stage one consisted of evaluating several SCC mixtures with varying mixture parameters established by the researchers, considering the input from WisDOT; 2) stage two consisted of selecting the highest quality SCC mixtures from each plant based on the results observed in stage one. The materials used in each SCC mixture were defined by cement, water, coarse aggregate 3/4”, coarse aggregate 3/8", fine aggregate, HRWR, and VMA. Different SCC mixtures were created considering two values of S/Agg (0.45 and 0.5) and two values of w/c ratios (0.33 and 0.35). Appendix B provides specific mixture materials and parameters for all mixtures in stages one and two.

5.3.1 Mixing and Curing Procedures

SCC mixtures were made in five cubic-foot batches using a drum mixer. In some cases, not all fresh tests were necessary to perform, therefore, the size of the batch was smaller. The mixing procedure was carried out per the procedure provided by the Portland Cement Association (PCA), and was held consistent for every mixture sample. Aggregates were placed in the drum first, with the cement then added on top. These materials were mixed in the drum for approximately 30 seconds before the water was slowly added to the mix, avoiding large powder clumps and thus guaranteeing equivalent distribution. The admixtures were then slowly added to the drum. As specified by the admixture provider, admixtures were not combined with the water prior to adding both to the drum. All the constituents were mixed together for approximately eight minutes before any testing began to ensure proper mixing. An image of the drum used to mix the SCC is shown in Figure 5.2.

Figure 5.2 Drum used to mix SCC

Fresh properties were measured immediately after mixing was complete. Slump flow, J-Ring, and column segregation tests were completed in the respective order in a lapse of 30 minutes at the completed stage of each mixing. Concrete cylinders were finally made after the fresh property testing concluded. Note that for the preparation of the cylinders, no rodding was done as it is unnecessary for SCC. For each mixture, compressive strength was tested after 18 hours of curing to simulate the estimated time of curing at the identified plants before strands release. To simulate steam curing, a water bath was used as seen in Figure 5.3. Cylinders were placed in the water bath for 18 hours at a temperature of 110 °F.

Figure 5.3 Water bath to simulate steam curing of SCC cylinders

5.3.2 Stage One

Prior to mixing any batches, some parameters of the mixture design were established by the researchers with some input from WisDOT. These parameters include cement content, aggregate type and size, and blending of coarse aggregate. Modifications to these parameters were made based on performance of workability of each mixture. Table 5.3 provides the initial parameters established for stage one and the corresponding values. It should be noted that the coarse aggregate blending variation shown in Table 5.3 was considered the main parameter for this stage.

Table 5.3 Mixture parameters and corresponding values

Mixture Parameter	Value
Cement Content	800 lbs/yrd^3
w/c	0.35
S/Agg	0.50
Coarse Aggregate Blending	20% variation of 3/4"

SCC mixture proportions were designed based on the material properties of each plant. Table 5.4 illustrates the 12 SCC mixtures studied. They are divided according to their respective prestress plant, coarse aggregate blending, cement type, S/Agg, and w/c ratio. As shown in Table 5.4, for each mix, the blending of coarse aggregate followed intervals of 20% between 3/8” and 3/4” coarse aggregate. Janesville and Roberts utilized cement Type III and cement Type I/II, respectively. Note that mixtures of Spancrete were not used for the initial investigation due to a lack of materials from the precaster. However, after investigating the workability and strength of Janesvillle and Roberts SCC mixtures, the researchers, considering the recommendation from the Project Oversight Committee (POC), were able to select the most appropriate blending configuration, which did include several mixtures from Spancrete for stage two.

Table 5.4 Test matrix for stage one

Plant	Mixture No	Aggregate Size (3/8”)						Cement Type		w/c	S/Agg
		100%	**80%**	**60%**	**40%**	**20%**	**0%**	**Type III**	**Type I/II**	**0.35**	**0.50**
Janesville	1	X						X		X	X
	2		X					X		X	X
	3			X				X		X	X
	4				X			X		X	X
	5					X		X		X	X
	6						X	X		X	X
Roberts	7	X							X	X	X
	8		X						X	X	X
	9			X					X	X	X
	10				X				X	X	X
	11					X			X	X	X
	12						X		X	X	X

5.3.2.1 Results of Stage One

The SCC mixtures used for stage one were investigated to determine if the initial parameters were satisfactory in identifying the highest quality SCC for PSC girder production. The overall workability of the tested SCC mixtures for the Janesville and Robert plants were determined to be satisfactory, as the fresh properties were within the target range listed in Table 5.2. Table 5.5 summarizes the workability results and compressive strengths for all SCC mixtures. Note that slight adjustments to the dosage of HRWR and VMA were necessary to meet the minimum requirements for SCC flowability and passing ability as specified in Table 5.2. Admixture dosages were slightly increased every trial batch until the values of Table 5.2 were met. Final admixture dosages for each mixture trial are listed in Appendix B. Generally, the HRWR dosage ranged from 5 to 9 cwt, while the VMA dosage varied from 0 to 2 cwt. Each plant has used different admixtures for SCC mixture production. Specifically, county material mixtures contained ADVA Cast 575 and V-MAR 3 manufactured by Grace, while Spancrete admixtures were manufactured by SIKA where Viscocrete 2100 serves as HRWR and Stabilizer 4-R was the VMA.

Table 5.5 Stage one results

Janesville Plant						
No	**Percent of 3/8"**	**Slump Flow (in)**	**T20 (s)**	**J-Ring (in)**	**Column Segregation (%)**	**18-hr. Compressive Strength (psi)**
1	**100**	24	9.4	24.5	2.76	6442
2	**80**	24	7.54	24	6.32	7027
3	**60**	24.5	12	25	6.47	6756
4	**40**	25	9	23.5	8.17	7658
5	**20**	22.8	10.6	25	9.18	8432
6	**0**	23	7.32	24.5	10.1	7049
Roberts Plant						
No	**Percent of 3/8"**	**Slump (in)**	**T20 (s)**	**J-Ring (in)**	**Column Segregation (%)**	**18-hr. Compressive Strength (psi)**
7	**100**	24.5	10	22.5	1.67	5221
8	**80**	26	7	24.5	3.33	5524
9	**60**	24.5	9	23.5	5.15	6187
10	**40**	24.8	3.4	23.5	8.01	7113
11	**20**	24.5	4.9	24	9.9	7135
12	**0**	26	5.71	24.3	11.8	5870

Flowing ability

The flowing ability quantified via the slump flow ranged from 22.8 in. to 26 in., which was within the acceptable range for the slump flow listed in Table 5.2. The slump flow diameters for the Janesville mixtures experienced a range of 22.8 in. to 25 in. The mixtures with a higher percentage of 3/8” aggregate size exhibited higher spread diameters compared with those with a low percentage of 3/8” aggregate (excluding mixture 4). Roberts spread diameter had a range from 24.5” to 26” as listed in Table 5.5. The results from the Janesville and Roberts mixtures are illustrated in Figure 5.4, and it can be concluded that the Roberts mixtures experienced better overall flow ability compared with Janesville. The mixture having 40% of 3/8” aggregate was found to be the best blended configuration, as it was the closest to the target value of 25” specified in Table 5.2.

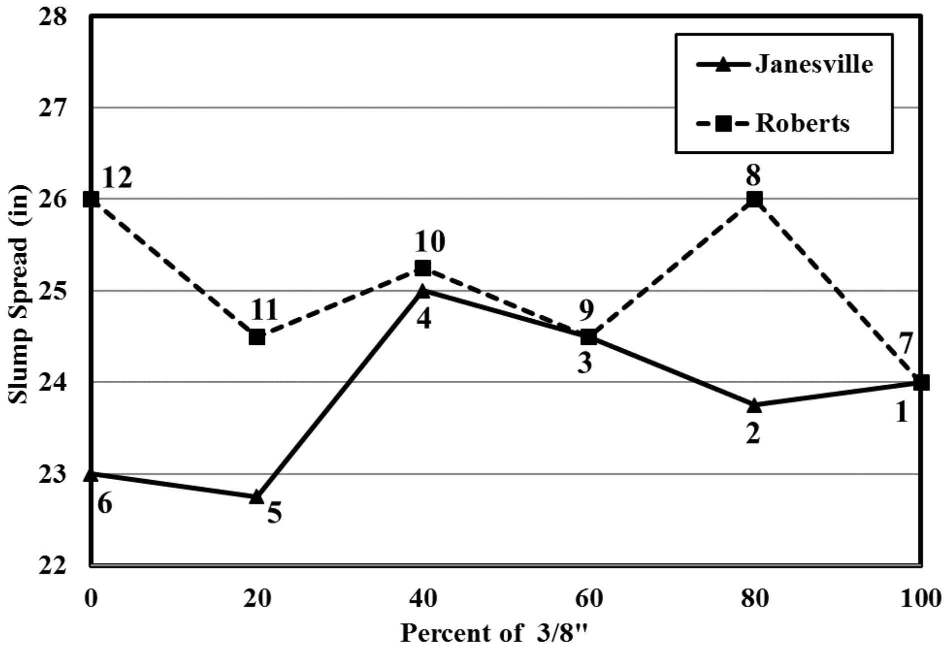


Figure 5.4 Slump flow results for Janesville and Roberts mixtures

From the slump flow tests for both Janesville and Roberts plants, T20 values were recorded, (presented in Table 5.5) to quantify the viscosity of each mixture. In the Roberts mixtures, T20 values tended to decrease as the percentage of 3/8" aggregate decreases. Janesville mixtures did not follow the same trend seen in the Roberts mixtures; rather, the T20 values were more inconsistent with a few ups and downs. The discrepancy in T20 values between Janesville and Roberts mixtures may be caused by the effect of cement type.

Passing Ability

Passing ability is quantified by the difference in diameter between slump flow and J-Ring test methods. Figure 5.5 illustrates the passing ability trends for Janesville and Roberts mixtures. Passing ability for the Janesville mixtures ranged from 0.25 in. to 2.25 in., while the Roberts mixtures ranged from 0.75 in. to 1.75 in. Janesville mixtures showed the best passing ability for mixtures having a high percentage of 3/8" coarse aggregate. This trend was expected, as less blockage between the J-Ring bars is seen with smaller aggregate size; however, mixtures 4, 5, and 6 had a noticeable decrease in passing ability, whereas mixture 5 greatly exceeded the 2 in. established for the optimum workability. Again, results from Roberts are within a smaller range compared with the results from Janesville, as the percentage of 3/8" aggregate varies. Roberts had a similar trend, shown in Figure 5.5, where the best results were seen in mixtures 9, 10, and 11. Mixture 10 had the best passing ability for Roberts with a value of 0.75 in. During testing, it was observed with Roberts mixtures that as the percentage of 3/8" aggregate increased, the viscosity increased, resulting in less flow ability.

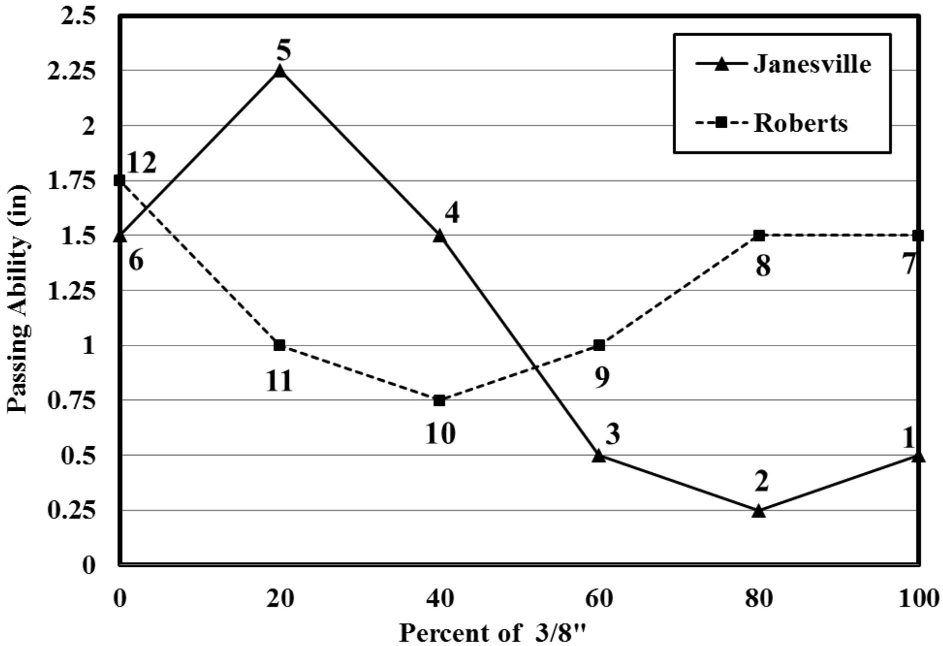


Figure 5.5 Passing ability results for Janesville and Roberts mixtures

Segregation

Segregation was measured using the column segregation test. This test calculated the percentage of segregation based on the percentage difference of the aggregate weight between the top and bottom sections of the cylinder. Segregation has a negative impact on the structural performance of SCC, and thereby a maximum of 15% segregation was allowed, as shown in Table 5.2. Figure 5.6 illustrates that the percentage segregation for both plants is under the maximum allowed. The segregation for both plants decreased as the percentage of 3/8” coarse aggregate increased. This behavior was expected as larger aggregate tends to segregate at a faster rate due to its self-weight. Results for both plants were under the 15% requirement, signifying that the mixture was viscous enough to prevent segregation or bleeding.

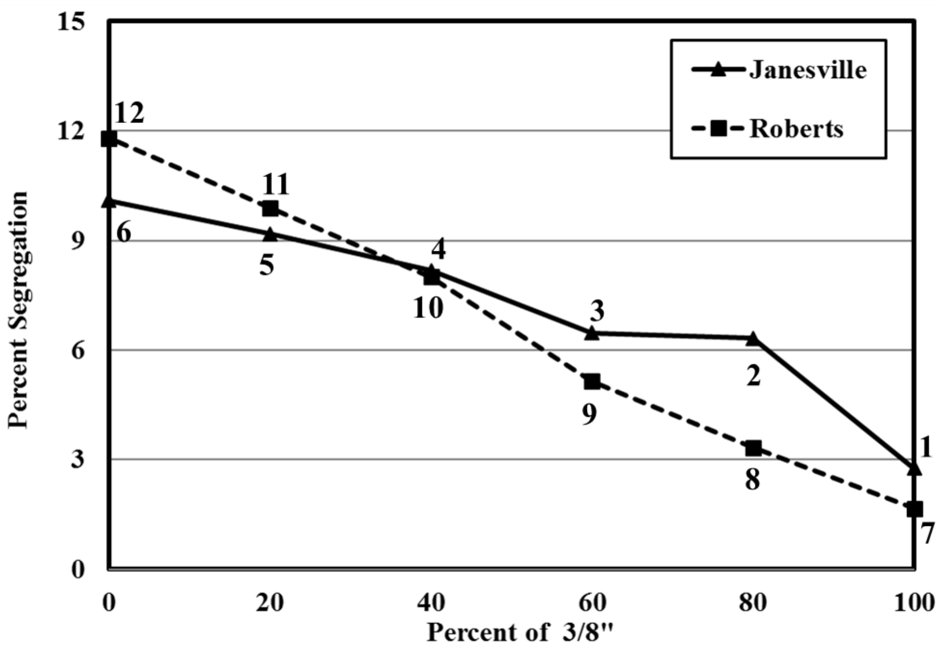


Figure 5.6 Segregation results for Janesville and Roberts mixtures

Compressive Strength

Compressive strength of all Janesville mixtures, at transfer, were higher than those from Roberts, as was expected, due to the cement types. Figure 5.7 shows the compressive strength results at 18 hours for Janesville and Roberts plants. As the percentage of 3/8” coarse aggregate decreased, the compressive strength of the concrete, in most cases, increased. Compressive strength of Janesville mixtures ranged from 6442 psi to 8432 psi, while Roberts compressive strength values ranged from 5221 psi to 7135 psi.

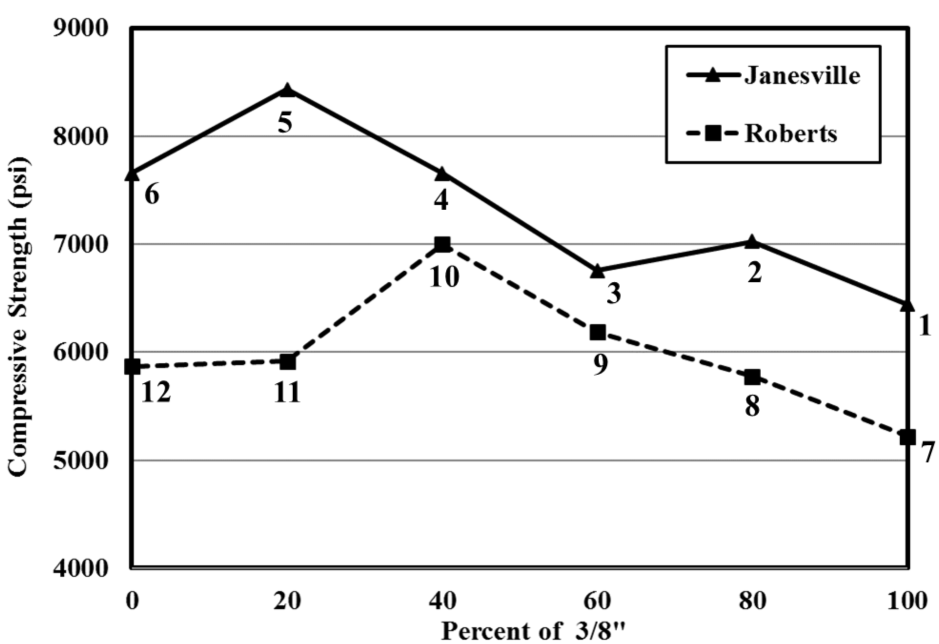


Figure 5.7 Compressive strength at transfer

Summary

Results from stage one indicated the mixtures having 60% and 80% of 3/4” aggregate provided the exceptional workability and compressive strength desired to produce the highest quality PSC girders for WisDOT. Mixtures 2 and 3 from the Janesville plant and mixtures 8 and 9 from the Roberts plant were selected for further testing. These mixtures were used for investigation of workability and compressive strength at release and after 28 days in stage two.

5.3.3 Stage Two

For stage two, S/Agg and cement content were modified within the identified mixtures illustrated in Table 5.6. For mixtures from the Roberts plant, which used cement Type I/II, it was decided to additionally modify the w/c from 0.35 to 0.33 because the 18-hour compressive strength results were low for the PSC girder production based on WisDOT requirements. As previously mentioned, mixtures of Spancrete were also used for this investigation to extensively cover all options in order to determine the most suitable SCC mixtures in the production of PSC bridge girders.

Table 5.6 Test matrix for stage two

	Roberts			**Janesville**			**Spancrete**		
Cement Content	**S/Agg**	**CA Blend**		**S/Agg**	**CA Blend**		**S/Agg**	**CA Blend**	
800 lbs	0.45	A	B	0.45	A	B	0.45	A	B
	0.50	A	B	0.50	A	B	0.50	A	B
750 lbs	0.45	A	B	0.45	A	B	0.45	A	B
	0.50	A	B	0.50	A	B	0.50	A	B

Note: A= 60% of ¾” and 40% of 3/8” aggregate, while B= 80% of ¾” and 20% of 3/8” aggregate

5.3.3.1 Results of Stage Two

The test matrix shown in Table 5.6 defines the SCC mixtures evaluated at the precast plants. Table 5.7 illustrates the laboratory testing results for mixtures from all three plants. Based on an examination of the results, comparison against the predetermined target values (see Table 5.2), and careful deliberation with the POC in WisDOT, five SCC mixtures were selected for the final workability and compressive strength testing at the plants and creep and shrinkage testing. Table 5.7 includes the selected five mixtures, provided in bold, which met the requirements previously established. Appendix C includes a compilation of all the detailed results of stage two. Note that the nomenclature in the mixture code is defined as follows: the first letter refers to the respective plant where R, J, and S represent Roberts, Janesville, and Spancrete, respectively. The first number refers to the cement content, where 800 lbs/yrd^3 and 750 lbs/yrd^3 were used. The second number denotes the S/Agg as shown in the test matrix table. Finally, the third number refers to the w/c where 0.33 was used for Roberts mixtures and 0.35 was used for Janesville and Spancrete.

Table 5.7 Results of stage two

No	Mixture Code	%= 3/4"	Slump Flow (in)	T20 (s)	J-Ring (in)	Column Segregation (%)	Air (%)	Temp. (F˚)	Compressive strength (psi)	
									18 hr	28 days
Roberts										
1	**R-800-0.50-0.33**	**60**	**24.75**	**3.4**	**23.50**	**2.1**	**2.2**	**83**	**7113**	**8750**
2	**R-800-0.45-0.33**	**60**	**24.6**	**3.6**	**23.75**	**10.2**	**1.9**	**80**	**6959**	**10393**
3	R-800-0.50-0.33	80	24.5	4.9	24.00	9.9	1.8	82	7135	9994
Janesville										
4	**J-800-0.50-0.35**	**60**	**24.75**	**3.9**	**23.50**	**2.8**	**2.2**	**87**	**6932**	**10164**
5	J-750-0.45-0.35	60	24.75	5.2	24.00	4.8	2.1	82	6957	9877
6	**J-800-0.50-0.35**	**80**	**25.25**	**4.8**	**24.50**	**4.3**	**1.9**	**84**	**7049**	**9427**
7	J-800-0.45-0.35	80	25.00	4.6	24.00	6.4	1.8	76	6994	9242
Spancrete										
8	S-800-0.50-0.35	60	25.75	6.11	23.5	2.3	2.1	81	6736	8587
9	**S-800-0.45-0.35**	**60**	**25.25**	**5.83**	**23.75**	**5.7**	**2.0**	**81**	**6923**	**9656**
10	S-750-0.45-0.35	60	24.5	5.34	22.25	2.5	2.1	82	6709	8684
11	S-800-0.50-0.35	80	26.25	3.11	24.5	12.1	2.4	84	6862	8923

Again, the mixtures in bold in the table were selected for further testing at the respective prestress plant. These five mixtures (1, 2, 4, 6, and 9) consist of different mixture parameters, which were investigated during time-dependent property testing. For instance, Roberts mixtures (1 and 2) were selected to compare the difference in S/Agg from 0.45 to 0.50. Janesville mixtures (4 and 6) were selected to investigate the effect of blending (60% and 80% of ¾”). Finally, Spancrete has only one mixture due to limited space in the creep frames to place samples; however, the Spancrete mixture was used to compare the effect of aggregate type against Janesville and Roberts.

