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A Study of Elastic Shortening Losses of High-Strength Self-Consolidating Concrete Prestress Girders

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Abstract: A comprehensive literature review of prestress losses revealed that the elastic shortening loss contributes to approximately 45% of total prestress losses. This paper examines the accuracy of existing standards methods (AASHTO LRFD and PCI)to estimate the elastic shortening of high-strength self-consolidating concrete (HS-SCC) prestressed girders. The HS-SCC is an innovative concrete that has the benefits of self-consolidating concrete (SCC), a high flow and a strong stability. It also benefits from strength gained from high-strength concrete (HSC) mix constituents. A testbed (Bridge A 7957 on Route 50 in Osage County, Missouri, USA) was utilized in this study. Two different spans with lengths 120 ft (36.57 m) and 100 ft (30.48 m) were fabricated with different properties of HS-SCC and instrumented to monitor internal strains. Vibration wire strain gages (VWSGs) with integrated thermistors were embedded throughout the each girder's cross-section to measure the internal strains and temperatures. The results gathered indicate that AASHTO LRFD and PCI each underestimated the elastic shortening of prestress girders by 7% and 27% respectively. The measured elastic shortening losses were compared to a comprehensive experimental database that was assembledduring this study.

Keywords: Code Models, Elastic Shortening, High-Strength Self-Consolidation-Concrete

I. INTRODUCTION

Long service life and cost efficiency have become recently major concerns in a bridge structures. High-strength self-consolidating concrete (HS-SCC) could potentially be used to address these concerns. The HS-SCC is a new innovation that has been developed by civil engineers. It has all of the benefits of self-consolidating concrete (e.g., as flowability and stability) with the added benefit of increased strength. It is beneficial in cases that require a congested steel cross-section because it can pass and capsulate the steel reinforcement, even in congested steel areas [1].

Overtime, HS-SCC is a potential alternative to conventional high-strength concrete (HSC) because it develops compressive strength levels of a similar magnitude. ACI Committee 363 currently defines HSC as a concrete that has a minimum compressive strength of 8,000 psi (55.2 MPa) or higher. The HS-SCC type has modifications on material proportions (e.g., reducing content and size of coarse aggregate, and increasing in the paste volume to enhance fluidity). A question is raised here regarding SCC's constituent make-up and effect of fluidity on the structural behavior of HS-SCC. Differences in the engineering properties (e.g., time dependent losses and modulus of elasticity in the concrete structure applications) are examples of an area under investigation. The efficient design of prestressed concrete (PC) member needs to be understood.

Prestress losses are the losses that occur in the tensile stress of prestress steel. These loses affect a prestressed section's performance. The tensile force in the tendon does not remain constant from the recorded value in the jacking gauge. It changes with time. These losses are classified into two categories: immediate and either long-term or time-dependent. Immediate losses take place when prestressing the tendon and then transferring the prestress to the concrete member. Both the elastic shortening (ES) and anchorage slip are immediate losses. In contrast, losses produce by creep of the concrete (CR), shrinkage of the concrete (SH), and relaxation of the tendon (RE) are considered time-dependent losses.

Elastic shortening produces the most significant effect on prestress losses. The concrete undergoes ES when the prestressing force is transferred from the end blocks of the casting bed to the girder after the concrete has sufficiently hardened. The strands are now shortened and the tensile force in the tendons is reduced because the strands are bounded to the concrete. These losses can be a significant portion of the total prestress losses and should be accurately accounted for in the design process. Under-predicting prestress losses can result in cracking at service loads. Over-predicting prestress losses can result in an overly conservative design for service load stresses.

High strength-self consolidating concrete has recently been used to investigate empirical models for prestress losses. Myers and Bloch (2010) [2] instreamed two precast prestressed high-strength concrete (HSC) and high HS-SCC bridges in Missouri. The HSC bridge spans a length of 48 ft (14.6 m) and has a width of 10 ft (3.0 m). The HS-SCC spans a length of 34 ft (14.6 m) and has a width of 10 ft (3.0 m). A total of 32 vibrating wire strain gages (VWSGs) with built-in thermistors were installed in the beams and decks. Two data acquisition systems (DASs) were used to monitor both bridges. Myers and Bloch (2010) incorporated two commonly used loss estimate models (AASHTO and PCI) for calculating total Prestress losses. They found that the ES in the HSC and HS-SCC bridges was 31% and 34%, respectively, of the total prestress losses. They concluded that the AASHTO model overestimated the HS-SCC's ES. The PCI model underestimated the type of concrete's ES materials when the measured modulus of elasticity was used them in predicted model.

Brewe and Myers (2009) [3] conducted a study on six reduced scale HS-SCC prestressed girders. They used demountable mechanical strain gauges (DEMACs) to monitor prestress losses. The measured prestress losses were compared to different code models. They concluded that the ES represented approximately 42% of total prestress losses. Both the PCI Design Handbook method and the AASHTO LRFD 2012 refined method underestimated the HS-SCCs ES.

