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A Compilation of Research on Self-Consolidating Concrete for Prestressed Bridge Girders

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A COMPILATION OF RESEARCH ON SELF-CONSOLIDATING CONCRETE FOR PRESTRESSED BRIDGE GIRDERS

BY

EDUARDO S. TORRES

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A COMPILATION OF RESEARCH ON SELF-CONSOLIDATING CONCRETE FOR PRESTRESSED BRIDGE GIRDERS

This thesis is approved as a creditable and independent investigation by a candidate for the Master of Science degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department

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El fruto de mi esfuerzo está dedicado a Dios por darme la oportunidad de cumplir mis metas. A pesar de las adversidades siempre su bendito manto me ha acompañado y mostrado los pasos. A pesar de los momentos difíciles que me tocaron vivir siempre logro mostrarme los lados positivos de la vida y darme mil razones para continuar con más ánimos.

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CONTENTS

ABSTRACT

A COMPILATION OF RESEARCH ON SELF-CONSOLIDATING CONCRETE FOR PRESTRESSED BRIDGE GIRDERS

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Self-Consolidating Concrete (SCC) is a relative new concrete technology developed in the 1980s in Japan. Since, SCC has been used for several applications around the world. Initially, SCC was used for on-site applications where it was difficult to place concrete. SCC workability benefits facilitated construction procedures by freely flowing, filling space and passing through dense reinforcement without vibration mechanism. Meanwhile, SCC has also been used in other applications such as the precast industry, where the benefits of the workability SCC delivers can be utilized to improve fabrication of prestressed girders. SCC has been used in the precast industry with a satisfactory performance. This was achieved by reducing fabrication time, decreasing health hazards due to excessive noise, and a much better finishing on the surface of the girder. However, difficulties maintaining uniformity, and resistance to segregation of the SCC mixtures have been reported by several producers. Ever since, several agencies and state Department of Transportation (DOT) have conducted research to study SCC characteristics with materials available in their region. Significate findings indicate that examination of fresh and hardened properties are necessary before application of prestressed girders. From particular findings, DOTs have developed guidelines for mixture constitution, and fresh and hardened properties required in their state for SCC production. However, due to different material proportions present on SCC mixtures

compared to Conventional Concrete (CC) or High-Performance Concrete (HPC) mixture different long-term behavior has been observed. Therefore, creep and shrinkage have been monitored for long-term behavior to accurately predict prestress losses, which are needed in the structural design of the bridges.

This thesis is composed of three research papers, for each paper a separate chapter is used, which investigates various aspects for the production of SCC utilizing materials available in the state of Wisconsin. Chapter one provides a summary of the current state-of-the-art and practice of technical documentation and specifications related to material properties and test methods for prestressed SCC bridge girders. Chapter two provides an experimental program designed to investigate the effect of material constituents on performance of SCC mixtures. From this experimental program specific mixture parameters were recommended for the application of SCC in Wisconsin DOT projects. Finally, chapter three consisted in monitoring samples of five SCC mixtures batched at three different precast plants from Wisconsin. Creep and shrinkage readings were taken for a period of 112 days to investigate the effect of specific mixture parameters of selected mixtures with performance desired by the Wisconsin DOT and precast plants.

Chapter 1: State-of-the-Art and Practice Review and Recommended Testing Protocol: Self-Consolidating Concrete for Prestressed Bridge Girders

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Abstract

Self-Consolidating Concrete (SCC) is a highly flowable, non-segregating concrete. Relevant technology and applications have steadily grown in various construction fields in the United States. Several State Departments of Transportation (DOTs) have performed significant research on SCC for prestressed bridge girders, resulting in their own guidelines. The objective of this study is to summarize the current state-of-the art and practice of technical documentation and specifications related to material properties for prestressed SCC bridge girders. To seek more practical information, a cursory survey among SCC experts at each DOT was performed and summarized herein. Key findings indicate that testing for the examination of fresh and hardened SCC properties are necessary for prestressed bridge girder applications. It is important to determine constituent proportions of the mixture and need of admixtures, as well as to require higher early compressive strengths required for prestressed SCC bridge girders. Based on the literature review and survey, a material property testing protocol to efficiently investigate SCC mix performance for prestressed bridge girders is recommended.

Keywords: Self-Consolidating Concrete, Prestressed bridge girders, Fresh and hardened properties, Literature review, Survey, Testing protocol

1. Introduction

Self-Consolidating Concrete (SCC) enables to smoothly take formwork shapes and easily pass through congested reinforcing bars with no vibration efforts, and SCC has been regarded as a more practical construction material when compared to normal concrete, making it a “smart concrete” (Shamsad et al. 2014). SCC is also able to enhance workability and economic efficiency under arbitrary environmental conditions. These features are manifested by reducing labor, shortening of the construction time, eliminating vibration and noise hazards, and simplifying the placing process (Skarendahl 2003). With the unique features, SCC has been used worldwide to date in various concrete structures. 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).

Extensive research on SCC mixture designs for prestressed bridge girders or other applications have been performed in several Departments of Transportation (DOTs) in the United States. For example, the South Carolina DOT was to study the use of SCC in drilled shafts (Ouchi et al. 2003) and in replacement of four structurally deficient bridges (Mallela et al. 2010). These studies have helped SCDOT use SCC in the drilled shafts and bridges. Additionally, the Kansas State DOT performed a study of the fresh and hardened properties of SCC for use in Kansas prestressed concrete bridge girders. KDOT built a three-span bridge using SCC in only one span while the remaining two spans were built using conventional concrete (Ouchi et al. 2003). The bridge was instrumented and monitored for five years to evaluate its long-term performance. In addition to the field studies, experimental studies for SCC concrete bridge girders have been carried out by the South Dakota DOT (SDDOT) in cooperation with South Dakota State University (Wehbe et al. 2009).

As a result of the DOT research projects, a SCC guideline for each DOT has been established based on the materials available in a specific region. Although these guidelines have been used for appropriately designing and implementing prestressed bridge girders at several particular state DOTs, some producers have had difficulty in maintaining uniformity of the SCC mixture during a field trial. Some issues related to excessive segregation of wet batches during placement have been observed in specific states. Hence, a testing protocol to appropriately investigate materials performance characteristics related to structural behavior of prestressed SCC bridge girders is required to be established throughout a detailed review of relevant technical documentation in conjunction with survey data from SCC experts in DOTs who can provide practical information.

This paper aims at not only providing the current state-of-the art review of published literature related to material fresh and hardened properties of SCC, but also establishing a testing protocol to determine an SCC mixture that meets desired prestressed bridge girder performance. To explore more practical data or limits associated with the prestressed bridge girder SCC mixture, state-level DOT specifications were reviewed and a brief survey to ask SCC experts in each DOT was carried out. This paper is structured into seven sections. Section 2 is devoted to a summary of the general information on desired SCC performance. Section 3 provides an overview of key SCC constituents and relevant research findings to achieve adequate material characteristics necessary for appropriately designing prestressed SCC bridge girders. Section 4 details conventional SCC material testing required for the investigation of fresh and hardened properties, modulus, shrinkage and creep related to the structural performance of prestressed bridge girders. Section 5 is dedicated to a summary of different state DOT survey responses and specifications specific to the SCC mixture. Section 6 presents a testing protocol for a proper SCC mixture based upon assembling the literature review and survey inputs. Lastly, Section 7 gives a summary and conclusions.

2. Desired SCC Performance

Achieving the desired SCC performance via testing-based SCC fresh properties are necessary for more efficient SCC construction management and planning. Specifically, adequate flowability, good passing and filling abilities, proper segregation resistance, and stability are required to satisfy the fresh property requirements. The required properties are achieved by proportioning the constituent materials and admixtures in a systematic way (Erkmen et al. 2008). Flowability can be divided into filling and passing ability. The filling ability is the ability to expand through the framework under its own weight, while the passing ability is the capability to flow through tight openings, such as narrow spacing between reinforcing bars (Wehbe et al. 2009). If the concrete does not possess adequate passing ability, it results in a non-uniform structure caused by blockage of coarse aggregate between reinforcing bars.

In addition to the flowability, SCC is more prone to segregation than high strength and conventional concrete (Bonen and Shah 2004). Segregation resistance is defined as the distribution of aggregate particles in the concrete that is relatively equivalent at all locations (Turkel and Kandemir 2010). Bonen and Shah (2004) suggested that the lack of segregation resistance might be caused by internal and external bleeding of water associated with differential accumulation of light ingredients and air voids, which results 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 paste, 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; Berke et al. 2003).

Increasing the powder content of the mixture helps to increase the cohesion between particles (Turkel and Kandemir 2010). Addition of viscosity modifying admixtures increases viscosity of the mixture by improving the absorption of water by the cement/filler particles (Long et al. 2014). SCC is susceptible to segregation at higher w/c ratios due to the decrease of viscosity on the mixture.

Stability is of high importance in SCC, for which fresh and hardened methods are used for quality control of the mixture. According to the recommendation by Long et al. (2014), 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, while 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, ground granulated blast-furnace slag (GGBS), fly ash and microsilica fume. The use of such powders can enhance the grain-size distribution and particle packing ensuring greater cohesiveness (Sonebi et al. 2007).

3. Overview of Key SCC Constituents

SCC constituents are proportioned to a specific type of SCC. Three types of SCC can be produced as follows: powder-type, viscosity modifying admixture (VMA)-type, and combination-type (Wehbe et al. 2009). The powder-type is characterized by the large amounts of powder which is in the range of 550 to 650 kg/m^3. In the VMA-type, the powder content is lower 350 to 450 kg/m^3. In the combination-type, the powder content is ranged between 450 and 550 kg/m^3 (Burgueno and Bendert 2007). Similar to conventional concrete constituents, the key constituents of SCC are coarse aggregate, fine aggregate, cement, and water along with admixtures. The following subsection details the characteristics on each constituent and relevant research findings focusing on prestressed SCC bridge girders.

3.1 Cement

Cement types that are in use for SCC vary for each state and precaster. According to the American Society of Testing Materials (ASTM 2011a) C150-05 guideline, this classifies Portland cement into five main types: Type I, Type II, Type III, Type IV, and Type V. Type I, Type III, and Type II are employed to produce SCC for the casting of prestressed girders in the United States. Type I is typically 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 exploited when high early strength is desired. Type IV is used when low heat of hydration is desired; while Type V is utilized when high sulfate resistance is needed following the ASTM C150 guideline.

3.2 Fillers

Fillers can be added to enhance a certain concrete property or reduce the amount of cement required; thus, fillers have been used as supplementary components or to be replaced with some of the cement in a concrete mixture. Most common fillers used for SCC mixtures include fly ash, ground granulated blast-furnace slag, silica fume, and limestone powder. Technical benefits of using fillers are as follows: 1) increase in early strength and bleeding control; 2) improvement of the concrete workability; 3) deformability, and 4) viscosity and reduction of porosity (Shamsad et al. 2014). The workability improves as a result of the reduction of internal friction between the particles (Sonebi et al. 2007). The reduction in friction can be achieved by increasing the distance between the particles and amount of paste (Khayat et al. 2009). The reduction in friction is also advantageous because it enables the reduction in water contents, while maintaining the required levels of flowability (Sonebi et al. 2007). Khayat and Mitchell (2009) studied the effect of different fillers on the performance of SCC. It was found that the fillers that were less reactive than cement slowed down the concrete hardening. By slowing down the hydration process the mixture remains fluid longer time; however, an excess on the replacement percentage of cement by fillers can transform its positive effects into negative by not allowing the cement to achieve complete hydration (Burgueno et al. 2007). As such, it was recommended to maintain the replacement percentage ranges listed in Table 1.

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

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

*Note: the presence of * indicates classes of fly ashes, including C, D, and F. Replacement percentage ranges are identical for Fly Ash no matter the class.*

3.3 Coarse Aggregate

Coarse aggregate has a marked effect on passing ability, filling capacity, and static stability of SCC. Maximum Size Aggregate (MSA) should be selected with consideration of the minimum clear spacing between the reinforcing bars and prestressing strands, the cover space over the reinforcement, and the geometry of elements to be cast (Khayat and Mitchell, 2009). The MSA must be chosen to avoid blockage, which can be caused by the collision of aggregates behind reinforcing bars so that the MSA should be smaller than the minimum spacing between the reinforcing bars (Sonebi et al. 2007). Long and Khayat (2014) developed a test matrix for SCC to study the effect of MSA in terms of workability and strength development. The MSA used in the test matrix were 19.0mm, 12.7mm, and 9.5mm. It was indicated that MSA of 19.0 mm showed better performance in comparison to that of 12.7mm and 9.5mm. It was recommended that the coarse aggregate size for SCC be between 19mm and 12.7mm, but not to be lower than 9.5mm. In addition to the MSA in flakiness index can have an effect on workability. Flakiness index is defined as the percent by weight of particles whose least dimension is less than a fifth of its mean dimension. Santhanam et al (2004) reported that flakiness does not have an impact on flowing ability; however, for mixtures having flakiness index above 23% the passing ability of the mixture was affected by causing excessive blockage.

3.4 Admixtures

Admixtures are ingredients in a concrete mixture other than cement, water, and aggregates that are added to the mixture to modify properties (Pellerin et al. 2005). Admixtures can be classified as a function of the following: 1) air-entraining admixtures; 2) water-reducing admixtures; 3) plasticizers; 4) viscosity modifying admixtures; 5) accelerating admixtures; 6) retarding admixtures; 7) hydration-control admixtures; 8) corrosion inhibitors; 9) shrinkage reducers; 10) alkali-silica reactivity inhibitors; and 11) coloring admixtures. Of these admixtures, air entraining, water-reducing, and viscosity modifying admixtures are used in the production of SCC, while the other admixtures are rarely utilized for SCC products. For example, air entraining admixtures are added to freshly mixed SCC to raise the air content. The main goal of increasing the air content in a SCC mixture is to improve durability (Wehbe et al. 2009). However, the effect of air entraining admixtures will increase the air content for a short term period, which will decrease in the long term period. The addition of air entraining admixtures can improve workability, cohesiveness, segregation, and bleeding resistance, yet decrease strength by 10-20% (Mindess et al. 2003).

Another example of helping to enhance flowability related to workability in SCC prestressed bridge girders is the use of water-reducing. In particular, High Range Water Reducing (HRWR) admixtures, also called superplasticizers, 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 30-60 minutes. These admixtures are added to decrease the water demand of concrete and create fluidity in the mixture (Kosmatka et al. 2002). Fluidity in the mixture 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, water is more readily available to hydrate the cement. As a result of the particle dispersion, HRWR admixtures can help make SCC mixtures with lower w/c ratio to have acceptable flowability and higher strength in accordance with the European Federation of National Associations Representing for Concrete (EFNARC 2006). Some relevant studies conducted by Erkmen et al. (2008) and Wehbe et al. (2009) have also shown that the HRWR was capable of increasing the compressive strength of concrete by 10-25%.

Viscosity Modifying Admixtures (VMAs) are high molecular weight polymers that enable an increase in the viscosity of a SCC mixture to the extent where there is no need to reduce the water content. Consequently, the VMAs are able to reduce segregation and bleeding in SCC applications. However, VMAs are not a remedy for poor quality constituents or mixture design. According to the EFNARC (2006), potential benefits of using VMA are the following: 1)Less sensitivity to variations in the moisture content of the aggregate; 2) Lower powder content; 3) Better quality control; 4) Allows more fluid mixes to be used without the risk of segregation; 5) Improving placing rate; and 6) Better surface appearance.

4. Conventional Test Methods

With an increase in demand of SCC in various structures, conventional SCC test methods have been used to determine workability of freshly mixed SCC and its hardened properties. The fresh test methods that were established by the ASTM include for slump flow, Visual Stability Index

(VSI), J-Ring, and Column Segregation tests (Mata 2004). Precast/Prestressed Concrete Institute (PCI) has also developed guidelines for SCC test methods and mixing procedures such as L-Box and Caisson test (PCI 2003). Nevertheless, EFNARC also has their own detailed information on each method with pertinent findings gained from literature review is presented in the following subsections.

4.1 Fresh Properties

As mentioned previously, there are three key characteristics of SCC in the fresh state as follows: 1) filling ability defined as the concrete capability to fill the form with its own weight; 2) passing ability which is known as the ability of fresh concrete to flow through congested spaces between reinforcements without segregation; and 3) resistance to segregation or stability which is the ability to maintain a homogeneous composition without excessive bleeding in the fresh state (Trejo et al. 2008). Table 2 lists what the aforementioned SCC fresh tests are used for each property according to which specifications are followed. Again, all the tests have standard guidelines from the ASTM with the exception of L-Box and Caisson test which are included in the Interim Guidelines written by PCI (PCI 2003) and V-funnel test included in the guidelines for the use of SCC created by EFNARC (EFNARC 2006).

Table 2. Test Methods for SCC Fresh Properties

Slump Flow	Filling Ability	ASTM C 1611
VSI	Segregation Resistance	ASTM C 1611
J-Ring	Passing Ability	ASTM C 1621
L-Box	Passing Ability	PCI
Column Segregation	Segregation Resistance	ASTM C 1610
Caisson Test	Filling Capacity	PCI
V-Funnel	Flowing Ability	EFNARC

The slump flow test (see Fig. 1) is the most widespread method for determining the free flowability of the mixtures (ASTM 2011e). 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 (Bonen and Shah 2004). The ASTM C1611 specifies a required diameter between 508mm-762mm. Also, EN-206 standard listed three ranges for slump flow values: 1) 550mm-650mm. 2)650mm-750mm and 3)750mm-850mm based on the mixture design. The diameter is measured when the SCC mixture is discharged from a standard cone under free flow conditions as seen in Fig. 1. The spread is measured as the average of two orthogonal diameters.

Fig. 1. Slump flow test (image by Eduardo Torres)

VSI has been used to evaluate the dynamic stability of the batch. The VSI is immediately performed after the slump flow. VSI levels are ranged from 0 to 3, indicating the degree of stable to unstable segregation. These levels are determined through visual inspection of the fresh batch after testing the slump flow. According to the American Concrete Institute (ACI 2007), VSI is a subjective test that can be used via precasters and cast in place by means of quality controlling of a SCC mixture. VSI also provides a visual image of the distribution of aggregates and the presence of excessive bleeding throughout the mixture (PCI 2003).VSI is divided in different levels as follows: 1) VSI of 0, meaning mass is homogeneous and no bleeding; 2) VSI of 1, indicating small bleeding observed in the surface; 3) VSI of 2, showing evidence of a mortar halo and water sheen; and 4) VSI of 3, concentration of coarse aggregate at center of concrete mass and presence of a mortar halo.

The passing ability of freshly mixed SCC can be evaluated using J-Ring or L-Box test. Both tests can determine the potential blockage or segregation. J-Ring test is more commonly used in the field site, while L-Box is used more in laboratory (Bonen and Shah 2004). The J-Ring test is similar to the slump flow, but the J-Ring is placed around the slump cone and the SCC is forced to pass through the legs of the J-Ring (Gutzmer 2008). Fig. 2 shows a picture for J-Ring testing with a SCC mixture. The average of two orthogonal diameters is recorded to be compared to the slump flow values. According to the ASTM C 1621 (ASTM 2011d), a difference of diameter less than 1 inch indicates good passing ability, and a difference above 2 inches indicates poor passing ability. The difference in heights between the concrete inside the ring and the concrete outside the ring can be compared to evaluate the passing ability. However, comparing these heights is neither commonly used nor accepted values specified by the ASTM C 1621. The aggregate size has the most influence on the results of this test as it can cause blockage between the reinforcing bars of the metal ring.

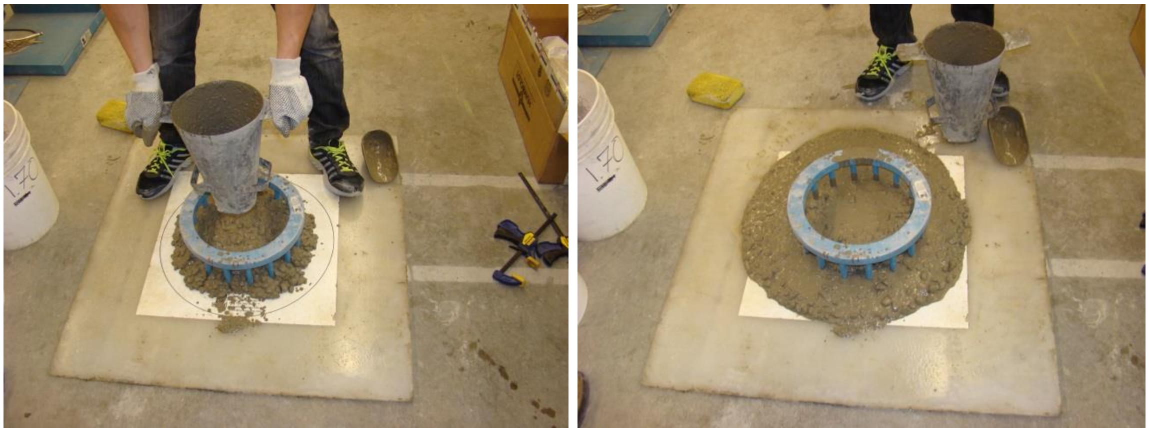

Fig. 2. J-Ring test (images by Junwon Seo)

The L-Box test is not the ASTM standard test, but a PCI manual-based testing method. Fig. 4 illustrates the setup of L-Box test. The test can be performed in accordance with the PCI interim guidelines (PCI 2003) and European standard EN 206 (2013). The measured L-Box values are expressed in terms of the ratio H2/H1. Both heights indicate the heights at the horizontal ends as seen in Fig. 3. Acceptable values of H2/H1 are between 0.80 and 1.00 in the recommended construction manual provided by the Japan Society of Civil Engineers (JSCE) (JSCE 1998) and the PCI interim guidelines (PCI 2003).

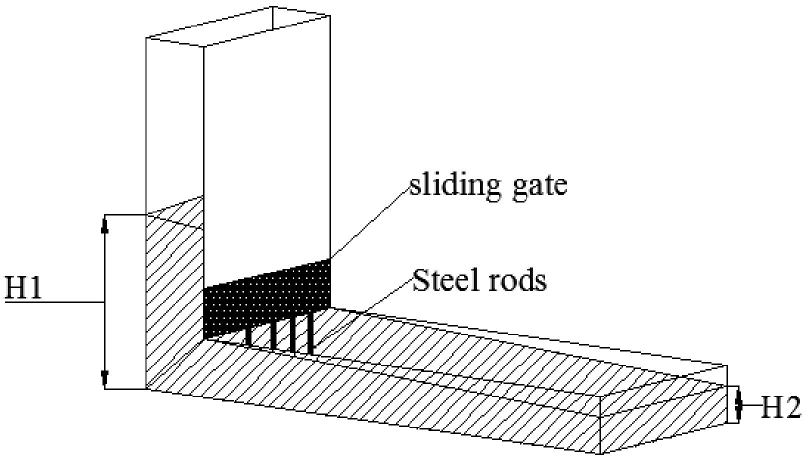

Fig. 3. L-Box test

ASTM C1610 test method also covers the determination of static segregation of a SCC mixture by measuring the coarse aggregate content in the top and bottom portions of a cylindrical specimen. According to the ASTM C1610 (ASTM 2010g), a SCC mixture is poured in the cylinder as seen in Fig. 4. The SCC mixture must remain in the mold without any disturbance for 15 minutes. The SCC at the top section of the column is removed and placed into a container and the middle sectional SCC is removed. The SCC is then disposed. The SCC in the bottom section is also placed in a container. The SCC from the top and bottom sections has to be washed separately over a No. 4 sieve so that only coarse aggregate remains on the sieve. The coarse aggregate is over dried to a constant mass. Column segregation values are expressed as the percentage ratio of the difference of aggregate mass between the bottom and top segments of the column to the total aggregate mass in the two segments (Mamaghani et al. 2010). The following equation can be used to determine the static segregation, depending on magnitudes for mass of coarse aggregate in the bottom and top sections:

$$S = 2\left[\frac{CA_B - CA_T}{CA_B + CA_T}\right] * 100; \text{ if } CA_B > CA_T \tag{1}$$

$$S = 0; \text{ if } CA_B \leq CA_T \tag{2}$$

where CA_B and CA_T indicate mass of coarse aggregate in the bottom section and mass of coarse aggregate in the top section, respectively.

