Evaluating the Time-Dependent Deformations of Pretensioned Bridge Girders Cast with Self-Consolidating Concrete

Kyle H. Larson, Graduate Research Assistant, Dept. of Civil Engineering, Kansas State University, Manhattan, KS
Robert J. Peterman, PhD, PE, Martin K. Eby Distinguished Professor in Engineering, Dept of Civil Engineering, Kansas State University, Manhattan, KS
Asad Esmaeily, PhD, Assistant Professor, Dept of Civil Engineering, Kansas State University, Manhattan, KS

ABSTRACT

Results from laboratory tests and field measurements, used to determine the material and bond characteristics of a proposed SCC mix for bridge girders, are presented. Development length, transfer length, creep, and shrinkage test results of the proposed SCC mix are compared with current design equations. Instrumentation of seven pretensioned girders in a five-span bridge located in Cowley County, Kansas consisted of the field portion for this study. Three of these girders utilized SCC, while the other four were cast with conventional concrete. Time-dependent deformations of the girders for each mix were measured using vibrating wire strain gages embedded in the girders. Companion creep and shrinkage specimens were also cast and the results are presented.

Keywords: Bridge Monitoring, Creep & Shrinkage, Prestress losses, Prestressed concrete, Self-consolidating concrete, Shrinkage

INTRODUCTION

Self-Consolidating Concrete (SCC) has rapidly become a widely used material in the construction industry. The primary reasons for the increased use of SCC are the economical advantages that SCC has over conventional concrete (CC). The Interim Guidelines for the use of Self-Consolidating Concrete in PCI Member Plants[1] define SCC as "a highly workable concrete that can flow through densely reinforced or complex structural elements under its own weight and adequately fill voids without segregation or excessive bleeding without need for vibration."

The Interim Guidelines also state in the commentary that the hardened properties of SCC may be different than those of conventional concrete. Where modulus, creep, and shrinkage are important design guidelines, it states that the mix should be properly investigated before using in design. When designing prestressed concrete members, these properties are very important for an accurate estimation of time-dependent losses.

PROBLEM STATEMENT

The main objective for this project sponsored by both the Federal Highway Administration (FHWA) and the Kansas Department of Transportation (KDOT) is to determine the time-dependent losses for pretensioned concrete bridge members using SCC. KDOT would like to use SCC in pretensioned bridge members to enhance the aesthetics and improve consolidation in congested areas. However, before allowing the use of SCC in state bridges girders, KDOT needed to investigate the time-dependent losses of an SCC mixture proposed by the local precaster. A study on development and transfer lengths was previously completed which investigated the bond between the prestressing strand and SCC. The test specimens performed satisfactory, passed all code requirements, and the results can be seen in the publication by Larson et al[2].

BACKGROUND

A five-span bridge containing 35 girders was chosen to be instrumented and long-term strain values were recorded. Of the 35 girders, 21 were cast with CC and the remaining 14 girders with SCC. The bridge was located on US Highway 160 in Cowley County just west of Winfield, Kansas. To determine the time-dependent losses, Vibrating Wire Strain Gages (VWSGs) were embedded into seven of the girders, four with CC and three with SCC. This is one of the first bridges with SCC to be monitored for long-term prestress losses. The girders used in this project were KDOT standard Type K3 girders, shown in Figure 1. Table 1 lists the geometric properties for this girder type. Companion creep and shrinkage specimens of the SCC mixture were also cast and long-term data was recorded and compared with the measured deformations of the bridge girders.

Table 1 Geometric properties of K3 girder

$A =$	525	$inch^2$	$V/S =$	3.56	inch
$I =$	127,490	$inch^4$	$w_o =$	547	plf
$H =$	45	inch	$A_{ps} =$	2.448	$inch^2$
$e =$	13.27	inch	$Y_{bot} =$	21.0	inch

BRIDGE INSTRUMENTATION

INSTRUMENTATION

In order to determine the long-term strains experienced by the girders, VWSG's were selected for use in this project. The strain gages selected were the Model VCE-4200 Vibrating Wire Embedded Strain Gage, manufactured by Geokon, Inc., Lebanon, New Hampshire. The manufacturer recommended this gage type for this project due to its long-term strain and temperature measuring capabilities.

The bridge instrumentation involved selecting seven girders and placing the VWSGs at various depths in the girder. Three total gages were placed at each location with one being at the height of the top strands, one at 21 inches from the bottom (neutral axis of the section), and one at the bottom strand height, Figure 1. All gages were placed at mid-span of the seven selected girders. Other gages were also placed at certain locations, but the results of them will not be addressed in this paper.