Ruiz et al. (2008) [4] instrumented 14 prestressed beams cast with 2 different HS-SCCs. These beams were 18 feet (5.5 m) long and had a 6.5 in. by 12 in. (165 mm by 304.8 mm) rectangular cross-section. Each beam contained two 0.6 in. (15 mm) Grade 270 low-relaxation prestressing strands [270 ksi (1860 MPa)]. The beams were instrumented with internal (VWSG) and external (Demec points) gages. Ruiz and his team found that the ES represented the largest portion of total prestress losses. They incorporated the AASHTO LRFD Refined Method to predict ES. The AASHTO LRFD Refined Method overestimated the ES loss.

II. BRIDGE DESCRIPTION

A7957 Bridge located on Highway 50 in Osage County, Missouri, USA (see Fig. 1) was constructed adjacent to bridge A3425 as part of a two lane expansion of the highway 50 in Missouri State. It has three continuous prestressed concrete spans, two exterior 100 ft (30.5 m) spans, and one interior 120 ft (36.6 m) span. Precast prestressed concrete panels extend between spans in the transverse direction below a cast-in-place concrete deck. Two intermediate bents and two abutments support the superstructure. Spans 2 and 3 of the HS-SCC Bridge were utilized in this study. Each span consisted of four precast-prestressed Nebraska University (NU53) girders. The girders prestressing forces were supplied by 0.6 in (15 mm) diameter Grade 270 [270 ksi (1860 MPa)] low-relaxation prestressing strands (38 strands were used for span 2 and 30 were used for span 3) . The D20 welded wire reinforcement (WWR) was provided for shear resistance at spacing intervals of 4 in., 8 in., and 12 in. (101.6, 203.2, and 304.8 mm, respectively) along the girder's length. The girders were designed as simply supported, but significant continuity steel was supplied at the interior pier supports to provide continuity for live-loading.

The high-strength self-consolidating concrete girders produced for Bridge A7957 Bridge were instrumented to obtain measured strain and temperature data. Vibrating wire strain gages were used within the NU girders to monitor the strain's behavior over time. The VWSGs were selected on the basis of their long-term stability and durability. Furthermore, they contain an integral thermistor for measuring temperature as well as strains [5]. A data acquisition system (DAS) was used to record data received from VWSGs. The VWSGs were embedded in a standard pattern on the bridge: at the mid-span and at the support of each of the instrumented girders. The standard pattern in the mid- span consisted of 5 gages over the height of the girder and 2 more in the slab above the girder.

Figure 1. Bridge A7957 (south view)

III. ELASTIC SHORTENING LOSS PREDICTION

Elastic shortening is the loss of prestress force that takes place when the strand becomes shorter. The forms are stripped and the prestressing strands are released after adequate strength is added to the casting bed. As a result, the concrete and strands shorten under the load. The ES loss comprise significant portion of the total prestress loss. Several methods of estimating ES losses have been proposed and are used by design engineers. AASHTO LRFDBridge Design Specification[6] and the PCI Design Handbook[7] provide models that are used to calculate ES. The most up-to-date models are summarized in Table 1.

Table 1. Code Models Used to Predict ES (Pretensioned Member)

Loss	AASHTO LRFD-2012 (ksi)	PCI, 2010 (ksi)
Elastic Shortening (Δf_{ES})	$\frac{E_p}{E_{ct}} f_{cgp}$ $f_{cgp} = \frac{P}{A_g} + \frac{Pe^2}{I_g} - \frac{M_{self}\, e}{I_g}$	$K_{es} \frac{E_{ps}}{E_{ci}} f_{cir}$ $f_{cir} = K_{cir}\left(\frac{P}{A_g} + \frac{Pe^2}{I_g}\right) - \frac{M_{self}\, e}{I_g}$
Conversion: 1000 psi = 6.895 MPa, 1 in=25.4 mm Here, $\mathbf{f_{cgp}}$is the stress in the concrete at the c.g. of the pretensioned strands at release (due to prestress and self-weight), fcir is the net compressive stress in the concrete at the c.g. at release, Ep both and Eps represent modulus of elasticity of prestressing steel, Ect both and Eci represent the modulus of elasticity of concrete at release, $\mathbf{K_{es}}$ is 1.0 for the pretention components, and $\mathbf{K_{cir}}$ is 0.9 for the pretensioned components.		

IV. RESEARCH PROGRAM

The program of this study was to examine the accuracy of existing standard methods to predicate the elastic shortening loss of HS-SCC' ES. Reported elastic shortening losses in the literatures was assembled and classified in this study. This database was used to validate the accuracy of existing standard methods to predicate HS-SCC' ES.

