PRESTRESS TRANSFER IN SELF-CONSOLIDATING CONCRETE MEMBERS WITH TOP STRANDS

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ABSTRACT

Lightweight self-consolidating concrete allows for reduced dead load and elimination of vibratory consolidation, both of which are beneficial for precast, prestressed members. The high fluidity of lightweight self-consolidating concrete combined with the tendency for some aggregate particles to collect near the top of the member has the potential to affect bond of prestressing strands with a significant amount of concrete below. Strand end slip and prestress losses were measured for rectangular beam specimens cast with lightweight self-consolidating concrete and normalweight self-consolidating concrete. Each member was prestressed with a single 0.5 in. special or 0.6 in. prestressing strand and cast with 12 in. of concrete either above or below the prestressing strand. Strand end slip was used to compare bond behavior over time, and prestress losses were measured for 90 days using surface strain at mid-span of the beam specimens. Transfer lengths calculated from the measured strand slip were compared to the ACI and AASHTO equations. Both strand diameters cast in normalweight SCC and 0.6 in. diameter strands cast in lightweight SCC exhibited larger strand slip for strands placed with 12 in. of concrete below.

Keywords: Lightweight, Self-Consolidating Concrete, Transfer Length, Strand Slip

INTRODUCTION

The main advantage of prestressed concrete is that it can be used for long spans with less material, thereby reducing the dead weight without sacrificing strength. This benefit is increased by utilizing lightweight aggregates and thereby reducing the dead weight even further. Self-consolidating concrete, which can flow, fill formwork, and consolidate entirely under its own weight is becoming increasingly common for use in precast, prestressed members. The study described in this paper was focused on the bond behavior and prestress losses of prestressed members cast using lightweight self-consolidating concrete with 0.5 in. special (13.3 mm) and 0.6 in. (15.2 mm) prestressing strands. Several factors affect the bond capacity of prestressed concrete members and the variables examined in this study included strand position, strand diameter, and concrete type. Bond performance was assessed using measured strand slip to quantify the transfer length. The measured transfer lengths were also compared to the code prediction equations. Prestress losses were measured using concrete surface strain at the level of the prestressing steel and were compared to the AASHTO LFRD[1] and Zia et al.[2] predictions.

BACKGROUND

Lightweight self-consolidating concrete (LWSCC) combines the benefits of reduced dead load from lightweight aggregates and the excellent workability of self-consolidating concrete. Structural lightweight concrete (LWC) involves the usage of lightweight aggregates and thus is lighter than conventional concrete, i.e. when conventional concrete typically has a density of 145 lb/ft^3 (2325 kg/m^3) LWC typically has a density of 70 lb/ft^3 to 120 lb/ft^3 (1120 kg/m^3 to 1920 kg/m^3)[3,4] depending on what proportion of fine and coarse aggregates are lightweight. LWC has the same minimum 28-day compressive strength as for normalweight concrete of 2500 psi (17.2 MPa).[3] The typically used lightweight aggregates include expanded shale, clay, and slate, blast-furnace slag, fly ash, vermiculite, pumice, and scoria. One of the most beneficial reasons to use LWC is to reduce the dead weight of the structure which leads to a smaller quantity of materials and total construction cost.[5] The use of LWC also benefits transportation and handling of precast elements due to the reduced weight of a particular size element.[3] Some of the other benefits of LWC include better durability and thermal insulation.[3,5] Improved durability results from internal curing from the water absorbed in the aggregates and good bond between the lightweight aggregate particles and the cement mortar. Self-Consolidating Concrete (SCC) is often used for precast, prestressed members to take advantage of the fact that SCC is highly flowable and cohesive and compacts itself without the need for mechanical consolidation. It spreads automatically under its own weight, adequately filling the voids without the need for mechanical vibration, and can be used in sections with heavy reinforcement, complex shapes of formwork, and where vibrators cannot be accessed.[6,7] Other advantages of using SCC include: improved pumpability, reduced labor cost, a smooth finish, elimination of vibrator noise, an improved work environment, reduced equipment wear, and shortened construction periods.

Prestress transfer length is the bonded distance along the strand in which the effective prestressing force at service level loads is fully transferred from the steel to the concrete. The variation of stress along the strand length is typically assumed to be linear with zero stress at the free end and full stress at the end of the transfer length.[1,4] Friction and mechanical resistance are the primary contributors to bond within the transfer length. Several factors have been shown to affect the transfer length such as strand diameter, jacking force, initial concrete compressive strength, strand surface condition, strand spacing and layout, and the rate of prestress transfer.[4,8-12] Concrete with poor consolidation will result in longer transfer lengths due to the lack of proper bond between the strand and concrete. Though the current codes do not explicitly specify an equation to evaluate the transfer length, it can be determined from the development length equation in ACI 318 Building Code Requirements for Structural Concrete and AASHTO LRFD Bridge Design Specifications as

$$l_t = \frac{f_{se}}{3} d_b \tag{1}$$

where f_{se} = stress in the prestressing steel after accounting for all losses (ksi) and d_b = nominal strand diameter (in.). The ACI[4] and AASHTO[1] codes also include the provisions of $50d_b$ and $60d_b$ respectively for use in shear design.

Strand transfer length is typically determined experimentally using concrete surface strain measurements[8,12-14] or using strand draw in along with the theoretical expression

$$l_t = \alpha \Delta_s \left(\frac{E_{ps}}{f_{si}}\right) \tag{2}$$

where Δ_s = strand end slip (in.), E_{ps} = modulus of elasticity of the prestressing steel (ksi), f_{si} = stress in the strand immediately after prestress release (ksi), and α = factor accounting for the bond stress distribution.[14-18] Values for α of 2.0 and 3.0, corresponding to a constant and linear variation of bond stress, respectively, have been proposed by previous researchers.[14-18]

The mixture composition of SCC and the inclusion of lightweight aggregate both have the potential to affect transfer length of prestressing strands. Lightweight aggregate leads to a reduced elastic modulus and the increased paste content required for SCC has the potential to do the same. Both lightweight concrete and SCC have a greater potential for shrinkage and the chemical admixtures used for SCC may influence bond. A number of studies have been conducted on the bond behavior of strands cast in SCC with somewhat varying results. Some studies have indicated a lower bond strength for SCC due to either the fine materials content[13,19,20] or the viscosity modifying admixtures used.[13] The type of cementitious materials and fines has also been shown to affect bond for SCC members. Angular powder materials which also produced a stronger matrix led to better bond,[12] while some members with fly ash had reduced bond strength.[13,20] Bond performance similar to conventional concrete was observed for most cases.[21-24] Measured transfer lengths for SCC mixtures were typically less than the ACI/AASHTO predictions,[12,21-23,25] but comparison to conventional concrete mixtures was not always consistent. Even when the measured transfer lengths were less than the code predictions, some researchers measured transfer lengths similar to or less than conventional concrete[21,22] and some greater than for conventional concrete.[12,13] Only a limited number of studies have been conducted on strands cast in LWSCC.[20,23,26] Lachemi et al[20] examined deformed reinforcing bars and indicated a lower bond strength for LWSCC compared to conventional SCC. Ward et al.[23] and Floyd et al.[26] measured transfer lengths less than the predictions of ACI/AASHTO for 0.5 in. (12.7 mm) and 0.6 in. (15.2 mm) strands respectively. Floyd et al observed transfer lengths similar to conventional SCC and that higher compressive strengths led to shorter and more consistent transfer lengths.