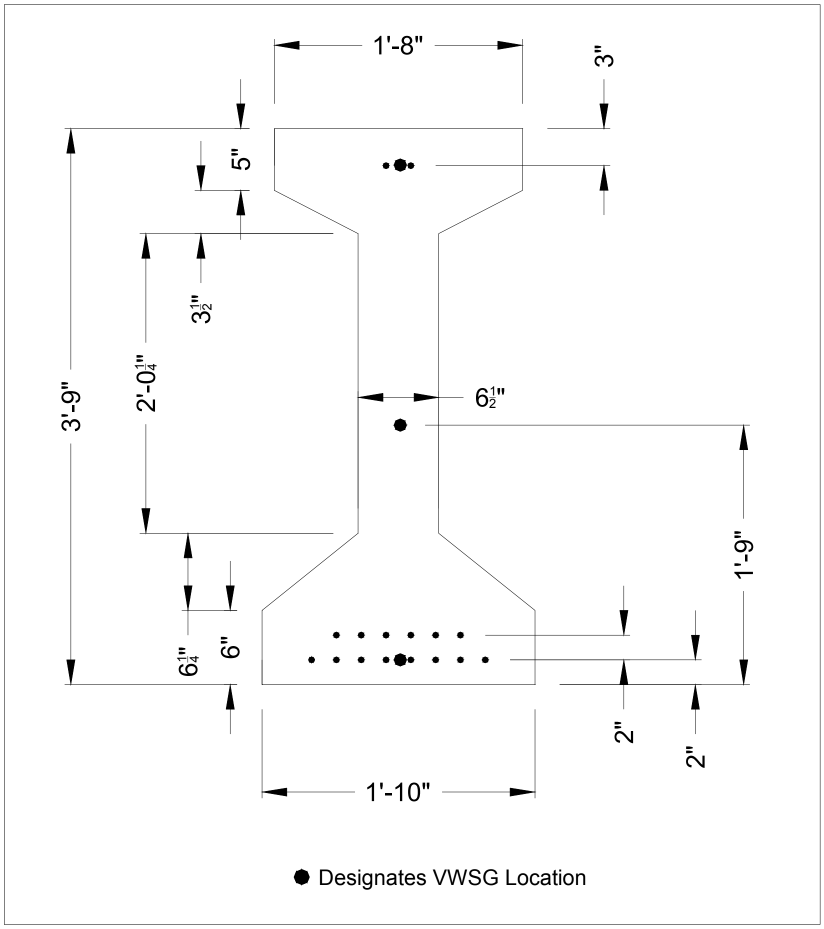

Fig.1 Cross section and VWSG location of K3 girder

BRIDGE LAYOUT

As mentioned above, the bridge consisted of 35 girders. The girder layout can be seen in Figure 2. Spans A-C were all cast with CC and spans D-E were cast with the proposed SCC mixture. The bridge was erected in two phases. All of the girders with embedded with VWSG's were part of Phase I. Girder lines 1-3 were part of Phase I and girder lines 4-7 were part of Phase II. The girders with embedded VWSG's were A3, B1, B3, C3, D1, D3, and E3.