1. Concrete materials and test results

Spans 2 and 3 were designed with a compressive strength of 10,000 psi (68.9 MPa) and 8000 psi (55.2 MPa), respectively. The compresssive strength of span 2 was higher to accomodate the longer span length. The HS-SCC mixture (see Table 2) was specified typically for transportation project applications. A barrage of material tests was completed to obtain measured properties that were used to accurately predict prestress losses. Air content, slump flow, column segregation, and J-Ring flow tests were preformed before each girder was poured. Thirty 4 x 8 in. (100 x 200 mm) cylinders per girder were collected to conduct maturity studies on compressive strength at release, 7, 14, 28, and 56 days. All of the tests were performed according to ASTM guidelines. A summary of both the fresh and the hardened test results are displayed in Table 3 and Fig. 2.

Table 2. HS-SCC Mixture Proportions

Constituent	Quantity	
	Span 2 (lb/yd^3)	Span 3 (lb/yd^3)
Coarse Aggregate	1340	1476
Fine Aggregate	1433	1433
Cement (Type I)	850	750
Water	280	269
Air Entraining Agent	17.0 oz/yd^3	17.0 oz/yd^3
Mid- Range Water Reducer	76.5 oz/yd^3	67.5oz/yd^3
High Range Water Reducer	25.5 oz/yd^3	25.5 oz/yd^3

Table 3. The mixture's Rheological Properties

Rheological Properties	ASTM No.	S2-G4	S3-G3	S3-G4
Air (%)	C231	7.6	6	8.3
Slump Flow	C1611	26	26.5	26.5
J-ring	C1621	25	25.5	25.5
Local Temperature (°F)	---	76	74	78
Segregation Column, S (%)	C1610	0	n/a	0
Concrete Temperature (°F)	---	80	80	82

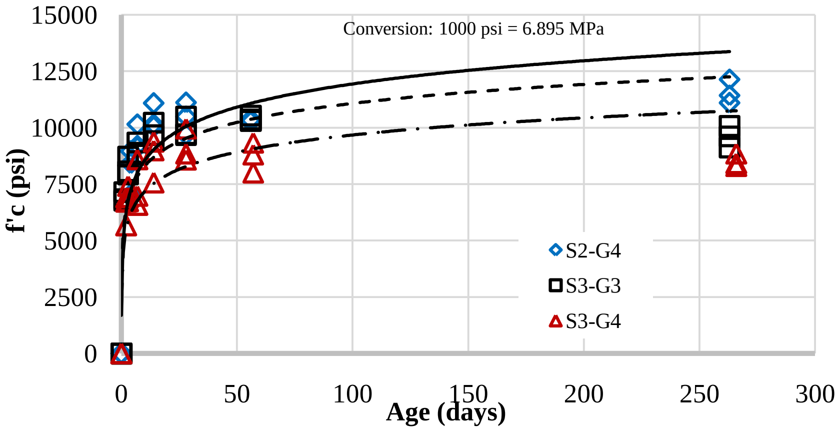


Figure 2. HS-SCC Compressive Strength Results

The ES losses were dependent on both the methodology and the modulus of elasticity (MOE) at transfer (E_{ci}). The measured modulus of elasticity was performed according to ASTM C469 [8]. The concrete's modulus of elasticity is affected by the aggregate, the cement paste matrix, the transition zone, and the testing parameters[4]. For concrete, there is a direct relation between the strength and the elastic modulus. Several models were developed based on concrete's strength. The modulus of elasticity test results for HS-SCC were compared to current empirical models from ACI 318 (2014) [9]for conventional concrete and ACI 363 [10](Equation 6-5 in ACI 363R-10 and ACI 363-97) for HSC displayed in equations (1), (2), and (3) consecutively. Measured material properties were used within these empirical models. The ACI 318-14 and ACI 316-10 equations in the majority of the tested data overestimated the modulus of elasticity. The ACI 363-97 equation was the lower bound predictor. The average modulus of elasticity, along with other collected data, was plotted against the square root of the compressive strength (see Fig. 3).

$$E_c = w_c^{1.5}\, 33\sqrt{f_c'}\text{(psi) (ACI 318-14)} \quad (1)$$

$$E_c = 4.86 * 10^6\, k_1 k_2 \left({}^{w_c}/_{150}\right)^2 \left({}^{f'_c}/_{8700}\right)^{1/3} \quad \text{(psi) (ACI 363-10} \quad (2)$$