When reinforcement is placed near the as-cast top of a member, bleed water may collect below the reinforcement, which reduces the local water-cementitious materials ratio (w/cm) and tends to create air voids. Consequently, this affects the bond capacity between the steel and concrete at the top of the member.[27-30] It is accepted that vertical reinforcement position affects reinforcing bar development as evidenced by the factors in the ACI development length equation for bars with more than 12 in. of concrete cast below.[4] No modification is included for prestressing strands with similar amounts of concrete below. Previous research has indicated that the loss of bond is more a function of the distance from the as-cast top of the specimen than the amount of concrete below the strands. Transfer length of strands near the as-cast top of SCC members has been shown to be larger than for strands cast near the bottom of similar specimens.[25,31] In a conventional concrete member aggregate particles tend to settle to the bottom of the member if any segregation occurs, while the opposite occurs in lightweight members. This fact, plus the increased fluidity of SCC may lead to reduced bonding capacity and thereby larger transfer lengths for top strands in lightweight SCC members.

Prestress losses can be defined as loss of tensile stress in the prestressing steel which results in a loss of compressive stress acting on the concrete member. These losses can be classified into two categories; instantaneous and long-term losses. Instantaneous losses result from elastic shortening (ES) of the concrete member under the applied prestress load. Elastic shortening is primarily influenced by magnitude of the initial prestress and the elastic modulus of the concrete. The elastic shortening of lightweight concrete members is expected to be greater due to the reduced modulus of elasticity and has been shown to be so by previous research.[32,33] Long-term losses include the effects of creep (CR), shrinkage (SH), and relaxation of prestressing steel (RE).[2,34] Larger long-term losses have been measured for lightweight concrete and LWSCC due to increased creep in spite of reduced prestress force from the larger elastic shortening and reduced shrinkage for LWSCC compared to normalweight SCC.[33,35] Holste et al.[35] measured total losses that were very similar for SCC and LWSCC. High performance lightweight concrete has even exhibited smaller losses than conventional concrete.[36]

Each of the prestress loss components is considered separately in the detailed methods for predicting prestress losses and factors are included to account for variability of conditions. The most commonly used prestress loss predictions are based on studies of conventional concrete[2] and conventional high strength concrete.[34] Limited factors are included to account for lightweight aggregate including both dedicated factors[2] and modulus of elasticity.[1] No modifications are included to account for effects of lightweight aggregate or SCC on creep and shrinkage. LWSCC has the potential to behave very differently from conventional concrete or even typical SCC and a change in concrete behavior for any one of the major prestress loss components will affect the magnitude of the overall prestress losses and the effectiveness of the loss prediction. Previous research has shown that the typical prestress loss prediction methods overestimate losses for members cast with SCC and LWSCC, primarily due to the creep portion, but no substantial modifications have been recommended.[23,32,33,35,37]

The composition of SCC, and specifically LWSCC, has the potential to affect the prestress transfer behavior of strands placed with large amounts of concrete below and time dependent deformation leading to prestress losses. Numerous factors affect transfer length and detailed information is needed on performance related to each of these factors in order to make informed predictions of behavior. Though the effect of strand position on full scale specimens or specimens fabricated with other concrete types has been studied in the past, its influence on LWSCC has not been thoroughly studied. Variability between measurements has been a concern for transfer length measurements made with typical methods for in previous research[38] and variation in results between researchers studying lightweight concrete and SCC has also often been observed.[12,13,21,22] Some of the same factors affecting prestress transfer have the potential to affect prestress losses for SCC and LWSCC and an accurate estimate of prestress losses is important for serviceability concerns including camber, deflection, and service load stresses.

BEAM CONSTRUCTION AND TESTING METHODS

A total of sixteen beam specimens were cast for measurement of transfer length and prestress losses, out of which eight were cast using conventional SCC and eight were cast using LWSCC. Both 0.5 in. special (13.3 mm) and 0.6 in. (15.2 mm) diameter prestressing strands were used to analyze the effect of concrete type, strand location, and strand diameter. Two specimens were fabricated for each variable combination. The specimens were designated as follows: type of concrete (L for LWSCC or N for normalweight SCC), strand position (T for top strand or B for bottom strand), and strand size (0.5 or 0.6). For example, LT0.6 refers to LWSCC top strand beam with 0.6 in. (15.2 mm) strand. The targeted compressive strength for both the LWSCC and SCC mixtures was 4000 psi (28 MPa) at 1 day (f'_{ci}) and 6000 psi (41 MPa) at 28 days (f'_c). The desired fresh properties were a slump flow of 25 in. to 30 in. (635 mm to 760 mm), T_{50} of 2 to 4 seconds, VSI of 1.0 or less, difference between slump flow and J-Ring flow less than 2 in. (50 mm), and air content of approximately 2%. Table 1 shows the mix proportions used for casting all beam specimens.

Expanded shale aggregate with a nominal maximum size of ¾ in. (19 mm), specific gravity of 1.47, and 24 hour absorption of 18% was used for the LWSCC mixture. Crushed limestone with a nominal maximum size of 1 in. (25 mm), specific gravity of 2.68, and absorption of 0.86% was for the conventional SCC specimens. Washed concrete sand with a specific gravity of 2.63 and absorption of 0.86% was used in all cases along with ordinary Type I portland cement. Lightweight aggregates were presoaked for approximately 24 hours before mixing to limit water absorption during mixing. An approximately 15 ft^3 (0.42 m^3) plastic tub with a removable drain plug was used to soak the aggregates.