Fig. 4. Column segregation test (images by Junwon Seo)

Caisson test detailed by PCI manual (PCI 2003) is a promising test to determine filling capacity. However, the caisson test is for laboratory use only and is not commonly used. Instead of using caisson test a combination of the slump flow and either the L-box or J-Ring test can be efficiently used to assess filling ability of a SCC mixture (Long et al. 2014).

V-Funnel test described in the EFNARC guidelines is used to assess the viscosity and filling ability of self-compacting concrete. V-funnel test addresses the time it takes to the concrete to flow through the funnel. For this test the MSA of the aggregate should not exceed 20mm. Also, the EFNARC guidelines provide detail information of the GTM screen stability test which is similar to the column segregation test. GTM screen stability test consists of collecting 10 liters of concrete, and then pour half of it on to a 5mm sieve of 350mm diameter. Allow the concrete to sit on the sieve for 2 minutes, before weighting the concrete that passed through the sieve. Then, the weight value recorded is expressed as the percentage of the weight of the original sample. The percent ratio considered satisfactory for this test ranges from 5-15%.

4.2 Hardened Properties

Determining hardened properties of SCC, encompassing compressive strength, modulus of elasticity, creep, and shrinkage, is important to estimate the structural performance of SCC in prestressed bridge girders. Specifically, measuring creep and shrinkage of SCC is necessary because these characteristics have a significant effect on overall losses of SCC prestressed girders. The following subsections will detail technical findings obtained through literature review for each hardened property.

4.2.1. Compressive Strength

SCC has demonstrated positive results in regard to compressive strength (Mamaghani et al. 2010) in some cases better than normal concrete. Prestressed bridge girders require a higher strength in comparison to other applications, such as columns and box culverts. Typically, a compressive strength can be experimentally measured according to the ASTM C36 (ASTM 2011). Readings are recorded at 18hr, 3, 7, 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 strengths gaining at an early age relative to moist curing (Hamilton et al. 2005).

A number of studies have been conducted to investigate the effects of different SCC constituents on the compressive strength. For example, Schindler et al. (2007) and Vilanova et al. (2012) studied the SCC compressive strength under variation of different constituents such as w/c ratio, Sand to total Aggregate (S/Agg) ratio, different cementitious materials and fillers, cement content and type, and aggregate type. From the two studies, it was concluded that cement content, w/c ratio, and coarse aggregate have a significant influence on the compressive strength. Attiogbe et al. (2006), Collepardi et al. (2005) and Wehbe et al. (2007) concluded that the compressive strength of SCC was comparable or higher than that of normal concrete of the same w/c ratio. Burgueno et al. (2007) also performed compressive strength testing for three different types of SCC: powder Type, VMA Type and combination Type I/II. It was indicated that the powder and VMA types showed higher strength than that of normal concrete at the early age. However, combination Type I/II developed slower strength gains compared to 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 affected properties of the SCC mixture. The results showed that SCC mixtures using limestone yielded substantially higher strength than those mixed with other mineral admixtures or fillers. The higher strength of SCC mixtures using limestone powder can occur due to the higher surface porosity of limestone. This creates higher reactivity of calcite as a result of the interaction between cement and limestone, enhancing the compressive strength (Turkel et al. 2010).

4.2.2. Modulus of Elasticity

According to the ASTM C469 (ASTM C469, 2011f), modulus of elasticity is known as the resistance to deform elastically when a force is applied. SCC may exhibit lower modulus of elasticity than that of normal concrete during a long period due to its relatively greater prestress losses in prestressed SCC components (Shamsad et al. 2004). However, it was found that the SCC has similar modulus of elasticity at 28 days compared to normal concrete. The modulus of elasticity in the SCC mixtures is affected by the use of mineral admixtures, paste volume and size of coarse aggregate. The following mineral admixtures increase modulus of elasticity in the following order: fly ash, limestone filler, and ground-granulated blast-furnace slag (Vilanova et al. 2012).

4.2.3. Durability

Prestressed bridge girders exhibit satisfactory structural performance and durability. However, cracking, damage and corrosion of the strands can be observed (Kim et al. 2011). Durability can be divided into the following parameters: 1) permeability, 2) diffusion coefficient and freeze-thaw resistance (Kim et al. 2011). Many studies have been performed to compare the durability of SCC with conventional concrete (CC). For instance, EFNARC in their guidelines for SCC states that SCC with the appropriate properties will exhibit low and more uniform permeability compared to CC. Assie et al. (2005) concluded that SCC mixtures containing limestone powder exhibited lower permeability compared to other SCC mixtures and CC mixtures of similar strength. Other fillers studied included fly ash and silica fume, which has shown to greatly enhance permeability at age of 56 and 91 days (Suksawang et al. 2006).

4.2.4. Shrinkage

Shrinkage is a phenomenon that is the result of moisture loss in concrete (Zhang et al. 2011). Volume change occurs as concrete loses water. Concrete can lose water on its surroundings through evaporation instead of being consumed in the hydration process. When the internal water evaporates, negative capillary pressures are formed that cause the paste to contract (Wehbe et al.

2009). Shrinkage can be experimentally measured according to the ASTM C157 (ASTM 2011c). The ASTM testing procedure is able to 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 (22.7 ± 1℃) and relative humidity (50%±4%) recommended by ASTM C157. Fig. 5 shows a length comparator to record volume reduction in the concrete prisms.

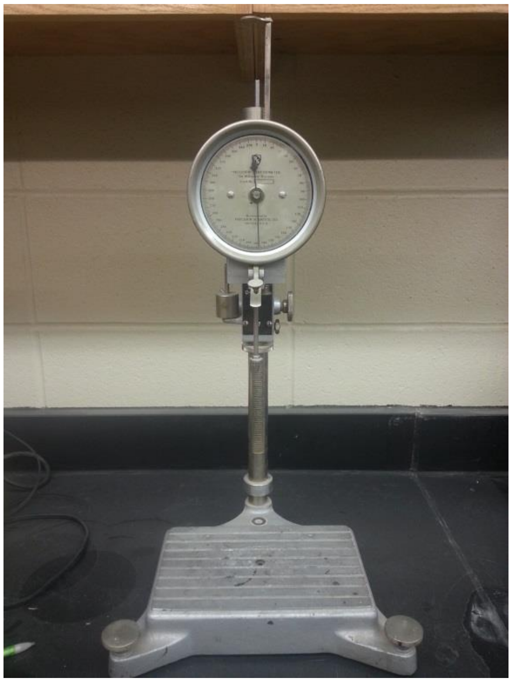

Fig. 5. Length comparator for SCC shrinkage test (image by Eduardo Torres)

A Volume-to-Surface area (V/S) ratio is used in shrinkage prediction equations. Higher V/S ratios typically lead to less shrinkage. For a SCC mixture, there are three cases of shrinkage that need special consideration as follows (Kosmatka 2002): 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; 3) drying shrinkage is the strain that is caused by water loss from hardened concrete when it is exposed to the environment. Lower autogeneous and higher drying shrinkage have been reported to have the higher effects on SCC structural performance (ACI 2007). The aggregate content is one of the main factors affecting drying and autogeneous shrinkage strains of SCC. The main function of the aggregate is to restrain the shrinkage deformations. The SCC mixture with a low aggregate content is associated with a higher shrinkage strain (Gomez et al. 2007). The SCC mixture made with higher binder content can exhibit greater drying shrinkage varying between 500 and 1000 micro strains after 300 days; however, substituting Portland cement by fillers substantially decreases drying shrinkage (Khayat et al. 2010).

Many studies (Mata 2004, Wehbe et al. 2009, Khayat et al. 2010) have focused on the effect of the shrinkage on the prestressed SCC bridge girder performance. For example, Wehbe et al. (2009) and Khayat et al. (2010) compared the experimental shrinkage values of SCC samples to those estimated from the American Association of Highway and Transportation Officials (AASHTO) 2007, American Concrete Institute (ACI) 209R and other shrinkage prediction models. Wehbe et al. (2009) concluded that the ACI model underestimated the shrinkage values of SCC specimens with w/c ratio higher than 0.35

for the first 24 hours, but prediction results were in agreement with readings at later days up to 115 days. Khayat et al (2010) found that the prediction models underestimated the shrinkage values of SCC specimens with more than 600 micro strains. On the other hand, Mata (2004) demonstrated that the experimental shrinkage values for SCC samples had higher volume reduction than samples made with the normal concrete mixture.

4.2.5. Creep

Creep is a volumetric change due to external loads. A test method used to determine creep is the ASTM C512 (ASTM 2011b). This 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 specimens must be less than 40% of the compressive strength. Fig. 6 shows a representative creep testing setup for several SCC specimens on the creep frames.

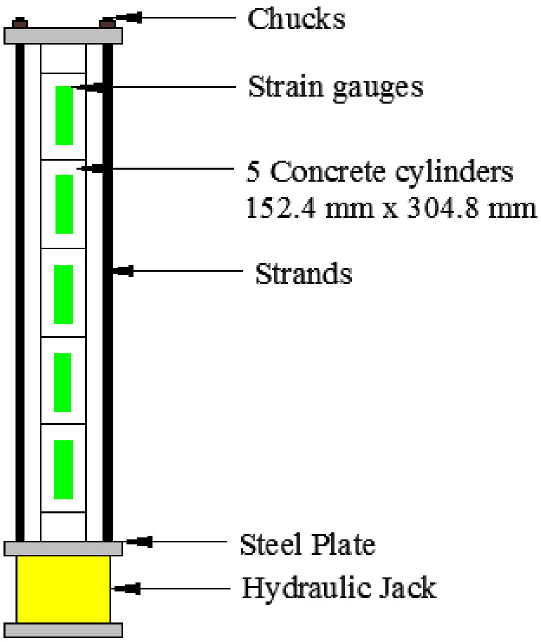

Fig. 6. Creep testing setup

Concrete experiences long term creep deformation due to an applied load. The creep shortening of concrete under consistent loading conditions is ranged from 0.5 to 4 times the initial elastic shortening according to the findings found by Trejo et al., (2008). The magnitude relies on the extent of concrete maturity at the time of loading (AASHTO 2006). Previous research on creep comparing High Performance Concrete (HPC) to SCC mixtures shows that SCC mixture may experience 10-20% more strain than HPC (Khayat and Mitchell 2009). Several mixture factors influence creep performance on SCC. For instance, SCC mixtures with high paste volumes may result in increased creep and prestress losses and deflections along with reduced capacities of prestressed concrete components (Kim et al. 2011). Also, aggregates used in a SCC mixture have a significant influence on the creep as well. For example, river gravel exhibits lower creep when compared to limestone due to its higher stiffness (Kim et al, 2011). Khayat and Long (2010) also found that w/c ratio had a slight effect on creep, while other parameters such as binder content, binder type, and S/Agg had a significant influence on it.

5. DOTs Survey Outcomes

A brief survey to get a better understanding of state-level SCC specifications and establishment of a testing protocol to determine desired performance of SCC prestressed bridge girders was conducted in each DOT. Note that the online-based survey for determining practical limits for fresh properties of SCC, and the survey form and relevant results are available from the authors. The survey form was distributed to each DOT, requesting information about individual current practices with the use of SCC. It is worthwhile to note that responses to the survey were not obtained by every DOT, and in some cases they solely provided their state specifications, instead of answering the particular questions. Table 3 shows the DOTs who responded and how they provided information to the project.

Table 3. Information Provided by State DOTs

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 that they filled out, SCC specifications or relevant research reports.

The survey was designed to cover three aspects of SCC. The first aspect was addressed to the practices and future planning for the use of SCC. The second aspect was to investigate the materials used in a state as well as specific parameters for its mixture. This aspect was of high importance because of the lack of specific guidelines for SCC in prestressed bridge girders. The third aspect was to gather data on each of the state-level requirements and test methods to approve a SCC mixture. The first two aspects related to the acceptance and applications of SCC to prestressed bridge girders in use in individual DOTs were covered by performing the survey.

5.1 Mixture Parameters

Several parameters in the survey form were considered to be of high important for the SCC mixture design for prestressed bridge girders. The most primary parameter that should be considered for the SCC mixture design is the cement content. The minimum amount of total cement content required is the initial step to determine the appropriate proportions of the SCC mixture. To obtain minimum compressive strengths for a specific DOT, each DOT has established a minimum amount of cement content. For example, some DOTs (i.e., Utah, South Dakota, Nebraska and Alabama) require the minimum cement content to be over 355 kg/m^3. Some other states may require higher cement content; this is the case of Florida DOT who requires a minimum of 446 kg/m^3. On the other hand, a few DOTs, such as Illinois DOT, have established an upper limit of 418 kg/m^3. Once the cement content is determined, w/c ratio has to be determined. Fig. 7 shows a range of maximum w/c ratios used by DOTs. It appears that the most common range of maximum w/c ratios is within 0.41 to 0.45.

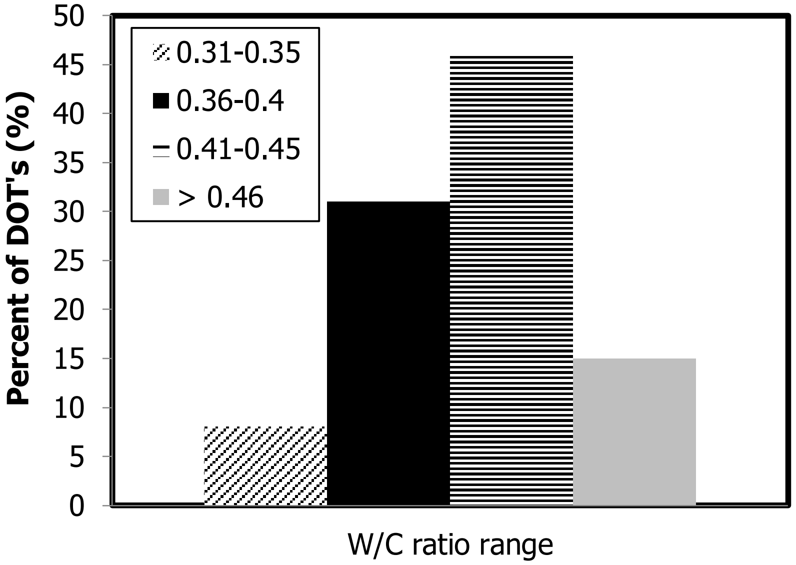

Fig. 7. Percent of DOTs who approve the range of maximum w/c ratio

Another important parameter to be considered for designing a SCC mixture is the replacement of cement by fillers. Fig. 8 illustrates the percent of DOTs who approve the use of fillers to be replaced with cement. It appears that around 30% of the DOTs approve the use of fillers. As described before, the most common fillers that have been widely in use across the DOTs are fly ash, ground granulated blast furnace, silica fume, limestone, metakaolin, and microsilica. For example, Florida DOT has used fly ash and ground granulated blast furnace slag (GGBFS), especially for the use of GGBFS that has been allowed to be replaceable up to 70% of the total cement content. Other DOTs, such as Georgia DOT, have used the same fillers as in the Florida DOT with the inclusion of metakaolin and microsilica. 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.

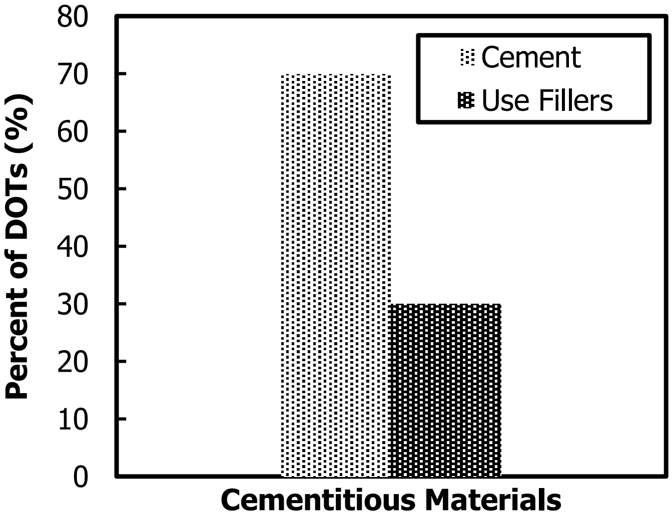

Fig. 8. Percent of DOTs who approve the use of fillers for a SCC mixture used in prestressed bridge girders

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 12.7mm and 19.0mm should be used as MSA. However, some DOTs such as North Carolina and Florida DOTs provide a wide range of MSA of 25.4mm, 19mm, 12.7mm and 9.52 mm corresponding to stone #57, #67, #78 and #89, respectively. Virginia DOT was the only state DOT 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 19mm of minimum clear spacing between bars and tendons.

5.2 Fresh Properties Requirements

The survey collected information on all the test methods required to determine the fresh and hardened properties of SCC mixtures used and what each of the DOTs consider a requirement for SCC fresh performance. Table 4 summarizes the requirements of each DOT for all the test methods. For instance, Illinois DOT has parameters for all fresh properties methods explained in this paper. For the slump flow, Illinois DOT has a lower and upper limit of 508.0mm and 711.2mm, respectively. However, the slump flow value should be within ± 50.8mm from the contractor target. VSI shall be a maximum of 1. The J-Ring value should be a maximum of 102.6mm, 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 stablish more strict guidelines based on their own SCC mixture design.

Table 4. SCC Fresh Property Requirements for Surveyed State DOTs

State	Slump Flow (mm)	J-Ring (mm)	VSI	L-Box	Column Segregation
Alabama	635 - 736.6	±76.2	0-1	N/A	N/A
Florida	685.8 ± 63.5	±50.8	0-1	N/A	Max 15%
Georgia*	Min 508	N/A	N/A	Min 0.8	N/A
Illinois*	508-711.2	Max 101.6	0-1	Min 0.6	Max 15%
Iowa	Max 685.8	N/A	N/A	N/A	N/A
Kentucky*	Provide Spread Limits, Production Records and Quality Control Procedures.				
Louisiana	508 -711.2	Provide Aggregate Gradations			
Michigan	685.8 ± 25.4	±15.24	0-1	Min 0.8	N/A
Minnesota	Max 711.2	±50.8	0-1	N/A	N/A
Nebraska	ASTM C1611	N/A	ASTM C1611	N/A	N/A
Nevada*	No specific guidelines.				
New York*	±50.8 Target	±50.8	0-1	N/A	Max 15%
North Carolina	609.6 - 762	±50.8	N/A	Min 0.8	N/A
Ohio	685.8 ± 50.8	N/A	N/A	N/A	N/A
Pennsylvania*	508 - 762	±50.8	0-1	N/A	N/A
Rhode Island	508 -660.4	±50.8	N/A	N/	N/A
South Carolina	Precasters in the state are hesitant in using SCC.				
South Dakota	508 – 711.2	±50.8	0-1	N/A	N/A
Texas*	558.8 – 685.8	±50.8	0-1	N/A	Max 10%
Utah	457.2 – 812.8	±25.4	0-1	N/A	Max 10%
Virginia	660.4 ± 76.2	±50.8	0-1	N/A	Max 15%
Washington	± 50.8 Target	±38.1	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).

5.3 Testing Protocol for Desired SCC Mixture Performance

The design of an appropriate SCC mixture that will be used for prestressed bridge girders is challenging to achieve fully desired structural performance of them without a systematic protocol for testing SCC property under ambiguous, non-uniform guidelines.

Based upon the literature review and survey input, laboratory-based data that can be obtained from a series of the fresh and hardened property tests under a suite of technical documentation are required to successfully and reasonably establish the SCC mixture. Therefore, a recommended protocol for designing the SCC mixture that meets all the criteria of implementing prestressed bridge girders is constructed herein. The protocol consisting of three steps from mixture proportioning to required testing is illustrated in Fig. 9.

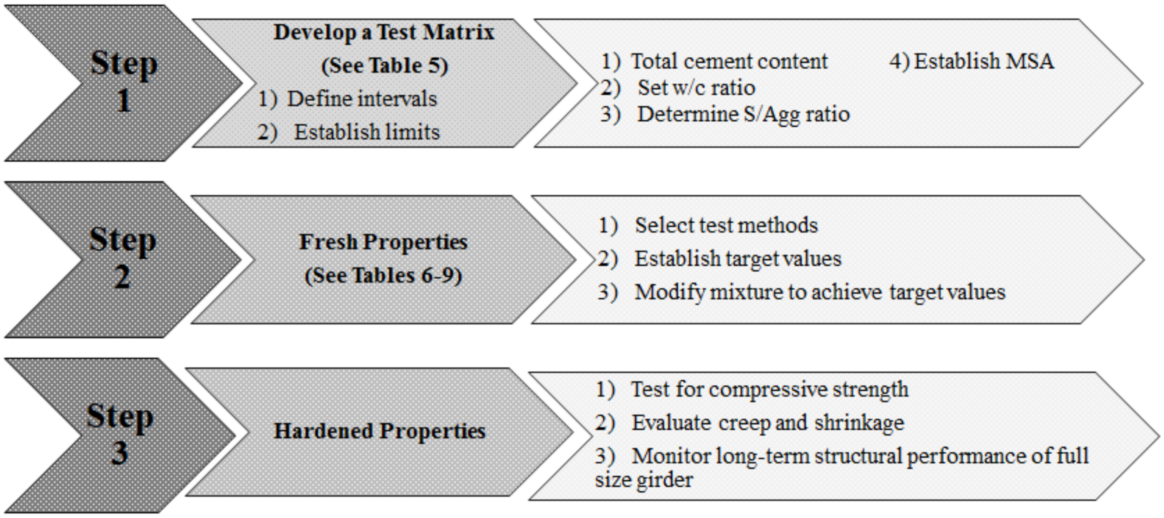

Fig. 9. Testing protocol for establishing an appropriate SCC mixture that can be used for prestressed bridge girders

Step 1 starts with developing a test SCC matrix. The matrix can be designed to properly evaluate the desired performance of SCC mixtures. Common variables for the matrix are type of fillers, type of aggregate, w/c ratio, S/Agg ratio and MSA. Intervals of each variable can be established according to relevant literature on SCC material testing setup. Table 5 shows an example of variables with intervals and limits. Once the matrix is determined, SCC mixtures can be designed based upon its matrix.

Table 5. Proposed Test Matrix for Desired SCC performance

Variables	Limits	Intervals							Property
w/c ratio	± 0.01	0.34	0.35	0.36	**0.37**	0.38	0.39	0.40	Workability
S/Agg ratio	±0.05		0.40	0.45	**0.50**	0.55	0.60		Segregation

Note: values shown are applicable for a specific mix design; thus, these values should be adjusted depending on an individual mix design.