$$E_c = 40{,}000\sqrt{f_c'} + 10^6 \quad \text{(psi)(ACI 363-97)} \quad (3)$$

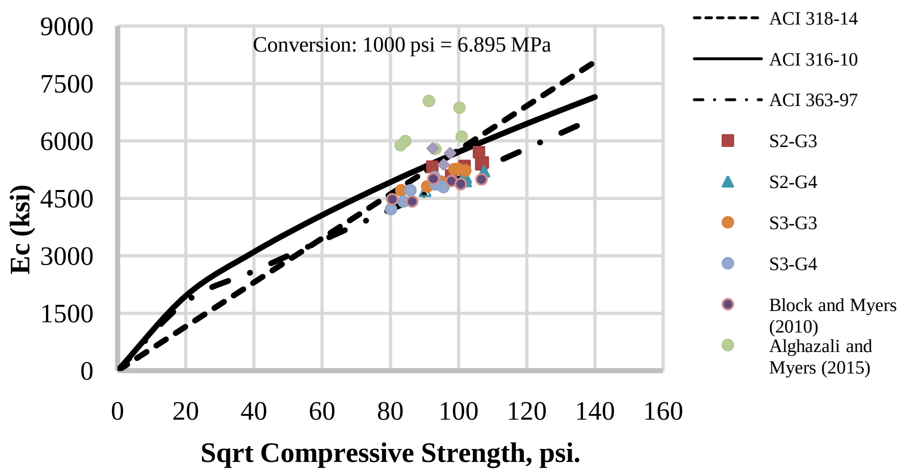
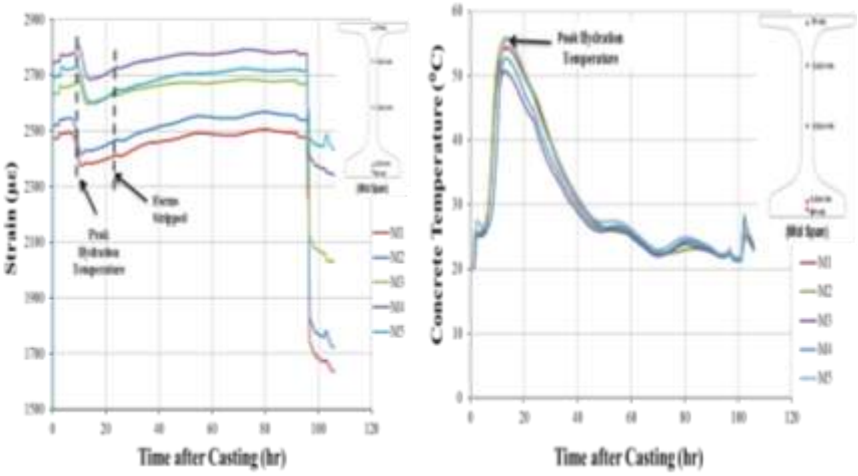


Figure3. Modulus of elasticity vs. compressive strength

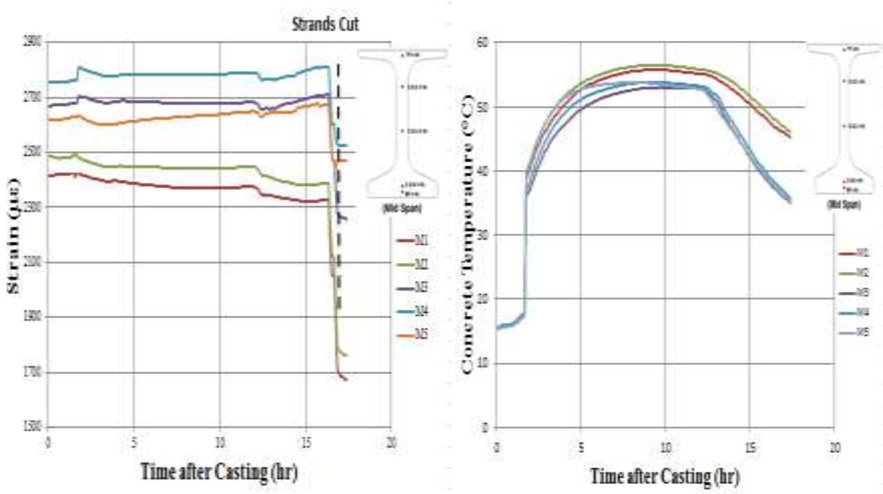
2. Measured Elastic Shortening Losses

Both concrete and strand experience instantaneous contraction when the prestress strands are released. The stress in the strand is reduced when the prestress force is transferred to the concrete. The VWSGs embedded in the concrete girder were utilized to measure ES as an indirectly measurement. These measurement were obtained by subtracting the strain reading immediately after release from the baseline strain measurement recorded just before release. The strains before and after release, as well as the concrete's temperature during this stage for all girders that were utilized in this investigation, are displayed in Fig. 4. Measurements were taken at the level of the strand's c.g.s. The measuring strain was corrected due to the thermal effect and multiplied by the modulus elasticity of the prestressing strands to calculate prestress losses as demonstrated in Equation (4) [11].