Slump flow, T_{50}, and visual stability index performed in accordance with ASTM C1611[39] were used to measure flowability and stability for each batch. Passing ability of the concrete mixtures was assessed using the J-Ring test run in accordance with ASTM C1621.[40] Air

Table 1: Mixture proportions and fresh properties for both concrete types

Material	**LWSCC**	**NWSCC**
Cement (lb/yd^3)	850	850
Coarse Aggregate (lb/yd^3)	780	1372
Fine Aggregate (lb/yd^3)	1432	1459
Water (lb/yd^3)	306	315
w/c	0.36	0.37
HRWR (fl oz/cwt)	5.0-7.0	5.0-7.0

Note: 1 lb = 0.454 kg, 1 oz = 29.57 mL, 1 yd^3 = 0.765 m^3, 1 in. = 25.4 mm, cwt indicates hundred pounds of cementitious material

content of the fresh concrete was measured using the volumetric method of ASTM C173[41] for the LWSCC mixtures and the pressure method of ASTM C231[42] for the conventional SCC. Concrete compressive strength was measured at 1, 7, and 28 days of age using 4 in. by 8 in. (100 mm by 200 mm) cylinders and the methods of ASTM C39.[43] The static modulus of elasticity was measured at 1, 7, and 28 days for each concrete type using 4 in. by 8 in. (100 mm by 200 mm) cylinders cast from a companion batch in accordance with ASTM C469[44]. All cylinders were stored in an environmental chamber maintained at 73 ± 3.5°F (23 ± 2°C) and 50% relative humidity. These conditions were chosen to be more representative of the beam specimen environment than curing at 100% relative humidity since no moist curing was used for the beam specimens.

All prestressing strands were Grade 270 seven wire strands with a ultimate strength of 270 ksi (1862 MPa) and a modulus of elasticity of 28,600 ksi (197,190 MPa). Strand rolls received from a local precast plant were covered with plastic sheets and were stored inside Fears Structural Engineering Laboratory at the University of Oklahoma to reduce the possibility of corrosion, damage, and dust accumulation and retain the as-received condition. The bonding quality of the strands was assessed using the methods of ASTM A1081.[45] The load corresponding to 0.1 in. (2.5 mm) of slip was recorded for all the specimens and was compared to the preliminary single test minimum value of 9000 lb (40 kN) and 10,800 lb (48 kN) for 0.5 in. (12.7 mm) and 0.6 in. (15.2 mm) strands respectively recommended by Ramirez and Russell.[46] The load values for all the six specimens were then averaged and compared to the preliminary minimum threshold of 10,500 (46.7 kN) and 12,600 lb (56 kN).[46] More recent research sponsored by PCI[47] recommended a minimum average pullout value of 14,600 lb (65 kN) for 0.5 in. (12.7 mm) strands, which could be extrapolated to 17,500 lb (77.8 kN) for 0.6 in. (15.2 mm) strand.

All the beam specimens had dimensions of 6 in. x 14 in. x 8 ft long (150 mm x 355 mm x 2.4 m) chosen based on previous research[25,26,48] for the sake of comparison and available fabrication capacity. A single prestressing strand was placed either 2 in. (50 mm) from the as-cast top or 2 in. (50 mm) from the bottom of the specimen with two No. 4 (No. 13) mild steel reinforcing bars placed at the bottom for top strand beams and at the top for bottom strand beams. The mild steel bars were provided to control cracking and the size was chosen based on the intensity of anticipated tension stresses in the cross section. Single No. 3 (No. 10) stirrups were provided 1.5 in. (38 mm) from each end to control cracking at prestress release,

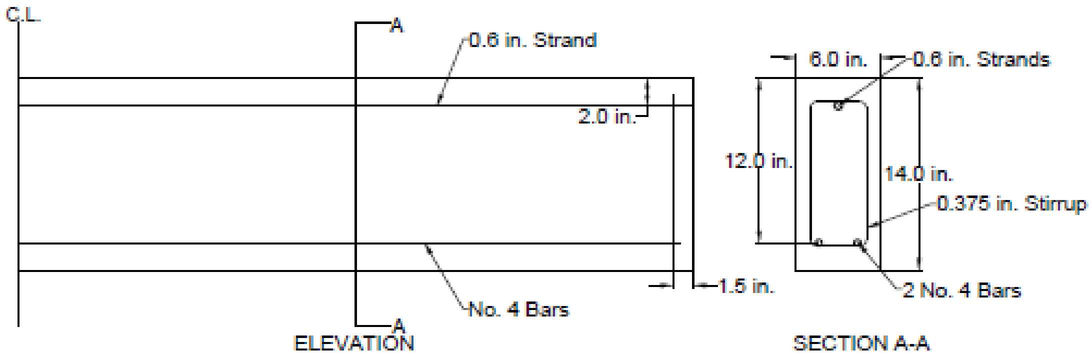

Figure 1: Cross-section details for a top strand beam, Note: 1 in. = 25.4 mm

but were not designed to resist any shear force. The cross-sectional view of a top strand beam is shown in Figure 1.

All beams were constructed at Fears Structural Engineering Laboratory at the University of Oklahoma in Norman, Oklahoma, using a self-contained prestressing setup adapted especially for this purpose. Each set of two beams could be constructed at one time. The strands for both beams were tensioned immediately before the concrete was mixed and placed. Center hole hydraulic rams were used to tension the strands individually. Figure 2 shows the prestressing setup with the forms aligned in position for casting. The end of the frame where the strand is anchored is referred to as the dead end and the end of the frame where the strand is actually tensioned is referred to as the live end.

