SP-247—7

Experimental Study of Prestress Land and Camber in High-Strength SCC Beams

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Synopsis: An experimental program was developed to investigate the time-dependent behavior of prestressed concrete beams constructed with high-strength self-consolidating concrete (SCC). The study involved eight concrete T-beams, each prestressed with a single deformed wire. Four of the beams were cast with high-strength self-consolidating concrete, while the other four were cast with conventional high-strength concrete. Half of the beams were loaded with a sustained load 29 days after release while the other half of the beams were kept unloaded. Testing consisted of monitoring concrete and reinforcement strains, prestress losses, and beam camber for a period of 300 days after release. Elastic modulus, creep, and shrinkage tests were simultaneously conducted on companion cylinder specimens to better define the material properties of the two mixes used in the study. Results showed that the time-dependent behavior of the high-strength SCC beams was inherently similar to that of the conventional high-strength concrete beams. However, the measured time-dependent prestress losses and camber were significantly greater for the self-consolidating high-strength concrete. Complex prediction methods that are flexible enough to consider the actual material properties of the SCC or HSC were found to do the best job of predicting results.

Keywords: camber; creep; high-strength concrete; prestress loss; prestressed; self-consolidating concrete; shrinkage

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INTRODUCTION

Self-consolidating concrete (SCC) may be defined as 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, all without the need for external vibration (PCI SCC Fast Team, 2003). SCC was first developed in the 1980's in Japan (Okamura 1997) and has garnered much interest by researchers and fabricators in the United States over the last several years because of the wide range of potential benefits it presents. Such benefits include faster construction time, a reduction in labor requirements, reduced noise levels during fabrication, better surface finishes, and improved durability (EFNARC 2002). However, the implementation of SCC has been slowed because of lingering questions regarding its short- and long-term performance in actual structures. For example, there is no consensus regarding the time-dependent performance of prestressed concrete members constructed using SCC, with respect to prestress losses and camber (deflection).

Self-consolidation is generally achieved by developing concrete mixture proportions that utilize a reduced coarse aggregate fraction, an increased paste content, and appropriate use of admixtures to achieve a highly flowable yet viscous fresh concrete that resists segregation. The reduced coarse aggregate fraction is of particular interest when considering prestressed concrete since this can result in a lower concrete stiffness and less dimensional stability over time. This decreased initial stiffness and greater time-dependent deformation would be expected to result in higher prestress losses and beam camber in prestressed concrete beams utilizing SCC.

At the same time, the different material characteristics of high-strength concrete (HSC) as compared to conventional concretes also impact prestress losses and camber. It is generally accepted that higher-strength concretes exhibit higher elastic moduli and lower creep deformations than conventional concretes. As the use of HSC became widespread in highway bridge structures over the past decade because of benefits such as longer span lengths and larger girder spacing, numerous studies were conducted to investigate prestress losses and beam camber in actual HSC bridge girders (Roller et al. 1995; Ahlborn et al. 2000; Gross and Burns 2000a; Huo and Tadros 2000; Stallings et al. 2003; Waldron 2004). In general, these studies showed that prestress losses and camber are highly dependent on the material properties of the specific concrete mixtures used in each project. Prestress losses and camber could be predicted to a reasonable degree of accuracy when using flexible prediction models that allow for the use of those specific material properties as input parameters. However, since most prediction models in existence at the time were relatively inflexible in terms of material properties, prestress losses and beam camber were often significantly overestimated by common prediction models. Eventually, these research studies led to the establishment of a National Cooperative Highway Research Program (NCHRP) study aimed at developing more flexible prestress loss prediction models that could be used for both conventional and high-strength concrete (Tadros et al. 2003).

The purpose of the experimental work discussed in this paper is to investigate the time-dependent prestress loss and camber of prestressed beams constructed using concrete that is both high-strength and self-consolidating. Clearly, the observed results will be greatly influenced by the concrete material properties of the SCC. The experimental work thus consists of a time-dependent monitoring program on a series of prestressed beams, as well as a parallel test program to investigate the material properties of the concretes used in fabricating the beams.

REVIEW OF PREVIOUS RESEARCH

While numerous research studies have reported the fresh and hardened concrete properties of various SCC mixes, only a few recent studies have investigated the long-term performance of prestressed concrete flexural members constructed with SCC. Even fewer studies have examined the performance of high-strength SCC. The results of these studies differ in their conclusions regarding prestress losses and camber.