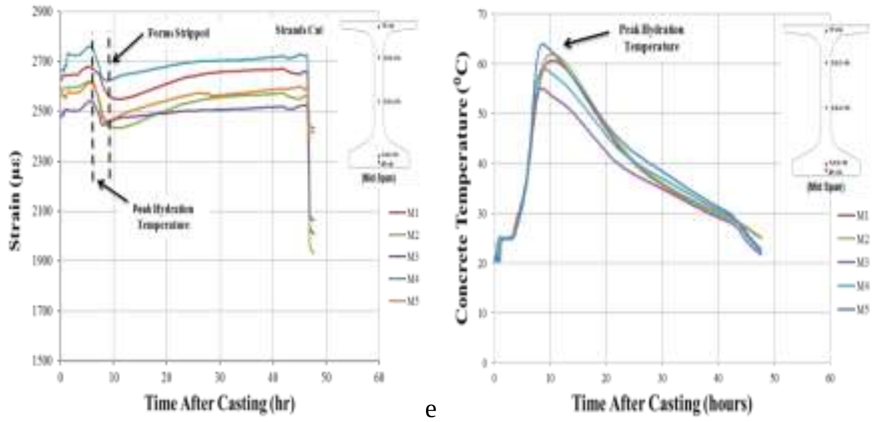
$$\Delta f_{P,Measured} = E_{ps}\,\varepsilon_{cgs} \quad \ldots\ldots\ldots\ldots(4)$$



a) Strain in S2-G4 b) Temperature in S2-G4



c) Strain in S3-G3 d) Temperature in S3-G3



e

e) Strain in S3-G4 f) Temperature in S3-G4

Figure4. Strains and temperatures at the HS-SCC girder's mid-span (before and after release)

3. Examination Elastic Shortening Code Models

The measured ES losses were compared to the predicted ES losses adopted by AASHTO LRFD (2012) and the PCI Design Handbook (2010) with the actual modulus of elasticity for HS-SCC. This comparison is summarized in Table 4. The measured ES value was typically higher than those predicted through either the AASHTO LRFD or the PCI methods. Both emprical expressions of AASHTO LRFD and PCI underestimated the measured ES when modulus of elasticity estimated using Eqs. 1, 2, and 3. Average differences between the measured and the AASHTO LRFD models were 19% and 22% using measured and estimated parameters, respectively, and 27% and 24 % average differences, respectively, when compared to the PCI Design Handbook model using measured and estimated parameters.

Table 4. Comparison Between ES Code Models Using Both Measured and Predicted Propeerties

Girder ID	E_{ci} (ksi)	ES Measured	Predicted ES				
			AASHTO LRFD 2012		PCI		
			Measured E_c	Estimated E_c (Eq. 1)	Measured E_c	Estimated E_c (Eq. 2)	Estimated E_c (Eq. 3)
S2-G4	4697	20.86	16.95	15.3	14.57	15.41	14.85
S3-G3	4706.7	17.24	14	13.74	12.13	13.56	13.19
S3-G4	4212.5	17.62	14	14.25	13.55	13.89	13.56

Conversion: 1000 psi = 6.895 MPa

4. Comparison with Previously Gathered Field Results

The measured ES losses gathered during this study were compared to those previously collected for 65 pretensioned girders and beams. The previously collected results represent a wide range of environmental conditions, concrete mechanical properties, curing regimes, and geometries. This variety created a challenge when attempting to compare previously collected data with recently collected data. A ratio of ES loss to total prestress losses was utilized to compare the results and address this challenge.

The collected data was classified into three groups according to concrete type. A group with 18 pretensioned girders represented a high strength concrete with a compressive strength above 8000 ksi (55.2 MPa). A second group represented the results of high performance concrete with 24 field study results. The rest of 65 data represent the results of high-strength self-consolidating concrete. This classification was used to determine whether or not the results gathered for the HS-SCC members contained a high variance. ES to total prestress loss ratio was calculated for each group. The coefficients of variance were calculated for each group of data. The HS-SCC members had a lower coefficient of variance (17.8%) than either the high performance concrete or HSC. The HPC and HSC coefficients of variance were 18.08 and 18.18 %, respectively, as indicated in Tables 5, 6, and 7.

In order to examine the accuracy of code models adopted by AASHTO LRFD and PCI, the measured ES losses were compared to predicted ES losses. Either the measured or estimated parameter was used to predict ES loss. Not all researchers [2], [3], [4], [5], [13], [14],[15], [16],[17], [18], [19], [20]compared the measured data with the estimated. Thus, only a portion of the data was used. Additionally, several studies failed to report all of the information needed to calculate ES loss with AASHTO LRFD and PCI. The R^2 values representing the degree of scattering to the mean line of predicted to measured ratio were higher when the measured parameter was used to predict ES for both the AASHTO LRFD and the PCI code models (see Fig. 5). In contrast, the AASHTO LRFD and PCI code models had a lower R^2 when estimated parameters were used to estimate ES losses. Even though the data base is somewhat limited, Tables 5, 6, and 7 show that the HS-SCC ratio losses (ES/T losses) within the trends of high strength concrete losses. There is no apparent significant different in the HS-SCC's ES losses. This point can give the infrastructure's designer a reasonable base to start to use the HS-SCC in different structural applications.