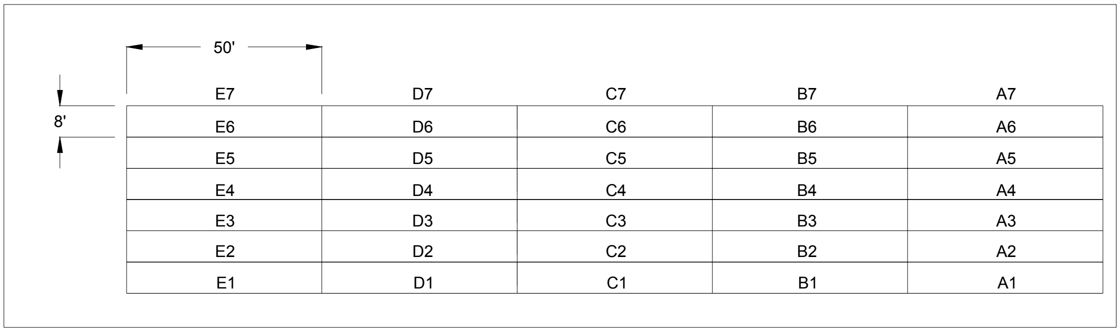

Fig. 2 Layout of bridge girders

MATERIAL PROPERTIES

The prestressing strand used in all the girders was 0.5 inch diameter, Grade 270 ksi. The modulus of elasticity (E_{ps}) for the prestressing strand was reported as 28,500 ksi by the manufacturer. A straight strand profile was used for every girder. As noted previously, two separate concrete mixtures were used in this study. The conventional and self-consolidating concrete mixtures are shown in Table 2. (It must be noted that the CC and SCC mixtures use different high range water reducer admixtures.) Since two different concrete mixtures were used in the bridge girders, the hardened concrete properties of both mixtures were different. This difference is important when comparing experimental results to code predictions. Figure 3 shows the measured modulus of elasticity (E_c) for release and 28 day modulus for both mixes. Figure 4 shows the measured compressive strength (f_c) for release and 28 day strength for both mixes. At the time of casting for the SCC girders with the VWSG's the release strengths were lower than normal. However, the average release strengths of the remaining un-gaged girders with SCC were much higher than those girders with CC.

Table 2 Mix designs of SCC and conventional concrete mixtures

	SCC	**Conventional**
Materials	**Quantity per yd^3**	**Quantity per yd^3**
Cement (Type III)	750 lbs	650 lbs
Fine Aggregate(MA1 Sand)	1500 lbs	1480 lbs
Coarse Aggregate (Max 3/4")	1360 lbs	1457 lbs
Air Entrainment	5 oz	6 oz
High Range Water Reducer	70 oz	26 oz
Viscosity Modifying Agent	0 oz	0 oz
Water	27 gal	31.6 gal
W/C ratio	0.30	0.41