Larson (2006) instrumented seven 45 in. (1.14 m) deep SCC I-girders and four companion conventional concrete girders in a Kansas highway bridge. Measured 28-day compressive strengths were approximately 6000 psi (41 MPa). Measured prestress losses for both sets of girders were found to be well less than estimated using a variety of prestress loss methods. Prestress losses in the SCC girders were significantly higher than for the conventional concrete girders due to the lower elastic modulus of the SCC.

Naito et al. (2006) monitored two SCC and two conventional high-strength concrete PCI bulb tee girders over a 28-day period after release. The target release and 28-day strengths for all four girders were 6000 and 8000 psi (41 and 55 MPa), respectively. Based on tests of companion cylinders, the elastic modulus of the SCC mix was found to be lower than for the conventional high-strength mix, and the creep and shrinkage characteristics of the SCC mix were found to be higher. However, lower elastic shortening, creep, and shrinkage losses were observed in the SCC girders than in the HSC girders. Measured losses were lower than predicted for all specimens.

Zia et al. (2005) compared the performance of three 5000 psi (34 MPa) AASHTO Type III girders, two constructed using SCC and one using conventional concrete. The measured moduli of elasticity were similar for the mixes, resulting in comparable initial camber measurements after release of prestress. However, the SCC girders exhibited more camber growth while in storage. In a similar study, Labonte and Hamilton (2005) compared the performance of six 8000 psi (55 MPa) AASHTO Type II girders, three constructed using SCC and three using conventional high-strength concrete. Little difference in camber was observed among the beams over 200 days.

EXPERIMENTAL PROGRAM

An experimental program was designed to investigate the time-dependent loss of prestress and change in camber of pretensioned concrete beams constructed with high-strength self-consolidating concrete. The specific objectives were to (1) directly compare the behavior of beams constructed with high-strength self-consolidating concrete (SCC) to the behavior of otherwise identical beams constructed with conventional high-strength concrete (HSC), and (2) compare the measured prestress loss and camber of both sets of beams to estimations obtained using existing prediction models found in the literature.

Test specimen design

Eight identical concrete T-beams were used in the study, each measuring 5.5 in. (140 mm) in depth. Each beam was constructed 124 in. (3.15 m) long to allow for testing on a 120 in. (3.05 m) span. Each beam was prestressed with a single 0.208 in. (5.3 mm) diameter deformed high-strength steel wire positioned 0.85 in. (22 mm) above the base of the beam. The cross-sectional area, modulus of elasticity, and ultimate tensile strength of the steel wire as reported by the material supplier were 0.034 in.^{2} (22 mm^2), 269 ksi (1.85 GPa), and 29000 ksi (200 GPa), respectively. The cross-section detail is shown in Fig. 1.

Design parameters and cross-section dimensions were carefully chosen to be reasonably representative of full-scale pretensioned beams while considering laboratory space and specimen handling limitations. A T-shape was chosen to facilitate placement of sustained dead load blocks during beam storage, and a span-to-depth ratio in the range of 20 to 25 was desired. Design iterations were conducted until acceptable stress conditions at both release and service were achieved, with a target condition of zero stress at the bottom (extreme tensile) fiber at service considered most important. Stress calculations for the final beam design are provided by Gaynor (2005).

The eight test specimens were split into two groups as summarized in Table 1. Four of the beams were cast with conventional high-strength concrete (identified by the label HSC), and four were cast with high-strength self-consolidating concrete (identified by the label SCC). Beams were fabricated in four pairs, with each pair consisting of two beams of the same concrete type. One beam per pair (beam A) was left in an unloaded condition and subjected only to its self-weight and the effects of the prestress force, while the other beam (beam B) was loaded with a sustained service load 29 days after release.