No.	Source	Concrete Type	Ag (in^2)	L (ft)	f'c (ksi)	Ec (ksi)	Age at Final (day)	ES loss (ksi)	Total Prestrss Loss (ksi)	ES/T losses (%)	Comments
1	NCHRP 496 (Nebraska G1)	HSC	903.8	127	9.025	5088	470	17.02	31.96	53.3	Measured E_c
2	NCHRP 496 (Nebraska G2)	HSC	903.8	127	9.025	5088	469	16.5	35.65	46.3	Measured E_c
3	NCHRP 496 (New Hampshire G3)	HSC	875.2	110	10.05	5396	490	25.17	43.51	57.8	Measured E_c
4	NCHRP 496 (New Hampshire G4)	HSC	875.2	110	10.05	5369	490	24.42	42.33	57.7	Measured E_c
5	NCHRP 496 (Texas G7)	HSC	1121	129.2	10.67	7395	400	12.88	25.35	50.8	Measured E_c
6	NCHRP 496 (Washington G18)	HSC	972	159	10.28	6114	380	27.62	42.06	65.7	Measured E_c
7	NCHRP 496 (Washington G19)	HSC	972	159.8	10.28	6114	380	25.49	39.98	63.8	Measured E_c
8	Gross et al. (1998) (W14)	HSC	788.4	128.96	10.13	5630	772	13.94	34.67	40.2	Measured E_c
9	Gross et al. (1998) (W15)	HSC	788.4	128.96	10.13	5630	772	14.73	34.41	42.8	Measured E_c
10	Gross et al. (1998) (W16)	HSC	788.4	128.96	10.13	5630	772	12.18	32.68	37.3	Measured E_c
11	Gross et al. (1998) (W17)	HSC	788.4	128.96	10.26	5360	767	12.8	30.51	42.0	Measured E_c
12	Myers et al. (2010) (HSC)	HSC	888	48	12.231	4538	365	3.054	9.84	31.0	Measured E_c
13	Roller et al. (2011) (S43)	HSC	1105	131.2	10.85	6100	651	19.56	35.07	55.8	Measured E_c
14	Trejo et al. (2008) (CC-R)	HSC	276	40	8.95	5500	130	6.61	11.5	57.5	Approximated E_c
15	Trejo et al. (2008) (CC-L)	HSC	276	40	9.19	5500	130	11.4	20.9	54.5	Approximated E_c
16	Ruiz et al. (2008) (HSC-3)	HSC	78	18	12.52	6952	265	15.9	28.6	55.6	Calculated E_c
17	Ruiz et al. (2008) (HSC-5)	HSC	78	18	10.7	6315	258	12.5	22.8	54.8	Calculated E_c
18	Ruiz et al. (2008) (HSC-6)	HSC	78	18	13.1	7155	258	12.7	23.8	53.4	Calculated E_c