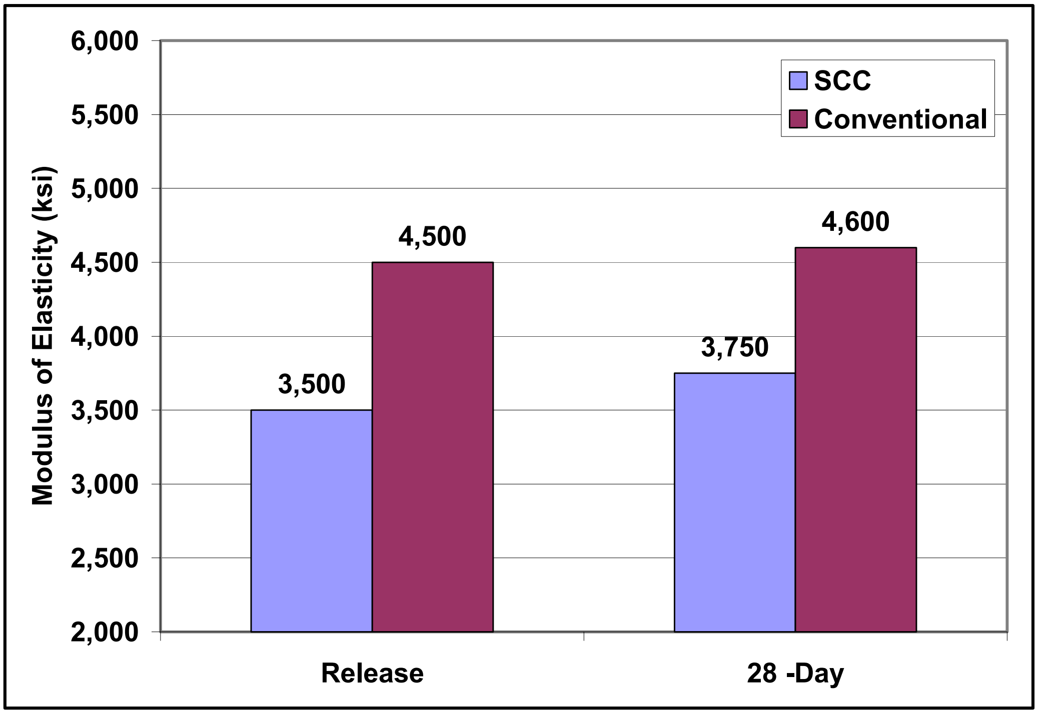

Fig. 3 Modulus of elasticity of concrete for both concrete mixtures

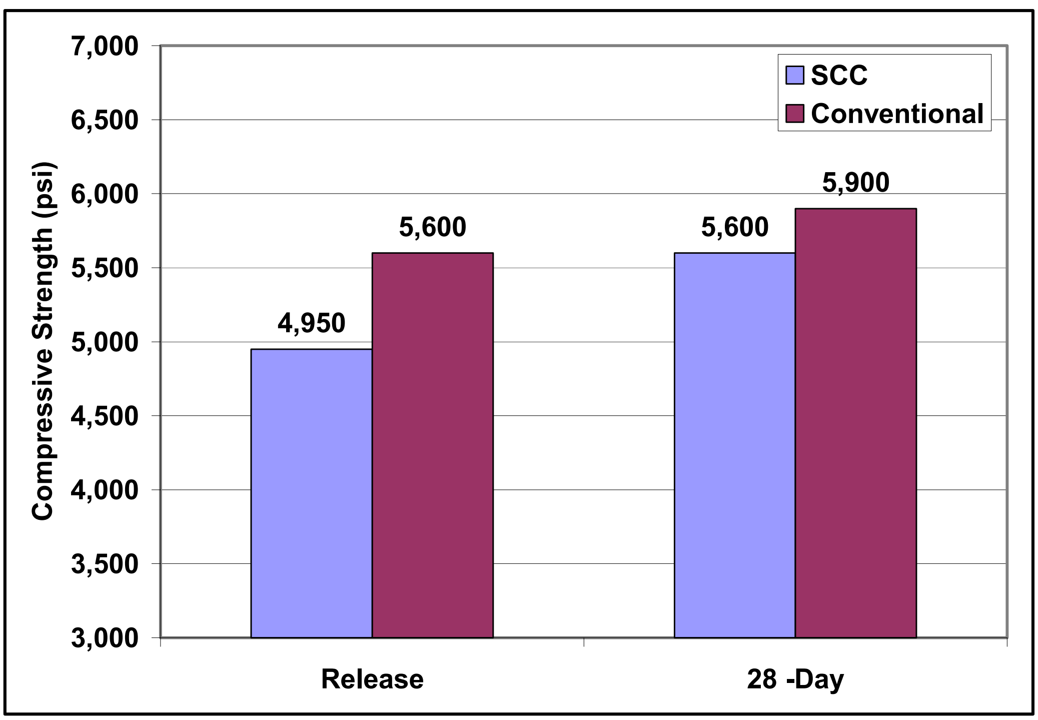

Fig. 4 Compressive strength of concrete for both concrete mixtures

PRESTRESS LOSS OF BRIDGE GIRDERS

CODE EQUATIONS

Prestress loss predictions were calculated using the method outlined in the PCI Design Handbook[3]. Other prediction methods provide very similar results. It must be noted that the differences in the modulus of elasticity for the concrete mixtures play a major role in both elastic shortening and creep losses. In order to estimate the creep and shrinkage values for periods less than two years, the expression by Corley and Sozen[4] (Equation 1) was used.

$$R = 0.13\ln\left(t+1\right) \tag{1}$$

where
R = the total time-dependent proportion;
t = time (days).

Other more complex models could have been used to estimate the creep and shrinkage values at intermediate time steps. However, since the applicability of these models to SCC has not been established, the authors chose to use the more general expression.

EXPERIEMTNAL RESULTS

The VWSGs yield results in strain. To compare these values with the code equations the strain values needed to be converted to stress. The code equations compute the prestress loss values at the center of gravity of the prestressing strands. Hence, the strain values located at the level of the bottom strand height was used for direct comparison. Hooke's Law was used to determine the corresponding stress at the bottom strand height.

$$\sigma = E\varepsilon \tag{2}$$

where
$E = \text{modulus of elasticity of prestressing strand}\left(28{,}500\,\text{ksi}\right);$
$\varepsilon = \text{strain value given by VWSG.}$

Figure 5 shows the effective prestress force in the girders after 300 days along with the code predicted results. The results are also shown in Table 3.