Step 2 is to select appropriate testing methods to determine fresh properties of SCC mixtures in Step 1. The testing methods include slump flow, VSI, J-Ring, L-Box, and Column Segregation tests in accordance with the ASTM C512 and PCI manual (PCI 2003). Target values for each test method aimed to match desired fresh properties specific to the SCC mixture should be established. Table 6 shows an example of accepted ranges that can be found in the ASTM and several DOTs specification requirements and target values that can be determined and varied by a researcher or contractor for specific performance of prestressed SCC bridge girders.

Table 6. Acceptable Range and Target Values for Specific Test Methods

Fresh Properties Tests	Acceptable Range	Target Value
Slump Flow (ASTM C1611):	508mm – 711.2mm	635 mm
J-Ring (ASTM C1621):	max 25.4 mm	max 25.4 mm
VSI (ASTM C1611):	≤ 1	≤ 1
L-Box (PCI 2003):	Min of 60%	Close to 80%
Column Segregation (ASTM C1610):	≤ 15 %	Close to 10 %

To achieve optimum workability, constituents are modified as shown in Tables 7 to 9. In detail, Table 7 shows suggestions to achieve desired slump flow results. Table 8 lists modifications to achieve optimal passing ability. Table 9 includes what factors have an influence on segregation.

Step 3 is to evaluate the SCC mixture so as to meet the requirements for prestressed SCC girders. Evaluating hardened properties are of importance to predict the long-term structural performance of prestressed SCC girders. Prestressed bridge girders typically require developing early high compressive strength specific to an individual DOT; thus, high strength of the mixture can be obtained by adjusting w/c ratio, determining appropriate minimum cement/cementitious material content, and identify what admixtures are needed. Further, creep and shrinkage must be monitored for a period of at least 90 days. Prediction models have shown to underestimate creep and shrinkage values. Therefore, it is necessary to obtain experimental data on the strain changes due to volume reduction caused by creep and shrinkage. Readings should be collected for a long period of time which is recommended to be approximately a year.

Table 7. Suggested Variables to Modify Flowability

Variables	Slump	Mix Effects
Add HRWR	Increase	Increase fluidity
Low fine aggregates	Increase	Decrease viscosity
Modify w/c ratio	Increase/Decrease	Cause bleeding/low cohesion
Add VMA	Decreases	Increases viscosity
Increase fine aggregates	Decreases	Affect drying shrinkage

Table 8. Suggested Variables to Modify Passing Ability

Variables	Passing Ability	Mix Effects
Add HRWR	Increase	Increase flowability
Decrease coarse aggregate size	Increase	Decrease cracking strength
Add VMA	Decrease	Increases viscosity

Table 9. Suggested Variables to Modify Segregation

Variables	Segregation /Stability	Effects on Mix
Add HRWR or VMA	Increases	Increases viscosity
Decrease aggregate Size	Increases	Decreases aggregate settling
Increase fines	Increases	Decreases sedimentation

6. Summary and Conclusions

1) There have been numerous studies and state-level specifications on fresh and hardened properties for Self-Consolidating Concrete (SCC) to date in various concrete structures. These studies and specifications that have been summarized in this paper have demonstrated that the SCC has several benefits for the production of prestressed bridge girders. However, developing a SCC mixture to be uniformly used for prestressed bridge girders across a region in the United States requires a high level of understanding its constituent parameters affecting both fresh and hardened properties to maintain the quality of SCC. Hence, a protocol to design a mixture for SCC prestressed girders was developed based on the literature review and survey results. The key conclusions from this study can be drawn as follows:

2) The literature review showed that SCC has higher or similar compressive strengths compared to normal concrete with similar characteristics; cement in a

SCC mixture can be replaced by fillers to obtain certain properties; lower w/c ratio can be used to attain higher strengths; a replacement of cement with fillers can result in reduction of concrete strengths; SCC is more sensitive to segregation and shrinkage in comparison to normal concrete; and prestress losses of SCC can be higher than normal concrete.

3) The survey indicated that SCC mixtures can be created with materials available in each state with the desired performance of prestressed bridge girders; MSA cannot exceed 19.1mm to obtain reasonably good passing abilities and avoid settling; maximum w/c ratio of SCC mixtures can be 0.45; only cement is preferred to be used for enhancing performance of SCC mixtures instead of combining cement with a filler; Maximum Size Aggregate (MSA) most used by state Departments of Transportation (DOTs) are 19.0mm or 12.7mm; and w/c ratio varies for each state according to strength needed, but the most frequent values were within the range of 0.41 to 0.45.
4) Fresh and hardened properties of SCC with the adjustment of its constituent proportions must be precisely tested to achieve desired structural performance. The protocol that was established based upon the literature review and survey input is anticipated to provide future SCC users to improve the quality of SCC mixture that has potential to be used in prestressed bridge girders. When using the protocol, the following attentions are required that a test matrix be designed reflecting the influence of each constituent on the SCC fresh and hardened properties and that creep and shrinkage that serve as the basis to obtain an adequate long-term structural performance be monitored for approximately a year.

To qualify SCC for the use of prestressed concrete bridge girders, further work regarding reinforcement details and casting techniques in SCC should be conducted.

7. Acknowledgements

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Chapter 2: Experimental Investigation of Self-Consolidating Concrete Mixture Constituents for Prestressed Bridge Girder Fabrication

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Abstract

Self-Consolidating Concrete (SCC) exhibits superior workability compared to conventional concrete (CC) having potential to increase precast production and growth, especially for production of prestressed concrete bridge (PSC) girders. To obtain desired fresh and hardened properties for the production of SCC PSC girders, considering many factors related to material characteristics and mixture proportioning is vital. An experimental comparison of fresh and hardened properties among SCC mixtures made with different material constituents is conducted in this study. The ultimate objective of this paper is not only to provide an experimental program enabling the investigation of the effect of material constituents on performance of SCC mixtures, but to gain more knowledge for better production of SCC PSC girders. The experimental program is established based upon technical findings from the literature review and additional input from survey to several State Departments of Transportation (DOTs). The mixture constituents consisting of type of cement, i.e., Type III and Type I/II, and size and type of coarse aggregate, i.e., limestone and river gravel are used for the SCC performance investigation. Testing methods include slump flow, Visual Stability Index (VSI), J-ring, column segregation and compressive strength. The testing results showed that the type, shape and size of coarse aggregate have a dominant effect in terms of fresh properties and compressive strength; specifically, mixtures having river gravel showed larger spreads that mixtures with crushed limestone; and mixtures using cement Type III developed higher early strength as expected in comparison to cement Type I/II.

Keywords:

Self-Consolidating Concrete, Prestressed concrete bridge girders, Experimental program, Material constituents; Fresh and hardened properties

1. Introduction

Self-Consolidating Concrete (SCC) has been called a “smart concrete” (Shamsad et al. 2014) because it can effortlessly flow through congested reinforcing bars with no vibration mechanism. SCC has expanded through Europe and the United States where it has been used in several cast in-place and precast applications. Several State Departments of Transportation (DOTs) have developed guidelines for the use of SCC through extensive research vis-à-vis materials, mixture design and fresh and hardened properties. SCC has been also utilized for PSC girders because of its unique benefits, such as reduction of labor and construction time, elimination of vibration mechanisms and noise hazards, and simplification of the placing process (Skarendahl 2003, Naik et al. 2012, Hemalatha et al. 2015, and Royce et al. 2015). SCC mixture consists of higher paste and lower coarse aggregate volumes compared to conventional concrete (CC) (Ghezal and Khayat 2002). Differences in the mixture proportions between SCC and CC can result in different fresh and hardened properties and associated structural performance of PSC bridge girders.

To develop guidelines for the use of SCC through extensive research vis-à-vis materials, mixture design and fresh and hardened properties and the application of SCC on PSC bridge girders, research has been conducted by the following agencies: the National Cooperative Highway Research Program (NCHRP), Precast/Prestressed Concrete Institute (PCI), and State Departments of Transportation (DOTs). The NCHRP presented findings regarding SCC mixture parameters, fresh and hardened properties for the use of SCC in prestressed structural components (Khayat and Mitchell 2009). The PCI also reported recommendations on SCC mixture constituents and guidelines for production, quality control, placing and finishing of SCC PSC girders (PCI 2003). Several DOTs have performed state-level research projects on SCC to establish their own state guidelines for the implementation of SCC using local aggregates available in their region. For example, Texas DOT reported that SCC has more adequate workability, excellent stability, higher compressive strength, and similar creep values relative to CC (Trejo et al. 2004). Besides, Florida DOT provided valuable findings regarding the structural performance of SCC PSC bridge girders (Labonte and Hamilton 2005). It was found that there were no notable differences between SCC and CC prestressed bridge girders in terms of prestress transfer length, mean camber growth, flexural capacity, shear capacity, and web cracking.

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

Although many national transportation agencies have developed guidelines related to SCC mixture development for PSC bridge girders, SCC producers still struggle at maintaining uniformity in terms of fresh and hardened properties with minimal segregation in the SCC mixture when transporting and placing of SCC. In detail, SCC with lack of segregation resistance can result in poor workability and performance of SCC by internal and external bleeding of water, differential accumulation of light ingredients, and settling of aggregate at the bottom (Bonen and Shah 2004). To that end, this study is intended to experimentally and statistically evaluate fresh and hardened properties of 28 different SCC mixtures within an appropriate mixture design setting for different precast Plants. This paper is divided into four sections: the next section deals with the background for SCC characteristics. The subsequent section provides an overview of the proposed experimental program to evaluate fresh and hardened properties for the SCC mixtures. Then, experimental and statistical results along with related discussion are presented. The final section gives a summary and conclusions along with highlights for future work.

2. Background

SCC typically consists of cement, water, aggregates, and chemical admixtures. SCC has higher amount of cement and less aggregate volume compared to CC. Due to the higher amount of cement, SCC tends to be more expensive than CC; thus, many precasters often replace cement content with mineral admixtures to reduce costs and maintain satisfactory workability and strength. Information on effects of individual constituents on SCC workability and strength that were found from the literature review is included in the following subsections.

2.1 Cement

Cement type is a key part of the SCC mixture constituents to achieve desired workability and strength for PSC bridge girder fabrication. Cement Type III and a combination of cement Type I/II have been commonly used for SCC bridge applications (Khayat and Mitchell 2009). Cement Type III is used when higher early strength is needed, although cement Type III tends to have higher water and High Range Water Reducer (HRWR) demands. On the other hand, cement Type I/II has shown to have longer durability and more consistency (Khayat and Mitchell 2009). Several studies (Burgueno et al. 2007, Trejo et al. 2008, Khayat and Mitchell 2009) have been performed to investigate SCC compressive strength and compare its strength against that of CC. For example, Burgueno et al. (2007) found that the compressive strength of SCC made with cement Type III showed higher strength than that made with CC, indicating cement content, w/c and coarse aggregate have the higher influence on the compressive strength.

2.2 Aggregates

Coarse aggregate has a significant influence on the workability and strength of SCC. The maximum size of the aggregate (MSA) should be selected depending on the minimum space between reinforcing bars (Sonebi et al. 2007). For example, SCC Specifications provided by the Virginia DOT state that the coarse aggregate size should not exceed 19mm, not be less than 1/5 of the narrowest dimension between the sides of the forms, and not less than 19mm of minimum clear spacing between bars (Torres and Seo, 2016). Long et al. (2014) in the research project performed by the NCHRP suggests that the coarse aggregate should be between 19mm and 9.5mm, while the EFNARC suggests that the MSA should be between 12mm and 20mm. Meanwhile, the type and size of aggregate have an impact on the strength of SCC. Trejo et al. (2008) and Khaleel et al. (2011) found that mixtures using crushed limestone developed higher strength than those containing crushed or uncrushed gravel and that the mixtures with coarse aggregate with a MSA of 10mm had higher compressive strength compared to those with a MSA of larger than 10mm.

2.3 Chemical Admixtures

Admixtures are used to obtain acceptable SCC performance based upon physical and chemical properties of the cement type (EFNARC 2005). Admixtures are able to reduce water content, improve deformability and stability, increase air content, accelerate strength development and retard setting time (Khayat and Mitchell 2009). The most common admixtures used for SCC are High Range Water Reducer (HRWR) and viscosity modifying admixtures (VMA). The addition of these admixtures depends upon SCC mixture parameters, such as w/c and binder type. For example, HRWR can be added in small amounts to freshly mixed SCC to improve its workability for a short period of approximately 30min. HRWR can be also added to mixtures with low w/c to obtain higher fluidity and higher strength. VMA can be used to increase the viscosity of the mixture to control segregation (Turkel et al 2010). According to the NCHRP report (Khayat and Mitchell 2009), VMA should be used for mixtures with less than 425kg/m3, or mixtures with w/c values greater than 0.40.

2.4 Fillers

Fillers also known as mineral admixtures can be added to improve workability, while reducing the amount of cementitious materials required for the mixture design. Benefits from the use of fillers in SCC applications include the following: 1) increase in early compressive strength, bleeding control, and viscosity 2) improve workability; and 3) reduce porosity (Shamsad et al. 2014). Fillers commonly used for SCC production include fly ash, ground granulated blast-furnace slag, silica fume, and limestone powder (Torres and Seo 2016). Suggested percentages of replacement of cement are listed in Table 1.

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

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

*Note: the presence of * indicates classes of fly ashes, including C, D, and F. Replacement percentage ranges are identical for Fly Ash regardless of the class.*

3. Experimental Program

Investigating how to obtain the desired workability and strength for implementing SCC in PSC girders is critical, and there is limited information (Mata et al. 2004 and Wehbe et al. 2009) on the impact of aggregate and binder types on them; thus, an experimental program accounting for various SCC mixture parameters is established herein. The following subsections describe material testing methods, testing matrix, fresh property criteria, and mixing and curing procedures in part of the experimental program.

3.1 Material Testing Methods

Material testing methods that have been commonly used for the evaluation of fresh and hardened properties of SCC are used for this study. The American Society of the International Association for Testing and Materials (ASTM) has developed guidelines to evaluate workability and performance of SCC mixtures. As mentioned earlier, the NCHRP, EFNARC and PCI provide technical descriptions for material testing methods. Table 2 summarizes such testing methods and corresponding guidelines. Note that the workability of SCC is evaluated in terms of flowing ability, passing ability, and segregation, while the performance of SCC is evaluated through compressive strength.

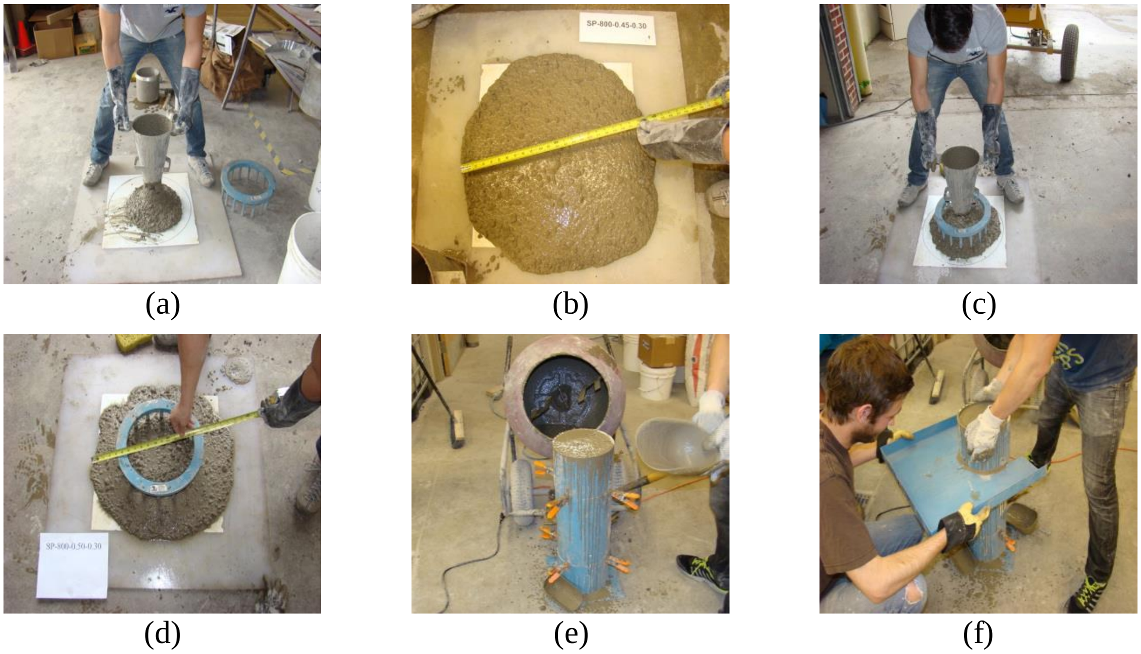
Table 2. SCC test methods with corresponding guidelines

Test Methods	Properties	Guidelines
Slump Flow	Filling Ability	ASTM C 1611/PCI/EFNARC
J-Ring	Passing Ability	ASTM C 1621/ PCI/EFNARC
Column Segregation	Segregation Resistance	ASTM C 1610/ PCI/EFNARC
Compressive Strength		ASTM C39

The slump flow test is one of the most well-known methods for determining the free flow ability of SCC mixtures. This test is frequently used in field work for the evaluation of the consistency of flow ability for target mixtures. The ASTM C1611 provides step-by-step guidance to perform the test. Fig. 1 (a) and (b) show photographs for slump flow setup and testing that were done for this study. A regular cone is placed in an upright position on a plate in the center of the board. The cone is filled with the SCC mixture, and then it is pulled up in approximately 3 seconds in Fig. 1(a) allowing the mixture to flow. Once the concrete stops flowing, the diameter is measured at two different orthogonal directions Fig. 1(b). The ASTM C1611 documentation recommends the SCC diameter to range between 533 mm and 737 mm. Meanwhile, Khayat et al. (2009) suggests that the slump spread diameter of SCC for prestressed elements be ranged from 597mm to 737 mm. The spread diameter is not only the parameter to be measured, but also the T_{50} and visual stability index (VSI) can be obtained from the slump test. T_{50} is defined as the time it takes the concrete to flow and reach the 508 mm mark. T_{50} values provide information on the flow properties where longer values correspond to high viscosity. VSI is a visual inspection of the concrete to qualitatively assess the stability of the concrete. VSI is ranked from 0-3 according to the presence of bleeding or segregation (ASTM 2011a).

The passing ability of freshly mixed SCC can be evaluated using J-Ring test. Passing ability is most influenced by the MSA as it can cause blockage between the reinforcing bars of the ring. The J-Ring test procedure is similar to that of the slump flow explained previously. The J-Ring is placed around the cone, and the SCC passes through the legs of the open circular steel ring as seen in Fig. 1(c) and (d). The average of two orthogonal diameters is recorded and compared to those from the slump flow testing. If the difference is less than 25.4 mm according to the ASTM C 1621, it means a good passing ability. If the difference is above 50.8 mm, it indicates poor passing ability. The height difference between the concrete inside the ring and concrete outside the ring can also be used to evaluate the passing ability, but it is not specified by the ASTM C 1621 (ASTM 2011b).

Column segregation test is used to determine the segregation of SCC mixtures. According to the ASTM C 1610, the SCC mixture is poured into the cylinder within 2 minutes Fig. 1(e). The SCC mixture was let to rest for 15 minutes without any disturbance. Then, the SCC at the top and bottom segments of the cylinder were collected and placed in different containers as shown in Fig. 1(f). The SCC mixtures from the top and bottom segments were washed to discard any particles passing the No. 4 sieve. The weight of the aggregate retained on the No. 4 sieve was recorded for both top and bottom segment, respectively. The column segregation is expressed as the percentage ratio difference of aggregate mass between the bottom and top segments to the total aggregate mass in the two segments (ASTM 2011c).



(a) (b) (c)

(d) (e) (f)

Fig. 1. Workability test methods: (a) Slump flow setup, (b) Slump spread diameter measurement, (c) J-Ring setup, (d) J-Ring spread diameter measurement, (e) Column segregation set up, (f) Collecting top section of cylinder

3.2 Strength Testing

Compressive strength of SCC mixtures was tested according to the ASTM C39 using SCC cylinders of 304.8 mm x 152.5 mm as shown in Fig. 2. Fig. 2(a) shows a picture where a cylinder of the SCC mixtures is caped with a sulfur cap to ensure that compressive loads are uniformly distributed on the surface. Fig. 2(b) displays a cylinder that was fractured after 14 hours of curing necessary for PSC application. It is worthwhile to note that the compressive load rate was 0.23 MPa/sec following the ASTM C39 (ASTM 2011d) until the cylinder failure occurred.

a) Sulfur cap top/bottom of cylinder **b)** Diagonal crack of cylinder

Fig. 2. Compressive strength test

3.3 Fresh and Hardened Property Requirements

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

Table 3. DOT requirements for fresh properties test methods (Torres and Seo 2016)

State	Slump Flow (mm)	J-Ring (mm)	VSI	Column Segregation (%)
Alabama	635 - 736.6	±76.2	0-1	N/A
Florida	685.8 ± 63.5	±50.8	0-1	Max 15%
Georgia*	Min 508	N/A	N/A	N/A
Illinois*	508-711.2	Max 101.6	0-1	Max 15%
Iowa	Max 685.8	N/A	N/A	N/A
Kentucky*	Provide Spread Limits, Production Records and Quality Control Procedures.			
Louisiana	508 -711.2	Provide Aggregate Gradations		
Michigan	685.8 ± 25.4	±15.24	0-1	N/A
Minnesota	Max 711.2	±50.8	0-1	N/A
Nebraska	ASTM C1611	N/A	ASTM C1611	N/A
Nevada*	No specific guidelines.			
New York*	±50.8 Target	±50.8	0-1	Max 15%
North Carolina	609.6 - 762	±50.8	N/A	N/A
Ohio	685.8 ± 50.8	N/A	N/A	N/A
Pennsylvania*	508 - 762	±50.8	0-1	N/A
Rhode Island	508 -660.4	±50.8	N/A	N/A
South Carolina	Precasters in the state are hesitant in using SCC.			
South Dakota	508 – 711.2	±50.8	0-1	N/A
Texas*	558.8 – 685.8	±50.8	0-1	Max 10%
Utah	457.2 – 812.8	±25.4	0-1	Max 10%
Virginia	660.4 ± 76.2	±50.8	0-1	Max 15%
Washington	± 50.8 Target	±38.1	0-1	Max 10%

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

3.4 Target Values

Workability of SCC mixtures can be evaluated through acceptable ranges obtained from the ASTM/PCI test method guidelines. The DOT survey results can be also used to determine specific target values for each test method. If SCC mixtures do not meet the workability criteria shown in Table 4, it is necessary to adjust parameters of the SCC mixture design. For instance, by adjusting the dosage of admixtures, viscosity and flow ability of the mixture can be improved without modification of other mixture parameters. By decreasing the size of the coarse aggregate, the passing ability can be improved and segregation of the mixture will decrease. For compressive strength, the target values for 14hr and 28 days are also shown in Table 4. The target compressive strength values are the highest used by the Wisconsin DOT PSC girders to avoid concrete crushing due to the prestress force induced to the girder.