Table 5. Summary of HSC Prestress Losses Taken from Previously Reported Studies

Table 6. Summary of HPC Prestress Losses Taken from Previously Reported Studies

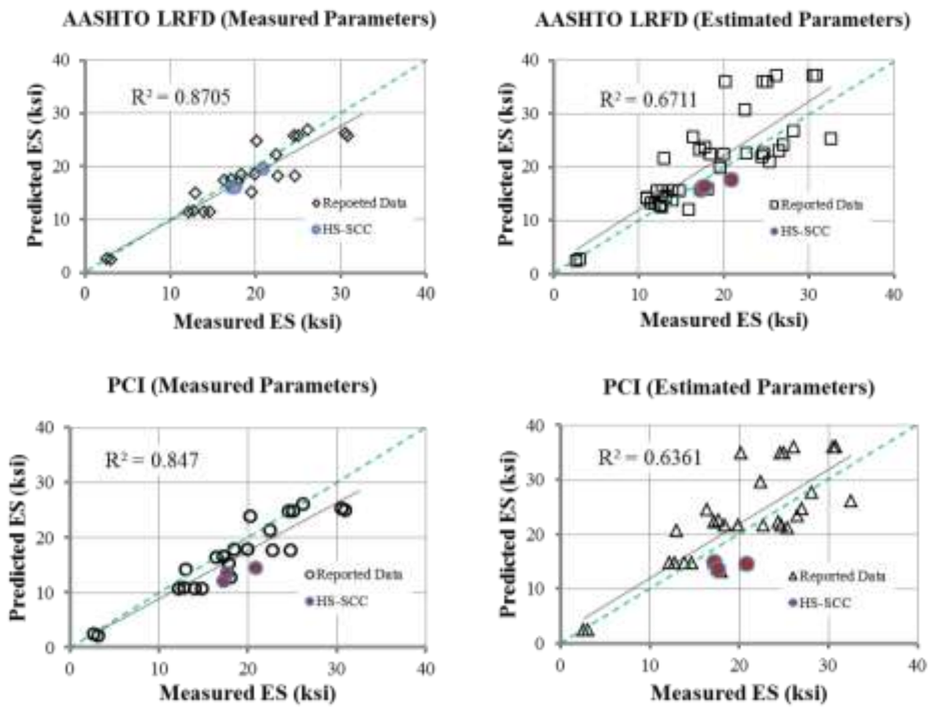
No.	Source	Concrete Type	Ag (in^2)	L (ft)	f'c (ksi)	Ec (ksi)	Age at Final (day)	ES loss (ksi)	Total Prestrss Loss (ksi)	ES/T losses (%)	Comments
19	Gross et al. (1998) (N32)	HPC	1120	134.18	13.63	5730	762	17.75	43.11	41.2	Measured E_c
20	Gross et al. (1998) (S15)	HPC	1120	119.44	14.32	6680	749	16.38	37.86	43.3	Measured E_c
21	Gross et al. (1998) (S16)	HPC	1120	121.02	13.29	6930	1263	17.16	40.26	42.6	Measured E_c
22	Gross et al. (1998) (S25)	HPC	1120	133.4	13.41	6460	1222	12.96	33.81	38.3	Measured E_c
23	Gross et al. (1998) (E13)	HPC	788.4	128.95	13.7	6460	423	25.03	50.61	49.5	Measured E_c
24	Gross et al. (1998) (E14)	HPC	788.4	128.95	13.7	6460	423	24.58	57.24	42.9	Measured E_c
25	Gross et al. (1998) (E24)	HPC	788.4	153.34	14.24	5560	405	20.19	51.51	39.2	Measured E_c
26	Gross et al. (1998) (E25)	HPC	788.4	153.34	14.83	6540	747	22.46	51.95	43.2	Measured E_c
27	Gross et al. (1998) (E34)	HPC	788.4	146.32	13.75	5680	317	30.86	57.43	53.7	Measured E_c
28	Gross et al. (1998) (E35)	HPC	788.4	146.32	14.49	6490	310	30.52	58.17	52.5	Measured E_c
29	Gross et al. (1998) (E44)	HPC	788.4	145.67	14.55	6110	306	26.15	55.63	47.0	Measured E_c
30	Myers et al. (2004) (B13)	HPC	310.6	50.26	11.647	6775	601	22.68	42.21	53.7	Measured E_c
31	Myers et al. (2004) (B14)	HPC	310.6	50.26	11.647	6775	601	24.72	42.79	57.8	Measured E_c
32	Myers et al. (2004) (B23)	HPC	310.6	55.18	12.808	6534	613	19.94	43.72	45.6	Measured E_c
33	Myers et al. (2004) (B24)	HPC	310.6	55.18	12.808	6534	613	18.37	39.05	47.0	Measured E_c
34	Barr et al. (2000) (1A)	HPC	747	80	10	5700	200	10.6	33.36	31.8	Designed f'_c and E_c
35	Barr et al. (2000) (1C)	HPC	747	80	10	5700	200	10.1	32.34	31.2	Designed f'_c and E_c
36	Barr et al. (2000) (2A)	HPC	747	137	10	5700	200	28	53.52	52.3	Designed f'_c and E_c
37	Barr et al. (2000) (2B)	HPC	747	137	10	5700	200	26.25	49.75	52.8	Designed f'_c and E_c
38	Barr et al. (2000) (2C)	HPC	747	137	10	5700	200	28.13	60.63	46.4	Designed f'_c and E_c
39	Waldron et al. (2004) (B1)	HPC	788.4	82.3	8	4583	890	26.5	36.9	71.8	Measured E_c
40	Waldron et al. (2004) (B2)	HPC	1013	64	8	NR	650	15.7	30.6	51.3	(2.4 RE assumed)
41	Waldron et al. (2004) (B3)	HPC	1013	64	10	NR	650	15.7	30.3	51.8	(2.9 RE), ES of first beam used
42	Waldron et.al. (2004) (B4)	HPC	746.7	62	8.7	NR	400	15.7	33.8	46.4	(3 RE assumed), ES assumed depends on first beam

NR – not reported

Table 7. Summary of HS-SCC Prestress Losses Taken from Previously Reported Studies