Concrete material properties

Both HSC and SCC concretes were designed to have a target 2-day release compressive strength of 6000 psi (41 MPa) and a target 28-day compressive strength of 8000 psi (55 MPa). Concrete mixture proportions were developed through a trial batching process in the laboratory, with consideration given to both fresh and hardened concrete properties. Passing ability, filling ability, and segregation resistance of the SCC mixes were evaluated using the slump flow and Kajima box ("Fill-box") tests. Final mixture proportions for both concretes are given in Table 2. Both concretes utilized ¾ inch (19 mm) maximum nominal size aggregate, Type III (high early strength) cement, 7 to 8 percent silica fume replacement of cement (by weight), and a high-range water reducing admixture (HRWR). However, the SCC mixture utilized a much smaller proportion of dry-rodded coarse aggregate by volume, 45% as compared to 67% for the HSC, and required a viscosity-modifying admixture (VMA) to improve segregation resistance.

All concrete used in fabricating the actual test beams was mixed in the laboratory's 12.5 ft^3 (0.35 m^3) capacity drum mixer, such that a single batch was required for each beam pair. Fresh concrete properties including air content, unit weight, slump (HSC), slump flow (SCC), and filling capacity (SCC) were measured for each batch using the appropriate tests. Companion 4 by 8 in. (100 by 200 mm) cylinders were cast for each beam pair and used to determine compressive strength and elastic modulus at release and 28 days. Cylinders were cast in plastic molds and cured alongside the beams for the first 24 hours. Thereafter, the cylinders were demolded and cured alongside the beams until testing to ensure that they were exposed to the same environmental conditions. Fresh and hardened concrete properties are reported in Table 2. It is noteworthy that the elastic modulus of the SCC mix at 28 days is about 22% lower than that of the HSC mix.

Companion creep and drying shrinkage tests were also conducted on 4 in. (100 mm) diameter cylinders constructed using the two mixes. One 28 in. (710 mm) long cylinder of each type was placed under a sustained load corresponding to 30% of its ultimate strength at 3 days, while a second cylinder of each type was left unloaded. Shrinkage measurements were obtained by recording the change in strain of the unloaded cylinders, while creep measurements were obtained using the change in strain of the loaded cylinders after compensating for strains observed in the unloaded cylinder. Shrinkage and creep test results are shown in Figures 2 and 3, respectively. Shrinkage results are reported for 28 days, while creep results are reported for 54 days. Regression analyses were conducted to determine the best-fit mathematical equations for shrinkage and creep of each material using equations of the form suggested by ACI 209 (ACI 1992). Corrections were then applied for average relative humidity and volume-to-surface ratio in accordance with ACI 209 such that the equations correspond to "normal" conditions as defined by ACI 209. The final model equations, which consist of a time function multiplied by an ultimate shrinkage strain or creep coefficient, are given in Table 2. The projected ultimate shrinkage strains and creep coefficients are 27% and 17% higher, respectively for the SCC mix than for the HSC mix. Additional details on these companion tests are provided by Gaynor (2005).

Beam fabrication

Beams were fabricated in the laboratory on parallel prestressing beds. After the side forms for each beam were positioned, the prestressing wire was stresssed to approximately 6.0 kips (26.7 kN) using a pair of hydraulic cylinders and a hand pump. A load cell was positioned at the dead (non-stressing) end of each bed for verification of the prestressing force. Actual jacking stresses for each beam may be found in Table 3. After the target load was reached, it was locked in and maintained using nuts and threaded rods at the live (stressing) end of each bed. The end forms for the beam were then positioned and the concrete was mixed in the laboratory's mixer and placed into the forms. The HSC beams were vibrated to achieve full compaction, but the SCC beams did not require vibration. A pair of test specimens on the prestressing beds shortly after concrete placement and finishing may be seen in Fig. 4.

A single resistance-based bonded strain gage was installed on the prestressing wire at midspan prior to stressing. Formwork was removed from the beams approximately 24 hours after casting to allow for installation of additional instrumentation on the surface of the concrete beams at midspan. The additional instrumentation included two resistance-based bonded strain gages applied to the concrete surface on opposite sides of the web, each at the depth of the prestressing wire, as well as one gage on the top surface of the beam and one gage at the centroidal depth of the cross-section on one side of the web. These locations may be seen in Fig. 1. A manual deflection measurement system, composed of a precision scale fixed to the beam at midspan and fixed wire guides at each end of the beam, was also installed at this stage. The components of this system are shown in Fig. 5. The use of this system allowed for the upward camber of the beam at midspan, relative to the chord connecting the two beam ends, to be measured simply and precisely with a tensioned wire.