Table 4. Target values for specific test methods

Evaluation Table for Fresh Properties		
Fresh Properties Tests	**Acceptable Range**	**Target Value**
Slump Flow	558.8 mm – 711.2 mm	635 mm
J-Ring	max 50.8mm	max 50.8mm
Column Segregation	≤ 15 %	Close to 10 %
T_{50}	3-10 sec	<6 sec
VSI	≤ 1	≤ 1
Compressive Tests	**Target strength**	
Strength	46.88 MPa (14 hours) 55.15Pa (28 days)	

3.5 Testing Matrix

A testing matrix for SCC mixtures to be evaluated in terms of workability and strength according to the predetermined target values was created considering cement type, aggregate type and size, and blending configuration. Two types of cement, including cement Type III and a combination of cement Type I/II, were used. Two types of coarse aggregate were selected, including crushed limestone and rounded river gravel, as they are widely used in the Wisconsin precast concrete industry. Note that three different providers of coarse aggregate were selected from different regions in Wisconsin. The aggregate size used was 19mm and 9.5mm as recommended by the NCHRP report (Khayat et al. 2009). To improve workability of the mixtures, however, several blending configurations combining both the sizes were included in the test matrix to study their impact on the workability performance, while maintaining satisfactory strength. The blending configuration was established using intervals of 20% from 100% to 0% of 19mm combined with 9.5mm.

Table 5 presents 28 mixtures that can be divided into three groups in terms of precast Plants to systematically evaluate the influence of binder type, type and size of coarse aggregate, w/c and S/Agg. Each group of mixtures is named as Plant A, Plant B, and Plant C: Plant A having cement Type III with crushed limestone; Plant B having cement Type I/II with crushed limestone, and Plant C having cement Type III with river gravel. In detail, Plant A cement had a specific gravity of 3.15. The specific gravity of the coarse aggregate was 2.66 and a percent absorption of 1.52%. Fine aggregates had a specific gravity of 2.65 and percent absorption of 0.59%. Plant B cement type had a specific gravity of 3.14. Plant B used crushed limestone from a different pit than Plant A. The coarse aggregate had a specific gravity of 2.59 and percent absorption of 2.64. The fine aggregate had a specific gravity of 2.65 and percent absorption of 0.69%. Plant C cement had a specific gravity of 3.15. The coarse aggregates had a specific gravity of 2.77 and the fine aggregates had a specific gravity of 2.76. The cement content was fixed at 362 kg/m3, to ensure a higher compressive strength needed for prestress bridge girders. It should be noted that the mixtures had only cement as cementitious materials as the use of filler was not part of the testing. Referring to Table 6, details for the mixture designs are presented. To facilitate the interpretation of the data in both Tables 5 and 6, there is a letter next to the mixture number which is the letter A, B and C that was included to denote which Plant each mixture belongs.

Table 5. Parametric testing matrix

Agg. Type	Mixture No	Aggregate Size (9.5mm)						Cement Type		w/c		S/Agg	
		100%	80%	60%	40%	20%	0%	Type III	Type I/II	0.35	0.33	0.50	0.45
Crushed Limestone	1A	X						X		X		X	
	2A	X						X		X			X
	3A		X					X		X		X	
	4A			X				X		X		X	
	5A			X				X		X			X
	6A				X			X		X		X	
	7A				X			X		X			X
	8A					X		X		X		X	
	9A					X		X		X			X
	10A						X	X		X		X	
	11A						X	X		X			X
	12B	X							X	X		X	
	13B		X						X	X		X	
	14B			X					X	X		X	
	15B				X				X	X		X	
	16B				X				X		X	X	
	17B				X				X		X		X
	18B					X			X	X		X	
	19B					X			X		X		X
	20B					X			X		X	X	
	21B						X		X	X		X	
Round Gravel	22C				X			X		X		X	
	23C				X			X		X			X
	24C				X			X		X			X
	25C					X		X		X		X	
	26C						X	X		X			X
	27C						X	X		X			X
	28C						X	X			X	X	

Note: X indicates inclusion of the specific mixture parameter per a SCC mixture.

Table 6. Composition for selected SCC mixtures

Mixture No	Water Kg/m^3	Cement Kg/m^3	Coarse Aggregate Kg/m^3		Fine Aggregate Kg/m^3	HRWR L/m^3	VMA L/m^3
			9.5mm	19mm			
1A	127	474	839	0	832	1.18	0.24
2A	127	474	992	0	807	1.18	0.47
3A	127	474	671	168	832	1.42	0.47
4A	127	474	503	335	832	1.18	0.00
5A	127	474	607	397	807	1.18	0.24
6A	127	474	335	503	832	1.30	0.71
7A	119	474	397	612	826	1.42	0.54
8A	127	474	168	671	832	1.42	0.24
9A	127	474	198	793	807	1.66	0.35
10A	127	474	0	839	832	1.42	0.24
11A	127	474	0	992	807	1.18	0
12B	127	474	861	0	832	1.18	0
13B	127	474	689	172	832	1.42	0
14B	127	474	516	343	832	1.18	0.24
15B	127	474	343	516	832	1.18	0.24
16B	127	474	343	516	832	1.42	0.35
17B	127	474	343	516	807	1.18	0.35
18B	127	474	172	689	832	1.18	0.24
19B	127	474	172	689	807	1.42	0.47
20B	127	474	172	689	832	1.18	0.35
21B	127	474	0	861	832	1.18	0.47
22C	127	474	374	562	935	1.42	0.47
23C	127	474	412	523	841	0.95	0.47
24C	119	444	421	532	861	1.42	0
25C	127	474	187	749	935	1.42	0
26C	119	444	0	1050	861	1.66	0.47
27C	127	474	0	1032	841	1.66	0.47
28C	127	474	0	936	935	2.13	0.24

3.6 Mixing and Curing Procedures

All the SCC mixtures were made in batches of five cubic feet using a drum mixer. Mixing procedure was consistent for every mixture according to the procedure provided by Portland Cement Association (PCA 2005). Sand, coarse aggregate and cement were placed in the drum and let to be mixed for 30 seconds, and then the water was slowly added to the mix ensuring equal distribution. After 1 minute of mixing the admixtures were added to the mix. It was specified by the admixture provider to not combine admixtures with the water. Once the admixtures were added, the concrete was remixed for 8 minutes. 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 min at the complete stage of each mixing. A certain testing time window is required to ensure that the admixtures consistently affect each mixture. For each mixture, compressive strength was tested at 16 hours to simulate time of curing used at prestressed Plants before strands release. To simulate steam curing, a water bath was used as seen in Fig. 3. Cylinders were placed in the water bath for 16 hours at a temperature of 43.3°C applicable to the curing regimen of the Plants.

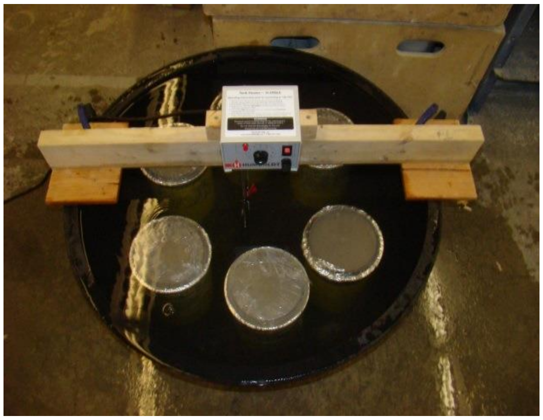


Fig. 3. Water bath to simulate steam curing.

4. Results and Discussion

4.1 Fresh Properties

The overall fresh properties of the SCC mixtures were evaluated by comparing the test results against the target values that were determined based upon inputs from the survey and literature review. The resulting fresh properties for each mixture, including slump flow, J-Ring, passing ability, filling capacity, T50, column segregation, are summarized in Table 7. Note that the results of the compressive strength are also included in the table and some tests such as column segregation were not performed for all the mixtures due to limited availability of materials. The current tabulated dataset was able to reasonably examine the effect of SCC mixture constituents on the fresh properties of SCC.

Table 7. SCC fresh Property and compressive strength results

Mixture No	Slump Flow, mm	J-Ring, mm	Passing Ability, mm	Filling Capacity %	VSI	T$_{50}$, s	Column Segregation %	Compressive Strength, MPa	
								14 hr	**28 days**
1A	610	622	12	84,8	0	9.4	2.7	44.42	82.73
2A	610	-	-	-	0	7.4	-	41.00	-
3A	603	610	0	83,1	0	5.3	6.3	48.45	81.87
4A	622	610	12	83,7	0.5	12.0	6.4	46.58	76.23
5A	622	-	-	-	0.5	8.5	-	44.71	-
6A	629	622	7	85,7	1	3.9	2.8	47.98	70.08
7A	629	610	19	84,0	1	5.2	4.7	49.20	68.10
8A	578	635	57	85,0	0	10.6	9.1	58.14	-
9A	641	622	19	86,3	1	4.8	4.2	48.60	65.00
10A	635	610	25	84,3	1	4.6	6.3	48.22	63.72
11A	584	622	0	85,4	0	7.3	10.1	49.94	68.32
12B	622	571	51	78,2	0	6.3	1.6	36.00	55.59
13B	660	622	38	87,3	1	7.1	3.3	38.06	60.13
14B	622	597	25	81,9	0	9.3	5.1	42.66	62.39
15B	643	622	21	86,4	1	13.6	8.0	48.25	-
16B	629	597	32	82,2	0.5	3.4	2.0	49.05	60.33
17B	625	603	22	82,9	0	3.6	10.1	47.98	71.66
18B	622	597	25	81,9	0	8.2	9.5	40.81	-
19B	635	597	38	82,5	0.5	5.9	-	46.11	-
20B	622	610	12	83,7	0	4.8	9.9	49.29	68.91
21B	660	616	44	86,4	1	5.7	11.8	40.47	67.08
22C	667	635	19	83,5	1	6.1	5.1	46.45	57.28
23C	641	603	38	83,7	1	5.8	3.4	47.73	61.58
24C	622	565	57	77,4	0	5.3	2.2	46.26	58.72
25C	667	622	45	87,6	1	3.1	9.9	47.31	62.58
26C	610	571	39	77,6	0	2.5	4.7	34.77	46.38
27C	610	597	13	82,1	0	3.4	3.1	37.59	46.98
28C	610	603	7	84,8	0	4.0	12.2	41.22	49.17

Note: the presence of - in a field indicates that it is placed when the test method was not performed for the mixture.

The slump flow spread diameter ranged from 578 to 635mm for Plant A, 622 to 660mm for Plant B, and 610 to 667mm for Plant C. Though the slump flow values are consistent for all the mixtures, it can be observed that the mixtures from Plant C (i.e., 22C to 28C) using round gravels have higher spread diameter than those from Plants A and B. This behavior can be attributed to the smoother surface of the gravel aggregate facilitating movement. Minor difference was observed when comparing the effect of cement Type III (Plant A) with cement Type I/II (Plant B) in terms of slump flow values. Recall that the target value for slump flow was 635mm as stated on Table 4. To study the effect of blending configurations on slump flow, S/Agg was fixed at 0.5 and w/c at 0.35. The dosage of admixtures was slightly modified to have a stable mixture. Fig. 4 shows that the size of the coarse aggregate had an impact on the slump flow results. Mixtures containing 40% of 9.5mm (5A, 15B and 22C) showed consistently larger spread diameters than the target value of 635mm. This can be attributed to the fact that as the percentage of 9.5mm increased the mixture had higher viscosity, while as the percentage of 19mm increased less movement of particles was observed due to larger particle size.

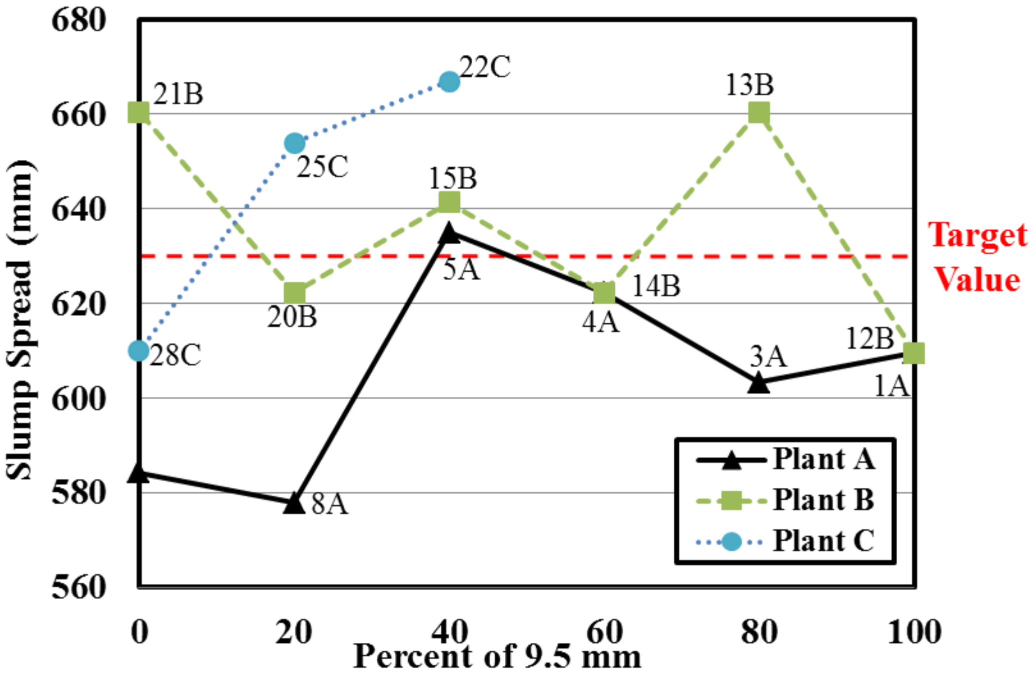


Fig. 4. Slump flow spread diameter results with w/c 0.35

J-Ring spread diameters with varying blending configuration are shown in Fig. 5. Similar to slump flow results, the values of S/Agg and w/c were fixed at 0.50 and 0.35, respectively. While the results for Plants A and B do not show the effects of change in blending, for Plant C the spread diameters increase as the blending percent of 9.5mm increases. The J-Ring values were used to determine the passing ability and filling capacity of the SCC mixtures. The ASTM C1621 describes (ASTM 2011b) the definition of passing ability as the difference between the spread diameter of J-Ring and slump flow. As stated before, the survey from the state DOTs that were contacted and the ASTM have established the target value of passing ability of ± 51mm. Mixtures 8A, 12B and 24C exceeded the target value as shown in Table 6. As shown in Fig. 6a for the passing ability trend of each plant against the respective blending configuration, it was observed that the mixtures representing Plant B made of cement Type I/II exhibited the best results compared to Plants A and C with cement Type III. This observation was expected as cement Type I/II tends to develop better workability than cement Type III due to lower water consumption.

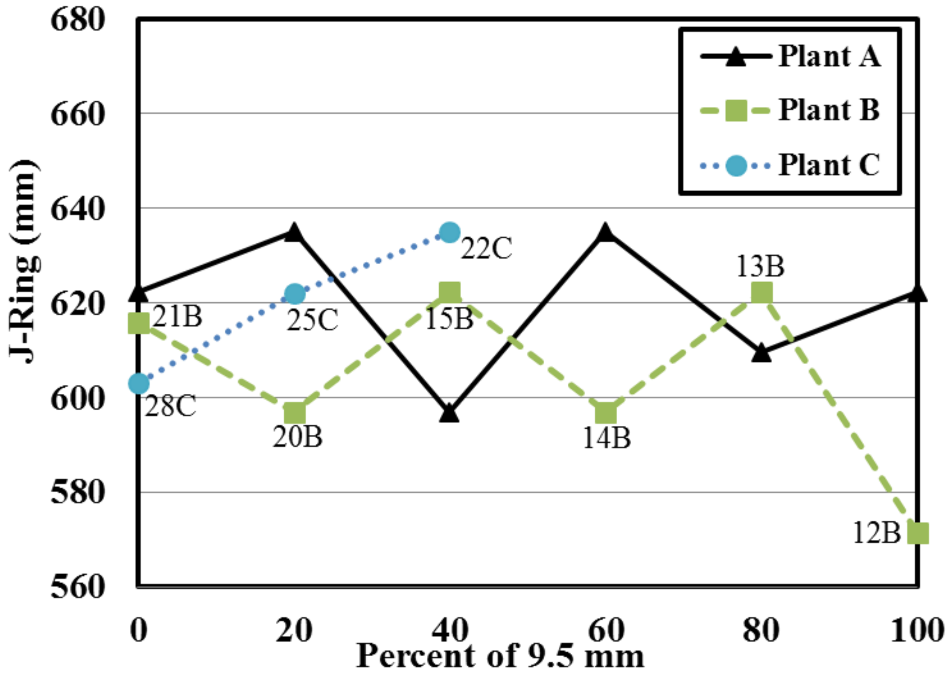


Fig. 5. J-Ring spread diameters

The filling capacity of all the mixtures was assessed using the value recommended in the previous publication (Long et al. 2014; Khayat and Mitchell 2009) for SCC mixtures, indicating that the filling capacity values are considered acceptable if they are equal to or larger than 80%. As seen on Fig. 6 (b) and Table 7, most mixtures meet the filling capacity requirements, with the exception of Mixtures 12B, 24C and 26C. Overall, higher values of filling capacity were observed by the mixtures in Plants A and B made of crushed limestone compared to the rounded gravel mixtures in Plant C. However, it should be noted that Mixtures 12B, 24C, and 26C had large difference in spread diameters between slump flow and J-Ring, causing their lower filling capacities. This is because these mixtures had higher percentage of 19mm coarse aggregate, resulting higher blockage.

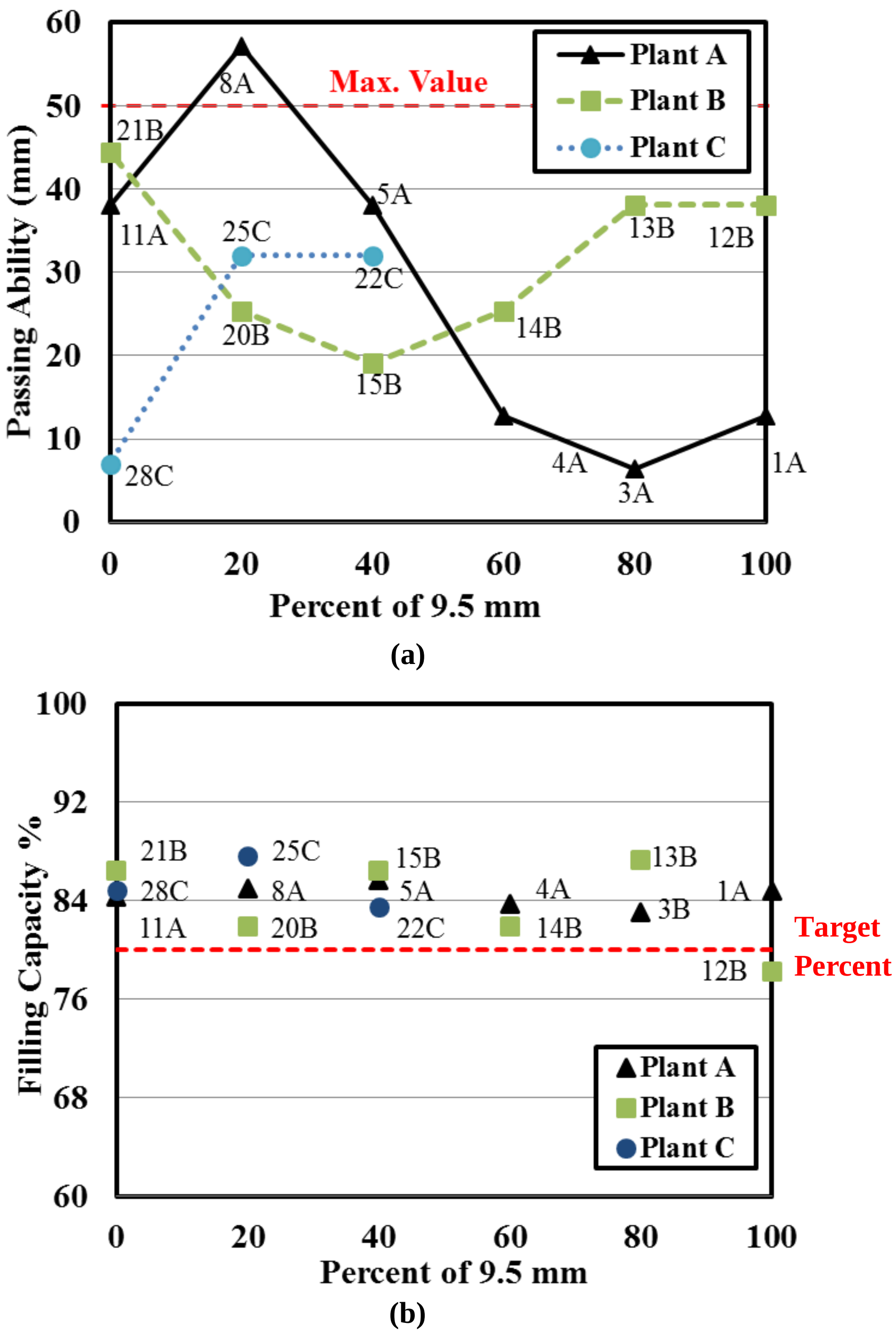
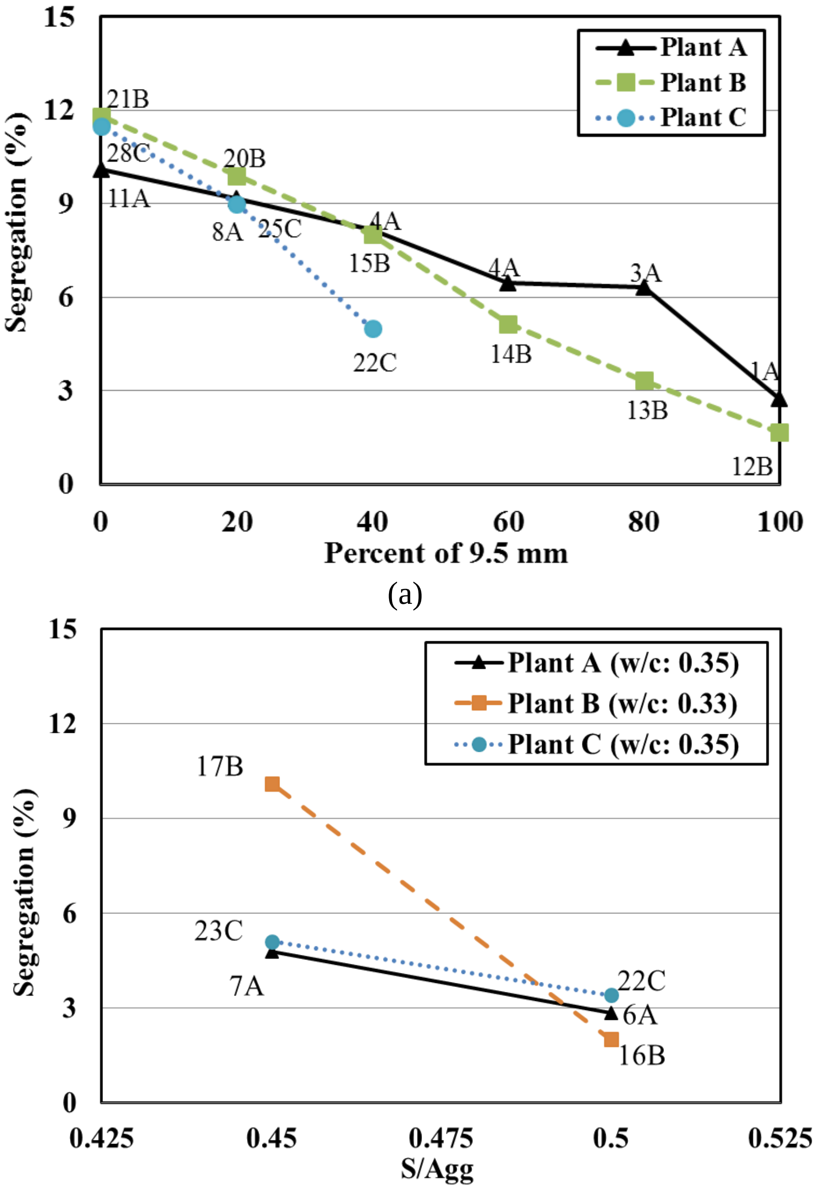


Fig. 6. Workability assessment a) passing ability and b) filling capacity

T50 values for all the mixtures (see Table 7), excluding Mixtures 4A, 8A, and 15B were within the acceptable ranges listed in Table 4. Generally, there were little noticeable trends in terms of T50 due to variation of certain mixture parameters studied. Meanwhile, segregation resistance was investigated using the column segregation test. The cement and aggregate type did not have a significant influence on the segregation resistance of the mixtures. However, it should be mentioned that from the perspective of the coarse aggregate size, it was clear that as the percent of 9.5mm decreases, segregation (%) increases, leading to lesser segregation resistance as shown in Fig. 7(a). This is attributed to the fact that the weight of the aggregate increases and a higher settlement rate occurs. All the mixtures (see Table 7) were less than the segregation limit of 15% pre-established. A pair of specific mixtures per Plant was selected to study the effects of S/Agg in terms of percent segregation of the mixtures. Mixtures included are 6A, 7A, 16B, 17B, 22C, 23C having blending configuration fixed at 40% of 9.5mm aggregate and a w/c of 0.35 for Plant A and C and 0.33 for Plant B. As shown in Fig. 7(b), to compare the percent segregation as the S/Agg changes from 0.45 to 0.50. It was observed that the segregation increases as S/Agg reduces from 0.50 to 0.45. This behavior was expected as the higher amount of fine aggregates is directly related to the viscosity of the mixture.



