BEHAVIOR OF PRECAST, PRESTRESSED CALCIUM SULFOALUMINATE CEMENT CONCRETE BEAMS

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ABSTRACT

Calcium sulfoaluminate cement is a very fast setting, hydraulic cement that produces concrete with high early strength, excellent durability, and limited shrinkage. The exceptionally fast strength gain has the potential to substantially increase the speed of production of precast members. Four 8 in. × 24 in. by 25 ft long rectangular beams prestressed with six 0.5 in. special prestressing strands were cast using calcium sulfoaluminate cement concrete. The pretension was released at 1.5 to 2.5 hours, depending on when the targeted 3500 psi compressive strength was achieved. Vibrating wire strain gages were installed on the bottom center prestressing strand along the length of the members to collect data for transfer length and prestress losses. Strand slip at prestress release was also measured as an indication of transfer length. Two of the beams were tested in flexure to examine the adequacy of the code specified development length, and the other two beams remain under continued monitoring to collect additional prestress loss data. The results of this project indicate that prestressed concrete members meeting required specifications, and exhibiting adequate performance, can be constructed rapidly using calcium sulfoaluminate cement concrete.

Keywords: Calcium Sulfoaluminate, High Early Strength, Transfer Length, Development Length, Prestress Losses, Self-Consolidating Concrete

INTRODUCTION

Calcium sulfoaluminate (CSA) cement is a very fast setting, hydraulic cement that produces concrete with high early strength and excellent durability. The compressive strength typically required for prestress release at 18-24 hours can be reached much more quickly, without the need for heat curing.[1] This fast strength gain has the potential to substantially improve the speed of production of precast, prestressed bridge girders and other precast products, but limited information is available concerning its use in structural members. The logistics of increasing production require consideration, but a potential increase in production could be very beneficial for precast producers attempting to meet the demand created as a push is made to repair and improve infrastructure across the United States. This study investigated the required production methods and behavior of four precast prestressed beams cast using calcium sulfoaluminate cement with prestress release occurring at between 1.5 and 2.5 hours of age.

BACKGROUND

Rapid setting CSA cement can achieve the compressive strength required for prestressed concrete construction in less than one-third the time required for conventional concrete mixtures. It also presents a number of other benefits related to the durability and sustainability of members made with this material. Calcium sulfoaluminate cement clinker is fired at a lower temperature than portland cement, produces less than half the carbon dioxide during production, and is easier to grind.[1-5] These differences lead to significant energy savings and reduced carbon emissions.[4,6,7] While CSA cements are not widely used in the United States and Europe, they have been used in China for many years in a wide variety of applications.[2,4-6] These have included some precast applications[1,5] and self-stressed concrete pipes.[8] On major disadvantage of using CSA cement is the cost, which can be three to four times that of regular cement. However, this disadvantage can be partly overcome by increases in speed of construction and production efficiency and increased demand would lead to lower material costs.

Calcium sulfoaluminate cement clinker is made from limestone similarly to conventional portland cement, but also bauxite or another aluminum source which increases material costs. Conventional portland cement is primarily composed of tricalcium silicate (alite, C_3S) and dicalcium silicate (belite, C_2S) which react with water to form calcium silicate hydrate (C-S-H), the main strength producing compound in hardened portland cement concrete. CSA cement is composed primarily of tetracalcium trialuminate sulfate, or ye'elimite ($C_4A_3\overline{S}$) and dicalcium silicate (belite, C_2S).[2-5,9] The $C_4A_3\overline{S}$ in the cement reacts quickly to form monosulfate and ettringite in a series of reactions depending on the combination of the interground materials.[2,4,6] Ettringite is the main resultant product of the cement reaction and produces a strong crystal structure and resulting high compressive strength at early ages.[1,8,10] The setting time depends on the specific composition, but typically varies between 30 min and 4 hours. The dicalcium silicate (C_2S) in the cement is then available to react and produce calcium silicate hydrate (C-S-H), which contributes to strength at later ages.[2,4,5]