5.4 Plant Mixtures

The selected mixture proportions for plant testing are shown in Table 5.8. Note that the mixtures were tested by each plant prior to the research team visiting their plant. Each plant was given the option to determine the admixture dosage that would satisfy the necessary requirements (see Table 5.2). After each plant provided satisfactory results, the research team visited the plant for further testing and specimen collection.

Table 5.8 Mixture proportions for plant testing

Mixture	1	2	4	6	9
Plant	Roberts	Roberts	Janesville	Janesville	Spancrete
Cement Type	I/II	I/II	III	III	III
Aggregate Type	Limestone	Limestone	Limestone	Limestone	Gravel
Blending (XX-YY)[3]	60-40	60-40	60-40	80-20	60-40
w/c	0.33	0.33	0.33	0.33	0.33
S/Agg	0.50	0.45	0.50	0.50	0.45
Cement Content (lbs/yrd^3)	800	800	800	800	800
Coarse Aggregate 3/4" (lbs/yrd^3)	856	948	905	1202	1064
Coarse Aggregate 3/8" (lbs/yrd^3)	570	633	616	322	709
Sand (lbs/yrd^3)	1435	1337	1503	1510	1457
Water (lbs/yrd^3)	264	240	264	252	272
HRWR (oz/cwt)	13.1	13.1	13.0	13.1	12.4
VMA (oz/cwt)	6.5	6.5	4.1	4.9	0.0
Admixture Supplier	Grace	Grace	Grace	Grace	SIKA

It should be noted that mixing procedures varied for each plant according to its installations. In general, the batch size at each plant was 4-5 cubic yards. The main difference between laboratory and plant mixings was the ambient temperature. Plant mixing was made during the winter months, which resulted in lower concrete curing temperatures.

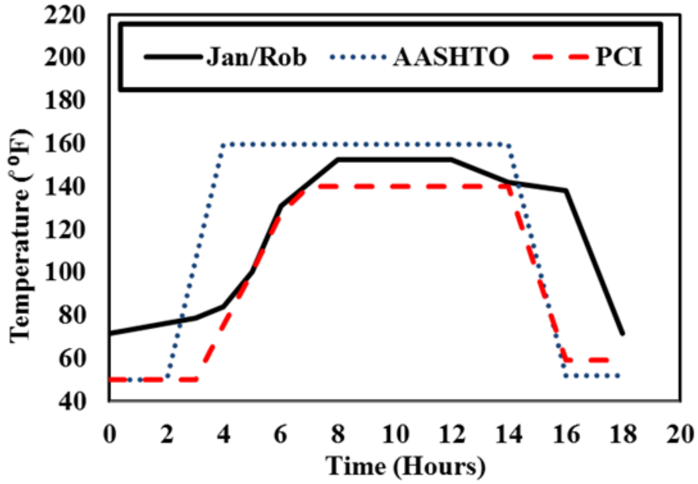
5.4.1 Curing

All samples made at the plants were steam cured to obtain high early compressive strengths. The samples were placed adjacent to the girder bed of each plant and covered with a plastic layer as shown in Figure 5.8. They were then cured for 18 hours following the steam curing regimen of each plant that was compatible to those from the AASHTO and PCI. According to the AASHTO Specifications (AASHTO 2009), the maximum temperature of the concrete should not exceed 160℉ and the rise in temperature is limited to an increase of 71℉ per hour, similar to what is recommended for the cooling rate. The PCI (2012) recommends a rate of heating of 71℉ per hour and a maximum temperature of 140℉.

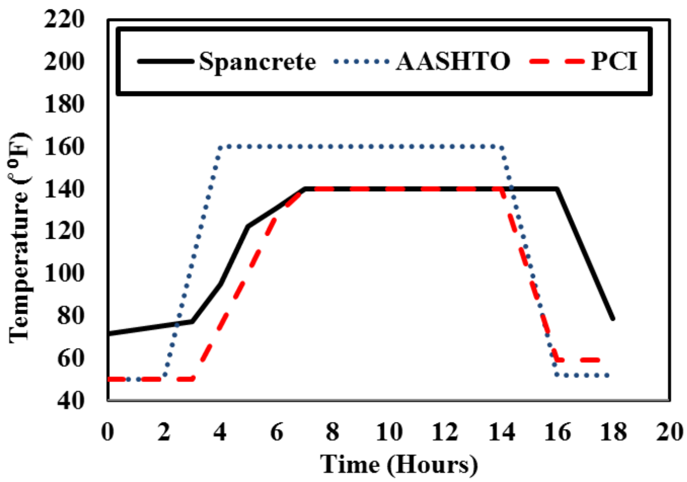
Figure 5.9 shows a graphic representation of the steam curing regimen provided by the precast plants and the AASHTO and PCI. Figure 5.9 (a) shows the recommendation from both AASHTO and PCI for steam curing, plotted against the temperatures from the county materials plants. It appears that the regimen of both plants were similar to the PCI recommendation where the only difference was the maximum temperature: a value of 152℉ was recorded for both plants. Figure 5.9 (b) shows the steam curing regimen for Spancrete against both AASHTO and PCI recommendations. The Spancrete curing regimen was more similar to the PCI recommendation than the county plants, and the maximum temperatures were identical. Testing was performed during winter months when the outside temperature was approximately 0℉, and could have potentially lowered the steam temperature in the girder bed. Note that lab concrete samples were cured at a constant temperature of 110°F, which was not adjusted during the curing period.

To investigate the effects on shrinkage of steam curing and transportation of specimens from the precast plant to the laboratory, it was decided to also cast samples in a laboratory setting. The laboratory samples made for shrinkage tests were moist cured for 18 hours at a temperature of 73 ± 4˚F. Then the samples were removed from the metal molds and placed in a temperature controlled room to be air cured with the plant samples. This environment experienced controlled temperatures, with recordings taken twice a week showing a range between 72˚and 73˚F. The humidity experienced some changes, with recordings dropping from a weekly average of 50% at day 140.

Figure 5.8 Creep samples placed adjacent to girder bed for steam curing



(a)



(b)

Figure 5.9 Steam curing regime: (a) Roberts and Janesville and (b) Spancrete with standard regime

5.4.2 Results

Fresh and hardened properties from each plant are listed in Table 5.9. Recall that each plant was given the option to individually adjust the admixture dosage to obtain their desired performance in terms of fresh properties and to meet the required compressive strength. Roberts mixture 1 was the most fluid in comparison with all mixtures. However, the higher level of fluidity may have had an impact on the segregation of the mixture and the compressive strength at approximate 18 hours. Mixtures 4 and 6 showed similar performance, with mixture 6 being slightly more flowable than mixture 4. It should be noted that mixtures 1 and 6 were batched in a different building within Janesville and Roberts before being transported in a ready-mix truck to the testing building. The wet mix was then collected in a wheelbarrow for the respective testing.

Roberts mixtures exhibited high concrete temperatures because the Roberts facility provided more protection in terms of cold temperature as shown in the results in Table 5.9. Janesville and Spancrete mixtures experienced low temperatures; thus, this might have affected the performance of the chemical admixtures. Note that in the case of mixture 9, the slump flow and J-Ring values were found to be lower than expected. For this mixture, the HRWR dosage used, was the maximum allowed by the admixture provider. Therefore, one option to improve the fresh properties of the mixture would be to increase w/c, as this mixture showed high early compressive strength.

Table 5.9 Fresh and hardened properties results of plant testing

Mixture	1	2	4	6	9
Air Content (%)	0.9	1.7	1.6	1.1	2.6
Unit Weight (lbf/ft^3)	151.0	150.2	147.0	151.4	143.6
Concrete Temperature (˚F)	80	78	69	70	65
Slump Flow (in)	28.5	26.0	25.5	26.3	23.0
J-Ring (in)	28.5	24.8	24.8	26.1	20.0
VSI	1	0.5	1	1.5	0
Column Segregation (%)	4.15	0.85	10.8	7.7	5.6
18hr. Comp. Strength (psi)	4291	5914	6094	4740	9148
28d. Comp. Strength (psi)	11618	13048	12444	12696	11718

6. TIME-DEPENDENT SCC MATERIAL CHARACTERISTICS

SCC has a variety of material constituent proportions compared with CC, resulting in different time-dependent material characteristics, including creep and shrinkage. It is necessary to experimentally evaluate these characteristics prior to the application of SCC to PSC bridge construction. Testing results for creep and shrinkage of the five SCC mixtures and their comparison with the codified values from the AASHTO and ACI specifications are presented in the following subsections.

6.1 Creep

Included in this section are testing setup, measurement, and results and discussion for creep of the identified SCC mixtures along with comparison between measured and codified creep coefficients.

6.1.1 Testing Setup

Creep testing was executed following the ASTM 512 Standard Test Method for Creep of Concrete in Compression (ASTM, 2011). For this project, three creep frames, which included all five mixtures (mixtures 1, 2, 4, 6, and 9) identified in Section 5, were fabricated to induce a consistent compressive load maintained for 280 days as shown in Figure 6.1(a). Prestressed chucks were added at the ends of the tension strands to sustain the applied load, while the dual plates at one end of the frame were used to maintain the load. The ASTM 512 specifies that the induced load should not exceed 40% of the compressive strength of the samples at the age of loading.

To simulate the placement of the concrete deck on the girder, the load induced into the creep frames was 2000 psi, which was below 40% of the compressive strength. To ensure uniform distribution and transmission of the load between cylinders, neoprene pads were placed at the ends and between cylinders. Five 6” x 12” cylinders were placed in each frame as shown in Figure 6.1(a). Note that three cylinders for each of the identified mixtures were made, resulting in 15 total cylinders. Each cylinder was outfitted with two metal tabs on opposite sides of the cylinder, with 10-in. spacing between them. This method allows for a comparison of each side of each cylinder, and to develop the overall compression of each cylinder through an average of both measurements. The metal tabs were embedded in cylinders shown in Figure 6.1(b).

(a)

(b)

Figure 6.1 Creep test setup: (a) loaded creep frame and (b) cylinder with brass inserts on both sides

6.1.2 Creep Measurement

A multi-length strain change extensometer was used to measure strain changes between the metal tabs for each of the cylinders per frame [see Figure 6.2(a)]. Each reading with the extensometer had a precision of 0.0001 in. Three readings were taken on each side of the cylinder with calibration bar measurements taken between each reading, and then the average from both sides of the cylinder was used to obtain the final strain change at a specific age [see Figure 6.2(b)]. The first reading was taken when the cylinders were removed from steam curing. Readings were then taken immediately after placing the cylinders in the creep frame with the sustained, compressive load. The difference between these two readings was considered to be the instantaneous elastic strain of each cylinder. Additional readings were taken six hours after the compressive load was induced in the frame. Control readings were performed when transporting the frames from the precast plants to the SDSU Structures Laboratory to ensure that the frame did not suffer any damage. Following transfer to the laboratory, daily readings were taken for the first week, weekly readings were taken for the first month, and then monthly readings were taken until 280 days.

(a) (b)

Figure 6.2 Representative pictures of creep samples: (a) all creep frames and (b) measurement taken on creep frame

6.1.3 Results and Discussion

The creep values of the 15 cylinders (6 in. x 12 in.) tested until 280 days ranged from 1094 to 1440 microstrain. The average creep growth for all five mixtures at ages of 28, 56, 84, 112, and 280 days is summarized in Table 6.1, and all the creep values are illustrated in Figures 6.3(a) through 6.3(e) for mixtures 1, 2, 4, 6, and 9. Note that creep data for all the mixtures are provided in Appendix D. It appears that creep strains mostly occurred during the first 28 days of curing as expected. Note that the creep results shown in this figure also include the strain changes caused by drying shrinkage. Due to the difference between creep and shrinkage specimens, the researchers were unable to adjust strain changes caused by only shrinkage (4 in. x 4 in. x 10 in. prims). The readings for each cylinder were averaged using both sides of the cylinder for each mixture, and then the average of all three cylinders in each mixture were plotted on graphs shown in Figures 6.3(a) through 6.3(e).

Table 6.1 Average creep strain change over time

Time	Creep strain on SCC mixtures (με)				
	Mixture 1	**Mixture 2**	**Mixture 4**	**Mixture 6**	**Mixture 9**
28	700	670	861	832	875
56	836	789	973	947	1012
84	920	876	1064	1066	1107
112	1001	925	1117	1144	1180
280	1203	1094	1278	1306	1440

Note: Strain values shown in this table are caused by combined creep and drying shrinkage.

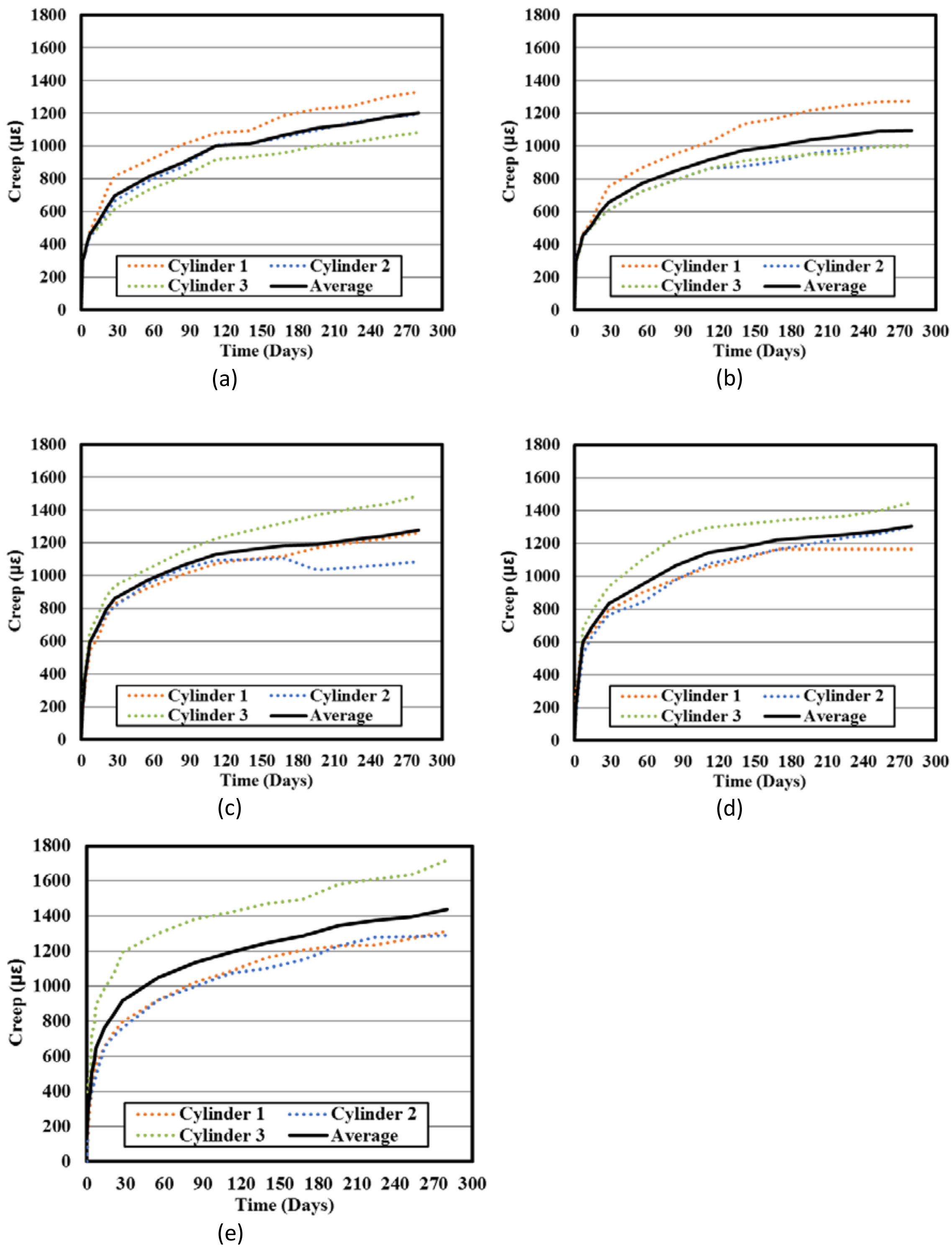


Figure 6.3 Measured creep up to 280 days: (a) mixture 1, (b) mixture 2, (c) mixture 4, (d) mixture 6, and (e) mixture 9

Overall creep behavior for all the mixtures was similar [see Figures 6.3(a) through 6.3(e)]. Mixture 9 had a large difference between cylinder 3 and cylinders 1 and 2, with a gap of 429 microstrains as shown in Figure 6.3(e). Remarkably, mixture 9 (composed of cement Type III and S/Agg of 0.50) exhibited the highest creep strain with a value of 1440 microstrain, while mixture 2 (made of cement Type I/II and S/Agg of 0.45) exhibited the lowest creep showing 1094 microstrain. This result was expected as a higher amount of coarse aggregate helps to restrict creep deformation in concrete. Further, the cement type had a significant impact on creep values, indicating that the mixtures using cement Type III exhibited higher creep values compared with cement Type I/II. This behavior was observed in past studies (Long and Khayat 2011), revealing that this was attributed to the greater surface area and chemical composition of cement Type III, which promotes early setting.

6.1.4 Comparison with Codified Creep

All the measured creep strains for each cylinder were converted to creep coefficients, referring to the relevant codified process in the AASHTO and ACI specifications and using the instantaneous elastic strain recorded after loading of the cylinders. The calculated creep coefficients were compared with those acquired from the AASHTO and ACI models using relative humidity (RH) of both 0.40 and 0.45 as shown in Figures 6.4(a) through 6.4(e) for mixtures 1, 2, 4, 6, and 9, respectively. These RHs were selected as they fit the RH in the room where the specimens were stored. However, the room did not have special accommodations to maintain RH readings, and values outside of the presented range could occur with changes in outside temperature. Through these figures, it appears that the ACI model with the two RH values overestimates the creep coefficients for all five mixtures, while the AASHTO model underestimates them.

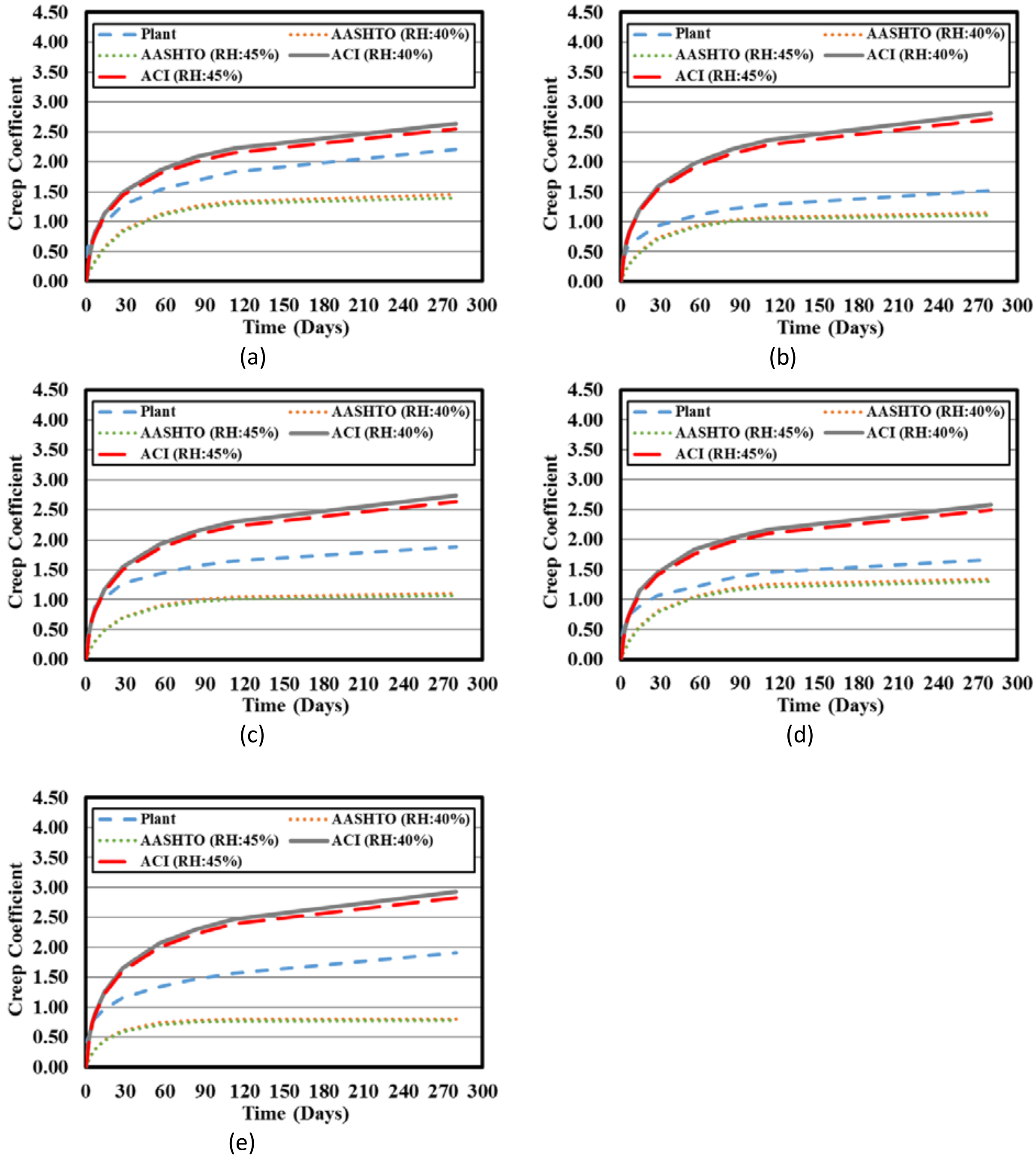


Figure 6.4 Comparison between measured and predicted creep coefficients: (a) mixture 1, (b) mixture 2, (c) mixture 4, (d) mixture 6, and (e) mixture 9

To explicitly examine the difference in creep coefficients at certain ages (28 and 280 days) of the cylinders, the percentage difference between the measured coefficient and ACI values for the 0.4 and 0.45 RHs are listed in Table 6.2. In this table, the difference varies from 5.9% to 27.9% for 28 days, and 14.7% to 59.6% for 280 days. As a result of the comparison, the ACI model is considered conservative by overestimating values at both 28 and 280 days for all SCC mixtures; thus, the model needs to be modified to provide a more accurate prediction, taking into account mixture parameters and loading condition. It was also found that the variation in RH had a slight impact on the predicted creep coefficients.