Approximately 48 hours after casting, after verification of adequate concrete compressive strength via tests of companion cylinders, the prestress force was released to the beams. This was accomplished by first loosening the locking nuts at the live end of each bed and then gradually reducing the hydraulic pressure in the system. Full release of prestress typically required about 60 seconds. Strain measurements were recorded continuously from stressing through release using the laboratory's data acquisition system. Deflection scale measurements were recorded just before release to establish the baseline reading, and again just after complete release of prestress to determine the upward beam camber at release.

Long-term measurements

Long-term measurements involved the monitoring of concrete and reinforcement strains, and beam camber for a period of 300 days after release. Immediately after the completion of post-release measurements, each beam was moved to an environmental enclosure for long-term storage and monitoring. The enclosure was designed to minimize severe fluctuations in ambient temperature and relative humidity during the test program, and a consisted of heavy-duty polyethylene sheeting supported by a dimensional lumber framework. A humidifier was used to maintain the relative humidity within the enclosure between 50 and 70 percent. Inside the enclosure, beams were placed on roller supports fixed to the tops of concrete masonry walls. Additional threaded rod supports, which can be seen in Fig. 5, were also installed to support the flange at each end and ensure the stability of the beam. The supported beams can be seen within the enclosure in Fig. 6.

Strain gages and their associated cables were kept connected to the data acquisition system during the movement of the beams into the storage enclosure. Immediately after the placement of each beam in its final position, a linear variable displacement transducer (LVDT) was placed directly under midspan and connected to the data acquisition system. All instrumentation was then monitored continuously over the duration of the storage period.

Four of the eight beams were loaded with a sustained service load of 530 lb (240 kg) at 29 days after release. Concrete masonry units were filled with pea gravel to achieve the exact load. The load was transferred to the top flange of each beam through two wood supports centered one foot (0.3 m) to each side of midspan, as shown in Fig. 7. A small gap exists between each beam and between the loading arrangements above each beam such that each beam is loaded independently of the others.

RESULTS

Pre-release

Strain measurements on the steel prestressing wire at jacking (stressing) served as a backup to the load cell for verification of the correct prestress jacking force. However, continuous measurements over the two-day period between jacking and release also revealed significant changes in steel strain occurring over this time period. In fact, a significant net decrease in strain (between jacking and release) was measured for all eight beams. Similar observations were reported by Gross and Burns (2000b) for high-strength concrete beams monitored in the field. Such a decrease in steel strain over this period would cause a loss of prestress, resulting in a lower effective prestress at release.

These strain changes can be attributed to variations in strand temperature over this time period and volume changes in the concrete during hydration. Unfortunately, modeling of these effects is complicated by factors such as the development of bond between the concrete and steel wire and the restraint provided by the formwork and casting bed. Because of the difficulty in defining such factors, and the high degree of variability in measured strain changes observed in this study, a simple estimate of 3.5 percent prestress loss prior to release (relative to the jacking stress) was used in appropriate calculations throughout this study. This estimate also includes consideration of relaxation of the steel wire over the two day period between jacking and release.

Release

Concrete and steel strains resulting directly from the release of prestress were obtained by taking the difference between strain measurements recorded immediately before and immediately after release. These strains from the five gages identified in Fig. 1 are plotted as a function of depth for beam SCC2A in Fig. 8 to show a typical strain profile resulting from release. Note the linear strain profile indicating that plane sections remain plane, as well as the small tensile strain at the top fiber of the beam. This tensile strain was observed in all beams, with measured values ranging from a low of 16 millionths to a high of 39 millionths. The highest tensile strain occurred in beam SCC1B, and corresponds to a tensile stress of approximately 200 psi (1.4 MPa), or $2.5\sqrt{f'_{ci}}$ based on the measured elastic modulus of the concrete at 2 days. No flexural cracking was observed in any of the beams at release as a result of these small tensile strains.

The loss of prestress due to elastic shortening of the concrete beam at release can be determined by taking the measured strain change at release, at the depth of the steel prestressing wire, and multiplying this value by the modulus of elasticity of the prestressing steel. Prestress loss values calculated in this manner are reported in Table 3. The tabulated strain changes are taken by averaging the measurements recorded by all three gages at the depth of the prestressing wire, including the two concrete gages on either face of the web and the gage on the steel wire itself (gages 1, 2, and 5 in Fig. 1). Losses within each group of four beams separated by concrete type can be seen to be relatively consistent. However, the average elastic shortening loss for the SCC beams is about 3.6% of the jacking stress on average, which is 37% higher than the average of 2.6% of the jacking stress for the HSC beams.