The reaction of $C_4A_3\bar{S}$ requires a water-cement ration (*w*/*c*) of between 0.40 and 0.60 to completely hydrate calcium sulfoaluminate cement as opposed to the 0.20 to 0.25 required for portland cement.[2,3] The wide range of *w*/*c* for CSA cement is due to current limitations in the understanding of CSA cement. The increase in chemically required water allows for a *w*/*c* high enough to produce excellent workability, yet the majority of water is consumed quickly, reducing the water available to contribute to concrete porosity and shrinkage. The reduction of porosity and shrinkage are additional benefits of using this material in a prestressed concrete application above and beyond early age compressive strength. Research has shown that shrinkage of CSA cement concrete not proportioned for expansion is negligible.[4] The high early strength development of CSA cement concrete may lead to reduced creep as well, due to a more mature concrete at early ages. Smaller values of creep and shrinkage have the potential to reduce prestress losses. The rapid strength gain and early maturity of the concrete may influence bond behavior of prestressing strands, potentially reducing the transfer length. Higher compressive strengths have been shown to produce shorter transfer lengths.[11,12]

Prestress transfer in pretensioned prestressed concrete members is known to be influenced by several factors, including magnitude of the initial prestress, strand diameter, strand surface condition, concrete compressive strength, and method of strand release.[13-16] Only strand diameter and effective prestress are included in the transfer length portion of the ACI/AASHTO LRFD[16,17] development length equation given as Equation 1,

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

where f_{pe} = stress in the prestressing steel after accounting for all losses (ksi) and d_b = nominal strand diameter (in.). The ACI[16] and AASHTO[17] codes also include the specific transfer length provisions of $50d_b$ and $60d_b$ respectively for use in calculating stresses within the transfer length, as in for shear design. Development length of prestressing strands is affected by the same factors as prestress transfer. The ACI/AASHTO prediction for development length only includes the stress in the prestressing strand and the strand diameter. It is given as Equation 2 in the form found in ACI[16] section 12.9 (a) AASHTO LRFD 6th Edition[17] section 5.11.4.2 (b),

$$l_d = \left(\frac{f_{pe}}{3}\right) d_b + \left(f_{ps} - f_{pe}\right) d_b \tag{2a}$$

$$l_d = \kappa \left(f_{ps} - \frac{2}{3} f_{pe}\right) d_b \tag{2b}$$

where f_{ps} is the stress in the strand at nominal flexural strength. The two equations are the same other than the factor κ, which is 1.0 for pretensioned panels, piles, and other pretensioned members with a depth less than or equal to 24.0 in. (610 mm) and 1.6 for pretensioned members with a depth greater than 24 in. (610 mm). The expression for transfer length given as Equation 1 is not explicitly stated, but is included as part of the development length equation given in Equation 2. Current code equations were developed using conventional portland cement concrete. Numerous research projects have focused on specialty concrete types, all using portland cement, including high strength,[11,12] self-consolidating,[18,19] lightweight,[20-22] and ultra-high performance.[23-25] No previous work involving strands cast in CSA cement concrete was noted by the authors in their review.

Strand transfer length is typically determined experimentally using concrete surface strain[13,15,18,26] or using strand draw in along with the theoretical expression

$$l_t = \alpha \Delta_s \left(\frac{E_{ps}}{f_{si}}\right) \tag{3}$$

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.[26-29] 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.[26-30] Transfer length measurements have been attempted using strain gages bonded to the prestressing strands,[26] but these are often damaged during prestress transfer or by moisture within the concrete making them unreliable. Vibrating wire strain gages embedded at the level of the prestressing strands are a promising alternative to traditional methods of measuring transfer length.

Prestress losses are affected by the elastic shortening of the prestressed member at prestress release, concrete creep, concrete shrinkage, and relaxation of the prestressing steel.[31,32] Each of these components is considered separately in the detailed methods for predicting prestress losses and factors are included to account variability of conditions. Prestress loss predictions are based on studies of conventional concrete[31] and conventional high strength concrete,[32] and no factors are included to quantify the effects of reduced creep or shrinkage related to cement type. 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 corresponding prediction.

The compressive strength gain, high durability, and low shrinkage of CSA cement concrete make it a very appealing material for use in pretensioned prestressed concrete applications. However, little published research was found focusing on the production or behavior of CSA cement concrete members. The structural and functional performance of the material must be proven before it can be safely used in a particular application.