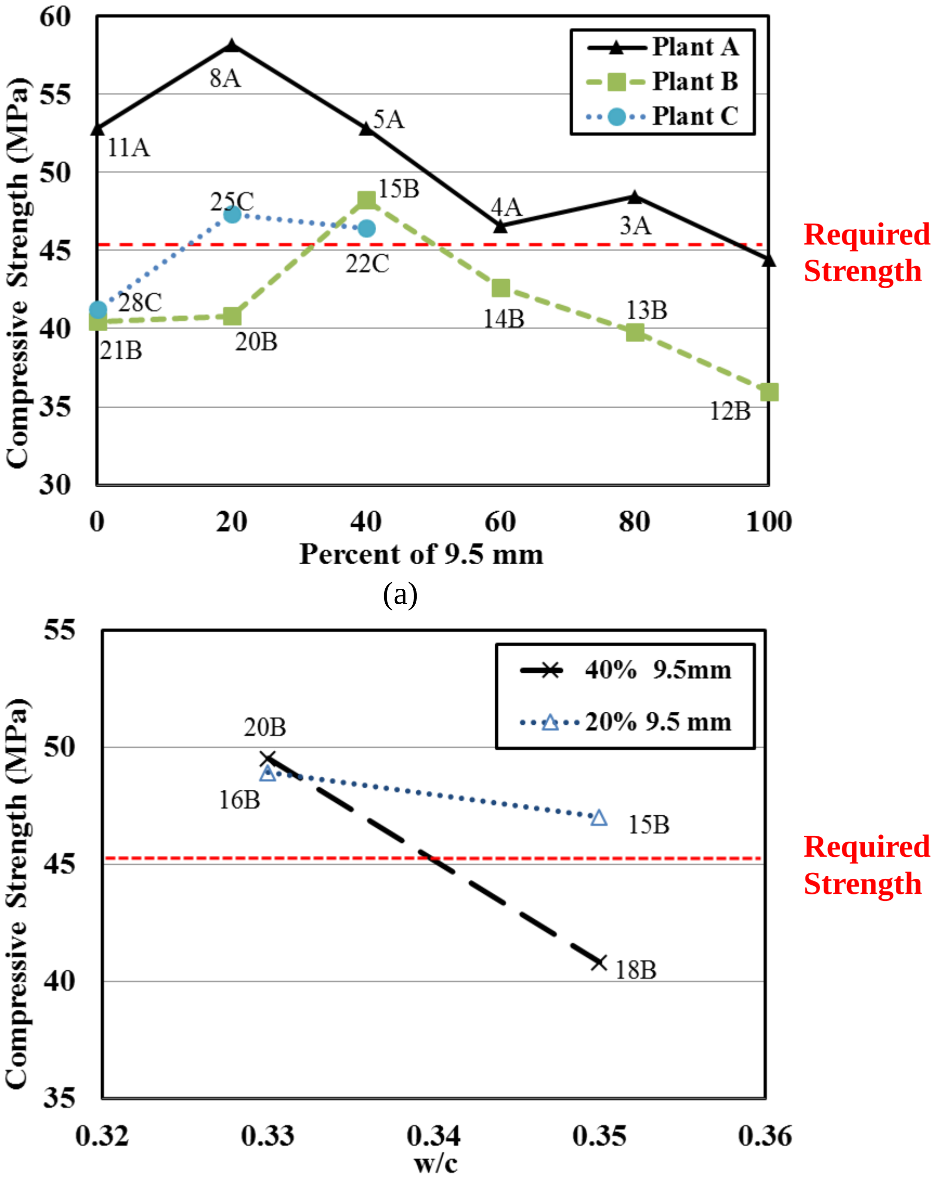
(a)

(b)

Fig. 7. Percent segregation analysis: a) Column Segregation Results based on blending configurations, b) Representative Percent Segregation for S/Agg 0.45-0.50 of mixtures having 40% 9.5mm aggregate.

4.2 Compressive Strength

Compressive strength of all the mixtures at 16 hours for Plant A are higher than those from Plant B and C. Note that the mixtures of Plant C made of rounded river gravel and cement Type III developed lower compressive strength than those from Plant A using cement Type III and limestone. This can be attributed to the smooth surface of the rounded gravel, resulting in weak interfacial transition zone. Fig. 8(a) shows the compressive strength results for 16 hours of Plants A, B, and C with w/c of 0.35 and S/Agg of 0.50. It appears that as the percent of 9.5mm coarse aggregate ranged from 100% to 40% decreases, the compressive strength of Plants A and B mixtures tend to increase. Compressive strengths of Plant A mixtures range from 41.0 MPa to 58.1 MPa, the values are larger than those from Plant B (36.0 – 49.3MPa) and Plant C (37.6 – 47.7 MPa). Fig. 8(b) illustrates the compressive strength for Plant B mixtures 15B, 16B, 18B and 20B with w/c of either 0.33 or 0.35 that were selected to explore the effect of w/c on the strength. It appears that as the w/c ratio increases the compressive strength decreases. However, the decrease in strength is more abrupt for the mixtures (18B and 20B) using 20% of 9.5mm (see Fig. 8b). From the results, it can be inferred that for SCC mixtures using cement Type I/II the w/c ratio may be less than 0.35 to meet the required strength showed in Table 4 for SCC PSC girder fabrication. It should be noted that the testing matrix for cement Type III mixtures do not have variability in w/c ratios.



(a)

(b)

Fig. 8. Compressive Strength at Transfer: a) Compressive strength for blending configurations, b) Compressive strength for Plant B using 0.33 and 0.35 w/c.

The compressive strength for all the mixtures at 28 days was above 49 MPa (required strength) as shown in Fig. 9. Similar to the results for 16hr strength, Plant A had the higher strength than those for Plants B and C. It appears that 28 day compressive strength for Plant A is almost proportional to the percent of 9.5mm. Note that the behavior of strength development is the opposite to what occurred for strength at 16 hours when compared to the percent of 9.5 mm. For Plant B, this figure shows that the compressive strength decreases as the percent of 9.5mm aggregate increases. The trend of Plant B appears to be similar to that of the 16 hour strength. At 0% and 20% of 9.5 mm, the compressive strength of both Plant A and B were similar, whereas for 40% to 100% of 9.5mm, the difference in strength between Plants A and B increased. Plant C has the lower 28 day compressive strength relative to the other Plants and the difference in strength can be attributed to the aggregate type.

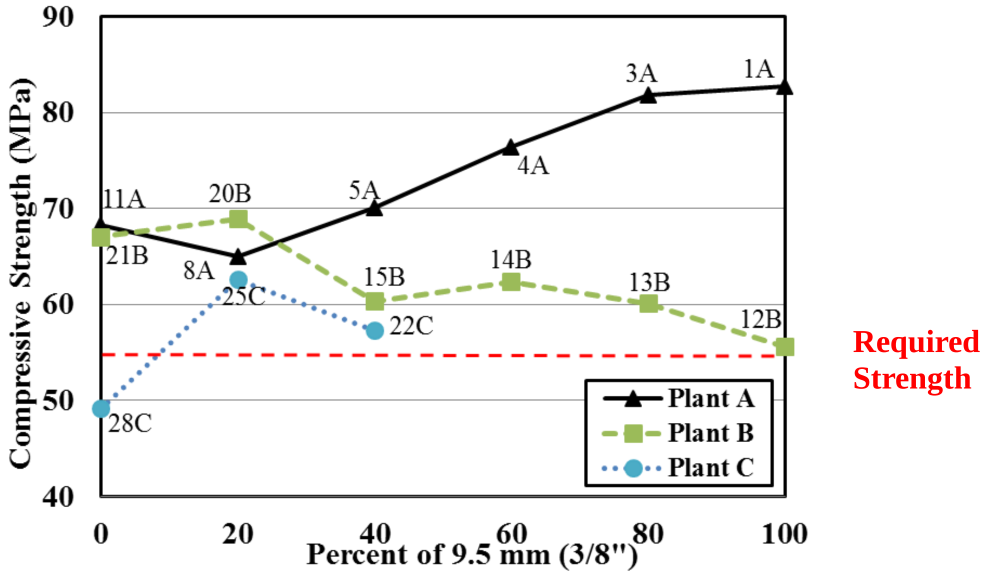


Fig. 9. Compressive strength at 28 days

5. Statistical Results

A multi-variable regression model was created and simulated to statistically determine the significant mixture constituents on the tested mixture fresh and hardened properties (e.g., slump flow). Five mixture constituent variables were considered in the statistical model including: percent of 9.5 mm coarse aggregate, percent of 19 mm coarse aggregate, content of fine aggregate and dosages of HRWR and VMA. The standard level of significance was set at α = 0.05 and intercept to be zero for this analysis.

Table 8 shows the resulting P-value of each mixture constituent variable with respect to the fresh and hardened properties. Based on the investigation of the p-values, it was found that fine aggregate was the most significant variable affecting all the fresh and hardened properties for all the mixtures and that the content of 9.5mm aggregate has a significant effect on segregation. The reason why the content of fine aggregate considered statistically significant is that it has a direct impact on the viscosity of the mixture, resulting in the substantial change of slump flow, J-Ring, and segregation.

Table 8. P-values obtained from the regression statistical analysis to evaluate fresh and hardened properties of SCC.

Parameter	Slump Flow	J-Ring	Column Segregation	Compressive Strength (16 hours)	Compressive Strength (28 Days)
Coarse Aggregate (9.5 mm)	0.227	0.352	0.008	0.830	0.653
Coarse Aggregate (19 mm)	0.280	0.378	0.062	0.965	0.937
Fine Aggregate	$3.8\text{x}10^{-9}$	$3.1\text{x}10^{-6}$	0.001	0.001	0.026
HRWR	0.052	0.171	0.282	0.193	0.118
VMA	0.278	0.273	0.307	0.528	0.394

6. Summary and Conclusions

The paper was to investigate the effect of material constituents on fresh and hardened properties of SCC mixtures, in order for better fabrication of SCC PSC girders. To that end, an experimental program considering different material constituents and methods along with target values obtained from the survey and literature review was developed. The material constituents consist of type of cement and size and type of coarse aggregate, and testing methods include slump flow, VSI, J-ring, column segregation and compressive strength. Experimental and statistical comparisons of the fresh and hardened properties among SCC mixtures made with different material constituents per plant located in a different area was performed. The following conclusions are drawn based on the experimental and statistical results:

1) Slump flow spread diameter results showed that the Plant C mixtures obtained larger spread diameters due to the rounded shape of the river gravel, resulting in less blockage compared to the flaky and angular shape of the crushed limestone used in Plant A and B. Plants B and C exhibited slump flow values similar or above the target value of 635mm, while Plant A had values below the target value resulting in unsatisfactory flow ability.
2) Passing ability and filling capacity were evaluated using the results from slump flow and J-Ring. The best passing ability results according to the target value of ±50.8mm were seen by the mixtures of Plant A containing larger percentages of 9.5mm. The filling capacity results exhibited similar performance with most values above 80%; therefore no effect was observed of the material constituents studied.
3) Segregation results developed similar behavior for all Plants which are satisfactory according to the maximum value of approximate 15%, whereas the percent of 9.5mm decreased more segregation was seen. This behavior was expected as large size particles will settle at a faster rate. Extra segregation was observed for the mixtures using 0.45 S/Agg compared to 0.50 S/Agg due to lower viscosity.

4) Higher compressive strength was found in the mixtures of Plant A made of cement Type III. It can also be inferred from the results that the mixtures using crushed limestone developed higher compressive strength compared to mixtures using river gravel. For the mixtures using cement Type I/II, it was observed that a change of w/c ratios (0.35 to 0.33) would considerably increase the strength.
5) P-values obtained from the statistical analysis indicated that fine aggregate is the parameter with more significant effect in terms of fresh and hardened properties. This was found to be true as the variation of fine aggregate has direct impact on the viscosity of the mixture.

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Disclaimer

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Chapter 3: Time-Dependent Material Characteristic Evaluation of Self-Consolidating Concrete for Prestressed Bridge Girders

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Abstract

Self-Consolidating Concrete (SCC) has different constituent proportions compared to conventional concrete (CC), resulting in dissimilar time-dependent material characteristics, including creep and shrinkage. Hence, it is required to prudently evaluate these characteristics before the application of SCC, especially to prestressed bridge girder construction. To that end, this paper establishes an experimental platform to examine time-dependent materials characteristics focusing on creep and shrinkage utilizing vastly different SCC mixtures made at three different precast plants and at a laboratory. The considered SCC mixtures vary depending on cement type, aggregate type and size, and Sand to Aggregate Ratio (S/Agg). Experimental strains were measured for a period of 112 days where both creep and shrinkage samples were stored in controlled environmental conditions. In addition to the experimental investigation, creep and shrinkage prediction models stipulated by American Association of State Highway and Transportation Officials (AASHTO), and American Concrete Institute (ACI) Specifications were used to compare them against experimental results at a certain age. Significant findings showed that the AASHTO and ACI prediction models overestimate the creep and shrinkage change in length at specific maturity; specifically, the ACI prediction values were more conservative than those from the AASHTO model.

Keywords:

Self-Consolidating Concrete, Experimental Investigation, Time-Dependent Material Characteristics, Creep, Shrinkage, Prediction Model.

1. Introduction

SCC that has been considered a highly flowable concrete is able to spread through the formwork and fill space with no additional mechanical vibration. SCC has been widely applied to the precast industry to improve the production and durability in prestressed girders. To achieve desired workability performance on such girders, SCC mixtures have typically consisted of higher paste volumes, smaller maximum size of aggregate (MSA), lower coarse aggregate volume, and higher S/Agg ratio compared to conventional concrete (CC) (Kim et al. 2011). Due to mixture designs with distinct material constituent proportioning, SCC can develop different values of creep and shrinkage compared to CC, which can sustainably affect structural performance of prestressed bridge girders over time. Hence, it is important to have an accurate estimation of creep and shrinkage behavior to avoid overestimating or underestimating prestress losses. Note that overestimating losses will result in higher induced prestress force which will cause higher camber (Bymaster et al. 2015), while underestimating prestress losses will lead to higher deflection causing excessive cracks in the bottom fibers of the girder (Long et al. 2011).

This study aims to evaluate creep and shrinkage on different SCC mixtures at a laboratory and different local precast plants. Five SCC mixtures with different material constituents and mixture design parameters are investigated to determine their effects on strain changes over time caused by creep and shrinkage. This paper is divided into six sections. Section 2 provides a background of previous studies in terms of creep and shrinkage on SCC for prestressed girder applications. Section 3 describes the SCC mixtures used for this study. In the aforementioned section material, fresh and hardened properties, and curing methods are described. Section 4 relates to the specific test methods used to determine creep and shrinkage over a long term period. Both creep and shrinkage tests were performed following existing standard guidelines. Section 5 states both AASHTO 2013 and ACI 209R prediction models for creep and shrinkage. Section 6 entails the discussion of experimental results and comparison of experimental results with both prediction models. Finally, section 7 provides a summary and conclusions of the study.

2. Background

Creep and shrinkage behavior of SCC have been a focus of study for the fabrication of prestressed concrete (PSC) girders. Creep behavior is mostly affected by compressive strength, binder content and coarse aggregate properties. On the other hand, shrinkage of SCC mixtures is highly attributed to binder content and coarse aggregate volume. A summary of findings for both creep and shrinkage is introduced in the following subsections.

2.1 Creep

Several studies [Mata (2004), Persson (2005) Reindhart et al. (2008), Kavanaugh (2009), Khayat and Long (2011) and Alghazali and Myers (2014)] have shown inconsistency in the results of SCC creep values over time compared to High-Performance Concrete (HPC) or CC. For example, Long and Khayat (2011) compared SCC mixtures with HPC mixtures of the same w/c ratio. It was found that SCC exhibited 10-20% higher creep at 300 days compared to HPC. This was attributed to the lower amount of coarse aggregate used for SCC. In comparison to CC, Mata (2004) concluded that SCC developed up to 1.5 times more creep than CC due to low coarse aggregate content. Reindhart et al. (2008) compared also compressive strengths between SCC and CC mixtures, indicating that SCC mixtures exhibited higher creep values over time. The other studies done by Persson (2005) and Kavanaugh (2009) compared SCC and CC mixtures with similar mixture design proportions, revealing both SCC and CC developed similar creep values over time.

Other studies (Khayat and Mitchell 2009, Kavanaugh 2009 and Kim et al. 2011) have focused on the comparison of creep behavior of SCC mixtures with different mixture parameters such as binder content, cement type, and S/Agg, For instance, Kim et al. (2011) studied 16 different SCC mixtures with a target compressive strength of 34.47MPa and 48.26MPa using either limestone or river gravel as coarse aggregate. It was found that the SCC mixtures with the target compressive strength of 48.26MPa developed lower creep values; similarly, SCC mixtures with river gravel developed lower creep. The difference in creep behavior between river gravel and limestone was attributed to the fact that river gravel has higher stiffness than limestone. Alghazaly and Myers (2014) compared SCC mixtures based on strength and cement content. It was concluded that High Strength SCC (HS-SCC) mixtures developed about 13% higher creep than Normal Strength SCC (NS-SCC). The results reported by the National Cooperative Highway Research Program (NCHRP) (Khayat and Mitchell 2009) reported that SCC mixtures using cement Type I/II showed lower creep values than those made of cement Type III. It was also reported that creep values increase as the paste volume increases. For SCC mixtures, cement content is commonly replaced by mineral fillers such as fly ash or Ground Granulated Blast Furnace (GGBS) to reduce costs of the mixtures. Kavanaugh (2009) monitored different SCC mixtures during a period of 365 days having fly ash or GGBS, it was observed that mixtures with fly ash tend to have higher creep than mixtures with GGBS.

2.2 Shrinkage

Shrinkage that can be divided into autogeneous and drying shrinkages are of concern for SCC is known as the change in volume due to internal and external loss of water. Specifically, autogeneous shrinkage occurs when the hydration process of cement causes a volume reduction internally, while drying shrinkage is caused by water loss when exposed to long-term environmental conditions (Kosmatka 2002). Note that both autogeneous and drying shrinkages mostly occur during the first 28 days where they reach 80% of their final shrinkage deformation (Khayat and Long et al. 2010). According to ACI 237R-07 (ACI 2007), it was reported that SCC has lower autogeneous shrinkage and higher drying shrinkage compared to CC mixtures.

Some studies (Mata et al. 2004, Mamaghani et al. 2010, and Khayat and Long 2010) have attempted to compare total shrinkage covering both autogeneous and drying shrinkage among different mixtures, including SCC, CC, and HPC. Mamaghani et al. (2010) compared SCC and CC mixtures of similar mixture design, indicating both mixtures developed similar shrinkage over a period of 112 days. Mata et al. (2004) demonstrated that SCC mixture samples had higher shrinkage than CC mixtures. Khayat and Long (2010) compared SCC with HPC mixtures. It was found that the binder type did not have any effect on SCC or HPC mixtures where both developed similar autogeneous shrinkage. However, for mixtures with the same w/c, SCC mixtures developed 5-30% higher drying shrinkage than HPC. It was found that as w/c decreased, shrinkage values in SCC increased 100-350 microstrain.

A number of studies (Tia et al. 2005, Khayat and Mitchell 2009 and Alghazali and Myers 2014) have evaluated SCC mixture properties to determine what mixture parameters significantly affect shrinkage. In general, shrinkage on SCC mixtures has been attributed to higher binder content and lower coarse aggregate volume (Khayat and Mitchell 2009). Some studies have been focused on finding alternatives to reduce shrinkage on SCC by replacing cement with fillers. For instance, Tia et al. (2005) studied several SCC mixtures using fly ash and slag as mineral fillers. It was revealed that both mineral fillers reduced shrinkage over time; however, the mixtures using slag had a higher impact on lowering the shrinkage results. Curing methods used at precast plants can also have an effect on shrinkage by modifying the environmental conditions such as temperature and humidity. Alghazali and Myers (2014) monitored three different mixtures under the same curing condition with different steam curing time, reporting that steam curing exposure time is directly proportional to shrinkage behavior.

2.3 Summary

The findings from the literature review have shown that SCC mixtures may exhibit higher creep and shrinkage deformations due to mixture composition. The main factor affecting creep was found to be the binder content, especially for SCC used in PSC girders where higher amounts of binder content is required to meet the desired compressive strength. On the other hand, shrinkage deformation is mostly attributed to the lower volume of coarse aggregate present in SCC. Though the findings regarding the effects of mixture constituents on creep and shrinkage were discussed in the existing publication, the majority of the mixtures that were batched in a laboratory setting were tested for their creep and shrinkage evaluation.

3. Experimental Program

To evaluate creep and shrinkage of various SCC mixtures in a systematic manner, an experimental program was created with three different precast plants using different mixture parameters and constituents. Fig.1 shows the step-by-step procedure of the experimental program. The first step was to determine mixture parameters that could affect creep and shrinkage behavior. The parameters under investigation include: type of cement, S/Agg, coarse aggregate blending and type of aggregate. Step two consisted of batching each mixture at the respective plant as indicated in Table 1, where Plant A and B had two SCC mixtures and Plant C had one mixture. Note that at each plant the size of the batch was of at least 4 cubic yards to simulate the batch size that the plants will apply in the future for the production of SCC. Step three was to steam cure the samples next to the girder bed for 18 hours. The intention was to approximate the curing time and temperature girders undergo at each plant. Steps four was to measure initial readings of creep and shrinkage, and immediately apply the load to the creep frame. More details on the testing procedure will be discussed in further sections. Then samples were transported to The J. Lohr Structures Laboratory at South Dakota State University. For the fifth step, shrinkage samples were also batched at the laboratory to compare against the plant samples to account for any negative effects caused by the environmental conditions during transportation of the samples from the plant to the laboratory. Finally, the sixth step was to monitor creep and shrinkage samples for a period of 112 days.