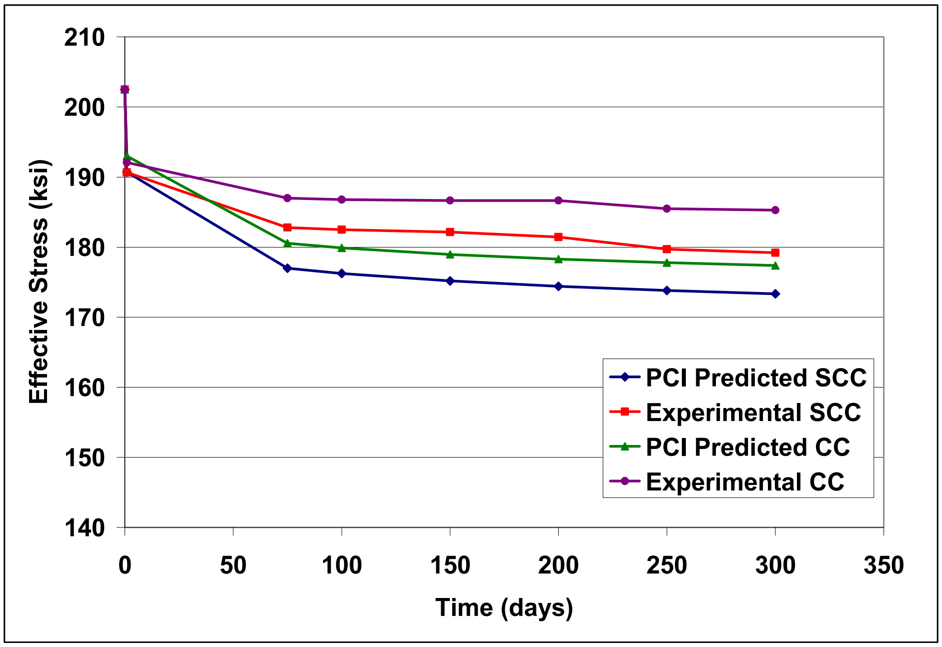

Fig. 5 Effective stress for experimental data and code predicted values

Table 3 Values for predicted versus experimental stresses

Day	Conventional		SCC	
	Predicted Stress*	Experimental Stress	Predicted Stress*	Experimental Stress
Release	193.0	192.1	190.7	190.7
75	180.6	187.0	177.0	182.8
100	179.9	186.8	176.2	182.5
150	179.0	186.7	175.2	182.2
200	178.3	186.7	174.4	181.4
250	177.8	185.5	173.8	179.7
300	177.4	185.3	173.3	179.2
Ultimate	172.8	--	168.1	--

* using PCI Design Handbook method

CREEP AND SHRINKAGE MODELS

Creep and shrinkage are important factors in determining the time-dependent deformations of precast members. Creep is defined as the time-dependent deformation of hardened concrete subjected to sustained stress[5]. Shrinkage is defined as the contraction of concrete due to drying and physiochemical changes, dependent on time but not on stresses induced by external loading[5].

CREEP

ACI Committee 209[6] presents the following equation for predicting the creep coefficient (ratio of creep strain to initial elastic strain) of concrete at any time

$$v_t = \frac{t^{\Psi}}{d + t^{\Psi}} v_u \tag{3}$$

where

v_t = creep coefficient at any time t;

t = time in days after loading;

Ψ = constant, $(0.40 < \Psi < 0.80)$;

d = constant, $(6 < d\ 30$ days); and

v_u = ultimate creep coefficient, $(1.30 < v_u < 4.15)$.

Creep tests were conducted as outlined in ASTM C512, Standard Test Method for Creep of Concrete in Compression[7]. Four, 4 inch x 4 inch x 24 inch, specimens were used in determining the ultimate creep coefficient. The ends of each specimen were capped with a sulfur-based high strength capping compound. The specimens were then loaded into the creep frame (Figure 6) and loaded to 40 percent of the compressive strength. Surface strains of the concrete were measured using Whittemore locating points (Figure 7). Each specimen had six strain measurements taken. For the duration of the test, strain measurements of the creep specimens were measured and recorded periodically.

Fig. 6 Creep apparatus

Fig. 7 Whittemore points

SHRINKAGE

ACI Committee 209[6] presents the following equation for predicting the shrinkage strain of concrete at any time

$$\left(\varepsilon_{sh}\right)_t = \frac{t^{\alpha}}{f + t^{\alpha}}\left(\varepsilon_{sh}\right)_u \tag{4}$$

where

$\left(\varepsilon_{sh}\right)_t$ = shrinkage strain at any time t;

$t =$ time in days after loading;

$\alpha =$ constant, $(0.90 < \alpha < 1.10)$;

$f =$ constant, $(20 < f < 130$ days); and

$\left(\varepsilon_{sh}\right)_u$ = ultimate shrinkage strain, $(415\,x10^{-6} < \left(\varepsilon_{sh}\right)_u < 1070\,x10^{-6})$.