Table 6.2 Measured and predicted creep coefficients at 28 and 280 days

	Creep Coefficient (28 Days)				
	Mixture 1	**Mixture 2**	**Mixture 4**	**Mixture 6**	**Mixture 9**
Measured	1.28	0.93	0.88	1.06	1.16
ACI (RH: 40%)	1.50	1.60	1.56	1.47	1.67
% Difference	15.83	52.96	55.74	32.41	36.04
ACI (RH: 45%)	1.44	1.53	1.49	1.41	1.60
% Difference	11.76	48.78	51.48	28.34	31.88
AASHTO (RH: 40%)	1.34	1.08	1.05	1.25	0.80
% Difference	4.58	14.93	17.62	16.45	-36.73
AASHTO (RH: 45%)	0.83	0.70	0.69	0.78	0.59
% Difference	42.65	28.22	24.20	30.43	65.14
	Creep Coefficient (280 Days)				
	Mixture 1	**Mixture 2**	**Mixture 4**	**Mixture 6**	**Mixture 9**
Measured	2.20	1.52	1.88	1.67	1.91
ACI (RH: 40%)	2.64	2.81	2.74	2.58	2.93
% Difference	18.18	59.58	37.23	42.82	42.15
ACI (RH: 45%)	2.55	2.71	2.64	2.49	2.83
% Difference	14.74	56.26	33.63	39.42	38.82
AASHTO (RH: 40%)	1.45	1.15	1.10	1.34	0.80
% Difference	-41.10	-27.72	-52.35	-21.93	-81.92
AASHTO (RH: 45%)	1.40	1.11	1.07	1.30	0.80
% Difference	44.44	31.18	54.92	24.92	81.92

The AASHTO prediction model underestimated the creep coefficients at both 28 days and 280 days, and the percentage difference had a range from 4.6% to 65.1% for 28 days and 14.7% to 81.9% for 280 days. It was observed in Figures 6.4(b) and 6.4(d) that the AASHTO model provided the best prediction for mixtures 2 and 6 compared with the other mixtures. It is evident that the percentage difference in mixtures 2 and 6 is the smallest at 280 days relative to the other mixtures (see Table 6.2). Interestingly, for mixture 9, the AASHTO prediction model with RH of 0.4 underestimated the creep coefficients at 28 and 280 days by -36.7% and 81.9%, respectively. This underestimation can be attributed to the higher compressive strength of this mixture at the loading time as shown in Table 6.2. It should be noted that the AASHTO model used to predict creep coefficients accounts for environmental, exposure, and compressive strength conditions. Due to the small number of variables in the prediction model, it results in more sensitivity to the variation of each parameter. In terms of creep testing, increased compressive strength significantly reduced the accuracy of the model.

To obtain a better understanding of creep behavior measured from this project, some discussion regarding the comparison of creep values gained from this project and past studies is needed. However, it is difficult to compare creep results to other studies due to the difference in the constant loading, age of loading, and mixture constituents. It should be also noted that the effect of only creep from the results cannot be isolated as the cylinders for creep had shrinkage deformations; and due to the limited spaces in the creep frame, control CC cylinders were not investigated throughout this project. Therefore, only mixture parameters can be compared to evaluate creep deformation among the five SCC mixtures.

Type of coarse aggregate was a parameter of interest. Trejo (2008) found that SCC mixtures made of limestone aggregate exhibited more creep values than mixtures made of river gravel aggregate. However, it was concluded that compressive strength had more impact on long-term creep values. These findings were not in agreement with those from this project. For instance, mixture 9 having river gravel exhibited more creep than the rest of the mixtures with the exception of mixture 1. Probably, other factors, such as type of cement and the shrinkage deformation, could have played a significant role on the final creep results; thus, a comprehensive matrix will be needed to have a better understanding of SCC creep behaviors.

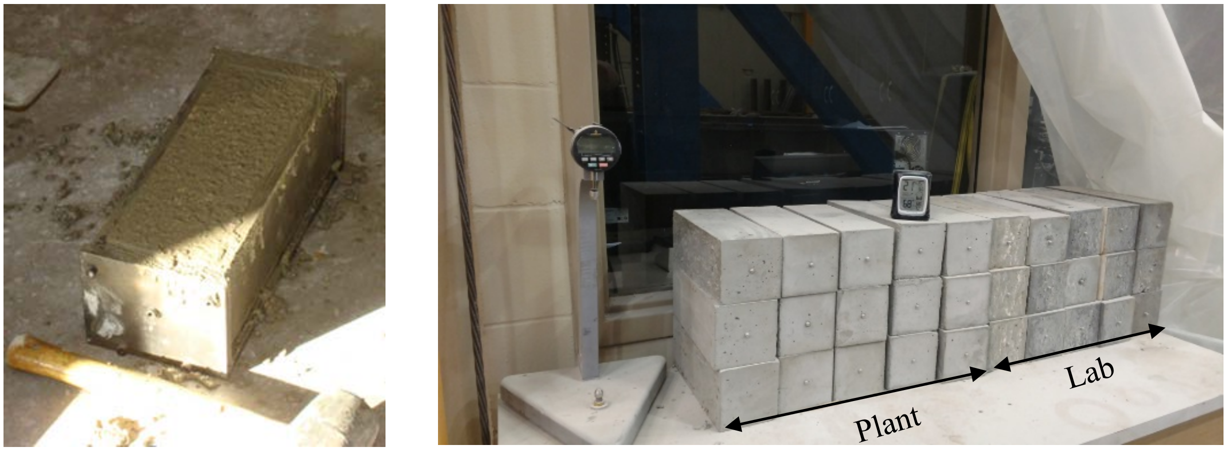
6.2 Shrinkage

This section focuses on testing setup, measurement, results and discussion, and comparison with codified values for shrinkage of all the mixtures used in the testing for creep.

6.2.1 Testing Setup

To investigate shrinkage behavior, two sets of SCC mixtures were cast. The first set consisted of mixtures made at each plant and then transported to the laboratory, while the second set consisted of mixtures made at the laboratory using the same proportions as mixtures made at the plants. The second set of samples was used to compare and determine the effect of the storing conditions on early shrinkage during transport.

Shrinkage tests were conducted following ASTM 157 “Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete” (ASTM 2011). ASTM 157 recommends shrinkage test specimens of 4” x 4” square prisms with a 10-in. length. Figure 6.5(a) shows a prism mold containing the freshly poured SCC mixture, prior to placement adjacent to the girder bed for steam curing. After 16 hours of steam curing, the samples were stored at a temperature of 73.4 ± 3.6 °F and 50 ± 4% relative humidity. Some deviations from the storage conditions recommended in ASTM 157 were made to simulate the actual conditions that a full-size girder would encounter. For example, the prisms were not stored in lime water for 28 days, but rather the prisms were placed in the temperature controlled room. However, the controlled room did not provide circulating air specified by ASTM 157. The two sets of shrinkage prisms can be seen Figure 6.5(b).



(a) (b)

Figure 6.5 Shrinkage samples: (a) preparation of shrinkage prism and (b) all shrinkage prisms having one set of lab prisms and the other set of plant prisms

6.2.2 Shrinkage Measurement

Similar to the creep measurements, the first reading was taken after the prisms were removed from steam curing. Afterward, daily readings were made for the first week, weekly readings for the first month, and monthly readings until 280 days. Readings were taken using an HM-250D length comparator with a digital indicator as shown in Figure 6.6. This apparatus took readings with a precision of 0.000098 in. The difference in length between the calibration bar and the prisms was recorded three times for each prism, and then the average was used for the respective curing age.

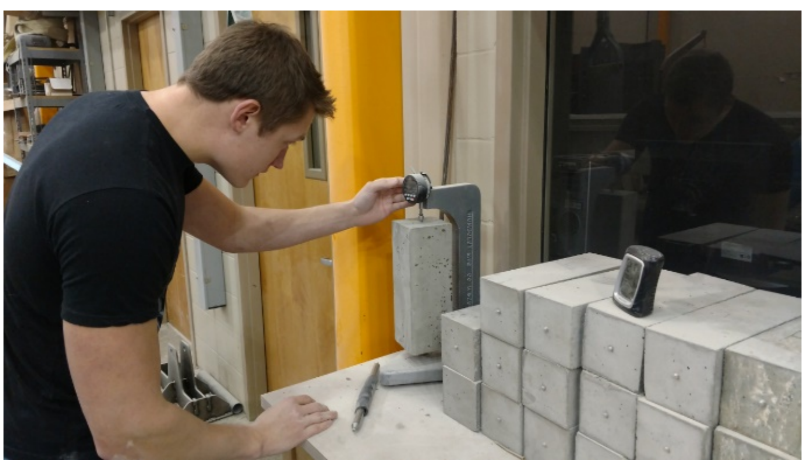


Figure 6.6 Display of shrinkage prisms sample measurement using a digital length comparator

6.2.3 Results and Discussion

The shrinkage results for the prisms made at the plants are shown in Figures 6.7(a) through 6.7(e) for mixtures 1, 2, 4, 6, and 9. In particular, these figures illustrate shrinkage growth for each prism and the average of all prisms of the respective mixture. After 120 days, some peaks and pitfalls were observed for mixtures 1 and 2, but the trend continued the anticipated path afterward. The average shrinkage values for all mixtures ranged from 567 to 850 microstrain at 280 days. Detailed shinkage results for all mixtures can be found in Appendix D.

As shown in Figures 6.7(a) and 6.7(c), mixtures 1 and 4 (made with S/Agg of 0.5) exhibited higher shrinkage values than those of the other mixtures. This can be mainly due to the decreased coarse aggregate in the mix design. Remarkably, mixture 6 exhibited the lowest shrinkage values compared with the rest of the mixtures [see Figure 6.7(d)], although this mixture was made with S/Agg of 0.5. Less shrinkage was attributed to the mixture being composed of only 20% 3/8" coarse aggregate, while the other mixtures had 40%. The effect of cement type was investigated with some contrasts in the results. For instance, mixtures 6 and 9 using cement Type III had low shrinkage values as expected, but mixture 4 having cement Type III developed similar shrinkage to mixtures 1 and 2 having cement Type I/II.

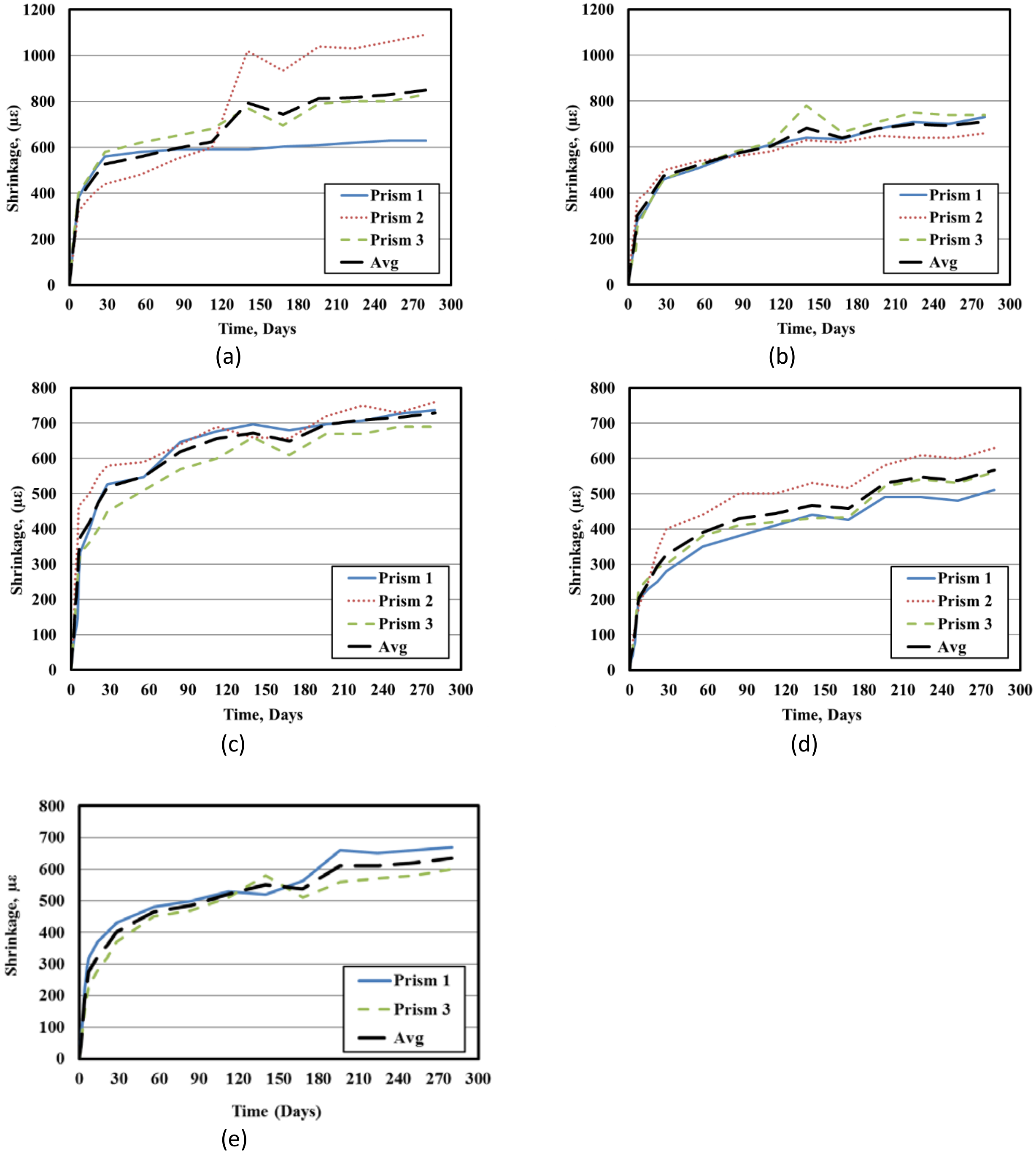


Figure 6.7 Measured shrinkage results for plant prisms: (a) mixture 1, (b) mixture 2, (c) mixture 4, (d) mixture 6, and (e) mixture 9 (*Note: shrinkage strains for prism 2 in mixture 9 were not available due to the broken knobs)*

The shrinkage strains for the prisms made at the laboratory are illustrated in Figures 6.8(a) through 6.8(e). It appears that overall shrinkage behavior between laboratory and plant prisms is similar. However, at an early age the shrinkage slope for the plant prisms for all mixtures (see Figure 6.7) is steeper than that of the lab prisms (see Figure 6.8). This behavior is due to the curing difference between the lab and plant prisms during the first day. It should be recalled that the plant prisms were cured with steam, while the lab prisms were placed in a humid room.

To better understand the difference in shrinkage between the plant and lab prisms, the researchers calculated the percentage differences for 28 and 280 days. These differences are listed in Table 6.3, showing that the difference for 28 and 280 days ranges from 5.9% to 65.4% and from 4.32% to 38.93%, respectively. It is obvious there is a larger percentage difference in developed shrinkage at 28 days rather than at 280 days, although the difference varies depending on the mixture as well. One example is that the differences for mixtures 1 and 2 between plant and lab prisms are 65.49% and 37.69% at 28 days, while those for 280 days are 38.93% and 4.32%.

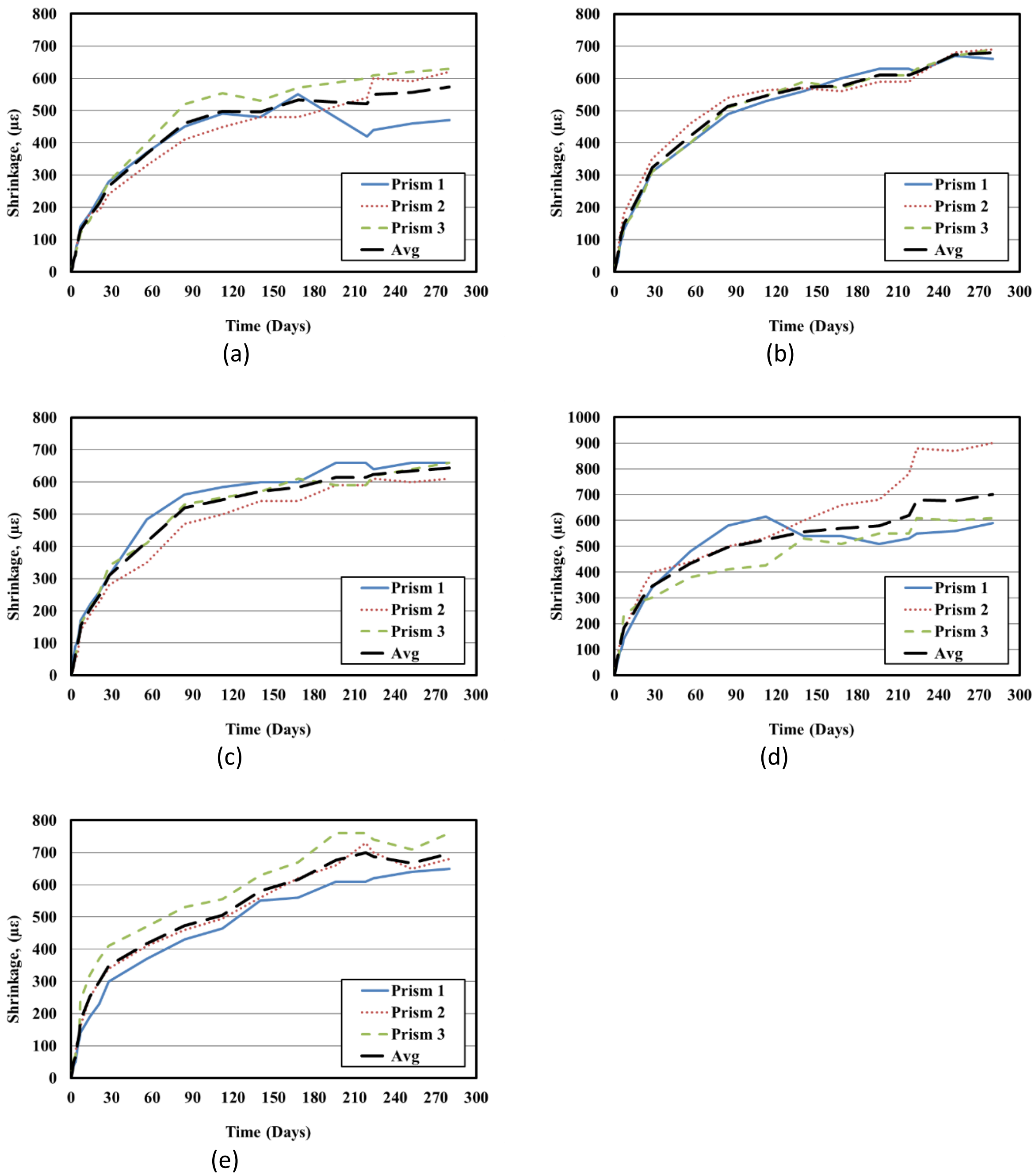


Figure 6.8 Measured shrinkage for laboratory prisms: (a) mixture 1, (b) mixture 2, (c) mixture 4, (d) mixture 6, and (e) mixture 9

Table 6.3 Comparison of average shrinkage between plant and laboratory prisms at 28 and 280 days.

Mixture	28 Days Measurement ($\mu\varepsilon$)		% Difference	280 Days Measurement ($\mu\varepsilon$)		% Difference
	Plant	Lab	Plant vs. Lab	Plant	Lab	Plant vs. Lab
1	527	267	+65.49	850	573	+38.93
2	473	323	+37.69	710	680	+4.32
4	519	310	+50.42	729	643	+12.54
6	327	347	-5.93	567	700	-20.99
9	400	350	+13.33	635	697	-9.31

Note: the presence of "+" or "-" indicates that plant values are higher or lower than those from the laboratory testing, respectively

6.2.4 Comparison with Codified Shrinkage

Shrinkage values calculated using the prediction models incorporating RH of 0.4 and 0.45 specified by the AASHTO and ACI specifications were compared to those measured from both plant and laboratory prisms as shown in Figure 6.9(a) through 6.9(e). It should be noted that the average shrinkage of each of the three prisms per mixture was used for this comparison. It is apparent that all the shrinkage values obtained from either the tests or models increase gradually, although the magnitude of the values are dissimilar. Overall, the AASHTO and ACI models significantly overestimated, in most cases, the shrinkage values measured from plant and lab prisms up to a period of 280 days.

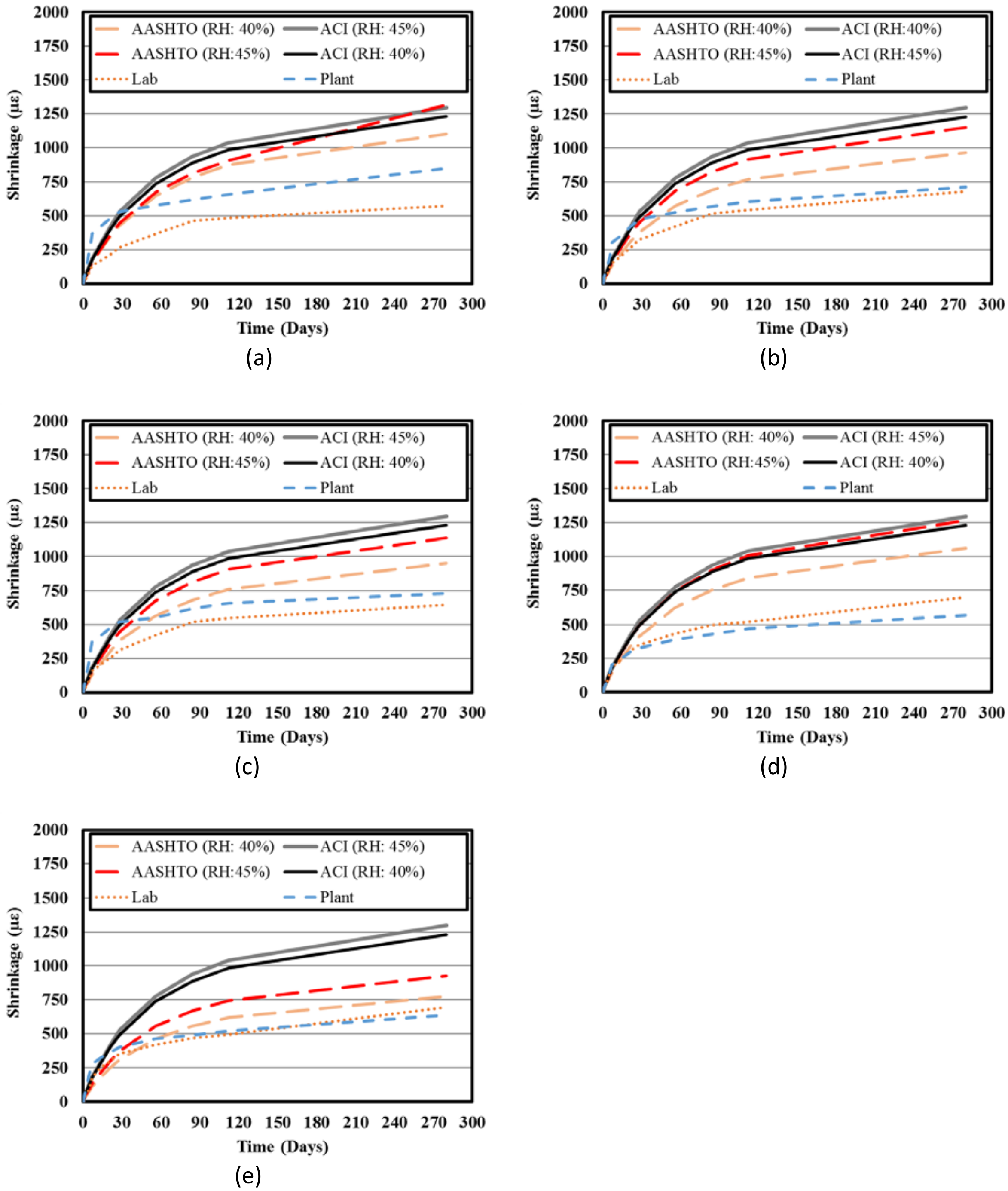


Figure 6.9 Comparison between measured and predicted shrinkage: (a) mixture 1, (b) mixture 2, (c) mixture 4, (d) mixture 6, and (e) mixture 9

To explore the difference between the measured and codified shrinkage values more in depth, the percentage difference was calculated with the comparison between the lab and plant shrinkages. The percentage differences for all the mixtures at 28 and 280 days are listed in Table 6.4. At 28 days, both the AASHTO and ACI models using RH of 0.4 and 0.45 underestimated the shrinkages for both sets of prisms. However, both the models are able to conservatively determine shrinkages for both sets of prisms at 280 days. This table indicates that the AASHTO model using RH of 0.4 provides a more accurate prediction of 280 day shrinkages compared with the corresponding ACI model, although for RH of 0.45, in some mixtures (e.g., plant mixtures 1 and 6), the ACI model predicts the values better than the ACI model. It can be concluded that, overall, the AASHTO model using RH of 0.4 was the best prediction for all the mixtures. These two models remain consistent with all the mixtures because their prisms were exposed to identical environmental and curing conditions. Meanwhile, comparison of the RH value used did not change the prediction outcome in a substantial manner.