No.	Source	Concrete Type	Ag (in^2)	L (ft)	f'c (ksi)	Ec (ksi)	Age at Final (day)	ES loss (ksi)	Total Prestrss Loss (ksi)	ES/T losses (%)	Comments
43	Myers et al. (2010) (HS-SCC)	HS-SCC	726	34	10.131	4872	365	2.615	7.691	34.0	Measured E_c
44	Paul et al. (2009) (G1A)	HS-SCC	1085	132.2	12.836	5510	300	18.33	29.8	61.5	Measured E_c
45	Paul et al. (2009) (G1B)	HS-SCC	1085	132.2	12.836	5510	300	19.16	29.8	64.3	Measured E_c
46	Paul et al. (2009) (G1C)	HS-SCC	1085	132.2	12.836	5510	300	16.57	29.8	55.6	Measured E_c
47	Paul et al. (2009) (G3A)	HS-SCC	1085	82.2	12.836	5510	210	8.48	16.1	52.7	Measured E_c
48	Paul et al. (2009) (G3B)	HS-SCC	1085	82.2	12.836	5510	210	10.02	16.1	62.2	Measured E_c
49	Paul et al. (2009) (G3C)	HS-SCC	1085	82.2	12.836	5510	210	8.98	16.1	55.8	Measured E_c
50	Trejo et al. (2008) (SCC-R)	HS-SCC	276	40	11.66	6000	130	7.09	12.6	56.3	Approx.E_c
51	Trejo et al. (2008) (SCC-L)	HS-SCC	276	40	11.8	6000	130	10.7	17.1	62.6	Approx.E_c
52	Kukay et al. (2007)	HS-SCC	788.4	89.25	11.5		300	9.23	23.2	39.8	Average of 4 girders SCC
53	Ruiz et al. (2008) (SCCI-3)	HS-SCC	78	18	11.32	6536	290	11	25.1	43.8	Calc. E_c
54	Ruiz et al. (2008) (SCCI-5)	HS-SCC	78	18	11.42	6571	286	11	21.3	51.6	Calc. E_c
55	Ruiz et al. (2008) (SCCI-6)	HS-SCC	78	18	11.74	6680	286	13.2	24.1	54.8	Calc. E_c
56	Ruiz et al. (2008) (SCCI-7)	HS-SCC	78	18	11	6422	274	11.5	24.6	46.7	Calc. E_c
57	Ruiz et al. (2008) (SCCI-8)	HS-SCC	78	18	12.03	6785	274	12.1	23.5	51.5	Calc. E_c
58	Ruiz et al. (2008) (SCCIII-3)	HS-SCC	78	18	10.34	6186	270	13.2	28.2	46.8	Calc. E_c
59	Ruiz et al. (2008) (SCCIII-5)	HS-SCC	78	18	12.89	7079	255	14	28.2	49.6	Calc. E_c
60	Brewe and Myers (2010) (1)	HS-SCC	66	15	9.026	4635	NR	28.17	66.5	42.4	Measured E_c
61	Brewe and Myers (2010) (2)	HS-SCC	69	15	9.026	4635	NR	32.6	70.7	46.1	Measured E_c
62	Brewe and Myers (2010) (3)	HS-SCC	72	15	9.026	4635	NR	27	64.5	41.9	Measured E_c
63	Brewe and Myers (2010) (4)	HS-SCC	75	15	9.026	4635	NR	26.5	62.9	42.1	Measured E_c
64	Brewe and Myers (2010) (5)	HS-SCC	78	15	9.026	4635	NR	25.5	67.4	37.8	Measured E_c
65	Brewe and Myers (2010) (6)	HS-SCC	81	15	9.026	4635	NR	21.6	57.7	37.4	Measured E_c

NR – not reported



* HS-SCC data represents the results taken from Bridge A7957.
Conversion: 1000 psi = 6.895 MPa

Figure 5. Comparison between the ES code models using measured and predicted properties

V. CONCLUSION

The accuracy of code models when predicting ES of HS-SCC PC/PS girders was examined. Three HS-SCC girders with different properties were instrumented and monitored for prestress losses. The measured values of ES were compared with the AASHTO LRFD and PCI models using both measured and predicted properties. The HS-SCC girders' ES was then compared to the data previously recorded in the literature. The following conclusions can be drawn from the results gathered during the study:

- Both the current AASHTO LRFD and the PCI models underestimated the HS-SCC girder's average ratio of ES.
- The AASHTO LRFD model underestimated the ES by 7%. It was, however, close to the measured value when the measured parameter properties were used in the predicted model.
- The PCI model was not as accurate as the AASHTO LRFD when estimating HS-SCC's ES. The PCI model underestimated the ES by 27% when the HS-SCC's measured parameter properties were utilized.
- Using the estimated modulus of elasticity to predict ES for both the AASHTO LRFD and the PCI expressions increased the degree of scattering to mean line of predicted to measured ratio (R^2).
- Data reported during previous studies indicated that the ES represented more than 45% of the total prestress losses.
- The HS-SCC had a lower coefficient of variance (COV=17.8) than did either the high performance concrete (COV=18.08) or the high strength concrete (COV=18.18).
- These code models can be modified for the HS-SCC material properties, which would improve the accuracy of prestress loss predictions. Additionally testing is needed, however, to expand the present database and confirm that this modification would be successful.
- The HS-SCC ratio losses (ES/T losses) within the trends of high strength concrete losses and there is no significant different in the HS-SCC's ES losses.

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