Companion shrinkage specimens were cast at the same time as the creep specimens were made. To provide the same exposed surface area as the creep specimens, the shrinkage specimens were also capped. This prevents the shrinkage specimens from exchanging moisture with the environment through their ends. The shrinkage specimens were stored in the vertical position, similar to the creep specimens. Identical to the creep specimens, surface strains were recorded by using a Whittemore gage. Both the creep and shrinkage specimens were stored in the laboratory where the temperature is close to 75 degrees Fahrenheit with 50% relative humidity. No controlled environment was provided to prevent fluctuation of the temperature and relative humidity.

CREEP AND SHRINKAGE SPECIMEN RESULTS

CREEP

Creep tests were conducted for a duration of over 300 days for the proposed SCC mixture, however only results up to 300 days will be presented. Immediately after loading, the initial deformation, representing the elastic response, was measured. Creep strains were then calculated by subtracting from the total strain, the initial elastic strain and the average shrinkage of the unloaded companion specimens.

The experimental creep coefficient is found by taking the creep strain, minus the initial elastic strain and shrinkage strains, then dividing that value by the initial elastic strain. Adjusting the parameters in Equation 3, the ultimate creep coefficient can be determined by plotting the experimental data against the values obtained in Equation 3. This is done while trying to match the predicted curve with the experimental curve. Using this trial and error approach, the creep parameters were determined to be 0.7 for Ψ, 16 for d and 1.75 for v_u for the SCC mixture, which are all within the given ranges suggested by ACI 209. The results can be seen in Figure 8.

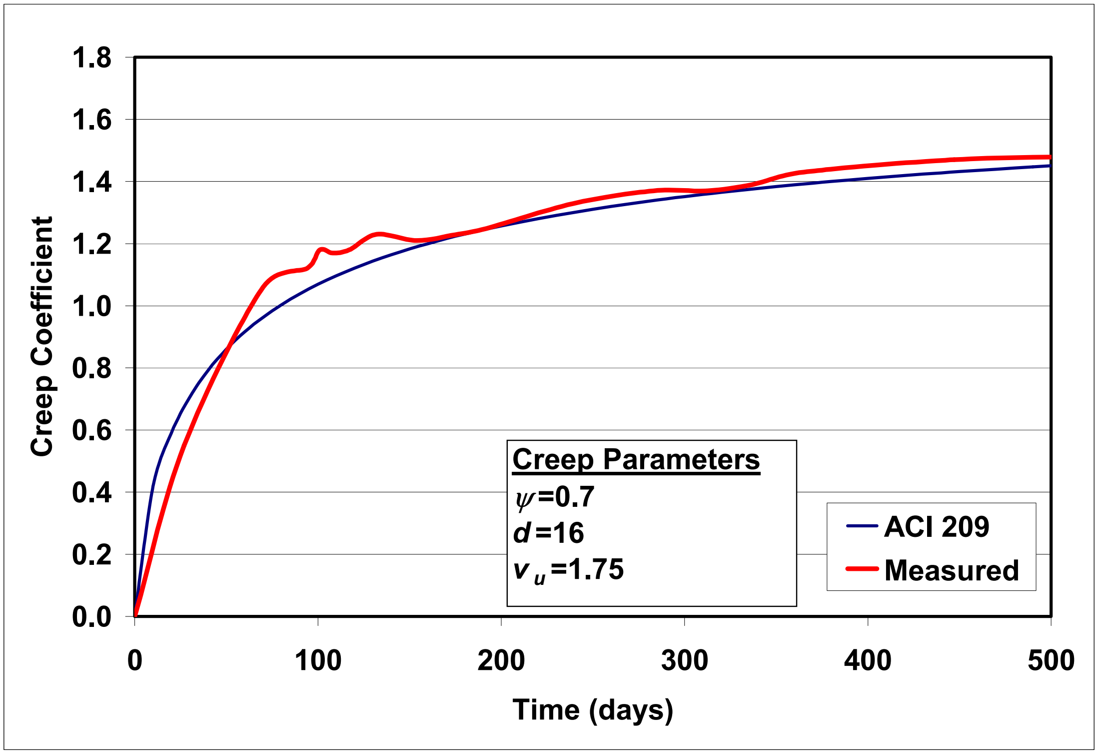

Fig.8 Creep specimen results

SHRINKAGE

Figure 9 shows the measured shrinkage strains with respect to time for the proposed SCC mixture. The shrinkage strains are calculated from equation 4. Along with the predicted ACI-209 value and measured strains, the strain results of an embedded VWSG are also shown. It can be seen that the dip in strain values occurred for both the strains measured with the Whittemore points and the VWSG. This suggests that the temperature and relative humidity changed during this portion. The shrinkage specimen parameters used in determining the predicted curve was 1.0 for α, 20 for f and 550 x 10^6 for the ultimate shrinkage value $(\varepsilon_{sh})_u$.