Measured camber at release is reported for all beams in Table 4. The release camber represents the algebraic combination of the upward deflection caused by the prestress force and the downward deflection resulting from the self-weight of the beam. Release cambers were about 19% higher on average for the SCC beams than for the HSC beams. The average release cambers for the SCC and HSC beams were 0.125 in. (3.2 mm) and 0.105 in. (2.7 mm), respectively.

Elastic behavior due to loading

The application of sustained load (in half of the beams) caused an immediate tensile strain (decrease in net compressive strain) in the concrete at the level of the steel wire, which in turn led to an increase in effective prestress. This gain in prestress can be easily computed in a manner similar to that used to measure elastic shortening losses, wherein the average change in strain at the level of the wire is multiplied by the elastic modulus of the steel. The average prestress gains in the loaded SCC beams and loaded HSC beams were 4.9 and 4.0 ksi (34 and 28 MPa), respectively. The average prestress gain is thus 24% higher in the SCC beams than in the HSC beams.

Measured deflections resulting from initial application of the sustained load are reported in Table 4. The average elastic deflection for the loaded HSC beams was 0.083 in. (2.1 mm). The average elastic deflection for the loaded SCC beams was 0.095 in. (2.4), which is 14% higher than for the HSC beams.

Time-dependent behavior

Time-dependent prestress losses occurred over the duration of the test program as a result of creep and shrinkage of concrete and relaxation of the steel prestressing reinforcement. Losses related to creep and shrinkage occurring after release were measured directly using the same technique as that used for computing losses due to elastic shortening and initial application of the sustained load. Relaxation losses after release were not measured directly, but were estimated using a common formula:

$$\Delta f_{ps,\,RE} = f_{pj} \cdot \left(\frac{\log_{10} t}{45} \right) \cdot \left(\frac{f_{pj}}{f_{py}} - 0.55 \right) \qquad \text{Eq. 1}$$

In Eq. 1, f_{pj} and f_{py} are the jacking and yield stresses of the prestressing reinforcement, respectively, and t is the time in hours after jacking.

Plots of prestress loss versus time are provided for all specimens in Figures 9 (SCC) and 10 (HSC). All plots show the same general trend, with losses gradually increasing over time after release. Table 5 summarizes all prestress loss measurements made throughout the duration of the test program. Losses are broken into five components: pre-release (PR), elastic shortening (ES), elastic gain due to loading (EG), creep and shrinkage of concrete (CR+SH), and relaxation of steel (RE). Losses resulting from creep and shrinkage cannot be separated and are thus presented jointly as a single component. For the loaded beams, the CR+SH component represents total losses occurring during the periods before and after application of the load at 29 days.

Losses due to the CR+SH component were significantly higher in the SCC beams than in the HSC beams. CR+SH losses in the unloaded and loaded SCC beams were 33.5 and 20.5 ksi (231 MPa and 141 MPa), respectively, while similar losses in the unloaded and loaded HSC beams were 14.1 and 8.4 ksi (97 and 58 MPa), respectively. In comparison to the HSC beams, the CR+SH losses for the SCC beams are 138% higher for the unloaded beams and 145% higher for the loaded beams.

Average total losses for the unloaded SCC beams and unloaded HSC beams were 27.1% and 15.0% of the jacking stress, respectively. As expected, total losses for loaded beams were lower with averages of 16.7% and 9.9% for the SCC and HSC beams, respectively. In comparison to the HSC beams, total losses for the SCC beams are 80% higher for the unloaded beams and 68% higher for the loaded beams.