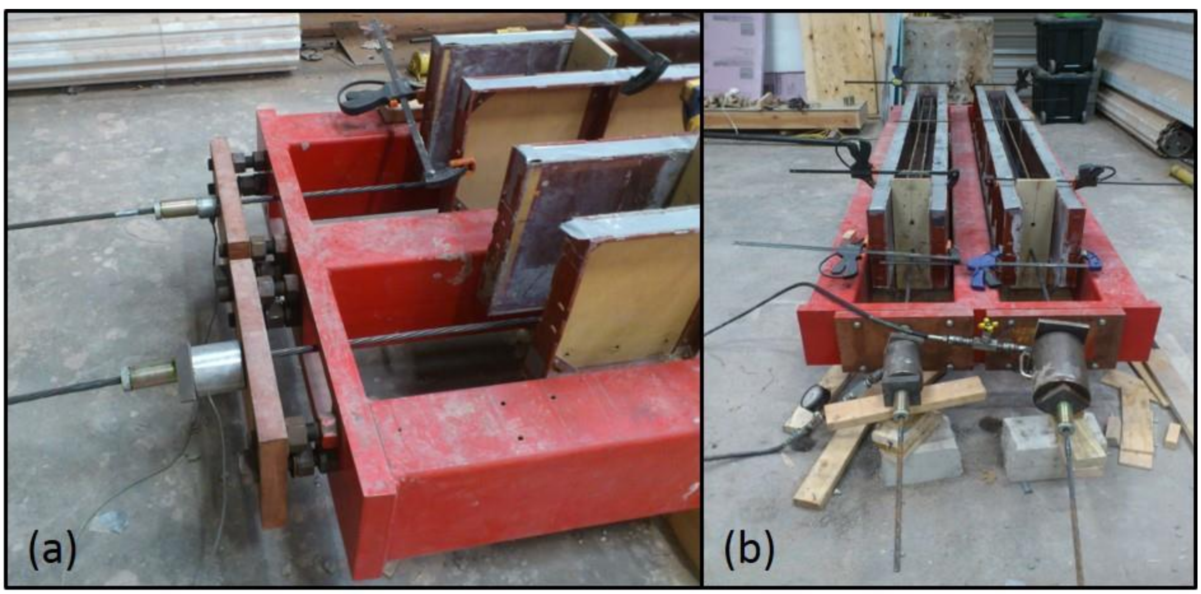

Figure 2: Prestressing setup showing (a) anchorage (dead) end and prestress release mechanism and (b) strand tensioning mechanism at the live end

Each set of two beams was cast using a single 13 ft^3 (0.37 m^3) batch. After 5-8 min of mixing time, the mixture was examined for its consistency. If the mix appeared to be very viscous, additional superplasticizer was added as required. The average overall mixing time was approximately 15-17 min. The concrete was transported from the mixer to the formwork and placed in one lift with no external consolidation using an approximately 9.5 ft^3 (0.27 m^3) concrete bucket and overhead crane. A sample of concrete was collected from the mixer and slump flow, T_{50}, VSI, J-Ring, and air content were performed. Nine 4 in. by 8 in. (100 mm by 200 mm) cylinders were cast from each batch for testing compressive strength at 1, 7, and 28 days. The concrete for beam sets LB0.5 and LT0.5 exhibited poor compressive strengths due to cold temperatures on the batching days. These mixes were redone and only the repeated data are reported in this paper.

The formwork was removed at approximately 18 hours of age and steel block clamps were installed on the strand at both ends of the beams. An initial reading was taken using a 1 in. (25 mm) depth micrometer before the strands were released as shown in Figure 3. Care was taken to ensure that the clamps were close enough to the beam ends to be within the range of the micrometer. Six steel DEMEC targets were attached to each side of the beam using a two part epoxy at the level of the prestressing strand arranged symmetrically around the midpoint. The first point was placed 40 in. (1015 mm) from the live end and he remaining points were placed at 4 in. (100 mm) intervals. An initial reading was taken using a 4 in. (100 mm) gage length DEMEC gage as shown in Figure 3. The tension was then released gradually by loosening the bolts on the dead end of the prestressing frame using a wrench. The nuts were loosened alternatively to avoid any eccentric forces. The second end slip and DEMEC readings were taken immediately after the strands were released. All beams were stored inside the main high bay area of Fears Structural Engineering Laboratory supported at the two ends on wooden supports. Additional end slip measurements were made at intervals of 3, 5, 7, 14, and 28 days and DEMEC measurements were taken at 3, 5, 7, 14, 28, 56, and 90 days. The difference between the initial measurement before prestress release and all the measurements that followed gave the end slip or surface strain.

The measured end slip included the elastic shortening of the strand along with the actual end slip so the actual length over which this shortening happened was determined from the measurement taken before prestress release. The elastic shortening of the free strand outside the beam end was then calculated using this measured length, the known initial prestress, and the modulus of elasticity of the strand. The five DEMEC measurements, shown in Figure 4 for a typical top-strand beam, were averaged in order to smooth the surface strain measurements along the beam. The average of both sides of each beam was then made to obtain the final strain values. Actual strain values were obtained by multiplying the gage readings by the gage factor given by the manufacturer. The measured change in strain over time was used along with the modulus of elasticity of the prestressing strand to determine the loss of prestress. Since strand relaxation cannot be determined from strain measurements the values presented in this paper do not include relaxation unless an addition to include relaxation is specified.

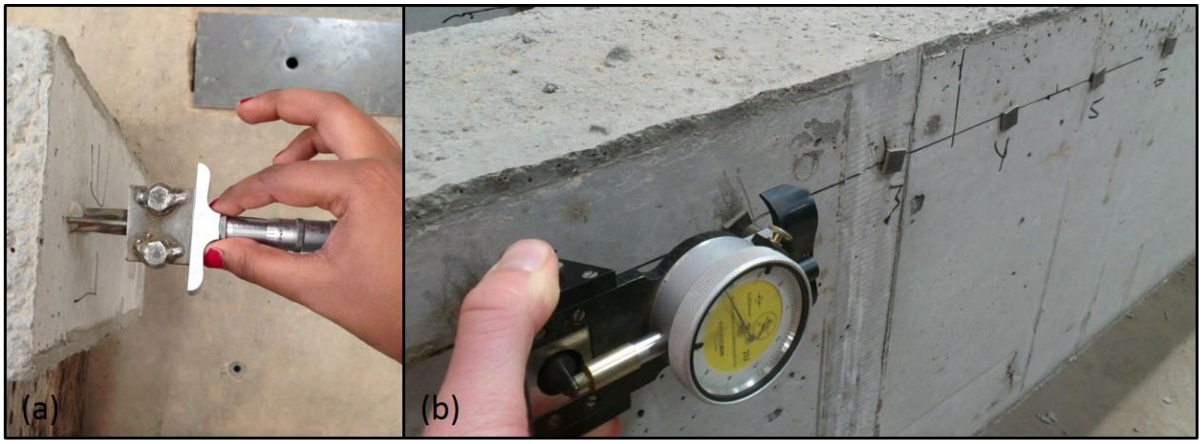

Figure 3: (a) End-slip measured using a depth micrometer and (b) DEMEC gauge used to measure surface strain for prestress losses