Fig.1. Flowchart of Experimental Program

Table 1. Test Matrix for Creep and Shrinkage Tests

Test Matrix					
	Plant A		**Plant B**		**Plant C**
Mixture	**1**	**2**	**3**	**4**	**5**
No. of Creep Cylinders	3	3	3	3	3
No. of Shrinkage Plant Prisms	3	3	3	3	2[*]
No. of Shrinkage Lab Prisms	3	3	3	3	3

[*] Plant C only has 2 prisms from the plant due to damage of one prism.

3.1 Materials

Five SCC mixtures with different material constituents were investigated. Table 2 summarizes the batch design of each mixture. The investigated parameters of the five mixtures include: binder type, coarse aggregate type, blending percentage, and S/Agg. At Plant A, Mixtures 1 and 2 were made of cement Type I/II with crushed limestone; Plant B had Mixtures 4 and 5, composed of cement Type III with crushed limestone; and Plant C only had Mixture 5 which consisted of cement Type III and river gravel. All mixtures had the same cement content and w/c values which were 475kg/m^3 and 0.33 respectively. Admixtures dosages were established by each plant to meet their desired workability for girder fabrication. High Range Water Reducing Admixture (HRWR) was relatively similar for all mixtures, with dosages from 2.93 L/m^3 to 3.10 L/m^3. Viscosity Modifying Admixture (VMA) was added in small quantities as needed. Note that for mixture 5 no VMA was added.

Fresh and hardened properties results of the SCC mixtures are summarized in Table 3. Standard tests such as Slump Flow, J-Ring, Visual Stability Index (VSI), Column Segregation and Compressive Strength were performed for each mixture as shown in Fig. 2. While workability of the mixtures was outside the scope of this paper, it is important to discuss some results as certain properties can be related to creep and shrinkage. For instance, it was observed that Mixture 1 had larger spread diameter values than the rest of the mixtures, which can be attributed to the cement type or S/Agg. Also, notice that Mixture 5 had the lowest spread values, and was considered a dry mixture during fresh property testing since it showed a lack of workability. Compressive strength values are often related to creep coefficients; it is important to observe that the 18 hour compressive strengths were low for Mixtures 1-4 and considerably higher for Mixture 5. However, at 28 days compressive strength values were similar for all mixtures varying from 80.11 MPa to 89.97MPa.

Table 2. Mixture Design for SCC mixtures

Mixture	**1**	**2**	**3**	**4**	**5**
Plant	A	A	B	B	C
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 (kg/m^3)	475	475	475	475	468
Coarse Aggregate 19mm (kg/m^3)	506	560	535	710	629
Coarse Aggregate 9.5mm" (kg/m^3)	337	374	364	190	419
Sand (kg/m^3)	848	790	888	892	861
Water (kg/m^3)	156	142	156	149	161
HRWR (L/m^3)	3.09	3.09	3.07	3.10	2.93
VMA (L/m^3)	1.54	1.54	0.98	1.15	0

[3] Percent of Blending was assigned as XX-YY, where XX is the percent of 19mm and YY is the percent of 9.5mm

Table 3. Properties of SCC mixtures

Mixture	**1**	**2**	**3**	**4**	**5**
Slump Flow (mm)	724	660	648	667	584
J-Ring (mm)	724	629	629	663	508
VSI	1	0.5	1	1.5	0
Column Segregation (%)	4.15	0.85	10.8	7.7	5.6
16hr. Compressive Strength (MPa)	29.59	40.78	42.02	32.68	63.08
28d. Compressive Strength (Mpa)	80.11	89.97	85.80	87.54	80.80

(a) (b)

(c) (d)

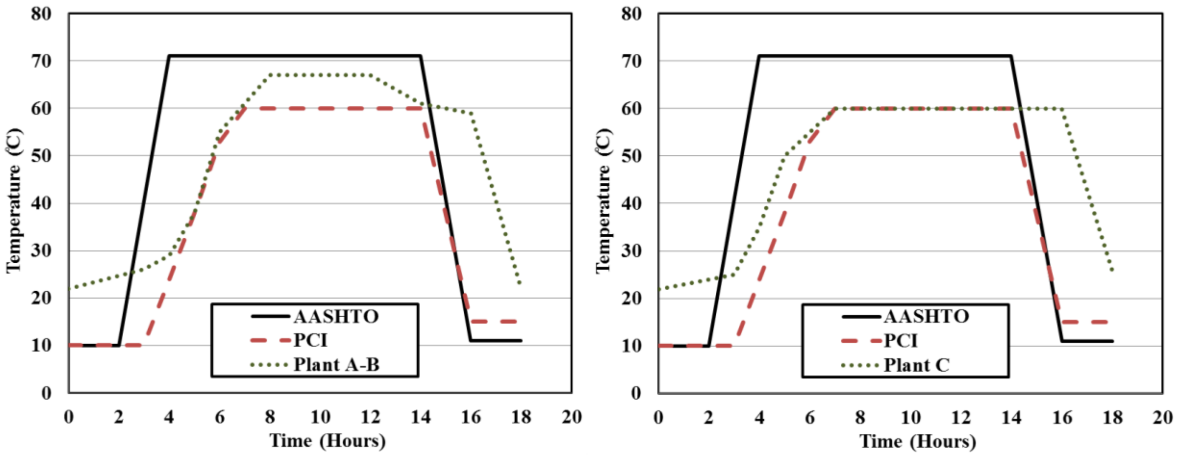
Fig. 2. Fresh Properties Testing where: (a) Slump Flow Test; (b) J-Ring Test; (c) Column Segregation; and (d) Cylinders for Compressive Strength Test.

3.2 Curing

All samples made at the plants were cured using steam 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 Fig. 3, and were cured for 18 hours following the steam curing regimen of each plant. According to AASHTO (2007), the maximum temperature of the concrete should not exceed 71℃. Also, the rise in temperature is limited to an increase of 22℃ per hour; similar to what is recommended for the cooling rate. PCI (2012) recommends a rate of heating of 22℃ per hour and a maximum temperature of 60℃. Fig. 4 shows a graphical representation of the steam curing regimen provided by different agencies and each plant. Fig. 4(a) shows the recommendation from both

AASHTO and PCI for steam curing plotted against the recorded temperatures at Plant A and B. As shown in Fig.4(a), the regimen used by Plant A and B was similar to PCI recommendation, where the only difference was the maximum temperature where a value of 67℃ was recorded for Plant A and B. Also, Fig. 4(b) shows the steam curing regimen for Plant C against both AASHTT and PCI recommendations. Again, Plant C is very similar to the PCI recommendation and the maximum temperatures are identical. Plant A and Plant B utilize the same regimen; which may be the reason why both plants had lower 18 hour compressive strength than plant C. Also, testing was performed during winter months where the outside temperature was approximately -17.7℃, and could have lowered the steam temperature in the girder bed as it was exposed to outside temperatures. Laboratory samples made for shrinkage test were moist cured for 18 hours at a temperature of 23 ±2 ˚C. After, the samples were removed from the metal molds and placed in a temperature controlled room to be air cured with the other samples.

Fig. 3. Creep samples placed next to girder bed prior steam curing.



(a) (b)

Fig. 4. Steam curing regime for: (a)Plant A and B with standard regime; (b) Plant C with standard regime.

4. Test Methodology

4.1 Creep

Creep tests were executed following the ASTM 512 “Standard Test Method for Creep of Concrete in Compression” (ASTM, 2011). For this study three creep frames were constructed to induce a constant compressive load for a period of 112 days as shown on Fig. 5(a). Prestress 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 are 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 age of loading. In order to simulate the placing of the concrete deck on the girder, the load induced into the creep frames was 2000 psi, which was below the 40% of compressive strength requirement. To ensure uniform distribution and transmission of the load between cylinders neoprene pads were placed between cylinders. Five cylinders of 152x304 mm were placed at each frame as shown in Fig. 5(a). Each cylinder had two metal tabs with 25.4cm in between each other. To improve readings accuracy two more tabs were placed on the opposite side of the cylinder to take strain readings and average both sides of the cylinder. The metal tabs were embedded in the concrete using the modified cylinders shown in Fig. 5(b). A multi-length strain change extensometer was used to measure strain changes between the metal tabs. Each reading with the extensometer had a precision of 0.0025mm. Three readings were taken on each side of the cylinder and then the average from both sides of the cylinder was used to obtain the final strain change at a specific age. The first reading was taken once the cylinders were removed from steam curing. The next reading was taken immediately after placing the cylinders in the creep frame with the compressive load. The difference between these two readings was considered the instantaneous elastic strain of each cylinder used to calculate creep coefficients later on. Also, another reading was taken 6 hours after the compressive load was induced in the frame. Also, control readings were taken when transporting the frames from the precast plants to the laboratory to ensure that the frame did not suffer any damage. After the load was induced, daily readings were taken for the first week. Then, weekly readings were taken for the first month. Lastly readings were taken until 112 days. Also, control readings were taken when transporting the frames from the precast plants to the laboratory to ensure that the frame did not suffer any damage.

(a) (b)

Fig. 5. Creep test set up: (a) Loaded creep frame; (b) Modified cylinder with brass inserts on both sides.

4.2 Shrinkage

To investigate shrinkage behavior of SCC two sets of mixtures were batched as mentioned earlier. The first set consisted of mixtures made at each plant which were transported to the laboratory. The second set consisted of laboratory mixtures with the same mixture design as the first set. The second set of samples was used to compare and determine the effect of the storing conditions during transport in terms of early shrinkage.

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 a 100mm x 100mm square prim with a length of 255mm. Fig. 6(a) shows the prism molds containing the fresh SCC mixture prior placing them adjacent to the girder bed for steam curing. After the 18 hours of steam curing the samples were stored at a temperature of 23 ± 2°C and 50% ± 4% relative humidity. Some deviations from the storage conditions recommended in ASTM 157 were made to simulate the real life conditions that a full size girder would encounter. For example, the prism samples were not stored in lime water for 28 days. Instead, the samples were placed in a temperature controlled room. However, the specified room did not provide moving air specified by the ASTM 157. Both creep and shrinkage samples were stored under the same conditions after steam curing. Therefore, similar to creep test; the first reading was taken after the cylinders were removed from steam curing. After, daily readings were taken for the first week. Then, weekly readings were taken for the first month. Lastly readings were taken until 112 days. . Readings were taken using an HM-250D Length Comparator with a digital indicator as shown in Fig. 6(b), this apparatus takes readings with a precision of 0.0025mm. The difference in length between the calibration bar and the prisms was taken three times for each prim and then the average was used for the respective curing age.

(a) (b)

Fig. 6. Shrinkage samples: (a) Preparation of shrinkage prism; and (b) Shrinkage measurements using digital length comparator.

5. Prediction Models

Measured creep and shrinkage readings were compared to the following prediction models: AASHTO 2013 (AASHTO, 2013) and ACI 209R (ACI 2008). The AASHTO 2013 creep model uses factors to account for volume to surface ratio (V/S), humidity, compressive strength and time development. The ACI 209R creep model considers more factors influencing creep such as: curing condition, humidity, air content, S/Agg, slump flow and thickness of the member. Both creep prediction models are further described in Table 5.

Shrinkage prediction models are similar to the creep models but with a more focus on environmental conditions as shown in Table 6. The AASHTO 2013 model uses factors to account for V/S, humidity, compressive strength and maturity of concrete. The ACI 209R shrinkage prediction model is similar to the AASHTO 2013 model, incorporating factors for humidity, specimen size, V/S and maturity of concrete. Note that other prediction models such as PCI were not used in this study because the 28 days compressive strengths of the samples exceeds the limit of established by those models.

Table 5. Creep prediction models

Creep Prediction Models		
Name	**Equations**	**Nomenclature**
AASHTO 2013	$\boldsymbol{\psi\ (t,t_i) = 1.9k_{vs}k_{hc}k_f k_{td} t_i^{-0.0118}}$ $k_{vs} = 1.45 - 0.0051\left(\frac{V}{S}\right) \geq 0.0$ $k_{hc} = 1.56 - 0.008RH;$ $k_f = \frac{35}{7 + f'_{ci}}$ $k_{td} = \left(\frac{t}{61 - 0.58f'_{ci} + t}\right)$	ψ = Creep coefficient; k_{vs}=Volume to surface ratio factor; k_{hc}= Humidity factor; k_f= Concrete strength factor; k_{td}= Time development factor; t= Maturity of concrete; t_i= Age of concrete at loading; $\left(\frac{V}{S}\right)$= Volume to surface ratio; RH= Relative humidity; f'_{ci}= compressive strength
ACI 209R	$\boldsymbol{\varphi_{28}\ (t,t_0) = \varphi_\infty\ (t_0)\ x\ \left(\frac{(t-t_0)^{0.6}}{10 + ((t-t_0)^{0.6})}\right)}$ $\varphi_\infty\ (t_0) = 2.35\,\gamma_c$ $\gamma_c = \gamma_{la}\gamma_{RH}\gamma_a\gamma_s\gamma_p\gamma_{at}$ $\gamma_{la} = 1.13\ (t_0)^{-0.094}$ $\gamma_{RH} = 1.27 - 0.0067RH$ $\gamma_a = 0.46 + 0.09a_0$ $\gamma_s = 0.82 + 0.00264\ x\ S_l$ γ_p= 0.88 + 0.0024 x P_a $\gamma_{at} = 1.14 - 0.00092\ x\ h_a$	$\varphi_{28}\ (t,t_0)$ = Creep coefficient at time; $\varphi_\infty\ (t_0)$ =Ultimate creep coefficient; t_0= Time of loading; γ_c= Creep correction factors; γ_{la}= Loading age factor (steam); γ_{RH}= Relative humidity factor; γ_a= air content correction factor; a_0= air content; γ_s= slump correction factor S_l= slump flow; γ_p= Aggregate ratio factor; P_a= Sand to aggregate ratio; γ_{at}= Correction factor for thickness; h_a= thickness of member;

Table 6. Shrinkage prediction models

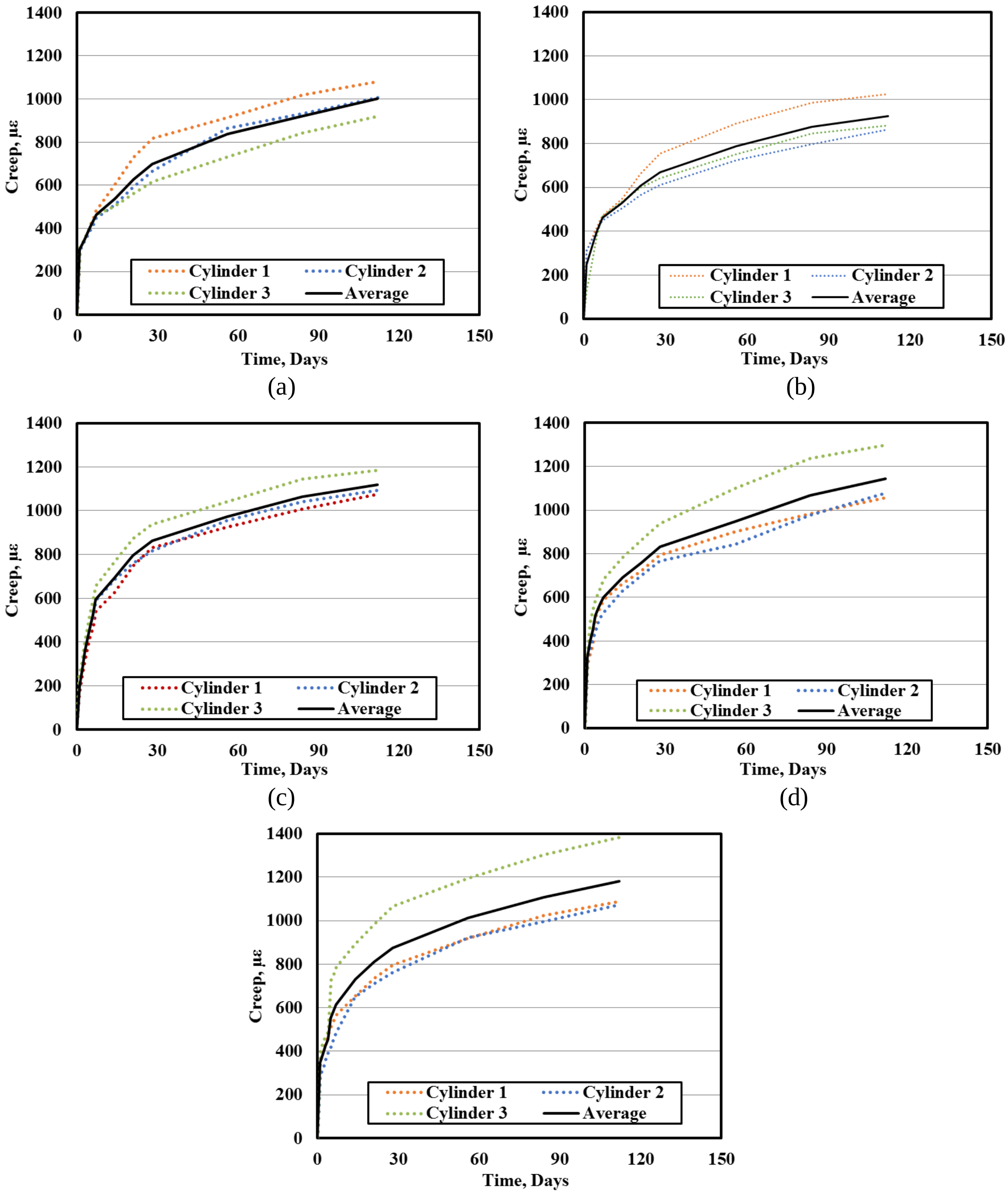
	Shrinkage	
Name	**Equations**	**Nomenclature**
AASHTO 2013	$\boldsymbol{\varepsilon_{sh} = -k_{vs}k_{hs}k_fk_{td}\ x\ 0.48x10^{-3}}$ $k_{vs} = 1.45 - 0.13\left(\frac{V}{S}\right) \geq 1.0$ $k_{hs} = 2.0 - 0.14RH;$ $k_f = \frac{35}{7 + f'_{ci}}$ $k_{td} = \left(\frac{t}{61 - 0.58f'_{ci} + t}\right)$	ε_{sh} = Drying shrinkage strain; k_{vs}=Volume to surface ratio factor; k_{hs}= Humidity factor; k_f= Concrete strength factor; k_{td}= Time development factor; t= Maturity of concrete; t_i= Age of concrete at loading; $\left(\frac{V}{S}\right)$= Volume-to-surface ratio; RH= Relative humidity; f'_{ci}= compressive strength.
ACI 209R	$\boldsymbol{\varepsilon_{sh} = \frac{t}{55 + t}(\varepsilon_{sh})_u}$ $(\varepsilon_{sh})_u = 780\ x\ 10^{-6}\ x\ \gamma_{sh}$ $\gamma_{sh} = \gamma_\gamma\ x\ \gamma_{vs}$ $\gamma_\lambda = 1.40 - 0.0102\,\lambda$ $\gamma_{vs} = 1.2\,e^{\left(-0.12\,x\,\frac{V}{S}\right)}$	ε_{sh} = Drying shrinkage strain; $(\varepsilon_{sh})_u$= Ultimate shrinkage strain; γ_{sh}= Shrinkage correction factor; γ_γ= Relative humidity factor; γ_{vs}= Specimen size factor; $\left(\frac{V}{S}\right)$= Volume-to-surface ratio; λ=Relative humidity; t= Maturity of concrete;

6. Results and Discussion

6.1 Creep

The creep values of the 15 cylinders tested until 112 days ranged from 865 to 1381 microstrain. The creep results are shown in Fig. 7. Note that the creep results shown in Figs. 7 include the strain changes caused by shrinkage. The readings for each cylinder were averaged using both sides of the cylinder for each mixture. After, the average of three cylinders was plotted on each graph as illustrated on Fig. 7. (a)-(e). In general, creep values for the three cylinders of each mixture were similar; however, Mixture 5 had a large difference between cylinder 3 with cylinder 1 and 2 with a gap of 311 microstrain a shown in Fig.7 (e).

Note that creep deformation mostly occurs during the first 28 days of curing. Table 7 shows the average creep growth for all five mixtures at ages of 28, 56, 84 and 112 days. Mixture 5 (composed of cement Type III, river gravel and S/Agg of 0.50) was the mixture that exhibit the higher change in strain with a value of 1180 microstrain. Mixture 2 (made of cement Type I/II and S/Agg of 0.45) exhibited the lowest creep which was 925 microstrain. This result was expected as higher amount of coarse aggregate helps to restrict creep deformation in concrete; therefore, less creep can be expected with more coarse aggregate content. The cement type had a significant impact on creep values. It was found that the mixtures using cement Type III exhibit higher creep values compared to Type I/II. This behavior was also found in past studies, and it was attributed to the greater surface area and chemical composition of cement Type III which promotes early setting (Long and Khayat 2011).



(a)

(b)

(c)

(d)

(e)

Fig. 7. Measured creep for 112 days: (a) Mixture 1, (b) Mixture 2, (c) Mixture 3, (d) Mixture 4, and (e) Mixture 5.