Figures 11 and 12 present plots of beam camber versus time for the SCC and HSC beams, respectively. The camber plots follow the same general shape as the prestress loss plots. Table 4 presents a summary of camber measurements taken throughout the duration of the test program. In general, the time-dependent growth in camber is higher for the SCC beams than for the HSC beams. For example, the average change in camber due to creep, shrinkage, and changes in prestress force during the first 29 days after release is 0.095 in. (2.4 mm) for the HSC beams and 0.188 in. (4.8 mm), or 97% higher, for the SCC beams. Similarly, the average net camber after 300 days for the unloaded beams was 0.225 in. (5.7 mm) for the HSC beams and 0.385 in. (9.8 mm), or 71% higher, for the SCC beams. Net camber after 300 days for the loaded SCC beams is also 73% higher than for the loaded HSC beams, 0.130 in. (3.3 mm) as compared to 0.075 in. (1.9 mm).

COMPARISON OF SCC AND HSC SPECIMENS

A visual inspection of the plots shown in Figures 9 through 12 indicates that the fundamental behavior of the SCC beams is inherently similar to that of the HSC beams. However, the values presented in Tables 4 and 5 clearly show that both prestress losses and net beam camber at the conclusion of the test program were substantially higher for the SCC beams. As noted previously, SCC prestress losses and beam camber in the unloaded beams were 80% and 71% higher, respectively, while SCC prestress losses and beam camber in the loaded beams were 68% and 73% higher, respectively. These differences are significant and can have a marked impact on the serviceability behavior of self-consolidating concrete prestressed beams.

These large differences can be traced directly to the differences in material properties between the SCC and HSC concretes used in this study. The measured elastic modulus of the HSC concrete at 29 days was 28% higher than the measured modulus of the SCC concrete. This is consistent with the observations of higher elastic shortening loss, higher elastic prestress gain due to loading, larger camber at release, and larger elastic deflection due to loading for the SCC beams, all by factors between 14% to 37%. Similarly, measured creep and shrinkage properties were higher for the SCC concrete than for the HSC. This led to the higher observed creep and shrinkage losses observed for the SCC as compared to the HSC for both loaded and unloaded specimens, as well as a higher increase in deflection over the first 29 days after release. Because the magnitudes of these time-dependent measurements are affected not only by the creep and shrinkage properties, but also by the higher magnitudes of the initial elastic values (e.g. a higher initial camber would be expected to lead to a higher time-dependent camber), the time-dependent measurements for the SCC were found to be as much as two or more times that for the HSC.

COMPARISON OF MEASURED AND PREDICTED VALUES

Experimentally measured values are compared to predicted estimates in this section. Predictions are based on a number of common methods available in the literature, including those found in current design codes. Measured concrete material properties including creep and shrinkage values are used in all cases where such input is required, so as to provide the most theoretically accurate prediction estimates and allow for the most impartial analysis of the accuracy of each model. In the interest of brevity, the prediction methods are not discussed in detail here, but all methods are discussed in detail by Gaynor (2005).

Elastic responses

Elastic responses include immediate prestress losses such as elastic shortening as well as immediate camber at release or immediate deflection due to loading, all of which are primarily affected by the concrete modulus of elasticity. Measured and predicted elastic shortening losses are tabulated in Table 3. Predicted elastic shortening losses are based on the fundamental principles of mechanics. Measured and predicted values show good agreement, and are within 15% for all eight beams in the study.

Measured initial (net) camber at release and measured immediate deflection due to applied load were tabulated for all beams in Table 4. Each of these measurements is higher than predicted for all eight beams. Release cambers are 25% higher on average, while deflections due to loading are 42% higher. Possible reasons for this discrepancy include differences between the moduli of elasticity between the companion cylinders and beam concrete, and the accuracy of the measurements since these values are all fairly small in magnitude. It is also conceivable that a small amount of creep is included in each measurement because of the time required to take readings and apply the loads.

Total prestress loss

Total prestress losses were estimated using eight different methods. The methods can be generally classified into three categories: approximate methods, lump-sum component methods, and detailed time-step methods. Table 6 summarizes the predicted prestress losses resulting from each of the eight methods. Table 7 summarizes the ratio of predicted-to-measured loss for each method. Predicted losses are so-called "long-term losses" except for the time-step method in which losses are predicted at 300 days. Measured losses are for values recorded at 300 days. In general, the more complex methods yielded the best predictions of losses.