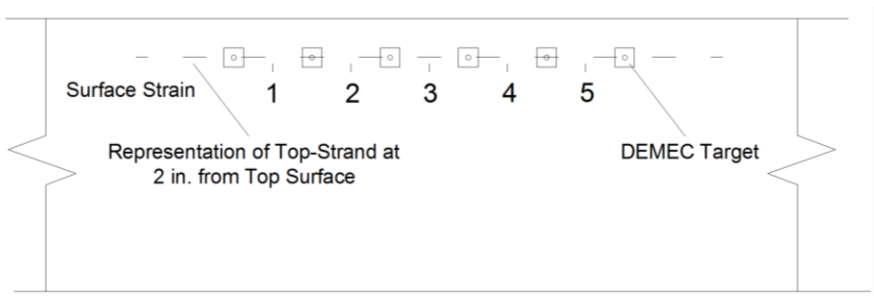

Figure 4: Representation of DEMEC Points and Surface Strain on a Typical Top-Strand Beam

RESULTS AND DISCUSSION

The fresh properties for each set of prestressed beams are presented in Table 2 and Table 3. All these sets had acceptable fresh properties except for the NT0.6 batch. This mix did not have adequate flowability evidenced by a slump flow less than 20 in. (500 mm). However, no sign of poor consolidation was observed externally for either of the NT0.6 beams. Compressive strengths at release and at 28 days are also presented in Table 2 and Table 3. The targeted compressive strength of 4,000 psi (28 MPa) at one day was achieved for all beam sets except NT0.5, which was within 2% of the targeted value. All batches had compressive strengths in excess of the targeted 6,000 psi (41 MPa) at 28 days, and half of the beam sets had compressive strengths in excess of 7000 psi (48 MPa) at 28 days. The measured modulus of elasticity for the two concrete mixtures at one and 28 days is presented in Table 4 along with the values predicted using the ACI equation. The ACI equation over-predicted the LWSCC elastic modulus by 13% at one day and under-predicted it by 9% at 28 days. The ACI equation under-predicted the elastic modulus of the normalweight SCC mixture by 21% at one day and 28% at 28 days. These results indicated that the limestone used for the normalweight SCC had a high stiffness.

Table 2: Fresh Properties and Compressive Strength for 0.6 in. (15.2 mm) Strand Beam Sets

Properties	**NB0.6**	**NT0.6**	**LB0.6**	**LT0.6**
Slump Flow, in.	26.5	18.0	20.0	21.0
J-Ring, in.	25.0	16.0	19.0	20.0
J-Ring Δ, in.	1.5	2.0	1.0	1.0
T_{50}, sec	1.6	--	3.0	2.4
VSI	0	0	0	0
Air Content, %	1.6	2.1	2.5	2.5
Temperature, °F	69	68	63	65
f'_{ci}, psi	4730	4130	4070	4290
f'_c, psi	7470	7130	6690	7110

Note: 1 lb = 0.454 kg, 1 in. = 25.4 mm, temperature in °C is calculated using $T_c = (T_F - 32)/1.8$, 1 MPa = 145 psi, -- indicates no measurement was taken

Table 3: Fresh Properties and Compressive Strength for ½ in. Special (13.3 mm) Strand Beam Sets

Material	**NB0.5**	**NT0.5**	**LB0.5**	**LT0.5**
Slump Flow, in.	21.0	22.0	29.0	22.0
J-Ring, in.	19.0	22.0	27.0	21.5
J-Ring Δ, in.	2.0	0.0	2.0	0.5
T_{50}, sec	3.0	3.0	3.0	3.0
VSI	0	0	1	0
Air Content, %	--	1.5	--	2.75
Temperature, °F	67	65	64	63
f'_{ci}, psi	4300	3920	4440	4580
f'_c, psi	7400	6740	6880	6960

Note: 1 lb = 0.454 kg, 1 in. = 25.4 mm, temperature in °C is calculated using $T_c = (T_F - 32)/1.8$, 1 MPa = 145 psi, -- indicates no measurement was taken

Table 4: Modulus of Elasticity of the LWSCC and NWSCC at one and 28 days

Concrete Type	**E_{ci}, ksi**	**ACI E_{ci}, ksi**	**E_c, ksi**	**ACI E_c, ksi**
LWSCC	2660	3000	4100	3720
NWSCC	5180	4080	6950	4980

Note: 1 MPa = 145 psi

The average pullout force for the 0.5 in. special (13.3 mm) strands in the ASTM 1081[45] bond test was 17,100 lb (75.6 kN), which exceeded the 10,500 lb (46.7 kN) recommended for 0.5 in. (12.7 mm) strands[46] by 63%. The individual pullout forces ranged from 13,800 lb to 19,400 lb (61.4 kN to 86.3 kN) which exceeded the 9000 lb (40 kN) minimum recommended for 0.5 in. (12.7 mm) strands.[46] The average pullout force for the 0.6 in. (15.2 mm) strands was 17,800 lb (79.2 kN) which exceeded the 12,600 lb (56 kN) minimum by 41%. The individual pullout forces ranged from 17,300 lb to 18,600 lb (77.0 kN to 82.7 kN). The average pullout forces exceed the minimums recommended by or extrapolated from more recent research by Polydorou.[47] Even though the recommendations were based on 0.5 in. (12.7 mm) and not 0.5

in. special (13.3 mm) strands, the exceedance of the minimums by more than 17% indicates that both strands utilized in this research had adequate bonding capability.

The four strand end slip measurements for the two specimens in each set of variables were averaged for each time increment over the first 28 days of age. Figure 5 and Figure 6 show a comparison of strand slip for the 0.5 in. special and 0.6 in. (13.3 mm and 15.2 mm) strand

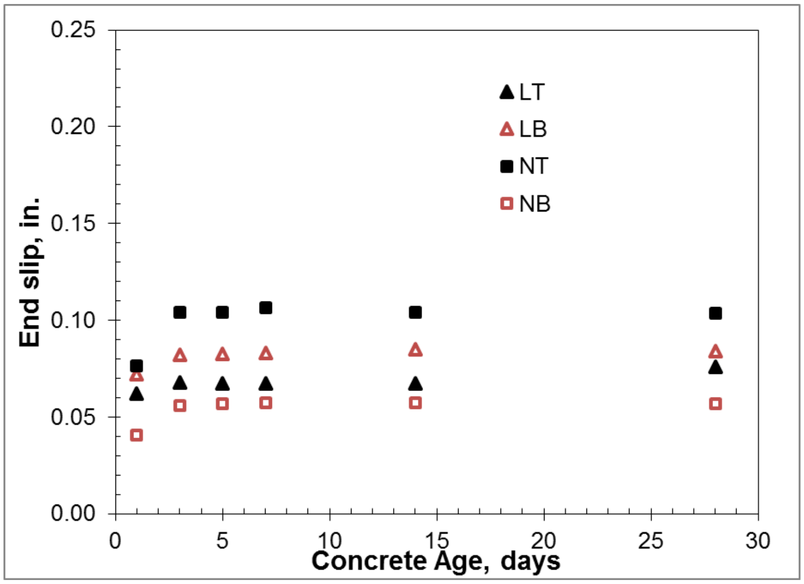

Figure 5: Comparison between all the 0.5 in. special specimens with averaged end slip values, Note: 1 in. = 25.4 mm