Table 7. Average creep strain change overtime

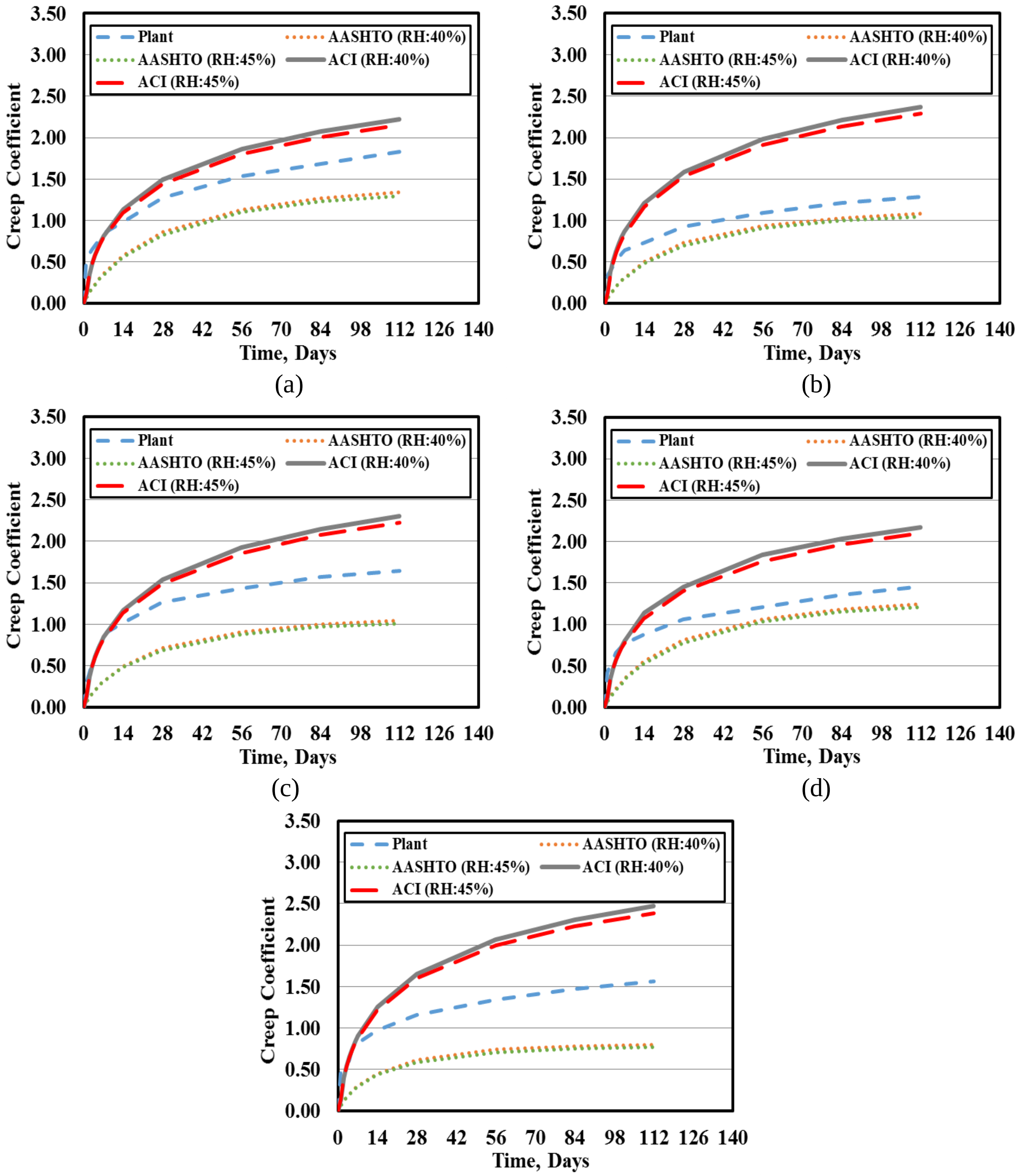
Time	**Creep strain on SCC mixtures (με)**				
	Mixture 1	**Mixture 2**	**Mixture 3**	**Mixture 4**	**Mixture 55**
28	699	670	861	832	875
56	836	789	973	947	1012
84	920	876	1064	1066	1107
112	1001	925	1117	1144	1180

Measured creep strain was converted to creep coefficients using the instantaneous elastic strain recorded after loading of the cylinders. Creep coefficients were compared to those computed from the AASHTO and ACI models as shown in Table 8 and Fig 8 using Relative Humidity (RH) of both 0.40 and 0.45. The ACI 209 model overestimates creep coefficients for all five mixtures. The percent difference of the prediction coefficient to the measured coefficient varies from 5.9% to 27.8% for 28 days and 8.1% to 29.8% for 112 days. The ACI model should provide a more accurate prediction as it takes into account mixture parameters and loading conditions. It was also found that the variation in RH had a small impact on the predicted creep coefficients.

Meanwhile, the AASHTO 2013 prediction model underestimated the creep coefficients at both 28 days and 112 days. The percent difference between the AASHTO 2013 prediction model and measured coefficient had a range from -32.57% to 8.8% for 28 days and -34.19% to -8.47%. It was observed on Fig. 8(b) and Fig. 8(d) that AASHTO provided the best prediction for Mixtures 2 and 4. Note that for Mixture 5, the AASHTO prediction model underestimate the creep coefficient at 29 days and 112 days by 32.57 % and 34.19% respectively. This was attributed to the higher compressive strength this mixture had at loading time as previously shown in Table 3. The AASHTO model only considers environmental, exposure and compressive strength conditions to predict creep coefficients. For this reason, an increase on the compressive strength affects the predictions result significantly.. Initially, higher compressive strength were expected for Mixture 1-4, as it was tested in previous trial batches. A higher compressive strength after steam curing could cause the AASHTO prediction model to underestimate the creep coefficients.

Table 8. Measured and predicted creep coefficients at 28 and 112 days

	Creep Coefficient (28 Days)				
	Mixture 1	**Mixture 2**	**Mixture 3**	**Mixture 4**	**Mixture 5**
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	7.91	26.48	27.87	16.21	18.02
ACI (RH: 45%)	1.44	1.53	1.49	1.41	1.60
% Difference	5.88	24.39	25.74	14.17	15.94
AASHTO (RH: 40%)	1.34	1.08	1.05	1.25	0.80
% Difference	2.29	7.46	8.81	8.23	-18.37
AASHTO (RH: 45%)	0.83	0.70	0.69	0.78	0.59
% Difference	-21.33	-14.11	-12.10	-15.22	-32.57
	Creep Coefficient (112 Days)				
	Mixture 1	**Mixture 2**	**Mixture 3**	**Mixture 4**	**Mixture 5**
Measured	1.83	1.28	1.65	1.46	1.57
ACI (RH: 40%)	2.23	2.37	2.30	2.17	2.47
% Difference	9.85	29.86	16.46	19.56	22.28
ACI (RH: 45%)	2.15	2.29	2.23	2.10	2.39
% Difference	8.04	28.29	14.95	17.98	20.71
AASHTO (RH: 40%)	1.34	1.08	1.05	1.25	0.80
% Difference	-15.46	-8.47	-22.22	-7.75	-32.49
AASHTO (RH: 45%)	1.30	1.05	1.01	1.21	0.77
% Difference	-16.93	-9.87	-24.06	-9.36	-34.19

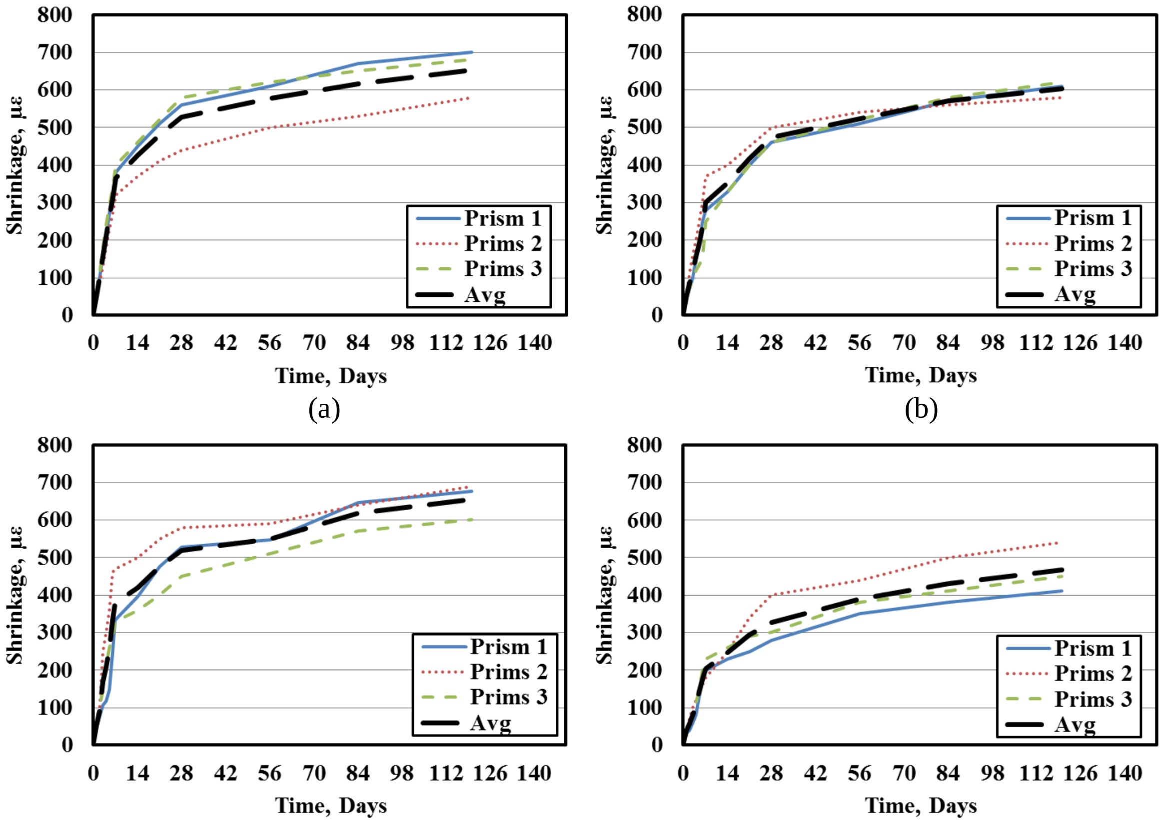


(a) (b) (c) (d) (e)

Fig. 8. Comparison between measured and predicted creep coefficients: (a) Mixture 1, (b) Mixture 2, (c) Mixture 3, (d) Mixture 4, and (e) Mixture 5.

6.2 Shrinkage

The shrinkage results for the samples made at the precast plants are shown in Fig. 8. The shrinkage values for Mixtures 1-5 ranged from 425 to 704 microstrain at 112 days. Note that in Fig.8.(a)-(e) the growth of shrinkage on each prism is shown with the respective average. In general, Mixture 1 and 3 exhibit higher shrinkage values, this was attributed to the S/Agg of 0.5. In particular, Mixture 4 had the lowest shrinkage values compared to the rest of the mixtures. This result can be attributed to the fact that this mixture was composed of only 20% 9.5mm coarse aggregate, while the other mixtures had 40%. The effect of binder type was investigated with some contrasts in the results. For instance, Mixture 4 and 5 using cement Type III had low shrinkage values as expected. However, Mixture 3 also having cement Type III developed similar shrinkage to Mixture 1 and 2 having cement Type I/II.

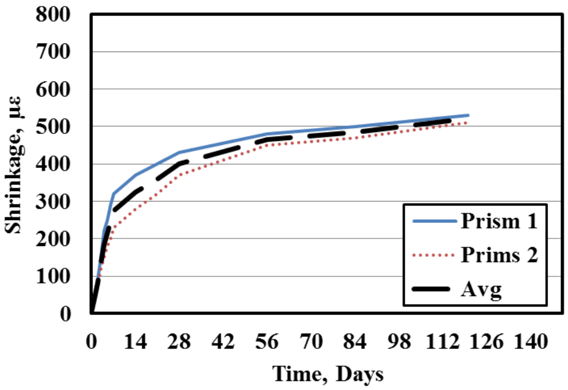


(a)

(b)

(c)

(d)

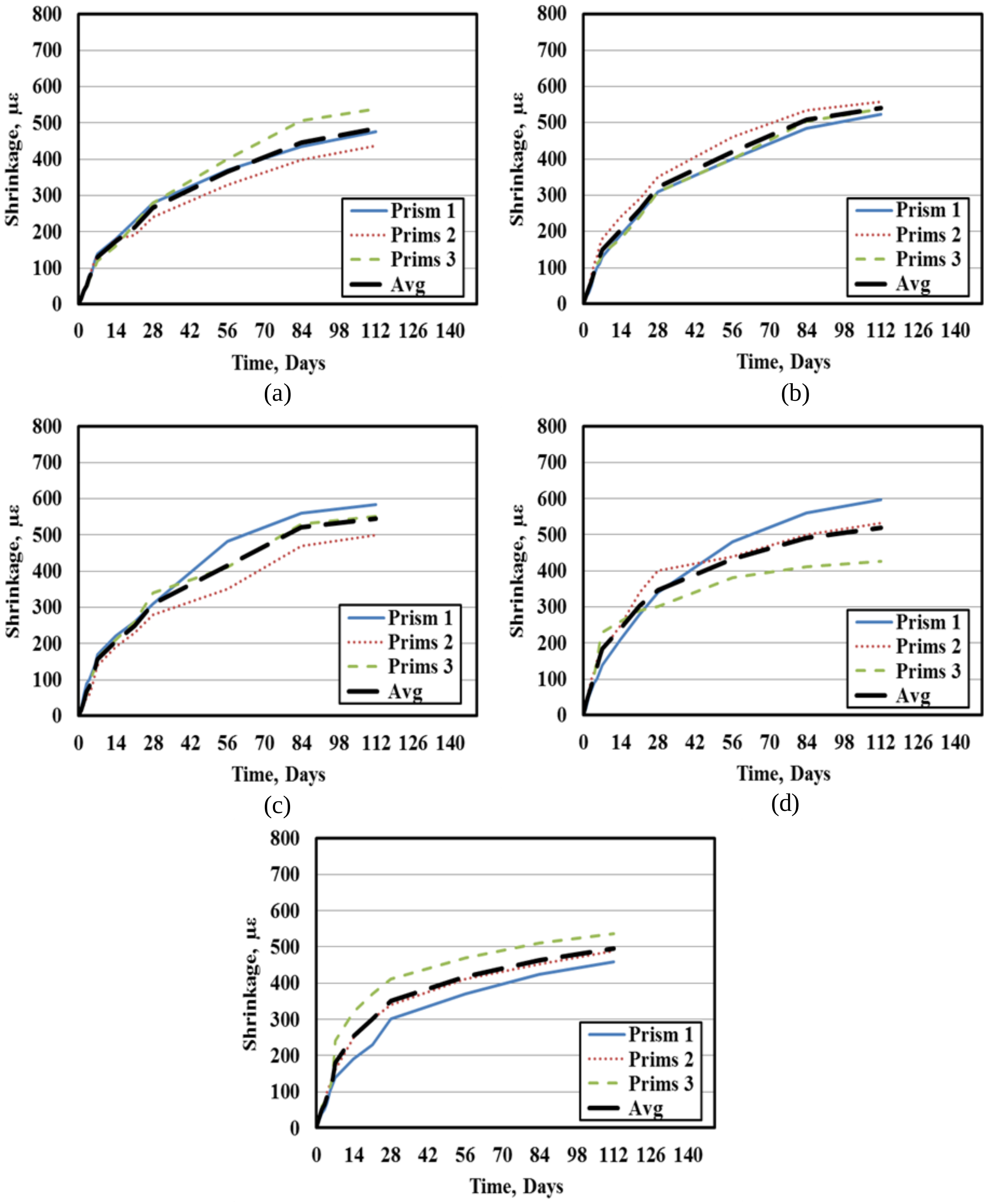


(e)

Fig. 8. Measured shrinkage results for plant prims: (a) Mixture 1, (b) Mixture 2, (c) Mixture 3, (d) Mixture 4, and (e) Mixture 5.

Laboratory samples as shown in Fig. 9 exhibited a different behavior in terms of shrinkage growth compared to Plant samples. The shrinkage values for Mixture 1-5 ranged from 410 to 580 microstrain at 84 days. Note that the shrinkage slope is steeper for the samples made at the plant, while for the samples made at the lab the slope is less steep. Table 9 shows the percent difference values of plant samples against lab samples. It was observed that there was a large difference in developed microstrain at 28 days. However, at 112 days of age the microstrain of samples made at both locations had similar values. This behavior is mostly attributed to the curing procedures. At the plant the samples were exposed to steam curing, accelerating the maturity of the concrete, while for the laboratory samples the curing procedure was moist-air. When comparing plant and lab samples, the results showed that at 112 days the samples made at the precast plants have higher shrinkage results. The difference between plant and lab samples changes depending on the mixture; for example, for Mixture 1 the difference is 157 microstrain between plant and lab samples. On the other hand, for Mixture 5 the difference is only 20 microstrain.

Independently, it was observed that laboratory samples had a smaller range varying from 520-660 microstrain. Similar to plant samples, Mixture 3 had the higher shrinkage microstrain. However, all mixtures had similar results. Therefore, it was difficult to attribute more shrinkage to a specific mixture parameter.



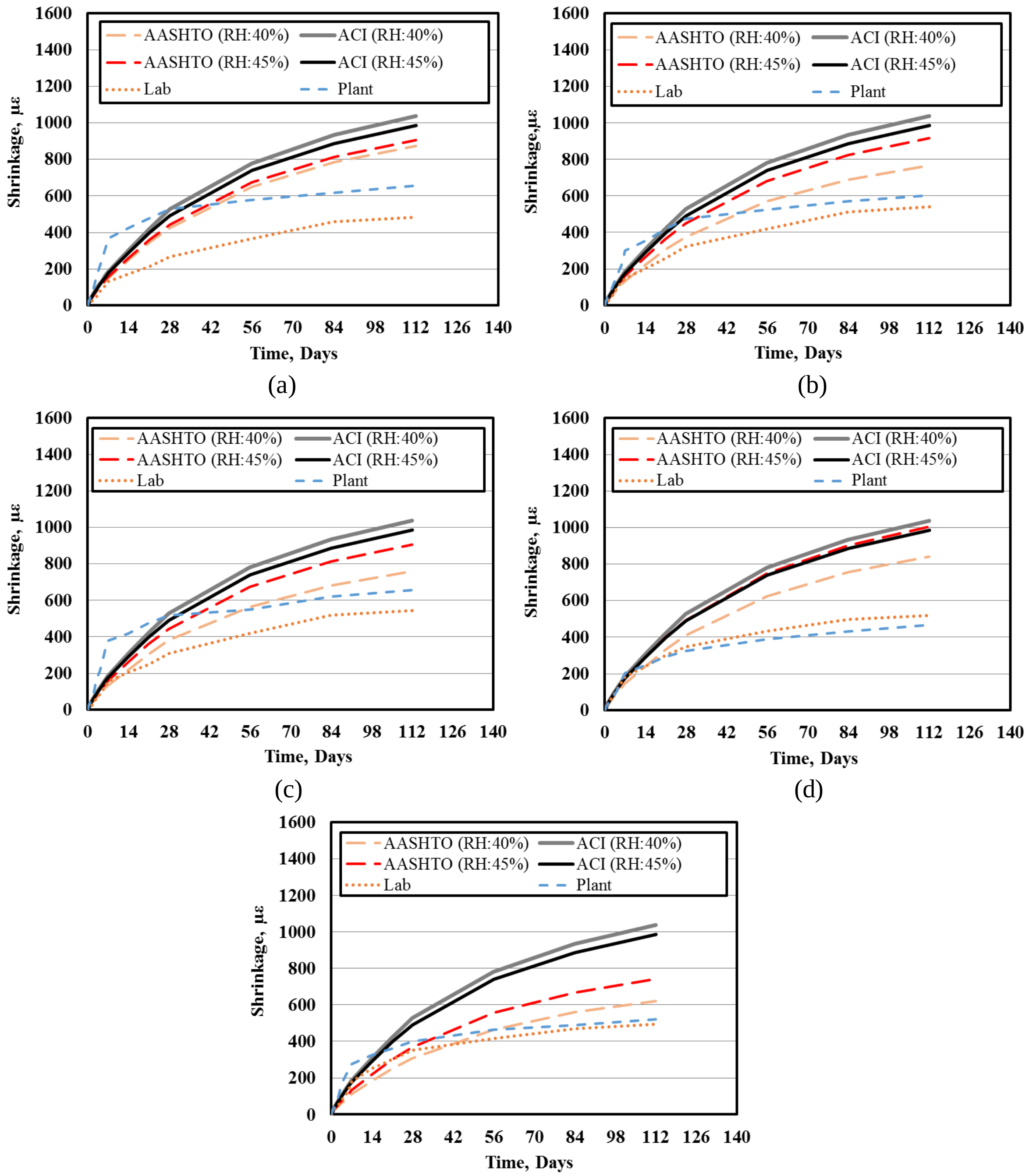
(a) (b) (c) (d) (e)

Fig. 9. Measured shrinkage for laboratory prims: (a) Mixture 1, (b) Mixture 2, (c) Mixture 3, (d) Mixture 4, and (e) Mixture 5.

Table 9. Comparison between Plant and Laboratory samples at 28 days and 122 days of age.

Mixture	28 Days Measurement		% Difference
	Plant	Lab	Plant Vs. Lab
1	527	267	32.7
2	473	323	18.8
3	519	310	25.2
4	327	347	-3.0
5	400	350	6.7
Mixture	**112 Days Measurement**		**% Difference**
	Plant	**Lab**	**Plant Vs. Lab**
1	655	484	15.0
2	603	540	5.5
3	656	545	9.2
4	467	518	-5.2
5	489	468	2.2

Prediction models were compared to both plant and laboratory samples as shown in Fig. 11 and Table 10. The average of each the three prisms of each mixture was used for comparison to the prediction models. As shown for all mixtures in Fig. 11 the ACI model is very conservative for all the mixtures at the end of 112 days. This model in particular remains constant for all mixtures as it mainly focuses on environmental conditions the samples are subjected to. ACI model provides a good estimate up to 28 days when using 40% of RH. While, when RH increases to 45% the prediction model underestimates shrinkage values. Although, as the time advances, the percent difference between measured results and predicted results at 112 days range from 20.1% to 48.2%. The AASHTO model provides a more accurate prediction at 112 days than the ACI model; however, AASHTO model also largely overestimates shrinkage behavior. Unexpectedly, the shrinkage values for the plant samples before 28 days are underestimated by both prediction models. Comparison of the RH value used did not change the prediction outcome in a great manner. For the ACI model 45% RH provided the best estimate, while for the AASHTO model RH of 40% was the best prediction.



(a)

(b)

(c)

(d)

(e)

Fig. 11. Comparison between measured and predicted shrinkage strain: (a) Mixture 1, (b) Mixture 2, (c) Mixture 3, (d) Mixture 4, and (e) Mixture 5.

Table 10. Percent difference between measured and predicted shrinkage values.

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
3	519	15.4	1.0	310	10.2	26.1
4	327	11.4	51.1	347	8.49	20.8
5	400	13.0	13.9	350	6.40	20.3

112 Days

Mixture	Plant (με)	% Difference		Lab (με)	% Difference	
		AASHTO (RH: 40%)	ACI (RH: 40%)		AASHTO (RH: 40%)	ACI (RH: 40%)
1	617	19.5	27.9	460	25.9	34.0
2	570	41.4	26.5	513	14.6	29.1
3	619	13.4	28.6	520	13.3	28.5
4	430	39.6	48.2	497	20.6	30.6
5	489	16.5	40.0	468	8.8	33.2

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
3	519	-7.8	-2.8	310	17.8	22.5
4	327	20.1	20.0	347	17.2	17.2
5	400	17.6	-2.9	350	20.0	-0.4

112 Days

Mixture	Plant (με)	% Difference		Lab (με)	% Difference	
		AASHTO (RH: 45%)	ACI (RH: 45%)		AASHTO (RH: 45%)	ACI (RH: 45%)
1	617	16.0	20.1	460	30.3	34.1
2	570	20.7	24.1	513	25.9	29.2
3	619	16.0	20.1	520	24.8	28.8
4	430	36.6	35.7	497	32.0	31.1
5	489	17.6	30.9	468	20.0	33.2

7. Conclusions

This paper evaluates time-dependent material characteristics of SCC mixtures used for prestressed concrete girder bridge construction. To that end, five SCC mixtures composed of different constituents were batched at three different precast plants and then the samples were transported to the laboratory. For shrinkage test extra prisms were cast at the laboratory to compare effects due to curing methods and transportation. The samples were monitored for 112 days in the case of the mixtures prepared at the precast plants and 84 days for the laboratory samples. Final readings were compared to both ACI 209 and AASHTO 2013 predictions models. From this study the following conclusions can be drawn:

1) The cement type was observed to have the most significant influence on creep. Mixtures 3, 4 and 5 made of cement type III exhibit 116 to 179 higher microstrain than mixtures made of cement type I/II.
2) For Mixtures 1 and 2 having cement type I/II, it was observed that as S/Agg decreased from 0.50 to 0.45 lesser creep was observed. This was attributed to the fact that coarse aggregate restraints creep deformation.
3) Creep deformation values for all the five mixtures studied vary between 925 to 1180 microstrain at 112 days of constant loading.
4) Both ACI 209 and AASHTO 2013 prediction models overestimate creep values at 112 days. However, it was concluded that ACI 209 can provide a more conservative prediction as it considers mixture parameters such as air content and S/Agg compared to the AASHTO model which only considers exposure and environmental conditions.