Table 6.4 Percent difference between measured and codified shrinkage values using RH of 0.4 and 0.45

28 days						
Mixture	**Plant (με)**	**% Difference**		**Lab (με)**	**% Difference**	
		AASHTO (RH: 40%)	**ACI (RH: 40%)**		**AASHTO (RH: 40%)**	**ACI (RH: 40%)**
1	527	-10.6	-0.3	267	+22.9	+33.0
2	473	+11.4	-5.6	323	+7.58	+24.1
4	519	-15.4	-1.0	310	+10.2	+26.1
6	327	+11.4	+51.1	347	+8.49	+20.8
9	400	+13.0	+13.9	350	+6.40	+20.3
280 Days						
Mixture	**Plant (με)**	**% Difference**		**Lab (με)**	**% Difference**	
		AASHTO (RH: 40%)	**ACI (RH: 40%)**		**AASHTO (RH: 40%)**	**ACI (RH: 40%)**
1	850	+12.8	+20.7	573	+31.5	+38.6
2	710	+15.2	+29.2	680	+17.3	+31.1
4	729	+13.2	+28.0	643	+19.3	+33.6
6	567	+30.3	+39.13	700	+20.4	+29.8
9	635	+9.9	+34.23	697	+5.36	+30.0
28 days						
Mixture	**Plant (με)**	**% Difference**		**Lab (με)**	**% Difference**	
		AASHTO (RH: 45%)	**ACI (RH: 45%)**		**AASHTO (RH: 45%)**	**ACI (RH: 45%)**
1	527	+8.5	+3.6	267	+25.0	+29.6
2	473	+2.6	+1.8	323	+16.3	+20.5
4	519	-7.8	-2.8	310	+17.8	+22.5
6	327	+20.1	+20.0	347	+17.2	+17.2
9	400	+17.6	-2.9	350	+20.0	-0.4
280 Days						
Mixture	**Plant (με)**	**% Difference**		**Lab (με)**	**% Difference**	
		AASHTO (RH: 45%)	**ACI (RH: 45%)**		**AASHTO (RH: 45%)**	**ACI (RH: 45%)**
1	850	+21.4	+18.2	573	+39.3	+36.4
2	710	+23.7	+26.7	680	+25.8	+28.7
4	729	+21.8	+25.5	643	+27.7	+31.3
6	567	+38.1	+36.8	700	+28.7	+27.4
9	635	+18.6	+31.8	697	+14.1	+27.6

Note: "-" indicate that the codified model underestimated shrinkage values resulting from either plant or lab testing at the respective age, while "+" means an overestimation of testing values.

Meanwhile, some discussion is provided regarding the shrinkage values measured from this project in comparison to values found in past studies. Oliva and Cramer (2008) measured shrinkage values for SCC and CC mixtures made with Spancrete and county material constituents. It was concluded that Spancrete SCC mixtures result in almost twice the amount of shrinkage values compared with CC, and that county material SCC mixtures developed less shrinkage than Spancrete SCC mixtures. Note that shrinkage testing for CC mixtures were not tested for this project. The shrinkage values measured from this project were lower than the values found in Oliva and Cramer (2008). Due to the uncertainty in the mixture proportions from the past project, unfortunately no specific conclusions can be made for the difference in values.

Another SCC shrinkage study conducted by Khayat and Long (2010) found that the SCC mixture with similar cement content and w/c ratio developed about 965 micro strain at 252 days. This value is higher than what was found in all county materials and Spancrete SCC mixtures both in the plant and lab. Other studies (Mata 2004 and Shamsad et al. 2014) found substantially low long-term shrinkage values. However, their mixtures had lower cement content and, in some cases, fillers such as fly ash was used to reduce shrinkage deformation. Overall, it can be concluded that drying shrinkage can be improved by making modifications to the mixture design if long-term behavior is of concern.

6.3 Discussion for Final Mixture Selection

To continue with full-scale testing, one mixture had to be selected for fabrication of the girder prior to the completion of creep and shrinkage measurement for a period of 280 days. Hence, creep and shrinkage results for all five mixtures at 28 days were analyzed to select the most suitable mixture for the full-scale testing (see Table 6.5). Note that the creep values listed in this table were combined creep and shrinkage from the creep testing. Selecting mixtures 4 and 9 was a reasonable choice to be used for full-scale SCC girder fabrication and testing (see Table 6.5) because they had the first and second highest creep and shrinkage strains, resulting in a significant amount of prestress loss during full-scale testing. County Materials Janesville offered to fabricate the girder, meaning that final selection was between mixtures 4 and 6. Mixture 4 was selected for investigation, anticipating the largest prestress losses to compare with the losses of the CC girder.

Table 6.5 Summary of creep and shrinkage for all five tested mixtures at 28 days

No	Creep (με)*				Shrinkage (με)			
	Cylinder 1	Cylinder 2	Cylinder 3	Ave.	Prism 1	Prism 2	Prism 3	Ave.
1	817	666	616	700	560	440	580	527
2	756	612	620	670	460	500	460	473
4	831	814	939	861	525	580	450	519
6	793	765	919	832	280	400	305	327
9	797	762	1065	875	430	370	-	400

** Values include combined creep and shrinkage.*

7. FULL-SCALE TESTING OF SCC AND CC GIRDERS

To determine the applicability and feasibility of the SCC mixtures to be used for actual PSC girder construction, one of the five previously selected and discussed mixtures was chosen to fabricate a full-scale prestressed SCC girder. It should be noted that another full-scale CC girder was fabricated as a reference girder. After the fabrication of SCC and CC girders, monitoring for transfer length, prestress losses, and camber of both girders was carried out at the Janesville plant in order to determine their structural performance. Long-term field monitoring was also conducted regarding prestress losses while both the girders were installed in a WisDOT bridge. This section presents details for both girders, a description of gage instrumentation, and discussions of monitoring data at the plant and bridge.

7.1 Girder Details

The CC and SCC girders tested for determining their transfer length, prestress losses, and camber were fabricated at the Janesville plant. Details on materials used for the CC and SCC girder fabrication at the Janesville plant can be seen in Table 7.1. Mixture 4, previously selected among mixtures 1, 2, 4, 6, and 9 in Section 6, was used for the SCC girder construction, while a standard CC mixture, normally used in prestressed CC bridge girders in Wisconsin, was used for the fabrication of the test CC girder.

Table 7.1 SCC and CC Girder Mixture Details

Material Constituent	CC Girder	SCC Girder
Cement (lbs/yrd^3)	752	800
Fine Aggregate (lbs/yrd^3)	1402	1503
Coarse Aggregate (3/8) (lbs/yrd^3)	-	616
Coarse Aggregate (3/4) (lbs/yrd^3)	1831	905
Water (Gallons)	29	31.6
ADVA Cast 575 (oz/cwt)	-	12.5
VMA-3R (oz/cwt)	-	4.1

Note: '-' means data are not available for given conditions

Both the SCC and CC girders are the Wisconsin Standard PSC 36W girder, and their details are shown in Figure 7.1. The span of the girder is of 40' with a cross section of 632.5 in^2. This girder uses twenty 0.6-in. diameter seven-wire low relaxation strands. Six strands in the middle placed in three rows are draped strands, while the rest are straight strands. The total prestress force induced to the girder is 879 kips.

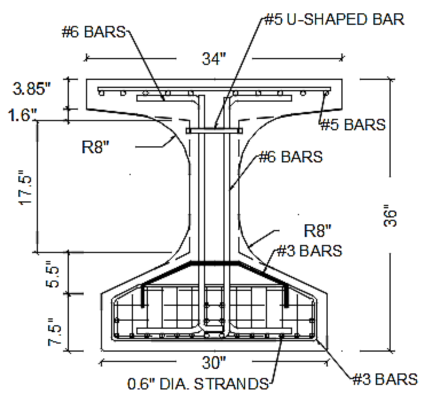


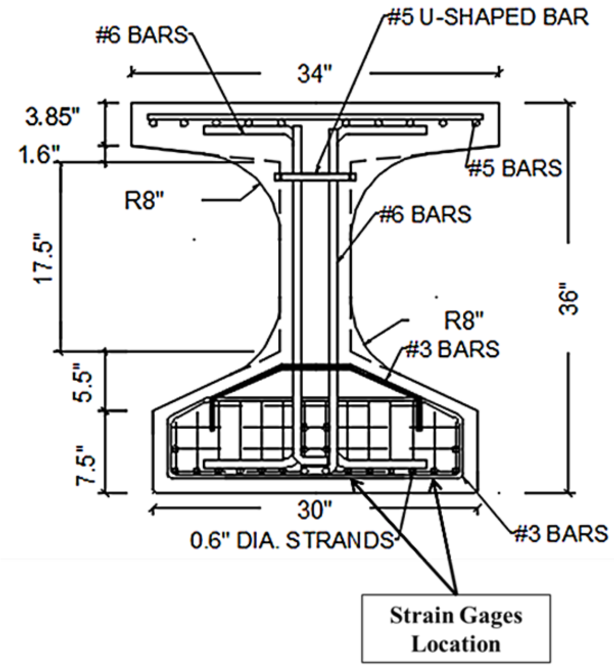
Figure 7.1 Details for Wisconsin standard PSC 36W girder

7.2 Instrumentation

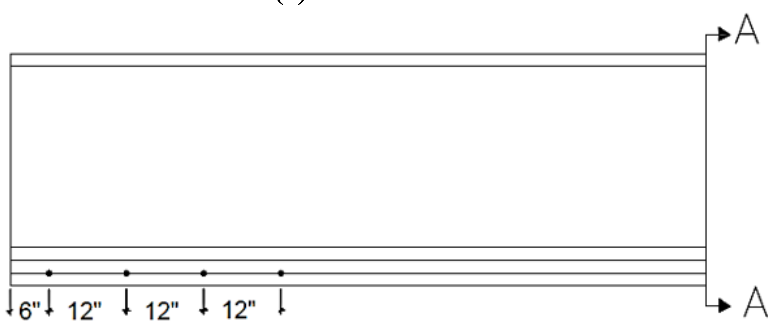
To obtain data for transfer length and prestress losses after the release of the strands, electric resistance strain gages and vibrating wire gages were installed in both girders. Camber monitoring consisted of piano wire strung over pulleys. Details for instrumentation are presented as follows.

7.2.1 Strain Gages

A network of strain gages was attached to strands of both test girders in order to determine transfer length. Specifically, a total of 16 gages (8 gages in each) were installed on prestressing strands in the SCC and CC girders near their ends. The strain gages installed were 0.08-in. gage length. The gages used on the strands were manufactured by Tokyo Sokki Kenkyujo Co. in Japan and supplied by Texas Measurements Inc in Texas (Texas 2016). The series of strain gages was FLA-2-120-2LT with a gage length of 0.078 in., resistance of 120 Ω, and length of 78.7 in. The strain gages were installed on two strands in the middle and side of the girder as shown in Figure 7.2(a). Each strand of the girder had four gages, and the gage closest to the end of girder was located at 6 in. off its end. The four gages were placed on the strand 12 in. apart of each other as shown in Figure 7.2(b).



(a)



(b)

SCC Girder North End CC Girder South End

(c)

Figure 7.2 Gage locations: (a) cross-section of girder, (b) side view of girder, and (c) specification of north end and south end of SCC and CC girders

Before placing the gages, a small prestressing force was applied to the strands to avoid any lag and align the gages in the specified location shown in Figure 7.2 (a) and 7.2 (b). The details of gage locations can be found in Appendix E. The 0.in. length strain gage was installed in one of the seven wires of the strand, and thereby the gage was installed in the direction of the wire, but not in the direction of the strand to avoid incorrect axial strain values.

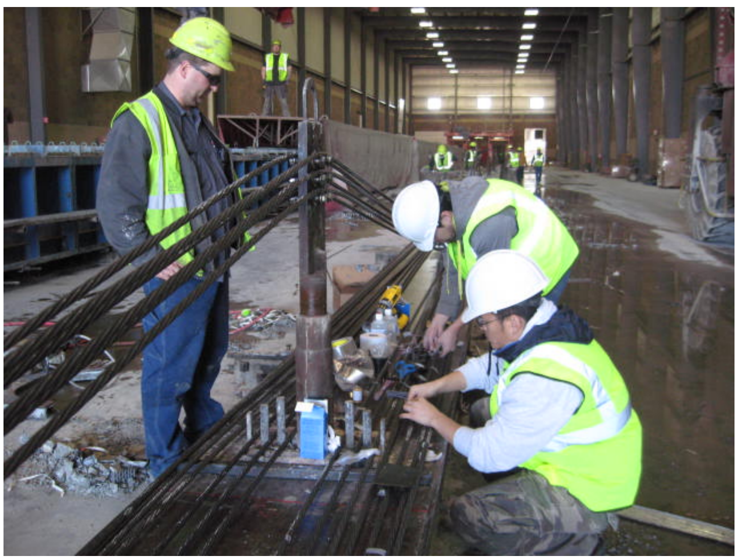
It is also important to note that when selecting the location of the gages on the prestress strand, the gages had to be placed 5 in. to 6.5 in. off their location in the girder. This placement was necessary to account for the extension of the strands during prestressing. An estimation of the deformation due to the jacking force was based on the material properties of the strands. As a result of the tensioning, the final strain gage locations were at the points shown in Fig. 7.2(b). Strain gages were installed in the North End of the SCC girder and in the South End of the CC girder (see Figure 7.2 (c)). The lead cables of the gages had to be connected to a data logger to retrieve data results; thus, both monitoring ends of the girders were placed next to each other to accommodate the installation of the gages.

The strain gages were installed using the following procedure to ensure appropriate adhesion between the gage and strand and protect the gages after installation.

1) The surface of the strand had to be prepared prior to contact with the gage. For that reason, the strand surface was degreased and wet sanded using phosphoric acid provided by the gage manufacturer;
2) The wet-sanding procedure was carried out using a cordless drill and three different sanding wheels. The sanding wheels were used in the respective order 240 grit, then 320 grit, aiming to apply the wheels on the prestress strand wire selected;
3) By hand, a 400 grit was used for the final step of the wet sand procedure. Between the application of each grit more phosphoric acid was added and wiped off in the same direction to clean the area. Once the sanding was complete, the surface was neutralized using an ammonia-based solution and wiped off; and
4) Once the surface was dry, the strain gage was glued to the strand.

Sample pictures of the installation of the gages on a wire of the strand can be seen in the Figure 7.3(a) and 7.3(b).

(a)



(b)

Figure 7.3 Sample pictures for strain gage installation: (a) a strain gage glued to a wire of prestress strand of tested SCC girder and (b) moment when installing gages on strands

After verifying that the gages were properly attached to the strands, several layers of protection were added on top of each gage. A thin layer of nitrile rubber was spread on top of the gage and then a small piece of Teflon tape was applied to cover the entire gage providing waterproofing. Butyl rubber was then placed on top of the Teflon tape to provide a cushion in case of aggregate impact during concrete pouring. At this point, strain relief was added by folding 2 in. to 3 in. of wire over the rubber. Then, the entire surface was covered with aluminum foil. More strain relief was applied before sealing the surroundings and the surface with electrical tape. The remaining lead wires inside the girders were covered with electrical tape as well. The completed protection gage and wires can be observed in Figure 7.4(a) and 7.4(b).

The aforementioned procedure of gage installation and protection was repeated to all gages on both girders. Note that extra wire was left attached to the gages to be able to ensure having enough wire to connect to the measuring devices and to accommodate any need required by the production staff during placing of the steel reinforcement, formwork, and concrete. A sample picture of completed installation and protection gage and wire can be seen in Figure 7.4(c). Readings of these gages were made after installation, after tensioning the strands, before and after concrete curing, after strand release, and once a week for 28 days.

(a)

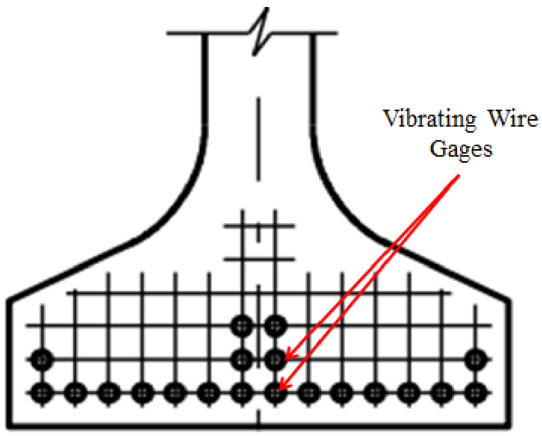
(b)

(c)

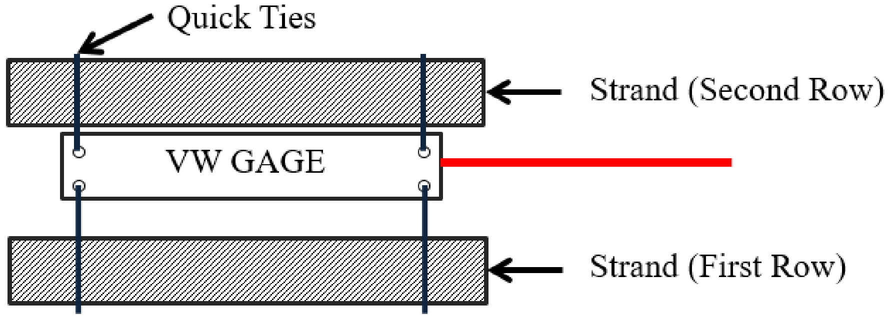
Figure 7.4 Sample pictures for gage installation and protection (a) strain gage with completed protection and (b) protection of lead wires, and (c) all strain gages installed in SCC girder

7.2.2 Vibrating-Wire Gages

Vibrating wire (VW) gages were used to monitor concrete strain which was utilized to determine prestress losses. These gages were installed in the midspan of both CC and SCC girder. Figure 7.5(a) shows the specific location and installation of these gages in the strands. The VW gage on each girder was placed in between strands on the first and second row of the girder as shown in Figures 7.5(a) through 7.5(b). The gage was firmly attached to the strand in the second row using quick ties. The quick ties were used to attach the same gage loosely with the strand in the first row near the bottom of the formwork as shown in the Figure 7.5 (b).



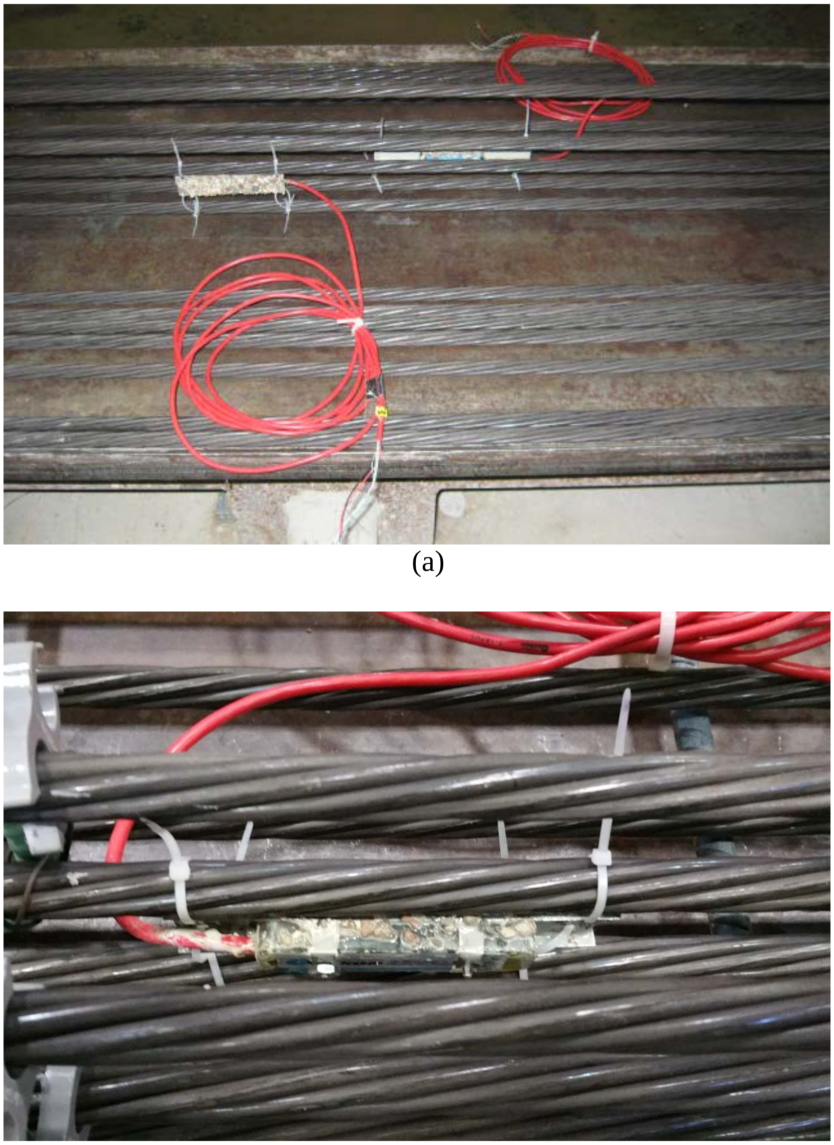
(a)



(b)

Figure 7.5 Installation of vibrating wire gages: (a) location of VW gages and (b) detailed view of VW gage installation

Readings were taken before and after the release of the strands, and once a week for 287 days. Figure 7.6 illustrates a VW gage installed on the SCC girder before concrete pouring.