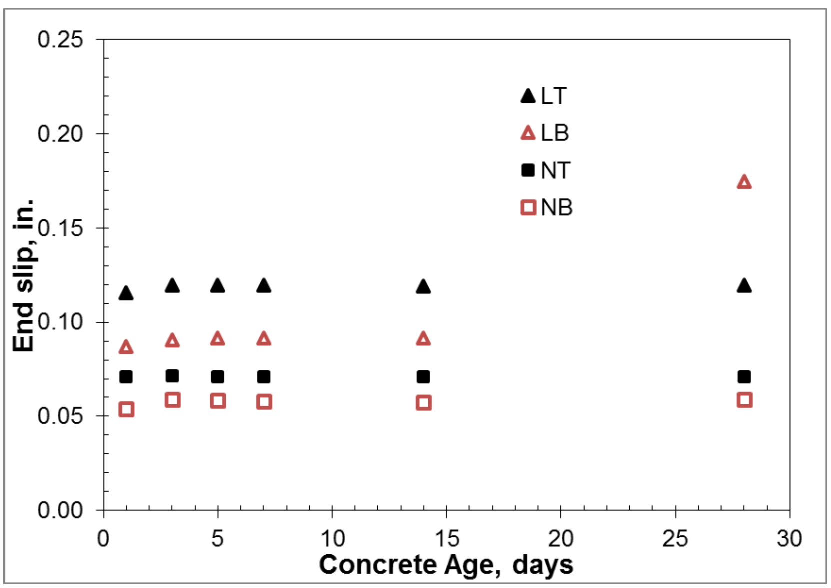

Figure 6: Comparison between all the 0.6 in. specimens with averaged end slip values, Note: 1in. =25.4 mm

diameters, respectively. In all cases except for the normalweight SCC with top strands, the LWSCC specimens had larger values of strand end slip. The average values indicated that the normalweight SCC specimens with 0.5 in. special (13.3 mm) strands located at the beam bottom had the best bonding capacity and the normalweight SCC specimens with strands located at the top had the poorest bonding capacity. Measured strand slip for the LWSCC specimens was in between, but indicated that specimens located at the bottom of the specimens had the poorer bonding capability. The specimens with 0.6 in. (15.2 mm) strands near the top had larger average values of strand end slip for both normalweight SCC and LWSCC. The 0.6 in. (15.2 mm) strand LWSCC specimens exhibited 42% higher slip compared to the normalweight SCC. The limited number of specimens examined in this study indicates that strands with at least 12 in. (305 mm) of concrete below have poorer bonding than specimens with only 2 in. (50 mm) of concrete below during casting. The top strands exhibited approximately 12% more slip than the bottom strands.

The end slip measurements for the 0.6 in. (15.2 mm) strand specimens exhibited less erratic behavior as compared to the 0.5 in. special (13.3 mm) strand specimens even though the slip values were higher for the 0.6 in. (15.2 mm) strand specimens. Higher slip values that were noted in most cases corresponded to the live end of a particular specimen. The lowest slip recorded for a group of specimens always corresponded to the dead end of a specimen.

Average transfer length for each LWSCC specimen set calculated from the average measured end slip using Equation 2 at 28 days is presented in Table 5. Each value represents the average of the two specimens cast for the specific variable combination. All comparisons made here were based on the value of α = 3 even though the actual experimental value described by the researchers was 2.86 in order to provide a conservative estimate of transfer length. The values calculated using the prediction equations from the ACI and AASHTO codes are also presented in Table 5. The average measured transfer length for the LT0.5 specimens based on all specimen ends was approximately the same as that predicted using Equation 1, but the average live end transfer length was at least 19% greater than all of the predictions. The average LB0.5 transfer length exceeded all predictions by at least 18% and both dead and live end values were greater than the predictions. The average transfer lengths for the 0.6 in. (15.2 mm) strands cast in LWSCC exceeded all code predictions for both the bottom and top strand positions.

Average transfer length for each normalweight SCC specimen set calculated from the average measured end slip using Equation 2 at 28 days are presented in Table 6. The average transfer length for the NT0.5 specimens was greater than all predicted values primarily due to a large transfer length measured for the live end. The dead end average measured transfer length for the NB0.5 specimens was less than all predictions. The live end value was approximately equal to the ACI 50d_b prediction, but was less than the other predictions. The average measured NT0.6 transfer length was less than or approximately equal to the values calculated using all of the predictions. Only the live end value was greater than the ACI 50d_b expression. The measured transfer lengths for the NB0.6 specimens were less than all predicted values. The transfer length equations given by ACI and AASHTO produced much better predictions for the normalweight SCC specimens than for the LWSCC specimens.

Table 5: Comparison of measured transfer length (in.) for LWSCC specimens at 28 days

Specimen	LT0.5	LB0.5	LT0.6	LB0.6
Dead End, in.	26.3	33.8	>48	>48
Live End, in.	38.1	39.9	>48	>48
Average, in.	32.2	36.8	>48	>48
ACI ($50d_b$), in.	26.0	26.0	30.0	30.0
AASHTO ($60d_b$), in.	31.2	31.2	36.0	36.0
ACI 318/AASHTO, in.	32.0	30.7	33.2	32.0

Note: 1 in. = 25.4 mm

Table 6: Comparison of measured transfer length (in.) for NWSCC specimens at 28 days

Specimen	NT0.5	NB0.5	NT0.6	NB0.6
Dead End, in.	27.6	22.4	28.0	20.4
Live End, in.	>48	26.3	32.5	29.5
Average, in.	NA	24.3	30.2	24.9
ACI ($50d_b$), in.	26.0	26.0	30.0	30.0
AASHTO ($60d_b$), in.	31.2	31.2	36.0	36.0
ACI 318/AASHTO, in.	30.3	32.4	33.5	35.0

Note: 1 in. = 25.4 mm

Transfer lengths at the live end were typically higher than those calculated at the dead end for a given specimen. Both 0.6 in. (15.2 mm) bottom strand LWSCC specimens had transfer length values calculated from the measured strand slip larger than the beam length, which was not physically possible. Except for one of the dead ends on these beams, all other ends had values considerably larger than 48 in. (1220 mm). When an inadequate length of concrete was available to anchor the prestressing strand at both ends, general bond slip would occur, which indicated a larger transfer length than what would occur given adequate concrete for anchorage. One beam from each set of the LWSCC top strand beams (both strand diameters) and the LB0.6 beams had transfer lengths calculated from the measured strand slip such that when the values for the two ends were added together the sum was greater than the length of the beam. This is greater than physically possible because it would leave no space for strand at an effective prestress and should result in general strand slip. . Only one normalweight SCC specimen exhibited a similarly overly long transfer length out of the eight cast. The LWSCC specimens exhibited cracking at prestress release due to the low tensile strength of the concrete, which likely contributed to the larger strand slip values and corresponding transfer lengths. The reduced stiffness of the concrete and the effects of aggregate interlock on the friction and strand expansion aspects of transfer bond may have contributed as well.