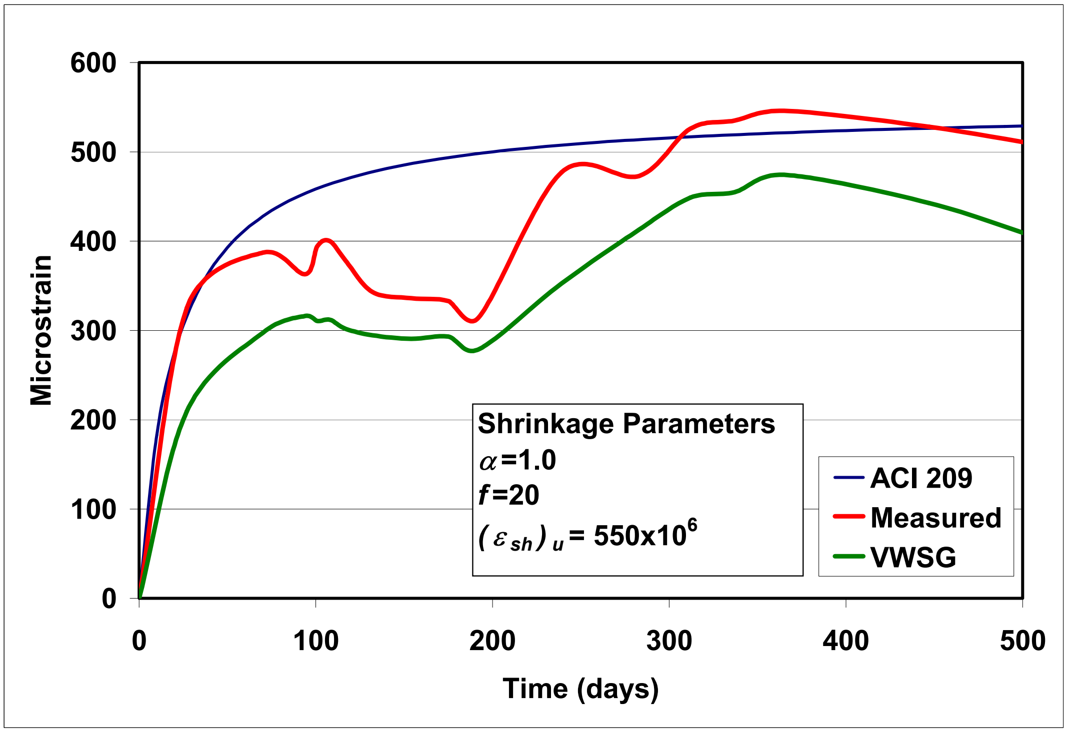

Fig. 9 Shrinkage specimen results

COMPARISONS

The creep and shrinkage coefficients for the proposed SCC mixture obtained in the previous section will be used to predict the prestress losses of the bridge girders cast with the SCC mixture. The method for predicting the prestress losses with the creep coefficient and shrinkage strain values are detailed in the ACI 209 document. The total losses are given by the following equation where the first term represents prestress loss due to elastic shortening, the second term is the prestress loss due to creep, the third term is prestress loss due to shrinkage, and the fourth term is the prestress loss due to steel relaxation

$$\lambda_t = (nf_c) + (nf_c)v_t\left(1 - \frac{F_t}{2F_0}\right) + \frac{(\varepsilon_{sh})_t E_s}{1 + n\rho\xi_s} + (f_{sr})_t \tag{5}$$

where

n = modular ratio, E_S/E_{ci} at the time of loading;

f_c = concrete stress such as at steel c.g.s. due to prestress and precast beam dead load in the prestress loss equations;

v_t = creep coefficient at any time;

F_t = total loss of prestress at any time minus the inital elastic loss;

F_o = prestress force at transfer, after elastic loss;

$(\varepsilon_{sh})_t$ = shrinkage strain at any time;

E_s = modulus of elasticty of steel;

ρ = reinforcement ratio;

ξ_s = cross section shape coefficient;

$(f_{sr})_t$ = stress loss due to steel relaxation in prestressed member at any time.

Figure 10 shows the experimental data compared against the values predicted by the ACI 209 equations for prestress losses. Table 4 presents the data for the ACI 209 predictions along with the breakdown of each individual loss.