(a)

(b)

Figure 7.6 VW strain gage attached to strand: (a) overview and (b) details

7.2.3 Camber

Camber of both test girders was monitored from transfer of prestress to 161 days after. The apparatus used to monitor camber consisted of piano wire strung over pulleys under the top flange of each girder (Figure 7.7). At one end of the girder, a concrete cylinder was used to maintain tension of the piano wire during monitoring period. The distance between the wire and the top flange was measured at the mid-span of the girder, as camber. It was recommended to take measurements early in the morning to avoid thermal effects due to the expansion of the flange with high temperature.

Figure 7.7 Experimental set up to measure camber

7.3 Transfer Length

The transfer length at the end of each girder was determined using the AMS method described in Section 2.4.1.2. Transfer length on both the SCC and CC girders was measured immediately after release and at 28 days of monitoring. At release, the transfer length for the CC girder was higher than that of the SCC girder, and the difference was 5 in. as listed in Table 7.2. Figure 7.8 shows a schematic for transfer length measurement between the tested SCC and CC girders at the plant.

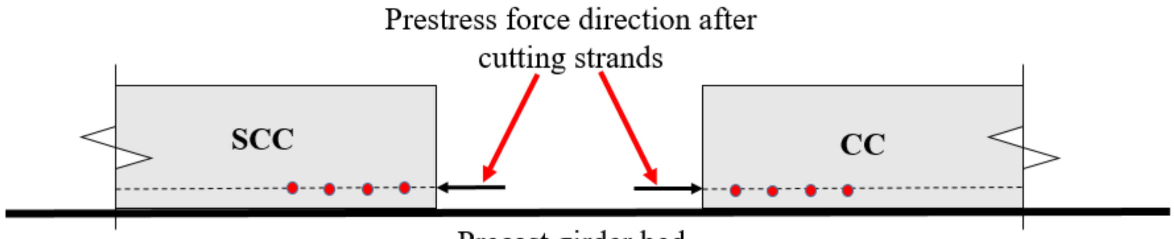
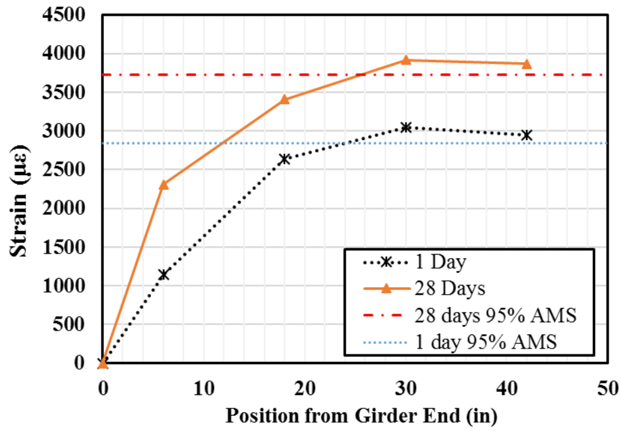


Figure 7.8 Experimental schematic to measure AMS plot-based transfer length: a) CC and b) SCC

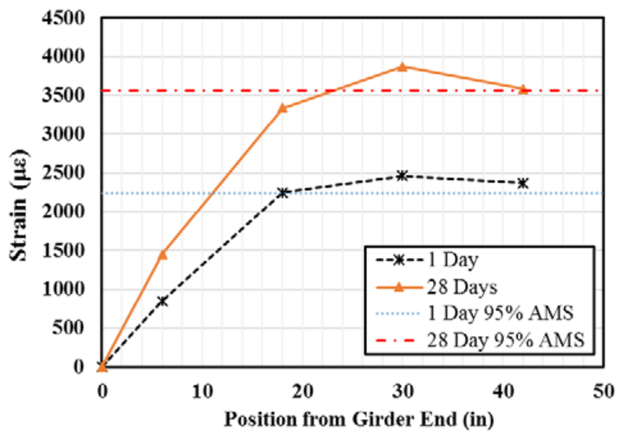
Table 7.2 Transfer length results

Time	South End CC (in)	North End SCC (in)	AASHTO: $60d_b$ (in)	ACI: $50d_b$ (in)
Immediately after release	24.0	19.0	36	30
28 Days	24.5	20.0		

Transfer length can increase over time due to time-dependent PSC properties such as creep, shrinkage and relaxation of the strands. It was observed that after 28 days the CC girder transfer length increased by 0.5 in., while that of the SCC girder increased by 1 in. (see Table 7.1). It is important to remark that transfer lengths for both girders are under $60d_b$ specified by the AASHTO LRFD Specifications (AASHTO 2012) and $50d_b$ stipulated from the ACI Codes (ACI 2009) as listed in Table 7.1. The transfer lengths for both the CC and SCC girders, determined using the AMS method, are illustrated in Figure 7.9.



(a)



(b)

Figure 7.9 AMS plots for transfer length determination: (a) CC and (b) SCC

7.4 Prestress Losses

Strain readings for prestress losses were measured using the VW strain gages. Readings were measured for a period of 287 days, which includes the four construction readings taken before shipping, after shipping, after placement, and after deck placement. Details for the four readings are illustrated in Figures 7.10(a) through 7.10(d). The first stage was immediately before transportation, while both girders were still simply supported at the plant. This allowed a datum to be established for any changes during transportation. An illustration of this is shown in Figure 7.10(a). The next reading was taken on site, before the girders were removed from the transport trucks, as depicted in Figure 7.10(b). This reading allows for inspection of the shipping process, and ensures no abnormal loads were experienced while being transported. The third stage reading was taken immediately after the crane placed each girder in its respective location in the bridge. This is shown in Figure 7.10(c), however, due to on site safety concerns, an excess amount of wiring was provided on each girder to hang down to ground level, so readings could be taken from a safe location while on site. The reading from this stage allowed for inspection of changes experienced while the crane lifted and placed the girders. The fourth stage reading was taken immediately after the placement of the deck on the girders, as shown in Figure 7.10(d). These construction readings were taken every time after the girder was moved to isolate any possible issues or major areas of concern.

Strain gages installed in both the SCC and CC girders, were connected to wires which extruded out of the middle of each girder and into a protective casing. This casing was run down the middle of the girders (through shear keys) to the end, with approximately 15-20 ft. of excess wire hanging down the side, allowing for easy and safe on-site measurements to be taken. This protective casing, as well as the wire it contains, was cast in the deck so readings could be taken immediately after deck placement and for an additional 90 days. A photograph of this setup is shown in Figures 7.11(a) and 7.11(b) for the SCC girder.

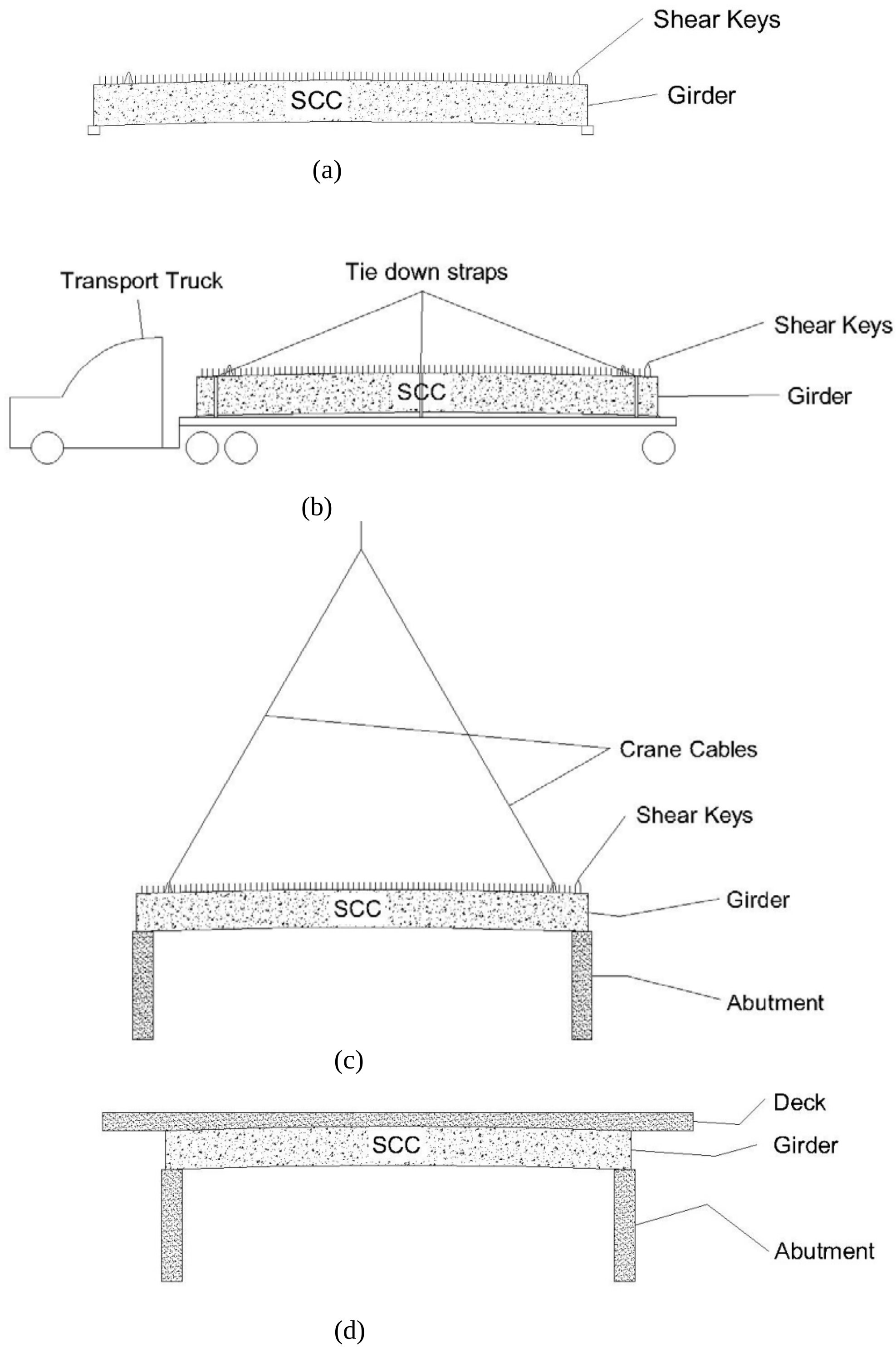
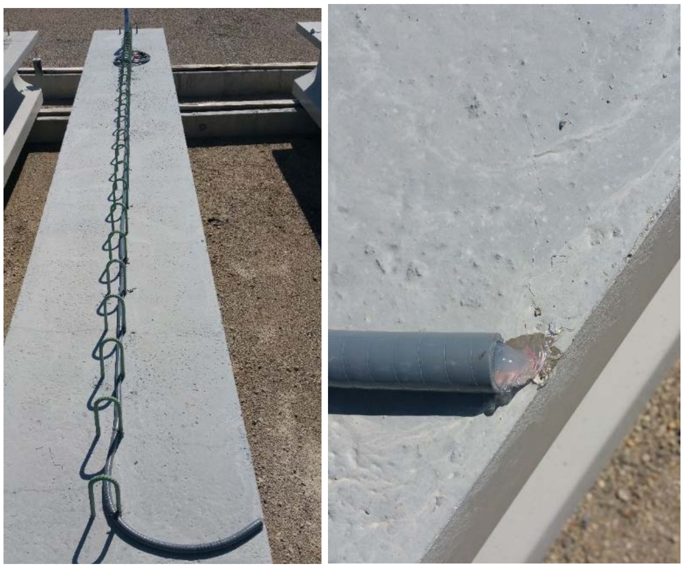


Figure 7.10 Construction strain readings: (a) before shipping; (b) after shipping; (c) after placement; and (d) after deck placement



(a) (b)

Figure 7.11 Photograph of strain gage protective improvement:
(a) strain gage cord protected with PVC conduit, (b) silicon to protect strain gage cord prior insertion in the PVC conduit

Discussions on the readings for all stages and each stage are presented herein. Overall prestress force per strand for both SCC and CC girders, due to their short- and long-term effects, can be seen in Figure 7.12. Referring to this figure, increase in prestress force for both SCC and CC girders follow an almost identical trend. Readings measured before release of the strands were taken as the datum. The difference between the readings, before and after release of the strands, was considered to be the elastic shortening losses shown in this figure. This figure shows the development of prestress force until the end of monitoring. The initial prestress force applied to the girders was computed to be 43.8 kips using the displacement of the strands before and after prestressing. Time-dependent losses were derived from the difference of the reading taken directly after release and weekly readings taken until day 287.

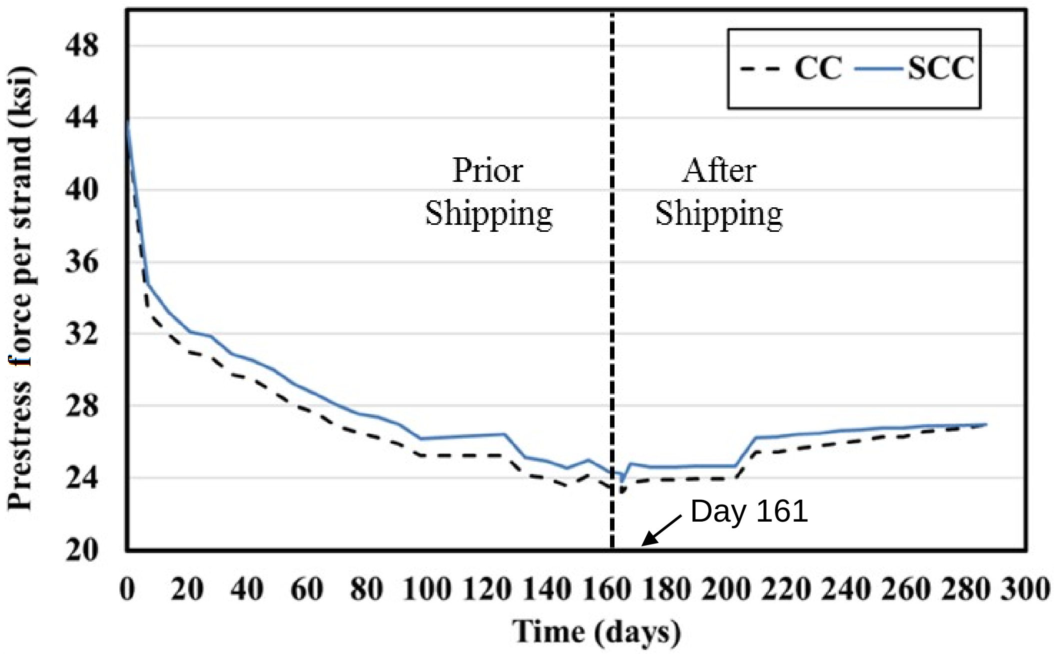
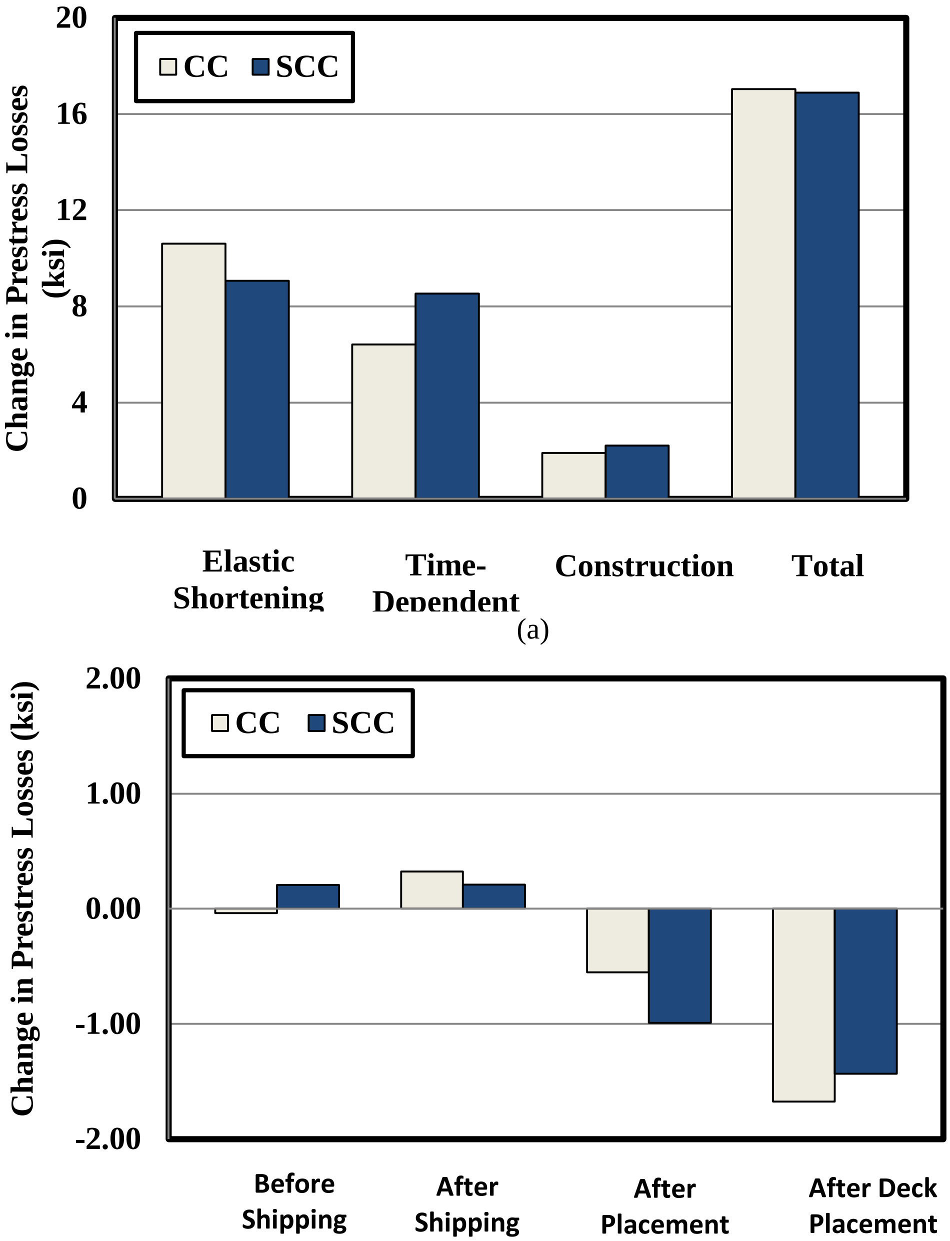


Figure 7.12 Change in prestress force for both SCC and CC girders over time

Prestress losses for both the CC and SCC girders are compared at three different stages and a completed stage: 1) elastic shortening, 2) time-dependent, and 3) construction, along with the total value. Figure 7.13(a) shows the difference in prestress losses between the CC and SCC girders for each stage. It appears the prestress loss for the CC girder due to the elastic shortening is slightly greater than that of the SCC girder, but due to the time-dependent and construction losses, the totals end up with less than a 0.3% difference. It was expected that the prestress losses continually increase as they did until day 161. Note that the strain readings were taken before shipping, while the girders were still placed in the yard at the plant. After day 161, the girders were shipped to the construction site.



(a)

(b)

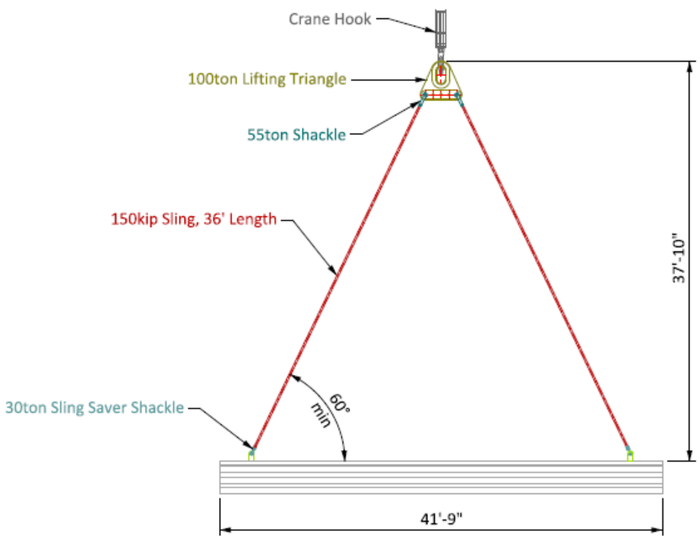
Figure 7.13 Prestress loss: (a) losses occurring during various periods and (b) change in losses due to construction stages

Prestress losses after shipping started to decrease with minor jumps due to construction. Figure 7.13(b) shows a bar graph of the immediate change in prestress losses from one stage to another, for each of the construction stages. This allows for a detailed analysis of the isolated effects due to each individual construction. It should be noted that readings were continually taken while the girders were secured for stability and safety. Interestingly, once the girders were erected and placed in the bridge, a sudden decrease in losses was observed, although support conditions (i.e., simply supported conditions) were similar at the precast yard, construction site, and bridge. The decrease might be attributed to the fact that the change in the support condition (i.e., the girders connected to two anchors to be lifted up using a cable) was made for the girder erection. Also, a lifting of the girder might apply a compression force near the girder top (the horizontal component of the cable force) and this could change gage readings. Sample pictures for the SCC girder erection and placement can be seen in Figures 7.14(a) and 7.14(b), while the girder erection details can be seen in Figure 7.14(c). Deck casting started 35 days after the girders were placed on the bridge, and can be seen in Figures 7.14(d) through 7.14(f). A decrease in losses was expected due to the action of the weight of the deck on top of the girders. The decrease in losses was 1.47 ksi and 1.61 ksi for the CC and SCC girder, respectively. It should be noted that the effect of the deck weight was discussed in Section 2 and illustrated in Figure 2.8 where the deck placement causes an elastic gain.