Approximate methods, including those found in the AASHTO LRFD 3rd Edition (AASHTO 2004) and AASHTO LRFD 4th Edition (AASHTO 2007), did a relatively poor job of estimating prestress losses. The AASHTO LRFD 3rd Edition approximate method greatly overestimated losses for the HSC beams, while the AASHTO LRFD 4th Edition approximate method, which is based on NCHRP Report 496, greatly underestimated losses for the SCC beams. It should be noted that the LRFD approximate method was derived by making many assumptions about typical composite bridge girders, and those assumptions are not necessarily valid for the small scale beams.

Lump sum component methods, in which the losses resulting from elastic shortening, creep, shrinkage, and relaxation are separately estimated and then summed, did a better overall job of predicting losses than approximate methods. These methods include the AASHTO Standard (AASHTO 2002), AASHTO LRFD 3rd Edition refined, AASHTO LRFD 4th Edition refined (based on NCHRP Report 496), PCI Design Handbook (PCI 1999), and PCI Bridge Design Manual (PCI 2003) methods. All five lump-sum methods typically underestimated losses for the SCC beams and overestimated losses for the HSC beams. The best lump sum component method for the SCC beams was the PCI Bridge Design Manual method, followed by the AASHTO LRFD 4th Edition refined method. These methods provide more flexibility than the other methods in utilizing the actual material properties of the concrete. The PCI Design Handbook method did the best job of predicting losses for the HSC beams, but this method significantly underestimated losses for the SCC beams.

The best overall loss prediction method proved to be a time-step analysis based on measured material properties. In the time-step method, the measured material properties are used in conjunction with the principles of mechanics to determine the losses over a series of incremental time-steps. The time-step method slightly underpredicted losses for the SCC beams and slightly overpredicted losses for the HSC beams, but yielded results within 23% of measured values for seven of the eight beams in the study. Complete details on the time-step method used in this study are provided by Gaynor (2005).

Time-dependent camber

Net camber at 300 days after release was estimated using three methods: the basic multiplier method suggested in the PCI Design Handbook (PCI 1999), an improved multiplier method suggested in the PCI Bridge Design Manual (PCI 2003), and a detailed time-step method similar to that used to estimate prestress losses. Table 8 summarizes the predicted net camber at 300 days and the ratio of predicted-to-measured camber for each method. As for losses, the more complex methods yielded the best predictions.

The basic and advanced multiplier methods are similar in that they estimate the net camber at a given stage as the algebraic sum of individual camber or deflection components associated with prestress, self-weight, or applied loads. A multiplier is applied to each individual component to account for time-dependent effects. In the basic multiplier method, the multiplier values are set, while in the improved multiplier method the values are determined as a function of the actual material properties of the concrete. The basic multiplier method significantly underpredicted camber for all beams, while the use of improved multipliers resulted in more accurate predictions for all beams.

The complex time-step method did a good job of predicting camber for the beams in this study. However, the increase in accuracy over the improved multiplier method is minimal. This reflects the inherent variability in camber and deflection data, particularly at 300 days after release when the net camber is affected by numerous elastic and time-dependent material properties and the loading conditions that have occurred over the life of the beam.

CONCLUSIONS

The following are the most important conclusions resulting from this study:

1. The time-dependent behavior of the high-strength SCC beams was inherently similar to that of the conventional high-strength concrete beams.
2. Measured prestress losses and net camber after 300 days were significantly higher in the SCC beams as compared to the HSC beams. This observation is directly related to the lower stiffness and greater time-dependent creep and shrinkage characteristics of the SCC concrete when compared to the HSC concrete.
3. More complex prediction methods, that are flexible enough to consider the actual material properties of the SCC or HSC concrete, did a better job of predicting prestress loss and camber for the beams tested in this study.

ACKNOWLEDGEMENTS

The authors wish to thank the American Concrete Institute for its support of this research program via the ACI Student Fellowship Program. The authors also thank High Concrete Structures, Lafarge North America, and Master Builders, Inc. for their material donations to support the experimental program.

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Table 1 -- Specimen identification

		Service Load Condition	
		Unloaded	Loaded
Concrete Type	Conventional High-Strength (HSC)	HSC1A HSC2A	HSC1B HSC2B
	High-Strength Self-Consolidating (SCC)	SCC1A SCC2A	SCC1B SCC2B
Number 1 or 2 in specimen ID denotes first (1) or second (2) casting of each concrete type. Four castings were: HSC1, HSC2, SCC1, SCC2			