5) Shrinkage values for all the five mixtures prepared at the plants ranged from 425 to 704 microstrain at 112 days. It was observed that the mixture having 20% of 9.5mm and 80% of 19mm coarse aggregate had the lowest shrinkage values. Mixtures 3, 4 and 5 having cement Type III exhibit lower shrinkage values than mixtures with cement Type I/II. This can be attributed to the fact that cement Type III requires more water for the hydration of the cement reducing the amount of water for long term evaporation.
6) Shrinkage values for all the five mixtures tested at lab ranged from 410 to 580 microstrain. It was observed that mixtures made at the plant exhibit higher shrinkage values for the first 14 days. This behavior was mainly attributed to the difference in temperature between steam curing at the plants and the moist curing used at the lab.

Both prediction models provided by the AASHTO and ACI overestimate shrinkage at 112 days. However, during the first 56 days both models tend to underestimate the values for the mixtures made at the plants. Note that accuracy of the models is affected due to size effects as the samples are relative small compared to full scale members. Also, this prediction models are based on data from conventional concrete. This suggests that the factors used for steam curing in the prediction model are not accurate for these SCC mixtures.

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Appendix

Appendix A

This appendix shows the mixture constituents of all the mixtures tested for chapter 2 in English units.

Mixture 1A		
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 2A		
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 3A		
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 4A		
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 5A		
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"	642.4	lbs/yrd^3
Coarse Aggregate 3/8"	963.6	lbs/yrd^3
Fine Aggregate	1310	lbs/yrd^3
HRWR	5	oz/cwt
VMA	1	oz/cwt

Mixture 6A		
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 7A		
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"	963.6	lbs/yrd^3
Coarse Aggregate 3/8"	642.4	lbs/yrd^3
Fine Aggregate	1310	lbs/yrd^3
HRWR	6.5	oz/cwt
VMA	2	oz/cwt

Mixture 8A		
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 9A		
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"	1284.8	lbs/yrd^3
Coarse Aggregate 3/8"	321.2	lbs/yrd^3
Fine Aggregate	1310	lbs/yrd^3
HRWR	7.5	oz/cwt
VMA	2	oz/cwt

Mixture 10A		
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 11A		
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 12B		
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 13B		
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 14B		
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 15B		
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 16B		
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 17B		
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 18B		
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 19B		
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 20B		
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 21B		
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 22C		
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 23C		
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 24C		
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 25C		
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 26C		
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 27C		
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 28C		
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 B

Mixture 1A		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24	inches
J-Ring	24.5	inches
VSI	0	index
T_{50}	9.4	seconds
Column Segregation	2.7	%
Compressive Strength		
18 hours	6442	psi
28 days	11998	psi

Mixture 2A		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24	inches
J-Ring	-	inches
VSI	0	index
T_{50}	7.4	seconds
Column Segregation	2.7	%
Compressive Strength		
18 hours	5946	psi
28 days	-	psi

Mixture 3A		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	23.75	inches
J-Ring	24	inches
VSI	0	index
T_{50}	5.3	seconds
Column Segregation	6.3	%
Compressive Strength		
18 hours	7027	psi
28 days	11874	psi

Mixture 4A		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24.5	inches
J-Ring	24	inches
VSI	0.5	index
T_{50}	12	seconds
Column Segregation	6.4	%
Compressive Strength		
18 hours	6755	psi
28 days	11056	psi

Mixture 5A		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24.5	inches
J-Ring	-	inches
VSI	0.5	index
T_{50}	8.5	seconds
Column Segregation	-	%
Compressive Strength		
18 hours	6484	psi
28 days	-	psi

Mixture 6A		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24.75	inches
J-Ring	24.5	inches
VSI	1	index
T_{50}	3.9	seconds
Column Segregation	2.8	%
Compressive Strength		
18 hours	6958	psi
28 days	10164	psi

Mixture 7A		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24.75	inches
J-Ring	24	inches
VSI	1	index
T_{50}	5.2	seconds
Column Segregation	4.7	%
Compressive Strength		
18 hours	7135	psi
28 days	9877	psi

Mixture 8A		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	22.75	inches
J-Ring	25	inches
VSI	0	index
T_{50}	10.6	seconds
Column Segregation	9.1	%
Compressive Strength		
18 hours	8432	psi
28 days	-	psi

Mixture 9A		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	25.25	inches
J-Ring	24.5	inches
VSI	1	index
T_{50}	4.8	seconds
Column Segregation	4.2	%
Compressive Strength		
18 hours	7048	psi
28 days	9427	psi

Mixture 10A		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	25	inches
J-Ring	24	inches
VSI	1	index
T_{50}	4.6	seconds
Column Segregation	6.3	%
Compressive Strength		
18 hours	6993	psi
28 days	9241	psi

Mixture 11A		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	23	inches
J-Ring	24.5	inches
VSI	0	index
T_{50}	7.3	seconds
Column Segregation	10.1	%
Compressive Strength		
18 hours	7243	psi
28 days	9908	psi

Mixture 12B		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24.5	inches
J-Ring	22.48	inches
VSI	0	index
T_{50}	6.3	seconds
Column Segregation	1.6	%
Compressive Strength		
18 hours	5221	psi
28 days	8062	psi

Mixture 13B		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	26	inches
J-Ring	24.5	inches
VSI	1	index
T_{50}	7.1	seconds
Column Segregation	3.3	%
Compressive Strength		
18 hours	5520	psi
28 days	8721	psi

Mixture 14B		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24.5	inches
J-Ring	23.5	inches
VSI	0	index
T_{50}	9.3	seconds
Column Segregation	5.1	%
Compressive Strength		
18 hours	6187	psi
28 days	9048	psi

Mixture 15B		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	25.3	inches
J-Ring	24.5	inches
VSI	1	index
T_{50}	13.6	seconds
Column Segregation	8.9	%
Compressive Strength		
18 hours	6998	psi
28 days	-	psi

Mixture 16B		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24.75	inches
J-Ring	23.5	inches
VSI	0.5	index
T_{50}	3.4	seconds
Column Segregation	2	%
Compressive Strength		
18 hours	7114	psi
28 days	8750	psi

Mixture 17B		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24.6	inches
J-Ring	23.75	inches
VSI	0	index
T_{50}	3.6	seconds
Column Segregation	10.1	%
Compressive Strength		
18 hours	6958	psi
28 days	10393	psi

Mixture 18B		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24.5	inches
J-Ring	23.5	inches
VSI	0	index
T_{50}	8.2	seconds
Column Segregation	9.5	%
Compressive Strength		
18 hours	5918	psi
28 days	-	psi

Mixture 19B		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	25	inches
J-Ring	23.5	inches
VSI	0.5	index
T_{50}	5.9	seconds
Column Segregation	-	%
Compressive Strength		
18 hours	6687	psi
28 days	-	psi

Mixture 20B		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24.5	inches
J-Ring	24	inches
VSI	0	index
T_{50}	4.8	seconds
Column Segregation	9.9	%
Compressive Strength		
18 hours	7148	psi
28 days	9994	psi

Mixture 21B		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	26	inches
J-Ring	24.25	inches
VSI	1	index
T_{50}	5.7	seconds
Column Segregation	11.8	%
Compressive Strength		
18 hours	5869	psi
28 days	9729	psi

Mixture 22C		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	26.25	inches
J-Ring	25	inches
VSI	1	index
T_{50}	6.1	seconds
Column Segregation	5.1	%
Compressive Strength		
18 hours	6737	psi
28 days	8307	psi

Mixture 23C		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	25.25	inches
J-Ring	23.75	inches
VSI	1	index
T_{50}	5.8	seconds
Column Segregation	3.4	%
Compressive Strength		
18 hours	6850	psi
28 days	89.31	psi

Mixture 24C		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24.5	inches
J-Ring	22.25	inches
VSI	0	index
T_{50}	5.3	seconds
Column Segregation	2.2	%
Compressive Strength		
18 hours	6709	psi
28 days	8516	psi

Mixture 25C		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	26.25	inches
J-Ring	24.5	inches
VSI	1	index
T_{50}	3.1	seconds
Column Segregation	9.9	%
Compressive Strength		
18 hours	6861	psi
28 days	9076	psi

Mixture 26C		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24	inches
J-Ring	22.5	inches
VSI	0	index
T_{50}	2.5	seconds
Column Segregation	4.7	%
Compressive Strength		
18 hours	5042	psi
28 days	6728	psi

Mixture 27C		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24	inches
J-Ring	23.5	inches
VSI	0	index
T_{50}	3.4	seconds
Column Segregation	3.1	%
Compressive Strength		
18 hours	5451	psi
28 days	6813	psi

Mixture 28C		
Fresh Properties Test	**Value**	**Unit**
Slump Flow	24	inches
J-Ring	23.75	inches
VSI	0	index
T_{50}	4	seconds
Column Segregation	12.2	%
Compressive Strength		
18 hours	5978	psi
28 days	7131	psi

Appendix C

Fresh and hardened properties results for each mixture of Chapter 3 are presented in English units. Also, creep and shrinkage strain readings are presented for the respective mixture.

Mixture 1:

Fresh and Hardened properties:

Date:	February 12-13, 2016		**Time:**	14:00 pm	
Company:	County Materials Roberts		**Temp:**	10 ˚ F	
Mixture:	1				
Fresh Properties					
	1	**Units**		**Notes**	
Slump Flow:	28.5	Inches			
VSI:	1	Visual Index			
T20:	2.2	Seconds			
J-Ring:	28.5	Inches			
Column Segregation:	4.15	%			
Air Content:	0.9	%			
Unit Weight:	151	lbs/ft^3			
Concrete Temp:	80	˚ F			
Hardened Properties					
	1	**2**	**3**		
Compressive Strength:	4380	4280	4220	psi	(16 hr)
	11257	11021	12217	psi	(28 days)

Shrinkage Plant Sample Measurements:

Mixture 1			
Time (Days)	**Prism 1 (in)**	**Prism 2 (in)**	**Prism 3 (in)**
0	-0.0059	-0.0476	-0.0486
1	-0.0064	-0.0481	-0.0491
2	-0.0069	-0.0485	-0.0497
3	-0.0075	-0.0489	-0.0504
4	-0.008	-0.0494	-0.051
5	-0.0086	-0.0499	-0.0515
6	-0.0091	-0.0503	-0.052
7	-0.0097	-0.0508	-0.0526
14	-0.0104	-0.0513	-0.0532
21	-0.011	-0.0517	-0.0538
28	-0.0115	-0.052	-0.0544
56	-0.012	-0.0524	-0.0547
84	-0.0126	-0.0531	-0.0551
112	-0.0129	-0.0536	-0.0554

Shrinkage Laboratory Samples Measurements:

Mixture 1			
Time (Days)	**Prism 1 (in)**	**Prism 2 (in)**	**Prism 3 (in)**
0	-0.0328	-0.0082	0.1116
1	-0.0326	-0.0081	0.1118
2	-0.0324	-0.0078	0.1119
3	-0.0323	-0.0076	0.112
4	-0.032	-0.0075	0.1123
5	-0.0319	-0.0072	0.1124
6	-0.0316	-0.007	0.1126
7	-0.0314	-0.0069	0.1128
14	-0.031	-0.0064	0.1132
21	-0.0305	-0.0063	0.1138
28	-0.03	-0.0058	0.1144
56	-0.0291	-0.0049	0.1156
84	-0.0283	-0.0041	0.1168

Creep Plant Measurements:

Mixture 1			
Time (Days)	**Cylinder 1 (με)**	**Cylinder 2 (με)**	**Cylinder 3 (με)**
0	0	0	0
1	304	298	309
2	329	323	332
3	357	347	356
4	383	370	385
5	420	393	413
6	444	416	437
7	480	448	463
14	600	509	503
21	729	593	561
28	817	666	616
56	915	863	733
84	1020	933	844
112	1080	1005	920

Mixture 2:

Fresh and Hardened properties:

Date:	February 12-13, 2016		**Time:**	15:00 pm	
Company:	County Materials Roberts		**Temp:**	10 ˚ F	
Mixture:	2				
Fresh Properties					
	1	**Units**		**Notes**	
Slump Flow:	25.5	Inches			
VSI:	0.5	Visual Index			
T20:	2.8	Seconds			
J-Ring:	24.75	Inches			
Column Segregation:	0.85	%			
Air Content:	1.7	%			
Unit Weight:	151.4	lbs/ft^3			
Concrete Temp:	78	˚ F			
Hardened Properties					
	1	**2**	**3**		
Compressive Strength:	4380	4280	4220	psi	(16 hr)
	12859	13241	13171	psi	(28 days)

Shrinkage Plant Sample Measurements:

Mixture 2			
Time (Days)	**Prism 1 (in)**	**Prism 2 (in)**	**Prism 3 (in)**
0	-0.0339	0.0221	-0.0478
1	-0.0344	0.0216	-0.0464
2	-0.0346	0.021	-0.047
3	-0.0349	0.0205	-0.0477
4	-0.0354	0.0201	-0.0481
5	-0.0358	0.0196	-0.0486
6	-0.0364	0.0191	-0.0493
7	-0.0367	0.0184	-0.0503
14	-0.0372	0.0181	-0.0511
21	-0.0379	0.0176	-0.0518
28	-0.0385	0.0171	-0.0524
56	-0.039	0.0167	-0.0530

84	-0.0396	0.0165	-0.0536
112	-0.04	0.0163	-0.0540

Shrinkage Laboratory Samples Measurements:

Mixture 2			
Time (Days)	**Prism 1 (in)**	**Prism 2 (in)**	**Prism 3 (in)**
0	-0.0061	-0.0579	0.1279
1	-0.0059	-0.0577	0.1282
2	-0.0058	-0.0574	0.1284
3	-0.0056	-0.0571	0.1285
4	-0.0053	-0.0568	0.1287
5	-0.0051	-0.0566	0.1290
6	-0.005	-0.0563	0.1291
7	-0.0048	-0.0561	0.1293
14	-0.0042	-0.0555	0.1297
21	-0.0036	-0.055	0.1303
28	-0.003	-0.0544	0.1310
56	-0.0021	-0.0533	0.1319
84	-0.0012	-0.0525	0.1303

Creep Plant Measurements:

Mixture 2			
Time (Days)	**Cylinder 1 (με)**	**Cylinder 2 (με)**	**Cylinder 3 (με)**
0	0	0	0
1	305	314	127
2	339	333	188
3	364	361	254
4	396	383	321
5	420	410	384
6	449	429	427
7	470	448	469
14	548	505	536
21	662	566	598
28	756	612	642
56	891	725	750
84	986	796	846
112	1027	865	883

Mixture 3:

Fresh and Hardened properties:

Date:	February 9-10, 2016		**Time:**	4:10 PM	
Company:	County Materials Janesville		**Temp:**	2˚ F	
Mixture:	4				
Fresh Properties					
	Value	**Units**		**Notes**	
Slump Flow:	25	Inches			
VSI:	1	Visual Index			
T20:	2.4	Seconds			
J-Ring:	24.75	Inches			
Column Segregation:	10.85	%			
Air Content:	1.6	%			
Unit Weight:	147	lbs/ft^3			
Concrete Temp:	69	˚ F			
Hardened Properties					
	1	**2**	**3**		
Compressive Strength:	6070	5905	6120	psi	(16 hr)
	12248	12643	12445	psi	(28 days)

Shrinkage Plant Sample Measurements:

Mixture 3			
Time (Days)	**Prism 1 (in)**	**Prism 2 (in)**	**Prism 3 (in)**
0	-0.0290	-0.0297	-0.0276
1	-0.0295	-0.0303	-0.0281
2	-0.0298	-0.0307	-0.0286
3	-0.0301	-0.0322	-0.0291
4	-0.0302	-0.0327	-0.0297
5	-0.0305	-0.0333	-0.0302
6	-0.0315	-0.0343	-0.0305
7	-0.0324	-0.0344	-0.0309
14	-0.033	-0.0347	-0.0312
21	-0.0338	-0.0352	-0.0316
28	-0.0343	-0.0355	-0.0321
56	-0.0345	-0.0356	-0.0327

84	-0.0355	-0.0361	-0.0333
112	-0.0358	-0.0366	-0.0336

Shrinkage Laboratory Samples Measurements:

Mixture 3			
Time (Days)	**Prism 1 (in)**	**Prism 2 (in)**	**Prism 3 (in)**
0	0.0542	-0.0121	0.0503
1	0.0544	-0.0122	0.0505
2	0.0548	-0.0124	0.0506
3	0.0551	-0.0126	0.0509
4	0.0552	-0.0127	0.0511
5	0.0554	-0.0129	0.0514
6	0.0556	-0.0132	0.0516
7	0.0559	-0.0135	0.0519
14	0.0564	-0.014	0.0524
21	0.0568	-0.0144	0.0529
28	0.0573	-0.0149	0.0537
56	0.0592	-0.0156	0.0544
84	0.0598	-0.0168	0.0556

Creep Plant Measurements:

Mixture 3			
Time (Days)	**Cylinder 1 (με)**	**Cylinder 2 (με)**	**Cylinder 3 (με)**
0	0	0	0
1	160	693	252
2	241	5	303
3	308	623	393
4	368	662	458
5	423	724	526
6	469	801	595
7	540	890	658
14	628	937	768
21	749	976	873
28	831	1002	939
56	925	1072	1041
84	1007	1116	1145
112	1073	1082	1185

Mixture 4:

Fresh and Hardened properties:

Date:	February 9-10, 2016		**Time:**	3:10 PM	
Company:	County Materials Janesville		**Temp:**	2˚ F	
Mixture:	6				
Fresh Properties					
	1	**Units**	**Notes**		
Slump Flow:	26.25	Inches			
VSI:	1	Visual Index			
T20:	2	Seconds			
J-Ring:	26.12	Inches			
Column Segregation:	9.74	%			
Air Content:	1.1	%			
Unit Weight:	151.4	lbs/ft^3			
Concrete Temp:	70	˚ F			
Hardened Properties					
	1	**2**	**3**		
Compressive Strength:	4995	4920	4485	psi	(16 hr)
				psi	(28 days)

Shrinkage Plant Sample Measurements:

Mixture 4			
Time (Days)	**Prism 1 (in)**	**Prism 2 (in)**	**Prism 3 (in)**
0	-0.0031	-0.0382	-0.0327
1	-0.0034	-0.0386	-0.0331
2	-0.0035	-0.0389	-0.0333
3	-0.0037	-0.0392	-0.0335
4	-0.0039	-0.0394	-0.0338
5	-0.0044	-0.0397	-0.0342
6	-0.0048	-0.0398	-0.0347
7	-0.0051	-0.04	-0.035
14	-0.0054	-0.0407	-0.0353
21	-0.0056	-0.0416	-0.0356
28	-0.0059	-0.0422	-0.0357
56	-0.0064	-0.0426	-0.0365

84	-0.0069	-0.0432	-0.0368
112	-0.0072	-0.0436	-0.0372

Shrinkage Laboratory Samples Measurements:

Mixture 4			
Time (Days)	**Prism 1 (in)**	**Prism 2 (in)**	**Prism 3 (in)**
0	0.001	-0.0382	-0.0327
1	0.0012	-0.0386	-0.0331
2	0.0015	-0.0389	-0.0333
3	0.0017	-0.0392	-0.0335
4	0.0019	-0.0394	-0.0338
5	0.002	-0.0397	-0.0342
6	0.0022	-0.0398	-0.0347
7	0.0024	-0.04	-0.035
14	0.0031	-0.0407	-0.0353
21	0.0038	-0.0416	-0.0356
28	0.0044	-0.0422	-0.0357
56	0.0058	-0.0426	-0.0365
84	0.0068	-0.0432	-0.0368

Creep Plant Measurements:

Mixture 4			
Time (Days)	**Cylinder 1 (με)**	**Cylinder 2 (με)**	**Cylinder 3 (με)**
0	0	0	0
1	296	321	354
2	342	364	489
3	384	412	542
4	512	446	593
5	533	488	618
6	561	511	651
7	589	531	683
14	662	628	781
21	719	699	862
28	793	765	939
56	900	842	1100
84	983	978	1237
112	1057	1078	1298

Mixture 5

Fresh and Hardened properties:

Date:	February 11-12, 2016		**Time:**	2:00pm	
Company:	Spancrete		**Temp:**	-1 ˚ F	
Mixture:	9				
Fresh Properties					
	1	**Units**		**Notes**	
Slump Flow:	23	Inches			
VSI:	0	Visual Index			
T20:	4.96	Seconds			
J-Ring:	20	Inches			
Column Segregation:	5.6	%			
Air Content:	2.6	%			
Mass (Pock.+Conc)	39.05	lbs/ft^3			
Unit Weight:	123.6	lbs/ft^3			
Concrete Temp:	65	˚ F			
Hardened Properties					
	1	**2**	**3**		
Compressive Strength:	9262	8966	9219	psi	(16 hr)
	11751	11416	11690	psi	(28 days)

Shrinkage Plant Sample Measurements:

Mixture 5			
Time (Days)	**Prism 1 (in)**	**Prism 2 (in)**	**Prism 3 (in)**
0	-0.0484	0.0112	-
1	-0.0489	0.0109	-
2	-0.0493	0.0105	-
3	-0.0499	0.01	-
4	-0.0506	0.0097	-
5	-0.0509	0.0094	-
6	-0.0513	0.0092	-
7	-0.0516	0.0089	-
14	-0.0521	0.0084	-
21	-0.0524	0.008	-
28	-0.0527	0.0075	-
56	-0.0531	0.007	-
84	-0.0534	0.0065	-
112	-0.0537	0.0061	-

Shrinkage Laboratory Samples Measurements:

Mixture 5			
Time (Days)	**Prism 1 (in)**	**Prism 2 (in)**	**Prism 3 (in)**
0	0.0853	-0.0195	0.0069
1	0.0855	-0.0193	0.0073
2	0.0857	-0.019	0.0075
3	0.0858	-0.0188	0.0076
4	0.086	-0.0185	0.0078
5	0.0863	-0.0183	0.008
6	0.0865	-0.0181	0.0083
7	0.0867	-0.0179	0.0093
14	0.0872	-0.017	0.0101
21	0.0876	-0.0165	0.0106
28	0.0883	-0.0161	0.011
56	0.089	-0.0154	0.0116
84	0.0896	-0.0149	0.0122

Creep Plant Measurements:

Mixture 5			
Time (Days)	**Cylinder 1 (με)**	**Cylinder 2 (με)**	**Cylinder 3 (με)**
0	0	0	0
1	351	295	395
2	394	316	442
3	442	361	470
4	477	396	491
5	512	421	726
6	538	457	752
7	568	488	788
14	651	650	893
21	734	711	985
28	797	762	1067
56	920	923	1194
84	1023	996	1303.333
112	1087	1073	1381