Table 7.3 shows a side by side comparison of critical dates for both girders over the 287-day period of analysis. The strain readings taken at release for the SCC and CC girders were 9.07 ksi and 10.61 ksi; thus, the CC girder exhibited about 17% higher elastic shortening losses than the SCC girder. The strain readings taken before shipping for the SCC and CC girders were 19.76 ksi and 20.26 ksi. These values follow the prior trend with a slight increase. The readings taken immediately after shipping while still secured to the semi-truck, for the SCC and CC girders, were 19.97 ksi and 20.58 ksi. These values increased by approximately the same amount as a week of sitting at the plant. This is a little larger increase than would be read if the girders were not moved from the plant, however, not a large enough change to suggest any error/damage. The readings taken immediately after the girders were set on the abutments were 18.97 ksi for the SCC girder and 20.03 ksi for the CC girder. This shows a decrease in losses. When comparing time-dependent losses, it is observed that CC developed about 4% higher losses than SCC girder at day 161 (immediately prior to construction losses). At day 287 the losses are extremely close with less than 0.3% difference between the SCC and CC girders.

(a)

(b)



Crane Hook
100ton Lifting Triangle
55ton Shackle
150kip Sling, 36' Length
37'-10"
60° min
30ton Sling Saver Shackle
41'-9"

(c)

(d)

(e)

(f)

Figure 7.14 Representative pictures of the test SCC girder erection: (a) SCC girder erection; (b) SCC girder placement; (c) SCC girder erection details; (d) concrete pump truck; (e) concrete deck being poured; and (f) finished bridge

Table 7.3 Overall prestress losses development

Time	CC (ksi)	SCC (ksi)	Type of Losses
1 Day (Immediately after release)	10.61	9.07	Elastic Shortening
Day 7	11.85	10.59	Creep, Shrinkage and Relaxation of the Strands
Day 161	20.29	19.55	
Before Shipping	20.26	19.76	During Construction
After Shipping	20.58	19.97	
After Placement	20.03	18.97	
After Deck Placement	18.36	17.54	
Day 203	18.34	17.49	
Day 287	16.87	16.82	

7.5 Camber

The initial camber was measured in each girder after the release of the strands to approximately 161 days after casting. Variation in camber from initial measurements are shown in Table 7.4, along with the calculated values using Eq. 2.15. The initial camber for the SCC girder was measured and calculated to be the exact same value, 0.5 in. The CC girder, however, was measured to be about 32% higher than the calculated value. Using Table 2.5, a long-term factor of 2.45 was chosen, yielding a calculated long-term camber (i.e., day 161) for the SCC and CC girder of 1.23 in. and 1.16 in., respectively. Camber, immediately after release, was higher for the CC girder, however at the end of monitoring the camber of the SCC and CC girder both reached the same value. A plot of the camber of each girder is shown in Figure 7.15. From this plot, it can be observed the camber of the SCC girder reaches its maximum value of 1.63 in. at day 91, while the CC girder reaches its maximum value of 1.38 in. on day 126. It should be noted that between 98 days and 126 days data was not available, and thereby the exact time the CC girder reached its maximum camber value cannot be concluded to be exact. This gap in readings caused by local instrument adjustments is over a period of minor changes, only in the CC girder, and therefore is deemed to be of minute significance.

Table 7.4 Variation in camber for both measured and calculated (using Eq. 2.15) values for SCC and CC girders

Time	**Measured CC (in)**	**Calculated CC (in)**	**Measured SCC (in)**	**Calculated SCC (in)**
Day 1	0.62	0.47	0.50	0.50
Day 28	1.0	-	1.25	-
Day 91	1.38	-	1.63	-
Day 161	1.38	1.16	1.63	1.23

Note: '-' means data is not available for given conditions

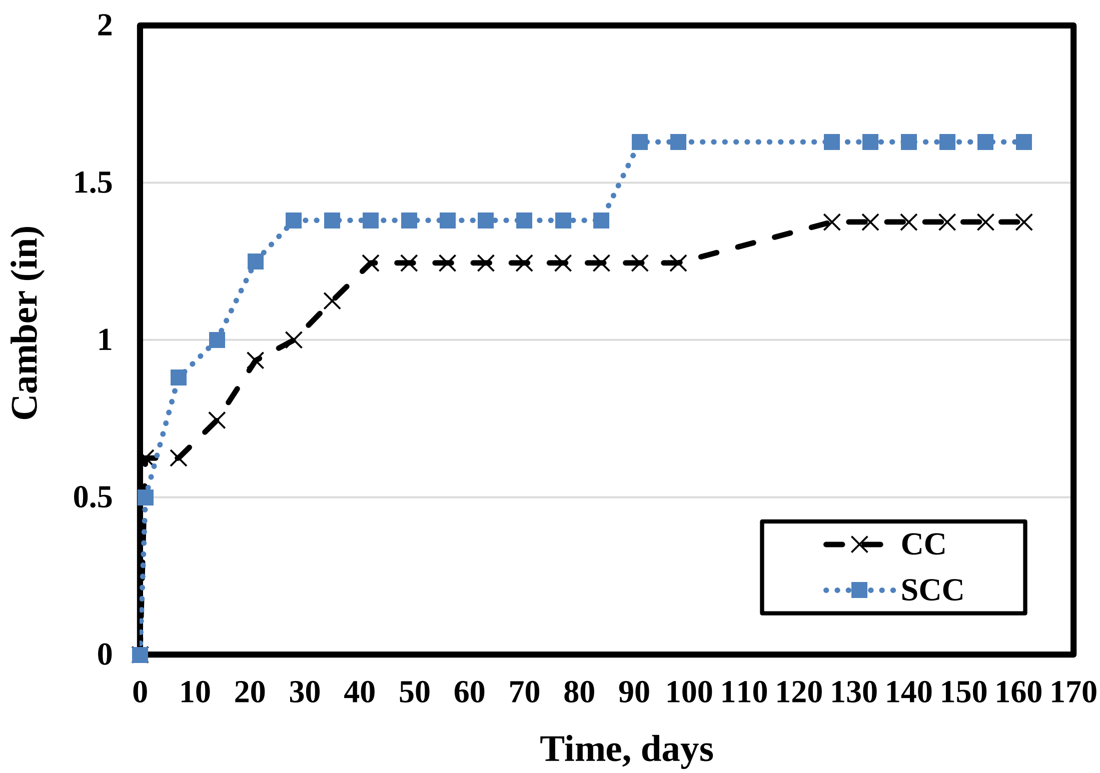


Figure 7.15 Camber of both CC and SCC girders

8. RECOMMENDATIONS FOR SCC GIRDER IMPLEMENTATION

This section provides motives by the researchers to recommend the implementation of SCC in Wisconsin DOT projects. Included in this section are a SCC mixture design specification that was developed based upon the findings throughout this project and recommendations for SCC girder implementation.

8.1 SCC Mixture Design Specification

1) Description: This section consists of requirements regarding mixture design and test methods for SCC fabrication on prestressed bridge girders.

2) Materials: Materials shall follow section 501.2 of the Wisconsin DOT standard specifications. A proposed mix design should be submitted for approval before application. The contractor should determine the proportions of the mix with the following limitations:

Water cementitious material ratio, w/cm .... 0.35 or less
Cement content .... 800 pounds per cubic yard
Sand to Aggregate ratio, S/Agg .... 0.50 or less
Coarse Aggregate:
Size.. Max of 3/4”
Blending....................................... 3/8” gradation is allowed up to 40% of total coarse aggregate
Admixtures................ Must be registered in the list of WisDOT approved products for concrete
Air content:
Prestressed bridge girders .... 2.0% - 4.0% maximum

3) Test Methods: To approve a new SCC mixture, submit slump flow, J-Ring, Visual Stability Index (VSI), T20, and column segregation. Mixtures that have been approved submit slump flow, J-Ring and VSI values for every truck load.

3.1) New Mixtures

(1) Slump flow test: Perform slump flow test following ASTM C1611. Target spread diameter should be between 25” - 28”. If slump flow value is above 28” reject the mixture. Also, the slump flow value shall be ± 2” of contractor target value. T20 value is recommend to range between 2 - 7 seconds.

(2) VSI: 0 - 1.

(3) J-Ring: Perform the J-Ring Ttest in accordance with ASTM C1621. J-Ring spread diameter should be within ± 2” difference compared with slump flow diameter.

(4) Column segregation: Perform the column segregation test according to ASTM C1610 guidelines. The percentage segregation should not exceed 15%. This test should be performed twice, allowing the concrete to sit on the cylinder for both 10 and 40 minutes.

3.2) Approved Mixtures

The contractor shall obtain SCC mixtures with the following properties:

Slump flow.. 25” - 28”

VSI ....0 - 1

J-Ring... ± 2”

Columns segregation..≤ 15%

8.2 Recommendations for SCC Girder Implementation

This study proved that the fabrication of PSC girders, made with SCC from material resources in Wisconsin, is feasible using the materials and construction techniques of local precasters. It is anticipated that precasters will have the option of fabricating girders using SCC, which can lead to cost benefit, simplified construction procedures, reduced vibrator noise hazard, and improved surface finishing where bug-holes may be rarely observed in comparison with CC girders (for an example of bug-hole reduction, see Figures 1-2 and 7-2). However, each precaster has the responsibility to develop SCC mixtures to meet required performance.

SCC mixtures can be developed by making trial batches to achieve consistent fresh and hardened properties. A high quality SCC mixture can be used to fabricate an SCC girder, which is able to produce adequate structural performance in terms of transfer length, camber, and prestress loss. It is expected that an SCC girder may exhibit similar structural performance as CC girders that have been used in Wisconsin. Based on the project results, the following recommendations are made:

1) WisDOT should allow the implementation of prestressed SCC bridge girders.
2) Mixture 4, where its material and structural performance was validated throughout this project, should be accepted by WisDOT for girder production without repeating all the testing provided in the proposed SCC mixture design specification. However, it is required that the other trial SCC mixes (e.g., Mixtures 2 and 9) be tested and evaluated for their structural performance to obtain WisDOT permission for their use in girder production.
3) Special provisions should be developed to set performance requirements for the fabrication of prestressed bridge girders. This project provided criteria recommended for quality control of new and day-to-day SCC mixtures.
4) Investigation of the implementation of supplemental cementitious materials to reduce the costs of SCC mixtures should be made to make it more feasible for local producers.
5) Monitoring of larger full-scale SCC girders is recommended to obtain valuable information regarding the long-term structural behavior of SCC girders.

9. SUMMARY, CONCLUSIONS, AND FUTURE WORK

This project developed a specific self-consolidating concrete (SCC) mixture design specification for the use of SCC in PSC bridges, and made recommendations on the fabrication and implementation of prestressed SCC girders in Wisconsin. This section summarizes significant findings gained from the project and its contributions, and it also outlines future work required to continue to promote the use of SCC in WisDOT PSC bridge projects.

9.1 Summary and Conclusions

This project was intended to evaluate mixture parameters that a SCC mixture made of local materials in Wisconsin must satisfy and its specification for the use of SCC in PSC bridges. To accomplish the objectives, the following tasks were completed: 1) literature review; 2) DOT survey; 3) precast plant identification; 4) SCC mixture design and laboratory testing; 5) time-dependent characteristic determination; 6) full-scale testing; and 7) recommendations for Wisconsin SCC girder fabrication. Brief summaries, as necessary, and key findings from each task include the following:

1) As a result of the comprehensive literature review related to material properties and structural characteristics of prestressed SCC bridge girders, specific parameters necessary for the SCC mixture design were determined in collaboration with WisDOT. The literature review revealed that SCC has similar, if not higher, compressive strengths compared with conventional concrete (CC). Cement in an SCC mixture may be replaced with fillers to obtain desirable fresh and hardened properties, although a replacement of cement with fillers may result in reduction of compressive strengths. The following benefits may be achieved: lower w/c ratio may be utilized to attain higher strengths, SCC is more sensitive to segregation and shrinkage relative to CC, and prestress losses of SCC girders may be higher than that of CC girders.

2) The survey indicated that SCC mixtures can be made with materials available in each state for obtaining the desired performance of prestressed SCC girders. Maximum size aggregate (MSA) should be less than or equal to 0.75 inches to obtain reasonably good passing abilities and avoid settling. Only cement is preferred to be used for enhancing the performance of SCC mixtures in lieu of combining cement with fillers. The values of MSAs that have been frequently used by the majority of departments of transportation (DOTs) were 0.5 in. and 0.75 in., and w/c ratio varied for each state according to strength needed, but the most frequent values were within the range of 0.41 to 0.45.

3) Three precast plants in Wisconsin participated in providing local materials needed for SCC mixtures: County Materials Roberts, County Materials Janesville, and Spancrete. SCC mixtures made with materials from each plant were adjusted in a laboratory setting by means of trial batches to attain acceptable workability criteria.

4) Multiple SCC mixtures were designed and tested in stages one and two to evaluate their fresh and hardened properties. For stage one, a mixture pool consisting of 12 SCC mixtures with varying mixture parameters (i.e., cement content, w/c, S/Agg, aggregate type and size, and blending of coarse aggregate) was tested in the SDSU structures laboratory. Note that the properties at fresh state were investigated through slump flow, VSI, J-Ring, and column segregation tests, while the hardened properties were evaluated through compressive strength testing. Results specific to the testing at state one can be found below:

- Slump flow results showed that, among all 12 mixtures, a range of 22.8 to 26 in. was found, which was within the acceptable range for slump flow (22 to 28 in.).

- Passing ability quantified by the difference in diameter between slump flow and J-Ring tests revealed that passing ability ranged from 0.25 to 2.25 in. The majority of the mixtures were less than the maximum passing ability (2 in.).
- Segregation measured by the column segregation test found that all the mixtures satisfied the required segregation percentage (15%), and the percentage segregation decreased as the percentage of 3/8” coarse aggregate increased.
- Compressive strength testing indicated that the strength of all the mixtures ranged from 5221 psi to 8432 psi where about half of the trial exceeded the required compressive strength.

Through the results at stage one, it was concluded that the trial mixtures having 60% and 80% of 3/4” aggregate provided adequate workability and compressive strength necessary for the production of the PSC girders for WisDOT. Hence, 11 SCC mixtures made with only 60% and 80% of 3/4’’ aggregate were selected at stage two for additional investigation at the fresh and harden states at certain plants (mixtures 1 through 3 for Roberts, mixtures 4 through 7 for Janesville, and mixtures 8 through 11 for Spancrete). Particular results from each plant are included as specified below:

- The fresh and hardened properties of all the mixtures for Roberts are acceptable based on the requirements.
- The performance was consistently acceptable among all Janesville mixtures in terms of the fresh and hardened properties.
- Passing ability of all the Spancrete mixtures were not as optimal as those obtained from the mixtures from the Roberts and Janesville plants. For hardened property, mixtures 8 and 10 did not reach the required compressive strength at 18 hours.

Based on the evaluation of the testing results from stage two and discussion with the project oversight committee (POC), it was recommended that mixtures 1, 2, 4, 6, and 9 be selected to be tested for the examination of time-dependent material characteristics, including creep and shrinkage.

5) According to the ASTM 512 Standard Test Method, creep testing for all five mixtures was completed. Three creep frames were constructed to measure their creep strains and were subjected to a consistent compressive load maintained for 280 days. Three cylinders were fabricated per mixture with three strain measurements on each side of each cylinder. The average from all three cylinders was utilized to obtain the final strain change at a specific age. Further, all the measured strains were used to calculate creep coefficients. These values were then compared against those acquired from the AASHTO and ACI Specifications. Specific findings from the creep testing include:

- Creep behavior for the three cylinders of each mixture was generally similar, although each mixture had different creep values.
- Mixtures using cement Type III exhibited higher creep values compared with those with cement Type I/II, and it was also found that a higher amount of coarse aggregate due to different S/Agg helped constrain creep deformation in concrete. Specifically, mixtures consisting of cement Type III and S/Agg of 0.5 (i.e., mixture 9) exhibits the highest creep strain with a value of 1440 microstrain, while mixtures consisting of cement Type I/II with S/Agg of 0.45 (i.e., mixture 2) exhibited the lowest creep showing 1094 microstrain.
- The creep model specified by the ACI code overestimated creep coefficients for all five mixtures, while the AASHTO model slightly underestimates them.

Following the ASTM 157 Standard Testing, shrinkage tests for two sets of all five SCC mixtures were completed. The two sets consisted of the same mixture design with one made at the plant and the other made at the laboratory. Similar to the creep test, the shrinkage strains were measured for 280 days.

Additionally, the measured shrinkages for each of the mixtures were compared with those from the AASHTO and ACI codified models. Results obtained from the test are described as below:

- The shrinkage values for all mixtures ranged from 470 to 900 microstrain at 280 days.
- At an early age, the slope of the shrinkage plot was steeper for the samples made at the plant compared with the samples made in the lab. This behavior is attributed to the curing differences between samples during the first day.
- The AASHTO model provided a more accurate prediction of shrinkage at the end of 280 days for all mixtures compared with the ACI model, which was considerably conservative for all the mixtures.

6) Two full-scale girders were constructed to determine applicability and feasibility, one made of SCC and the other made of CC. Many different mixture combinations were evaluated in this project, but only one mixture (mixture 4) was selected for full-scale testing of the SCC girder. Both girders were fabricated to the Wisconsin Standard PSC 36W girder specifications. Vibrating wire (VW) gages were installed in each of the girders for monitoring prestress losses spanning a 287-day period, which started at the transfer of prestress. This time period of analysis allowed for three stages of prestress losses to be analyzed: 1) elastic shortening, 2) time-dependent, and 3) construction losses. The following conclusions were drawn from the results for these three stages:

- Elastic shortening for the SCC girder was 9.07 ksi, while the CC girder was approximately 17% larger with a value of 10.61 ksi.
- The final prestress loss for the SCC girder was 8.53 ksi, a near 33% higher value than that of CC girder equal to 6.42 ksi.
- Construction losses were 2.22 ksi for the SCC girder and 1.90 ksi for the CC girder.
- The total prestress losses experienced by each girder were 16.89 ksi for the SCC girder, and 17.03 ksi for the CC girder.
- The prestress losses continued to climb until day 161, which is when the girders were shipped and placed on site, at which point the losses slowly started to decline until the final recording day 287.

In addition to prestress losses, camber was also monitored for each of the girders. Camber was recorded for 161 days, starting at transfer of prestress. Both the final camber reading and the variation in camber were recorded, and the results are as follows:

- A final reading for each girder was recorded at 4.5 inches, however this value for the SCC girder at day 91, while the CC girder didn’t reach this until day 126.
- The SCC girder climbed to a peak camber faster than the CC girder, which started with a higher value, but took longer to reach its peak.
- The variation in camber was 1.63 in. for the SCC girder and 1.38 in. for the CC girder.
- The variations in measured camber for the SCC and CC girders were higher than those in codified camber, respectively. Therefore, it is recommended to monitor camber of somewhat larger SCC girders in the precast plant, and to identify any crack or damage at both ends of each girder applied by transfer of prestress and upward deflection.

The final full-scale test performed was on the transfer length of each girder. These values were determined using the 95% Average Maximum Strain (AMS) method. Measurements were taken at two different times for each girder, immediately after release and 28 days later. The results from the measurements show:

- Immediately after release, the transfer length was 19.0 in. for the SCC girder and 24.0 in. for the CC girder.
- At 28 days, the transfer length increased for both girders. The SCC girder increased 1 in. to a final value of 20.0 in., while the CC girder increased 0.5 in. to a final value of 24.5 in.
- Because the AASHTO and ACI specified a transfer length of 36.0 and 30.0 in., respectively, both the codified formulas to determine the transfer length for each of the test girders were considered conservative.

7) Throughout this project, an SCC mixture design specification (*Section 8.1*) for the high quality control of SCC to be practical enough to build prestressed SCC girder bridges in Wisconsin was established. Technical recommendations for structural performance related to transfer length, camber, and prestress loss of SCC girders were made. However, it should be noted that the recommendations were made based on the lab and field data on only one mixture (i.e., mixture 4) through its full-scale testing. Therefore, there is need to validate any other mixture before permitting its use in prestressed SCC girder production.

As a final point, it is anticipated that the recommendations for SCC mixture design that achieves the desired performance for use in prestressed SCC girders for WisDOT will be widely accepted across Wisconsin and utilized for ensuring safety in its construction.

9.2 Future Work

Work from this project may be extended through future research in the following fields:

- Modifying SCC mixture designs for a better control of creep and shrinkage.
- Investigating shear strength of prestressed SCC bridge girders with different prestressing forces and making relevant design recommendations.
- Establishing a comprehensive prestressed SCC bridge girder design guideline by performing representative load testing on a full-scale SCC girder and a parametric study with variation in girder size, strength, prestressing force, and loss.
- Examining long-term structural behavior of prestressed SCC girder bridges under service loads using a structural monitoring system.
- Determining live load distribution factors (LLDFs) of prestressed SCC girders considering their prestress loss over time and developing reliable LLDF formulas that are compatible to those specified by the AASHTO.

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APPENDIX A

Summary of DOT Survey Results

Summary of information received by DOT representatives will be briefly explained in the subsections below. The survey was set up to determine requirements used in other states for mixture design and fresh and hardened properties. An example of the survey is shown below:

Survey on SCC Parameters and Application at Various Departments of Transportation

The goal of this survey is to collect data related to the use of Self-Consolidating Concrete by different states. The data collected will be analyzed and used to create a SCC mix for the Wisconsin DOT. This research will be conducted at South Dakota State University. Information provided by your state would be of great importance for the project success. Time frame for survey completion is two weeks.

Q1: Does your state have specific mix parameters for the application of Self-Consolidating Concrete (SCC)? If yes, for what applications have SCC been used? (E.g. girders, box culverts, etc.)

Q1.1. If your state has specific SCC mix parameters, please complete the following:

Description:	Amount (lbs/yrd$^{3)}$):
a. Type of cement used: ____________	____________
b. Cementitiuos materials used: ____________	____________
c. Coarse Aggregate/Size: ____________	____________
d. Fine Aggregate/Size: ____________	____________
e. Viscosity Modifying Admixture: ____________	____________
f. HRWR: ____________	____________
g. Water:	____________
h. W/C	____________
i. Other Admixtures: ____________	____________

Q1.2 Mark the following tests used to determine SCC properties and include acceptable range for each test.

Test:	Used:	Range/Values:
a. Slump Flow:	☐	____________
b. J-Ring Flow:	☐	____________
c. Column Segregation:	☐	____________
d. Visual Stability Index:	☐	____________
e. L-Box:	☐	____________
f. Compressive Strength:	☐	____________
g. Modulus of Elasticity:	☐	____________

Q2: Does your state have either past or ongoing research on SCC. If yes, please provide details (E.g. website, research report, etc.).