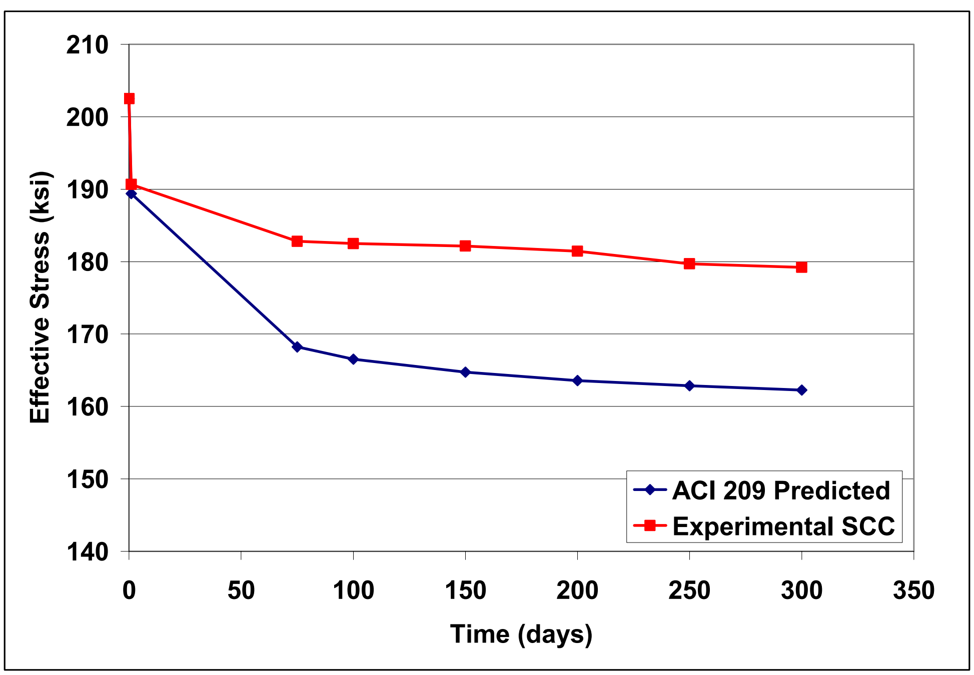

Fig. 10 Effective stresses of experimental values of SCC girders versus predicted values using ACI 209

Table 4 Values of stress for experimental and ACI 209 predicted values for the SCC girders

Day	Elastic Shortening	Creep	Shrinkage	Relaxation	Total Losses	ACI 209 Predicted	Experimental Stress
Release	11.5	0.0	0.0	1.6	13.1	189.4	190.7
75	11.5	7.5	12.0	3.3	34.3	168.2	182.8
100	11.5	8.2	12.9	3.4	36.0	166.5	182.5
150	11.5	9.0	13.6	3.6	37.8	164.7	182.2
200	11.5	9.6	14.0	3.7	38.9	163.6	181.4
250	11.5	10.0	14.3	3.8	39.6	162.9	179.7
300	11.5	10.3	14.5	3.9	40.2	162.3	179.2
Ultimate	11.5	13.4	15.4	5.1	45.4	157.1	--

It can be seen that the ACI 209 method is much more conservative than the predictions made by using the PCI Design Handbook method. A major difference is the prediction for the shrinkage loss. It can be seen in Table 5 that the shrinkage loss prediction by using the ACI 209 method is much greater than the PCI method. With a more accurate prediction of the shrinkage loss for the ACI 209 method it is assumed that the predicted and experimental values would be much closer.

Table 5 Shrinkage predictions for both ACI 209 and PCI methods

Day	ACI-209	PCI
Release	0.0	0.0
75	12.0	3.6
100	12.9	3.9
150	13.6	4.2
200	14.0	4.4
250	14.3	4.6
300	14.5	4.8
Ultimate	15.4	6.4

CONCLUSIONS

The following can be concluded from the experimental and analytical studies conducted so far:

- Total observed losses for the bridge girders were slightly less than those predicted by the current PCI design expressions.
- The girders containing SCC had slightly larger prestress losses and this can be attributed to a smaller modulus of elasticity of concrete for the SCC mixture.
- The prestress losses for the proposed SCC mixture are within the range of design guideline equations recommended by the PCI Design Handbook and no special design considerations need to be used when using this SCC mixture.
- The ACI 209 expression (Equation 3) overestimates the shrinkage for this proposed SCC mixture

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