High variability was noted for specimens cast with the same variable combination. In most cases, one specimen of each set of two behaved in a substantially different way from the other (i.e.) for instance the transfer length difference percentage between the pairs ranged between 4-406% at the dead end and 15-250% at the live end even though each had the same configuration and was cast the same way. One of several possible reasons leading to this kind of variable behavior is that some prestress force was lost between casting and release due to pressure loss in the hydraulic system. This may have led to the twisting of strands and reduced bond within the transfer length. The authors believe that a larger sample size is needed to verify the results of this study and have plans to test additional specimens. These additional tests will provide grounds for more definite conclusions than can be drawn from the present data.

The measured prestress losses were taken as the difference between the average value of the five smoothed DEMEC measurements centered on the beam midpoint, shown in Figure 4, before prestress release and at the specified time increment as described in the Beam Construction and Testing Methods section of this paper. They were computed as the difference in strains over time multiplied by the modulus of elasticity of the strand taken as the 28,600 ksi (197,200 MPa) provided by the manufacturer. It was assumed that the concrete and the strand deformed equally outside of the transfer length. The total average measured losses for each set of two beams is shown in Figures 7 and 8. The losses presented in Figures 7 and 8 do not include the relaxation of the strands since it cannot be measured using strain. Losses for each beam set reached a relatively constant value after 56 days. No influence of the strand location on prestress losses was observed. However, normalweight SCC total losses were typically less than LWSCC for the same location and strand size.

Total losses were higher for the 0.6 in. (15.2 mm) strand beams than for the 0.5 in. special (13.3 mm) strand specimens due to the greater creep resulting from the higher prestress force. The prestress of 75% of the strength of the strand resulting in a concrete stress of 1,020 psi (7.0 MPa) and 1,320 psi (9.1 MPa) at the level of the strands for the 0.5 in. special (13.3 mm) and 0.6 in. (15.2 mm) strand specimens respectively. Neither the temperature nor the humidity

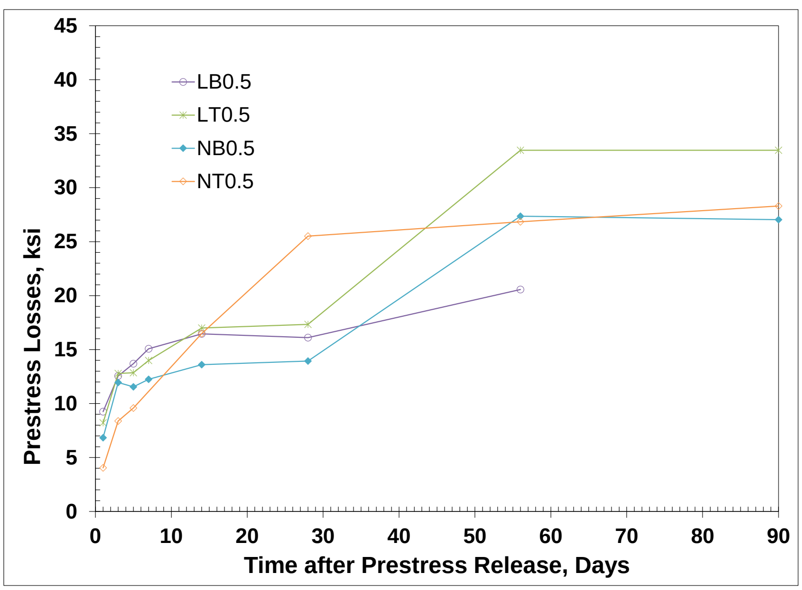

Figure 7 Total prestress losses of 0.5 in. special strand beam specimens, Note: 1 MPa = 145 psi

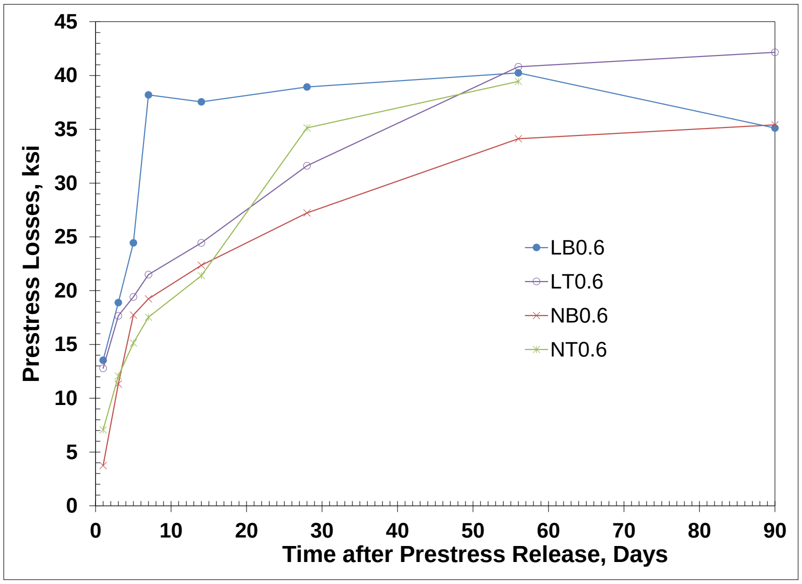

Figure 8. Total prestress losses of 0.6 in. strand beam specimens, Note: 1 MPa = 145 psi

was controlled in the area where the beams were stored. Both concrete mixtures were influenced by the environmental conditions. Delayed losses were observed for all LWSCC specimens except the LB0.6 beams. This may be attributed to the internal curing water from the pre-wetted lightweight aggregates causing drying shrinkage to be delayed to a later age. Measured transfer lengths indicated that at least one of the NT0.5, LT0.6, and LB0.6 beams had general bond slip. This should have resulted in a lower prestress force at mid-span and lower losses. However, these beams had higher losses than the other corresponding beam sets.