Q3: What is research plan for SCC characteristics and applications?

Q4: Any additional information and comments:

The information provided by the DOT who responded to the survey varies for each state. There was no consistency from the information provided by the different DOTs. However, each state provided important information regarding their experience with SCC. Information on the use of SCC specific to each state DOT, requirements for designing an SCC mix, and research projects for SCC is presented as follows:

A-1 Alabama

Alabama DOT has developed its own specifications for SCC based on previous research products. Alabama DOT requires a minimum amount of cement of 600 lb/yrd^3, a maximum w/c of 0.45 and maximum size aggregate of 3/4". Alabama SCC mix design should be based on 4.5 % air content where it is not allowed to exceed 6%. Multiple ongoing research projects on SCC for different applications (e.g., Implementation of SCC for prestressed applications) are conducted.

A-2 Florida

Florida DOT allows SCC to be used in prestressed and precast concrete products. SCC mix should meet the following guidelines: 1) Cement Type I/II with a minimum amount of 752 lbs/yrd^3; 2) Cementious materials used are fly ash and ground granulated blast furnace slag (GGBFS). Note that fly ash can replace up to 22 % of cement, while GGBFS can replace up to 70 % of cement content; 3) Coarse aggregate size: 57, 67, 78, 89 stone; and 4) Maximum w/c ratio is 0.41.

A-3 Georgia

Georgia DOT has created special provisions for the application of SCC. Precasters are responsible of all mix designs, which will be submitted for approval. However, Georgia DOT requires a minimum compressive stress at 28 days of 5000 psi. Also, the DOT allows the replacement of cement by fillers which should not exceed 20 %, or if two or more fillers are used the replacement of cement should be below 40 %. Fillers used by the DOT include fly ash, granulated iron blast-furnace slag, metakaolin and microsilica.

A-4 Illinois

Illinois DOT has had its own SCC specifications for precast products since 2007. Illinois DOT requires that every mix should be designed according to the Portland Cement Concrete Level III Technician. From this specification, it is required that the total cement content should not exceed 705 lbs/yrd^3. Maximum w/c ratio is 0.44. Fine aggregates should not exceed 50 % by weight of total aggregate used.

A-5 Iowa

Iowa DOT does not have specific SCC mix design, admixture supplier and precaster usually work together to develop a mix design. However, DOT has developed brief guidelines for approving and testing SCC mixes. These guidelines recommend aggregate gradation with ¾" top size aggregate. Sand to total aggregate ratio should be between 0.4 and 0.5. W/c should be between 0.25 - 0.44. Producers should also be able to demonstrate the compatibility between HRWR and VMA if used. Once, this requirement is met, mix should be submitted to materials engineer for testing and approval.

A-6 Kentucky

Kentucky Transportation Cabinet (KYTC) does not have specifications for SCC; however, they have created steps for the approval of a specific mix. This mix will be submitted to the materials engineer, where the producer should be able to demonstrate an adequate quality control plan for SCC. For the mix design its required minimum 564 lbs/yrd^3, a maximum w/c of 0.46 and air content of 6 ± 2%.

A-7 Louisiana

Louisiana does not have specification for SCC. However, they have used for pile end fills. For this application it was required to have a slump flow between 20" - 28". Louisiana DOT currently has research projects for the use of SCC to study slump flow, strength, segregation potential and washout resistance.

A-8 Michigan

Michigan requirements for SCC: 1) Use Type I or Type III cement; 2) All mixes are to be designed for a design compressive strength at 28 days of 5500 psi; 3) Level of entrained air content for all mixes shall be 6 ± 1.5 %. More recommendations for placement and structural details for girders can be seen in the appendixes.

A-9 Minnesota

Minnesota DOT currently does not have specific applications for SCC. SCC was used on a couple of projects in which the contractor requested to use it. The SCC was placed in drilled shafts and some heavily re-enforced cast-in-place structure applications. However, they are currently working with their precasters to create guidelines for SCC. Minnesota DOT attached to the survey a draft for the SCC specifications. Some of the most relevant requirements from the draft include: 1) Cement complying with ASTM C 150 Type I or I/II. Up to a total of 30 percent replacement by mass (weight) with fly ash conforming to ASTM C618, ground granulated blast furnace slag conforming to ASTM C 989, and/or Silica Fume conforming to ASTM C 1240 may be used. Replacement with Silica Fume shall not exceed 5 percent of the total cementitious material; 2) the mixture shall be designed and produced at a w/c of not greater than 0.45; 3) the air content shall be 6.5 percent plus 2.0 percent or minus 1.5 percent at the point of placement; 4) SCC anticipated strength of 4300 psi at 28 days.

A-10 Nebraska

Nebraska has created special provisions for the use of SCC. The contractor has to contact the Portland Cement Concrete Engineer 3-4 weeks in advance of the use of SCC for the purpose of a batch trial. Any modification to the mix proposed in the table below will have to be approved by the concrete engineer and trial batches should be performed. These provisions include a list of testing methods to determine SCC properties. However, these provisions do not include accepted range of values for each test.

Cement	**Fly Ash**	**Total Cementitious**	**Sand/Total Aggregate**	**Type of Coarse Aggregate**	**Air Content**	**W/C**	**Compressive Strength (28 day)**
607 lbs/yrd^3	203 lbs/yrd^3	810 lbs/yrd^3	75 ± 3	Limestone	6 %	0.37	6000 psi

Nebraska has performed research on: 1) Application of Ultra-High Performance Concrete to Bridge Girders and 2) Bond Strength of Self-Consolidating Concrete for Prestressed Concrete Applications.

A-11 Nevada

Nevada DOT does not have specific guidelines for SCC or any class of concrete. Nevada DOT has limits that contractors must meet when submitting mix designs for approval on NDOT projects. The limits are not included in this report because the limits attached to the surveys are not compatible with SCC guidelines in other states.

A-12 New York State
New York State DOT (NYS DOT) does not have specific mix parameters for building a SCC mixture. NYSDOT treats SCC as a performance based application and requires the contractor/producer to develop a mix for application as well as a quality control plan to maintain consistency and quality. SCC has been used for repair applications and precast products. Special notes were attached to the survey explaining test methods. That information was shown in Table 4.2. Not specific information on materials and proportioning was given by NYDOT.

A-13 North Carolina
North Carolina has used SCC for girders, box beams, voided slabs and box culverts. North Carolina has past research to determine the feasibility of SCC. From the research requirements are applied by North Carolina DOT as follows: 1) Portland Cement Type III or combination Type I/II; 2) cementitious materials used include fly ash, slag, and silica fume. Replacement amounts vary as needed; 3) coarse aggregate stone size: #57, 67, or 78M; 4) fine aggregate 2S or 2MS; 5) w/c max 0.40 if strength required is above 6000 psi. If required strength below 6000 psi then max w/c is 0.46; 6) admixtures are used upon request and mix performance. Admixtures used are: HRWR, VMA, air-entrainer, retarder, accelerator, and hydration control admixture.

A-14 Ohio
SCC has specifications for the use of SCC. SCC is used in precast/prestressed functions along with cast-in-place where there is rebar congestion. Contractors should include a quality control plan. Ohio specifications for SCC state that a minimum of 520 lbs/yrd^3 should be used. Also, cementitious materials used include fly ash or slag. Fly ash can be used to replace 25 % of cement, while slag can be used to replace 30 %. If slag and fly ash are combined cement can be replaced up to 50 %. Admixtures can be added upon manufacturer recommendation; however, admixtures should not be mixed between manufacturers. Ohio does not have previous or future plans for research on SCC.

A-15 Pennsylvania
PennDOT has been using SCC in precast and prestressed structural components since 2004, and will start using SCC in field cast caisson/drilled shaft construction. Pennsylvania specifications for precast concrete products include a section for SCC. This section explains test methods requirements for SCC, these requirements are shown in table 4.2. Mix design is in charge of producers and should be approved by the materials engineer.

A-16 Rhode Island
Rhode Island DOT (RiDOT) uses SCC for precast structures, abutments, culverts, deck slabs, beams and cast-in-place (repairs and drilled shafts). RiDOT has developed some guidelines for the use of SCC. RiDOT permits any concrete class mix with the exception of class B and Z. Concrete mixes can be modified to SCC. Requirements for the SCC mix include: 1) W/c should be less than 0.36; 2) Chemical admixture shall be added at a rate that is recommended by the admixture manufacturer with a tolerance of ± 3 percent by weight. RiDOT is considering analyzing the w/c maximum value to allow for a wider range in the future.

A-17 South Carolina
SCDOT has no specific mix parameters for SCC. SCDOT had a research project with The University of South Carolina (USC) a few years ago. The research was concerning the use of SCC for prestressed

girders. DOT representative stated that the precast concrete industry are hesitant to use SCC for their work; they would rather user higher slump**.**

A-18 South Dakota

South Dakota DOT has created guidelines for SCC based on quartzite and limestone aggregates. One research project for each aggregate was performed to study the structural performance of SCC of prestressed girders with the respective aggregates. South Dakota DOT guidelines state: 1) Minimum cement content of 700 lb/yrd^3; 2) maximum w/c of 0.37; 3) minimum coarse aggregate content of 40 %; 4) entrained air range of 5 to 7.5 %.

A-19 Texas

Texas DOT has created SCC specifications as well as a quality control plan. SCC specifications contain the acceptance range of values for test methods. However, the specifications received from the DOT do not contain specific values for designing SCC mix. SCC mix design will be submitted for approval, and several trial batches will be performed to ensure the performance of the mix. Based on the diversity of aggregates in Texas research was needed to determine the performance of the mix. Texas DOT sponsored research regarding “Characterization of Self-Consolidating Concrete for Design f Precast, Prestressed Bridge Girders”. Texas DOT representative mentioned that new guidelines for SCC will be used starting March 2015.

A-20 Utah

Utah DOT uses SCC for different applications that include girders, box culverts, noise walls and other precast applications. Utah DOT has been using SCC in pre-cast applications with great success for 10 years. A standard specification for SCC has been used since 2012. Requirements for the SCC mix include: 1) Type III cement and a minimum amount of 611 lbs/yrd^3; 2) fly ash class F is used to replace cement, within a range of 20 – 30 % of the total cementitious materials; 3) coarse aggregate size 3/4” or 1/2”; 4) maximum w/c is 0.4; 5) admixtures are added as needed to obtain desired performance.

A-21 Virginia

Virginia DOT uses SCC for bridges, beams, drilled shafts, prestressed beams and precast items. Parameters for SCC follow the same as normal concrete but with a different slump requirement and different admixtures. The parameters include that the coarse aggregate should not exceed 3/4", not less than 1/5 of the narrowest dimension between the sides of the forms, and not less than 3/4 of minimum clear spacing between bars tendons or ducts. W/c maximum value of 0.45. VMA must meet ASTM C494, Type S. Other admixtures are added as needed, e.g. shrinkage reducing admixtures may be added to control cracking. Virginia DOT uses SCC for several research projects, currently studying SCC in per caps for bridges.

A-22 Washington

Washington DOT approves the use of SCC for precast applications. Mix should be submitted for annual approval according to guidelines created by the DOT. These guidelines provide ranges of accepted values for fresh testing, which were shown in previous section. For precast products it is required to use Type III cement, however no other requirements are stated in the specification for the SCC mix. Washington DOT has not had previous research projects on SCC, and does not plan in having one for now.

APPENDIX B

List of Mixture Designs

Detailed mixture materials and parameters for all 28 different mixtures considered in this project. Parameters varied between 0.45 and 0.5 for S/Agg, and between 0.35 and 0.33 for w/c ratio.

Mixture 1		
Parameter		
W/C	0.35	
S/Agg	0.5	
Material		**Unit**
Cement	800	lbs/yrd^3
Water	280	lbs/yrd^3
Coarse Aggregate 3/4"	1460	lbs/yrd^3
Coarse Aggregate 3/8"	0	lbs/yrd^3
Fine Aggregate	1455	lbs/yrd^3
HRWR	5	oz/cwt
VMA	1	oz/cwt

Mixture 2		
Parameter		
W/C	0.35	
S/Agg	0.45	
Material		**Unit**
Cement	800	lbs/yrd^3
Water	280	lbs/yrd^3
Coarse Aggregate 3/4"	1606	lbs/yrd^3
Coarse Aggregate 3/8"	0	lbs/yrd^3
Fine Aggregate	1310	lbs/yrd^3
HRWR	5	oz/cwt
VMA	2	oz/cwt

Mixture 3		
Parameter		
W/C	0.35	
S/Agg	0.5	
Material		**Unit**
Cement	800	lbs/yrd^3
Water	280	lbs/yrd^3
Coarse Aggregate 3/4"	292	lbs/yrd^3
Coarse Aggregate 3/8"	1168	lbs/yrd^3
Fine Aggregate	1455	lbs/yrd^3
HRWR	6.5	oz/cwt
VMA	2	oz/cwt

Mixture 4		
Parameter		
W/C	0.35	
S/Agg	0.5	
Material		**Unit**
Cement	800	lbs/yrd^3
Water	280	lbs/yrd^3
Coarse Aggregate 3/4"	584	lbs/yrd^3
Coarse Aggregate 3/8"	876	lbs/yrd^3
Fine Aggregate	1455	lbs/yrd^3
HRWR	5	oz/cwt
VMA	0	oz/cwt

Mixture 5		
Parameter		
W/C	0.35	
S/Agg	0.45	
Material		**Unit**
Cement	800	lbs/yrd^3
Water	280	lbs/yrd^3
Coarse Aggregate 3/4"	642	lbs/yrd^3
Coarse Aggregate 3/8"	963	lbs/yrd^3
Fine Aggregate	1310	lbs/yrd^3
HRWR	5	oz/cwt
VMA	1	oz/cwt

Mixture 6		
Parameter		
W/C	0.35	
S/Agg	0.5	
Material		**Unit**
Cement	800	lbs/yrd^3
Water	280	lbs/yrd^3
Coarse Aggregate 3/4"	876	lbs/yrd^3
Coarse Aggregate 3/8"	584	lbs/yrd^3
Fine Aggregate	1455	lbs/yrd^3
HRWR	5.5	oz/cwt
VMA	2	oz/cwt

Mixture 7		
Parameter		
W/C	0.35	
S/Agg	0.45	
Material		**Unit**
Cement	800	lbs/yrd^3
Water	280	lbs/yrd^3
Coarse Aggregate 3/4"	963	lbs/yrd^3
Coarse Aggregate 3/8"	642	lbs/yrd^3
Fine Aggregate	1310	lbs/yrd^3
HRWR	6.5	oz/cwt
VMA	2	oz/cwt

Mixture 8		
Parameter		
W/C	0.35	
S/Agg	0.5	
Material		**Unit**
Cement	800	lbs/yrd^3
Water	280	lbs/yrd^3
Coarse Aggregate 3/4"	1168	lbs/yrd^3
Coarse Aggregate 3/8"	292	lbs/yrd^3
Fine Aggregate	1455	lbs/yrd^3
HRWR	6.5	oz/cwt
VMA	1	oz/cwt

Mixture 9		
Parameter		
W/C	0.35	
S/Agg	0.45	
Material		**Unit**
Cement	800	lbs/yrd^3
Water	280	lbs/yrd^3
Coarse Aggregate 3/4"	1284	lbs/yrd^3
Coarse Aggregate 3/8"	321	lbs/yrd^3
Fine Aggregate	1310	lbs/yrd^3
HRWR	7.5	oz/cwt
VMA	2	oz/cwt

Mixture 10		
Parameter		
W/C	0.35	
S/Agg	0.5	
Material		**Unit**
Cement	800	lbs/yrd^3
Water	280	lbs/yrd^3
Coarse Aggregate 3/4"	1460	lbs/yrd^3
Coarse Aggregate 3/8"	0	lbs/yrd^3
Fine Aggregate	1455	lbs/yrd^3
HRWR	6.5	oz/cwt
VMA	1	oz/cwt

Mixture 11		
Parameter		
W/C	0.35	
S/Agg	0.45	
Material		**Unit**
Cement	800	lbs/yrd^3
Water	280	lbs/yrd^3
Coarse Aggregate 3/4"	1606	lbs/yrd^3
Coarse Aggregate 3/8"	0	lbs/yrd^3
Fine Aggregate	1310	lbs/yrd^3
HRWR	5	oz/cwt
VMA	0	oz/cwt

Mixture 12		
Parameter		
W/C	0.35	
S/Agg	0.5	
Material		**Unit**
Cement	800	lbs/yrd^3
Water	280	lbs/yrd^3
Coarse Aggregate 3/4"	0	lbs/yrd^3
Coarse Aggregate 3/8"	1490	lbs/yrd^3
Fine Aggregate	1524	lbs/yrd^3
HRWR	5	oz/cwt
VMA	0	oz/cwt

Mixture 13		
Parameter		
W/C	0.35	
S/Agg	0.5	
Material		**Unit**
Cement	800	lbs/yrd^3
Water	280	lbs/yrd^3
Coarse Aggregate 3/4"	298	lbs/yrd^3
Coarse Aggregate 3/8"	1192	lbs/yrd^3
Fine Aggregate	1524	lbs/yrd^3
HRWR	6	oz/cwt
VMA	0	oz/cwt

Mixture 14		
Parameter		
W/C	0.35	
S/Agg	0.5	
Material		**Unit**
Cement	800	lbs/yrd^3
Water	280	lbs/yrd^3
Coarse Aggregate 3/4"	596	lbs/yrd^3
Coarse Aggregate 3/8"	894	lbs/yrd^3
Fine Aggregate	1524	lbs/yrd^3
HRWR	5	oz/cwt
VMA	1	oz/cwt

Mixture 15		
Parameter		
W/C	0.35	
S/Agg	0.5	
Material		**Unit**
Cement	800	lbs/yrd^3
Water	280	lbs/yrd^3
Coarse Aggregate 3/4"	894	lbs/yrd^3
Coarse Aggregate 3/8"	596	lbs/yrd^3
Fine Aggregate	1524	lbs/yrd^3
HRWR	5	oz/cwt
VMA	1	oz/cwt

Mixture 16		
Parameter		
W/C	0.33	
S/Agg	0.5	
Material		**Unit**
Cement	800	lbs/yrd^3
Water	264	lbs/yrd^3
Coarse Aggregate 3/4"	905	lbs/yrd^3
Coarse Aggregate 3/8"	604	lbs/yrd^3
Fine Aggregate	1544	lbs/yrd^3
HRWR	6	oz/cwt
VMA	1.5	oz/cwt

Mixture 17		
Parameter		
W/C	0.33	
S/Agg	0.45	
Material		**Unit**
Cement	800	lbs/yrd^3
Water	264	lbs/yrd^3
Coarse Aggregate 3/4"	996	lbs/yrd^3
Coarse Aggregate 3/8"	664	lbs/yrd^3
Fine Aggregate	1358	lbs/yrd^3
HRWR	5	oz/cwt
VMA	1.5	oz/cwt

Mixture 18		
Parameter		
W/C	0.35	
S/Agg	0.5	
Material		**Unit**
Cement	800	lbs/yrd^3
Water	280	lbs/yrd^3
Coarse Aggregate 3/4"	1192	lbs/yrd^3
Coarse Aggregate 3/8"	298	lbs/yrd^3
Fine Aggregate	1524	lbs/yrd^3
HRWR	5	oz/cwt
VMA	1	oz/cwt

Mixture 19		
Parameter		
W/C	0.33	
S/Agg	0.45	
Material		**Unit**
Cement	800	lbs/yrd^3
Water	264	lbs/yrd^3
Coarse Aggregate 3/4"	1328	lbs/yrd^3
Coarse Aggregate 3/8"	332	lbs/yrd^3
Fine Aggregate	1358	lbs/yrd^3
HRWR	6	oz/cwt
VMA	2	oz/cwt

Mixture 20		
Parameter		
W/C	0.33	
S/Agg	0.5	
Material		**Unit**
Cement	800	lbs/yrd^3
Water	264	lbs/yrd^3
Coarse Aggregate 3/4"	1207	lbs/yrd^3
Coarse Aggregate 3/8"	302	lbs/yrd^3
Fine Aggregate	1544	lbs/yrd^3
HRWR	5	oz/cwt
VMA	1.5	oz/cwt

Mixture 21		
Parameter		
W/C	0.35	
S/Agg	0.5	
Material		**Unit**
Cement	800	lbs/yrd^3
Water	280	lbs/yrd^3
Coarse Aggregate 3/4"	1490	lbs/yrd^3
Coarse Aggregate 3/8"	0	lbs/yrd^3
Fine Aggregate	1455	lbs/yrd^3
HRWR	5	oz/cwt
VMA	1.5	oz/cwt

Mixture 22		
Parameter		
W/C	0.35	
S/Agg	0.5	
Material		**Unit**
Cement	800	lbs/yrd^3
Water	280	lbs/yrd^3
Coarse Aggregate 3/4"	950	lbs/yrd^3
Coarse Aggregate 3/8"	633	lbs/yrd^3
Fine Aggregate	1581	lbs/yrd^3
HRWR	6	oz/cwt
VMA	1	oz/cwt

Mixture 23		
Parameter		
W/C	0.35	
S/Agg	0.5	
Material		**Unit**
Cement	800	lbs/yrd^3
Water	280	lbs/yrd^3
Coarse Aggregate 3/4"	884	lbs/yrd^3
Coarse Aggregate 3/8"	697	lbs/yrd^3
Fine Aggregate	1423	lbs/yrd^3
HRWR	5	oz/cwt
VMA	1	oz/cwt

Mixture 24		
Parameter		
W/C	0.35	
S/Agg	0.5	
Material		**Unit**
Cement	800	lbs/yrd^3
Water	280	lbs/yrd^3
Coarse Aggregate 3/4"	900	lbs/yrd^3
Coarse Aggregate 3/8"	712	lbs/yrd^3
Fine Aggregate	1456	lbs/yrd^3
HRWR	6	oz/cwt
VMA	0	oz/cwt

Mixture 25		
Parameter		
W/C	0.35	
S/Agg	0.5	
Material		**Unit**
Cement	800	lbs/yrd^3
Water	280	lbs/yrd^3
Coarse Aggregate 3/4"	1267	lbs/yrd^3
Coarse Aggregate 3/8"	316	lbs/yrd^3
Fine Aggregate	1581	lbs/yrd^3
HRWR	6	oz/cwt
VMA	0	oz/cwt

Mixture 26		
Parameter		
W/C	0.33	
S/Agg	0.5	
Material		**Unit**
Cement	800	lbs/yrd^3
Water	264	lbs/yrd^3
Coarse Aggregate 3/4"	1777	lbs/yrd^3
Coarse Aggregate 3/8"	0	lbs/yrd^3
Fine Aggregate	1456	lbs/yrd^3
HRWR	7	oz/cwt
VMA	2	oz/cwt

Mixture 27		
Parameter		
W/C	0.33	
S/Agg	0.45	
Material		**Unit**
Cement	800	lbs/yrd^3
Water	264	lbs/yrd^3
Coarse Aggregate 3/4"	1746	lbs/yrd^3
Coarse Aggregate 3/8"	0	lbs/yrd^3
Fine Aggregate	1423	lbs/yrd^3
HRWR	7	oz/cwt
VMA	2	oz/cwt

Mixture 28		
Parameter		
W/C	0.35	
S/Agg	0.5	
Material		**Unit**
Cement	800	lbs/yrd^3
Water	280	lbs/yrd^3
Coarse Aggregate 3/4"	1584	lbs/yrd^3
Coarse Aggregate 3/8"	0	lbs/yrd^3
Fine Aggregate	1581	lbs/yrd^3
HRWR	9	oz/cwt
VMA	1	oz/cwt

APPENDIX C

Summary of Fresh and Hardened Properties

Fresh and hardened properties for the 28 different mixtures considered in the project are presented in this appendix. The properties include: Slump Flow, J-Ring, VSI, T20, Column Segregation, and Compressive Strength for both 18 hours and 28 days.