Experimental elastic shortening losses were compared to the prediction methods at release given by the AASHTO LRFD Specifications,[1] and Zia et al[2] and are presented in Table 7. The predicted values were calculated using the actual prestress force at release read from the load cells. The compressive strength at release was taken as given in Tables 2 and 3 and the predicted losses were calculated using the determined modulus of elasticity given in Table 4.

Table 7: Experimental Elastic Shortening Losses Compared to Zia et al.[2] and AASHTO[1] Prediction Methods

Specimen Set	Measured, ksi	Zia *et al.*, ksi	*Measured/ Predicted*	AASHTO, ksi	*Measured/ Predicted*
LB0.5	9.2	9.6	*0.96*	10.7	*0.86*
LT0.5	8.2	9.8	*0.84*	10.9	*0.75*
NB0.5	6.8	5.0	*1.37*	5.5	*1.24*
NT0.5	4.1	5.0	*0.81*	5.6	*0.72*
LB0.6	13.5	12.5	*1.08*	13.9	*0.97*
LT0.6	12.8	12.4	*1.03*	13.8	*0.93*
NB0.6	3.7	6.5	*0.58*	7.3	*0.51*
NT0.6	7.1	6.5	*1.09*	7.3	*0.97*

Note: 1 MPa = 145 psi

Each method gave the closest result for approximately half of the specimens. The Zia et al.[2] method under predicted half (by up to 26%) and over predicted half (by up to 76%) of the elastic shortening losses. However, the Zia et al.[2] equation typically produced a better prediction for the LWSCC specimens. The AASHTO method over predicted elastic shortening losses for 7 of the 8 specimen sets, by as much as 97%. The LWSCC elastic shortening losses were higher than the SCC losses as expected due to the higher modulus of elasticity values for the SCC mix.

Predicted creep and shrinkage losses were compared to measured values at 28 days. The AASHTO[1] refined long-term losses were determined using the equations applicable for time of transfer to time of deck placement. The compressive strength at that day was taken as given in Tables 2 and 3. The experimental total prestress losses include the relaxation of the strands taken as 1.2 ksi from the AASHTO[1] method. The experimental creep and shrinkage losses and comparison to the prediction methods described by Zia et al.[2] and the AASHTO LRFD[1] refined method are presented in Table 8 and Table 9 respectively. For each method, half of the predictions are greater than the experimental values. However, the method proposed by Zia et al. is usually closer to the measured creep and shrinkage values which may be a problem at later ages since this method does not include a factor for time. The AASHTO Refined[1] and Zia et al.[2] methods both give reasonable estimates for the total losses at 28 days. The LWSCC specimens had higher elastic shortening losses which led to a lower remaining prestress force acting on the beams. This lower prestress force caused lower creep losses which may explain the overall LWSCC losses that are in the same range as the SCC losses. The current provisions provided a reasonable estimate for the instantaneous losses for LWSCC and SCC specimens, but the time-dependent loss predictions were affected by the creep and shrinkage properties of the concrete and require further consideration.

Table 8: Measured time-dependent losses at 28 days compared to the Zia et al.[2] method

	Measured, ksi		**Zia et al., ksi**		***Measured/ Predicted***	
Specimen Set	**CR+SH**	**Total**	**CR+SH**	**Total**	***CR+SH***	***Total***
LB0.5	6.9	17.3	17.1	30.7	*0.40*	*0.56*
LT0.5	9.1	18.5	17.3	31.0	*0.53*	*0.60*
NB0.5	7.1	15.1	14.6	23.8	*0.49*	*0.64*
NT0.5	21.5	26.7	14.7	23.9	*1.46*	*1.12*
LB0.6	25.4	40.1	20.1	36.3	*1.26*	*1.11*
LT0.6	18.8	32.8	20.0	36.1	*0.94*	*0.91*
NB0.6	23.5	28.4	17.0	27.6	*1.38*	*1.03*
NT0.6	28.1	36.3	16.9	27.5	*1.66*	*1.32*

Note: 1 MPa = 145 psi

Table 9: Measured time-dependent losses at 28 days compared to the AASHTO[1] refined method

	Refined, ksi		***Measured/ Predicted***	
Specimen Set	**CR+SH**	**Total**	***CR+SH***	***Total***
LB0.5	17.7	29.6	*0.39*	*0.58*
LT0.5	19.2	31.3	*0.48*	*0.59*
NB0.5	12.8	19.5	*0.56*	*0.78*
NT0.5	13.4	20.2	*1.60*	*1.32*
LB0.6	22.2	37.2	*1.14*	*1.08*
LT0.6	21.5	36.5	*0.88*	*0.90*
NB0.6	14.2	22.7	*1.65*	*1.25*
NT0.6	15.1	23.6	*1.86*	*1.54*

Note: 1 MPa = 145 psi

CONCLUSION

The study described in this paper investigated the effects of lightweight aggregate used in self-consolidating concrete on prestress transfer and prestress losses. The results obtained from the ASTM 1081[44] test clearly indicated that both strand diameters possessed very good bonding capacity. Transfer lengths determined using strand end slip were on an average 20% higher at the live end compared to the dead end for all specimens and the smallest strand end slip noted for each specimen set corresponded to a specimen dead end. The 0.6 in. (15.2 mm) strand lightweight specimens involving both top and bottom strands had larger values of strand end slip than the 0.5 in. special (13.3 mm) strand specimens. Overall, the LWSCC specimens exhibited poorer bond than the normalweight SCC specimens and a high amount of variability was observed between the two specimens cast for each variable combination. Moreover, since this study did not involve enough specimens to perform an analysis based on a statistical approach it was not possible to arrive at a definite conclusion and additional testing with a larger number of specimens, larger specimens with multiple strands, and a sudden release of prestress is needed to verify the transfer length results presented in this paper. Elastic shortening losses for LWSCC prestressed members were higher than for normalweight SCC members. Overall losses were in the same range for both concrete mixtures, but total creep and shrinkage losses were higher for the 0.6 in. (15.2 mm) strand beams due to higher prestress forces. The Zia et al. and the AASHTO refined methods for estimating prestress losses gave reasonable estimates of prestress losses and elastic shortening losses were better predicted than the long-term losses. The current provisions for prestress losses provided reasonable predictions but additional work is needed to provide a better representation of the creep and shrinkage behavior of LWSCC and SCC.

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