Mixture 1		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24	inches
J-Ring	24.5	inches
VSI	0	index
T20	9.4	seconds
Column Segregation	2.7	%
Compressive Strength		
18 hours	6442	psi
28 days	11998	psi

Mixture 2		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24	inches
J-Ring	-	inches
VSI	0	index
T20	7.4	seconds
Column Segregation	2.7	%
Compressive Strength		
18 hours	5946	psi
28 days	-	psi

Mixture 3		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	23.75	inches
J-Ring	24	inches
VSI	0	index
T20	5.3	seconds
Column Segregation	6.3	%
Compressive Strength		
18 hours	7027	psi
28 days	11874	psi

Mixture 4		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24.5	inches
J-Ring	24	inches
VSI	0.5	index
T20	12	seconds
Column Segregation	6.4	%
Compressive Strength		
18 hours	6755	psi
28 days	11056	psi

Mixture 5		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24.5	inches
J-Ring	-	inches
VSI	0.5	index
T20	8.5	seconds
Column Segregation	-	%
Compressive Strength		
18 hours	6484	psi
28 days	-	psi

Mixture 6		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24.75	inches
J-Ring	24.5	inches
VSI	1	index
T20	3.9	seconds
Column Segregation	2.8	%
Compressive Strength		
18 hours	6958	psi
28 days	10164	psi

Mixture 7		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24.75	inches
J-Ring	24	inches
VSI	1	index
T20	5.2	seconds
Column Segregation	4.7	%
Compressive Strength		
18 hours	7135	psi
28 days	9877	psi

Mixture 8		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	22.75	inches
J-Ring	25	inches
VSI	0	index
T20	10.6	seconds
Column Segregation	9.1	%
Compressive Strength		
18 hours	8432	psi
28 days	-	psi

Mixture 9		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	25.25	inches
J-Ring	24.5	inches
VSI	1	index
T20	4.8	seconds
Column Segregation	4.2	%
Compressive Strength		
18 hours	7048	psi
28 days	9427	psi

Mixture 10		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	25	inches
J-Ring	24	inches
VSI	1	index
T20	4.6	seconds
Column Segregation	6.3	%
Compressive Strength		
18 hours	6993	psi
28 days	9241	psi

Mixture 11		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	23	inches
J-Ring	24.5	inches
VSI	0	index
T20	7.3	seconds
Column Segregation	10.1	%
Compressive Strength		
18 hours	7243	psi
28 days	9908	psi

Mixture 12		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24.5	inches
J-Ring	22.48	inches
VSI	0	index
T20	6.3	seconds
Column Segregation	1.6	%
Compressive Strength		
18 hours	5221	psi
28 days	8062	psi

Mixture 13		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	26	inches
J-Ring	24.5	inches
VSI	1	index
T20	7.1	seconds
Column Segregation	3.3	%
Compressive Strength		
18 hours	5520	psi
28 days	8721	psi

Mixture 14		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24.5	inches
J-Ring	23.5	inches
VSI	0	index
T20	9.3	seconds
Column Segregation	5.1	%
Compressive Strength		
18 hours	6187	psi
28 days	9048	psi

Mixture 15		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	25.3	inches
J-Ring	24.5	inches
VSI	1	index
T20	13.6	seconds
Column Segregation	8.9	%
Compressive Strength		
18 hours	6998	psi
28 days	-	psi

Mixture 16		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24.75	inches
J-Ring	23.5	inches
VSI	0.5	index
T20	3.4	seconds
Column Segregation	2	%
Compressive Strength		
18 hours	7114	psi
28 days	8750	psi

Mixture 17		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24.6	inches
J-Ring	23.75	inches
VSI	0	index
T20	3.6	seconds
Column Segregation	10.1	%
Compressive Strength		
18 hours	6958	psi
28 days	10393	psi

Mixture 18		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24.5	inches
J-Ring	23.5	inches
VSI	0	index
T20	8.2	seconds
Column Segregation	9.5	%
Compressive Strength		
18 hours	5918	psi
28 days	-	psi

Mixture 19		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	25	inches
J-Ring	23.5	inches
VSI	0.5	index
T20	5.9	seconds
Column Segregation	-	%
Compressive Strength		
18 hours	6687	psi
28 days	-	psi

Mixture 20		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24.5	inches
J-Ring	24	inches
VSI	0	index
T20	4.8	seconds
Column Segregation	9.9	%
Compressive Strength		
18 hours	7148	psi
28 days	9994	psi

Mixture 21		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	26	inches
J-Ring	24.25	inches
VSI	1	index
T20	5.7	seconds
Column Segregation	11.8	%
Compressive Strength		
18 hours	5869	psi
28 days	9729	psi

Mixture 22		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	26.25	inches
J-Ring	25	inches
VSI	1	index
T20	6.1	seconds
Column Segregation	5.1	%
Compressive Strength		
18 hours	6737	psi
28 days	8307	psi

Mixture 23		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	25.25	inches
J-Ring	23.75	inches
VSI	1	index
T20	5.8	seconds
Column Segregation	3.4	%
Compressive Strength		
18 hours	6850	psi
28 days	89.31	psi

Mixture 24		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24.5	inches
J-Ring	22.25	inches
VSI	0	index
T20	5.3	seconds
Column Segregation	2.2	%
Compressive Strength		
18 hours	6709	psi
28 days	8516	psi

Mixture 25		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	26.25	inches
J-Ring	24.5	inches
VSI	1	index
T20	3.1	seconds
Column Segregation	9.9	%
Compressive Strength		
18 hours	6861	psi
28 days	9076	psi

Mixture 26		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24	inches
J-Ring	22.5	inches
VSI	0	index
T20	2.5	seconds
Column Segregation	4.7	%
Compressive Strength		
18 hours	5042	psi
28 days	6728	psi

Mixture 27		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24	inches
J-Ring	23.5	inches
VSI	0	index
T20	3.4	seconds
Column Segregation	3.1	%
Compressive Strength		
18 hours	5451	psi
28 days	6813	psi

Mixture 28		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24	inches
J-Ring	23.75	inches
VSI	0	index
T20	4	seconds
Column Segregation	12.2	%
Compressive Strength		
18 hours	5978	psi
28 days	7131	psi

APPENDIX D

Creep and Shrinkage Data

Creep and shrinkage readings taken every week for 280 days are tabulated as follows. Note that there are readings for each of the three cylinders/prisms per mixtures, along with an average of all three.

Creep

Mixture 1				
	Cylinder 1	Cylinder 2	Cylinder 3	Average
0	0	0	0	0
1	304	298	309	304
2	329	323	332	328
3	357	347	356	353
4	383	370	385	379
5	420	393	413	408
6	444	416	437	432
7	480	448	463	463
14	600	509	503	537
21	729	593	561	628
28	817	666	616	700
56	915	791	733	813
84	1010	873	814	899
112	1080	1005	920	1002
140	1094	1015	935	1015
168	1176	1056	960	1064
196	2071	2088	1404	1854
224	2071	2088	1404	1854
252	2071	2088	1404	1854
280	2071	2088	1404	1854

Mixture 2				
	Cylinder 1	**Cylinder 2**	**Cylinder 3**	**Average**
0	0	0	0	0
1	305	314	278	299
2	339	333	316	329
3	364	361	340	355
4	396	383	367	382
5	420	410	395	408
6	449	429	421	433
7	470	448	458	459
14	548	505	505	519
21	662	566	566	598
28	756	612	612	660
56	871	725	725	773
84	956	796	796	849
112	1027	865	865	919
140	1135	877	910	974
168	1169	906	929	1001
196	2640	1545	1055	1747
224	2640	1545	1055	1747
252	2640	1545	1055	1747
280	2640	1545	1055	1747

Mixture 4				
	Cylinder 1	Cylinder 2	Cylinder 3	Average
0	0	0	0	0
1	160	195	252	202
2	241	284	303	276
3	308	375	393	359
4	368	424	458	417
5	423	471	526	473
6	469	514	595	526
7	540	589	658	596
14	628	683	768	693
21	749	761	873	794
28	831	814	939	861
56	925	954	1041	973
84	1007	1041	1145	1064
112	1073	1093	1225	1130
140	1103	1098	1274	1158
168	1120	1108	1322	1183
196	1778	1285	1617	1560
224	1778	1285	1617	1560
252	1778	1285	1617	1560
280	1778	1285	1617	1560

Mixture 6				
	Cylinder 1	Cylinder 2	Cylinder 3	Average
0	0	0	0	0
1	296	145	182	208
2	342	212	276	277
3	384	320	373	359
4	512	370	449	443
5	533	428	525	495
6	561	482	604	549
7	589	531	683	601
14	662	628	781	690
21	719	699	862	760
28	793	765	939	832
56	900	842	1100	947
84	983	978	1237	1066
112	1057	1078	1298	1144
140	1102	1117	1319	1179
168	1165	1161	1338	1221
196	1165	2682	1649	1832
224	1165	2682	1649	1832
252	1165	2682	1649	1832
280	1165	2682	1649	1832

Mixture 9				
	Cylinder 1	**Cylinder 2**	**Cylinder 3**	**Average**
0	0	0	395	132
1	170	295	442	302
2	245	316	470	344
3	337	361	491	396
4	397	396	726	506
5	446	421	752	540
6	499	457	788	581
7	548	488	893	643
14	651	650	985	762
21	734	711	1067	837
28	797	762	1165	875
56	920	923	1303	1049
84	1023	996	1381	1133
112	1087	1073	1421	1194
140	1162	1102	1471	1245
168	1207	1151	1494	1284
196	1229	1230	1580	1347
224	1232	1277	1610	1373
252	1269	1281	1634	1395
280	1312	1289	1718	1440

Shrinkage of Plant Prisms

Mixture 1				
	Prism 1	Prism 2	Prism 3	Avg
0	0	0	0	0
1	50	50	50	50
2	100	90	110	100
3	160	130	180	157
4	210	180	240	210
5	270	230	290	263
6	320	270	340	310
7	380	320	400	367
14	450	370	460	427
21	510	410	520	480
28	560	440	580	527
56	580	480	620	560
84	590	550	650	597
112	590	600	680	623
140	590	1020	770	793
168	603	933	697	744
196	610	1040	790	813
224	620	1030	800	817
252	630	1060	800	830
280	630	1090	830	850

Mixture 2				
	Prism 1	**Prism 2**	**Prism 3**	**Avg**
0	0	0	0	0
1	50	50	42	47
2	70	110	73	84
3	100	160	95	118
4	150	200	120	157
5	190	250	135	192
6	250	300	150	233
7	280	370	250	300
14	330	400	330	353
21	400	450	400	417
28	460	500	460	473
56	510	540	520	523
84	570	560	580	570
112	610	580	620	603
140	640	630	780	683
168	633	620	663	639
196	680	650	710	680
224	710	640	750	700
252	700	640	740	693
280	730	660	740	710

Mixture 4				
	Prism 1	**Prims 2**	**Prims 3**	**Avg**
0	0	0	0	0
1	47	60	50	52
2	77	100	100	92
3	107	250	150	169
4	117	300	210	209
5	147	360	260	256
6	247	460	290	332
7	333	470	330	378
14	397	500	360	419
21	477	550	400	476
28	527	580	450	519
56	547	590	510	549
84	647	640	570	619
112	677	690	600	656
140	697	660	660	672
168	680	657	610	649
196	697	720	670	696
224	707	750	670	709
252	727	730	690	716
280	737	760	690	729

Mixture 6				
	Prims 1	**Prism 2**	**Prism 3**	**Avg**
0	0	0	0	0
1	30	40	40	37
2	40	70	60	57
3	60	100	80	80
4	80	120	110	103
5	130	150	150	143
6	170	160	200	177
7	200	180	230	203
14	230	250	260	247
21	250	340	290	293
28	280	400	300	327
56	350	440	380	390
84	380	500	410	430
112	410	500	420	443
140	440	530	430	467
168	427	517	433	459
196	490	580	520	530
224	490	610	540	547
252	480	600	530	537
280	510	630	560	567

Mixture 9			
	Prism 1	**Prism 3**	**Avg**
0	0	0	0
1	50	30	40
2	90	70	80
3	150	120	135
4	220	150	185
5	250	180	215
6	290	200	245
7	320	230	275
14	370	280	325
21	400	320	360
28	430	370	400
56	480	450	465
84	500	470	485
112	530	510	520
140	520	580	550
168	563	510	537
196	660	560	610
224	650	570	610
252	660	580	620
280	670	600	635

Shrinkage of Lab Prisms

Mixture 1				
	Prism 1	**Prism 2**	**Prism 3**	**Avg**
0	0	0	0	0
1	20	10	20	17
2	40	40	30	37
3	50	60	40	50
4	80	70	70	73
5	90	100	80	90
6	120	120	100	113
7	140	130	120	130
14	180	180	160	173
21	230	190	220	213
28	280	240	280	267
56	370	330	400	367
84	450	410	520	460
112	491	449	553	498
140	480	480	530	497
168	550	480	570	533
196	420	540	600	520
224	440	600	610	550
252	460	590	620	557
280	470	620	630	573

Mixture 2				
	Prism 1	**Prism 2**	**Prism 3**	**Avg**
0	0	0	0	0
1	20	20	30	23
2	30	50	50	43
3	50	80	60	63
4	80	110	80	90
5	100	130	110	113
6	110	160	120	130
7	130	180	140	150
14	190	240	180	203
21	250	290	240	260
28	310	350	310	323
56	400	460	400	420
84	490	540	510	513
112	529	564	546	546
140	560	570	590	573
168	600	560	570	577
196	630	590	610	610
224	630	590	610	610
252	620	610	630	620
280	670	680	670	673

Mixture 4				
	Prism 1	**Prims 2**	**Prims 3**	**Avg**
0	0	0	0	0
1	20	10	20	17
2	60	30	30	40
3	90	50	60	67
4	100	60	80	80
5	120	80	110	103
6	140	110	130	127
7	170	140	160	157
14	220	190	210	207
21	260	230	260	250
28	310	280	340	310
56	483	350	410	414
84	560	470	530	520
112	584	499	552	545
140	600	540	570	570
168	600	540	610	583
196	660	590	590	613
224	660	590	590	613
252	640	610	620	623
280	660	600	640	633

Mixture 6				
	Prims 1	Prism 2	Prism 3	Avg
0	0	0	0	0
1	20	40	40	33
2	50	70	60	60
3	70	100	80	83
4	90	120	110	107
5	100	150	150	133
6	120	160	200	160
7	140	180	230	183
14	210	250	260	240
21	280	340	290	303
28	340	400	300	347
56	480	440	380	433
84	580	500	410	497
112	616	532	427	525
140	540	600	530	557
168	540	660	510	570
196	510	680	550	580
224	530	780	550	620
252	550	880	610	680
280	560	870	600	677

Mixture 9				
	Prism 1	**Prism 2**	**Prism 3**	**Avg**
0	0	0	0	0
1	20	20	40	27
2	40	50	60	50
3	50	70	70	63
4	70	100	90	87
5	100	120	110	110
6	120	140	140	133
7	140	160	240	180
14	190	250	320	253
21	230	300	370	300
28	300	340	410	350
56	370	410	470	417
84	430	460	530	473
112	465	495	556	505
140	550	560	630	580
168	560	620	670	617
196	610	660	760	677
224	610	730	760	700
252	620	700	740	687
280	640	650	710	667

APPENDIX E

Lab Strain Data for Transfer Length and Layout of Gage Instrumentation

Strain readings for eight gages in both the tested girders (i.e., SCC and CC girders). Readings were taken at initial placement, after tensioning, after pouring, 16 hours after pouring, and after release, for a total of 28 days. Illustration of strain gage location through cross-section and top-views of both SCC and CC girders is included herein.

Strain Readings										
Gage No	**Gage Channel**	**Initial**	**After Tension**	**Pouring**	**16 hr**	**Release**	**Day**			
							7	**14**	**21**	**28**
SCC-C-1	**2.1**	0	6126	6117	4500	1500	691	672	624	585
SCC-C-2	**1.1**	0	3517	3258	2312	1560	750	703	510	508
SCC-C-3	**2.8**	0	5990	5979	3495	2070	1625	1710	1251	1120
SCC-C-4	**2.1**	0	2324	2254	2175	1546	1093	1062	1065	1028
SCC-S-1	**2.6**	0	6100	0	0	0	0	0	0	0
SCC-S-2	**2.5**	0	5890	5880	3280	825	507	443	231	45
SCC-S-3	**1.2**	0	5994	5933	1720	1180	-442	-513	-844	987
SCC-S-4	**2.3**	0	7881	7886	4150	3306	1873	1623	1269	1155
CC-C-1	**1.1**	0	6292	6234	5273	863	790	660	586	408
CC-C-2	**1.9**	0	6014	4372	2691	1520	490	485	282	167
CC-C-3	**1.8**	0	5875	5762	2234	1566	775	730	748	728
CC-C-4	**1.7**	0	6230	6181	2046	1960	908	802	663	557
CC-S-1	**1.6**	0	5570	5470	4334	420	-380	-364	-320	-315
CC-S-2	**1.5**	0	6166	0	0	0	0	0	0	0
CC-S-3	**1.4**	0	2934	2814	2408	870	1114	1113	1065	1065
CC-S-4	**1.3**	0	5275	5166	2723	2278	1592	1505	1410	1290

Note: gage locations (e.g., SCC-C-1) can be seen in Figure E-1

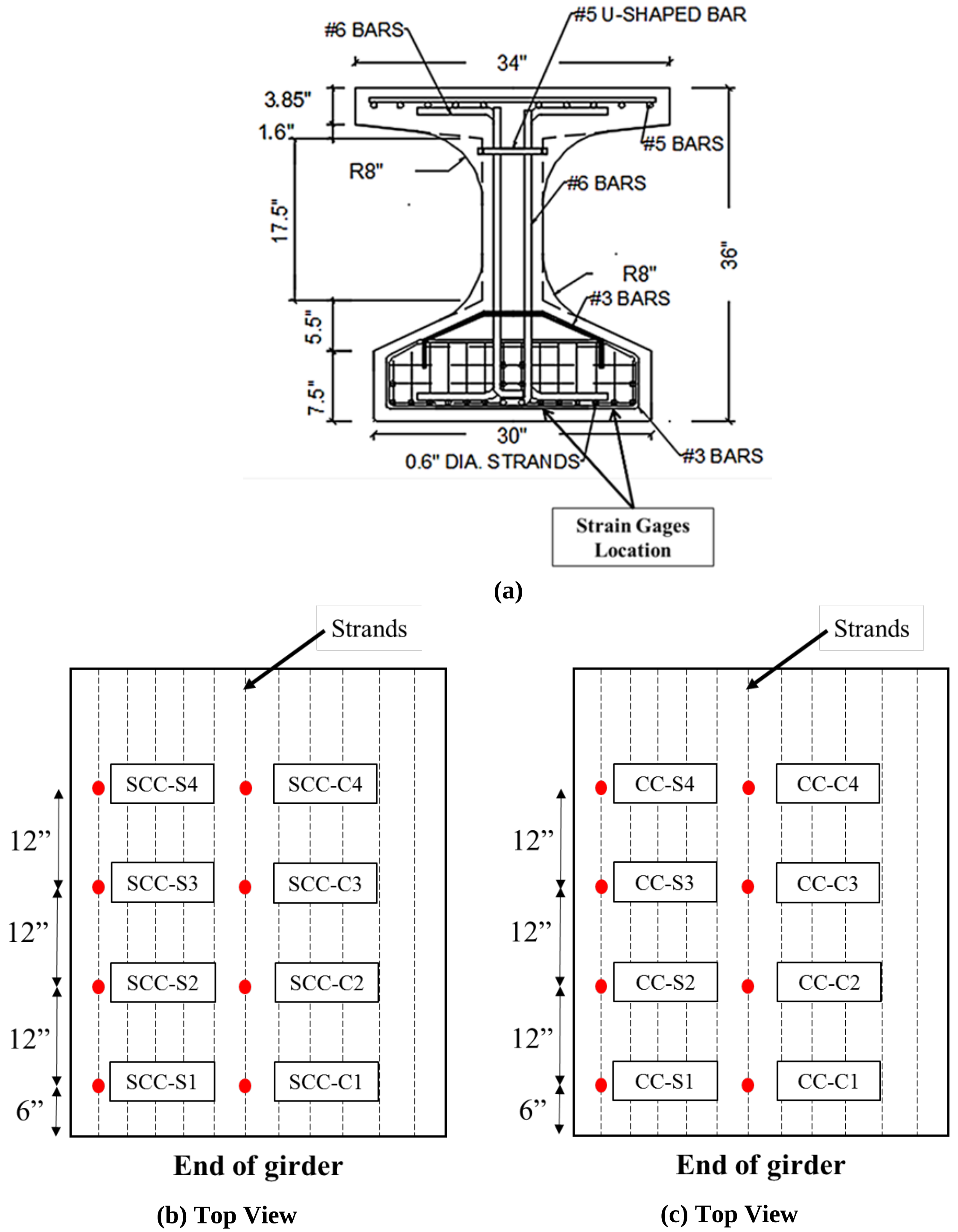

Figure E.1 Layout of gage instrumentation: (a) girder cross section; (b) strain-gage location for SCC girder; and (c) strain-gage location for CC girder