BEAM CONSTRUCTION

The experimental program was designed to assess the capability of producing multiple beams in one day from a given prestressing bed, and to examine the transfer length, development length, and shear behavior of the specimens. Four 8 in. × 24 in. × 24 ft long (200 mm × 610 mm x 7.3 m) rectangular beams were cast at a prestressing plant in Oklahoma City using calcium sulfoaluminate cement concrete over the course of two days. The beams were divided into two sets of two beams each and were cast in a 100 ft (30.5 m) long prestressing bed. The beams were concentrically prestressed with six ½ in. special (13.3 mm) prestressing strands. Three strands were located 2 in. (50 mm) from the bottom of the section and three strands were located 2 in. (50 mm) from the top of the section. One double-leg stirrup was provided at each end to resist bursting stresses and cracking during prestress release. The general beam cross-section is shown in Figure 1.

A total of 15 vibrating wire strain gages (VWSG) were placed throughout the length of each beam attached to the bottom middle strand of the beam. An example of gage placement is shown in Figure 2. Gages were placed before strand tensioning and were moved to final positions and fixed in place after strands were brought to final tension. Four VWSGs were placed at one end of each beam spaced approximately 18 in. (380 mm) on center with the first gage placed 6 in. (150 mm) from the beam end. One gage was placed directly at the centerline of each beam, and the remaining 10 were placed at the opposite end of the beam spaced at 8-10 in. (200-250 mm) on center with the first gage located 6 in. (150 mm) from the beam end. An additional VWSG was cast inside a 6 in. × 12 in. (150 mm × 300 mm) cylinder kept

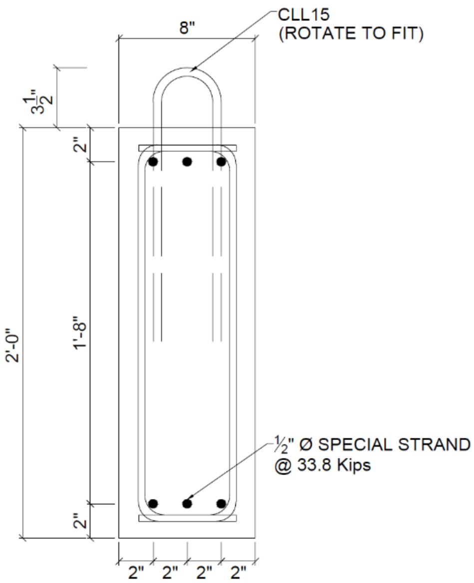

Figure 1. Beam cross-section showing the transverse reinforcement at the member ends

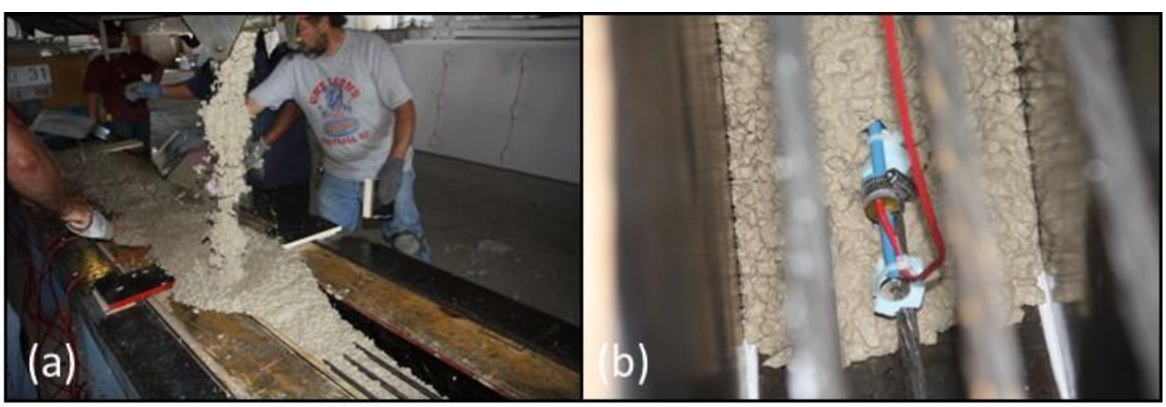

Figure 2. Placement of concrete (a) from the transport truck discharge boom and (b) around the VWSG placed on center bottom strand

alongside each beam to monitor free shrinkage. All strain gages were connected to a mobile datalogger before the concrete was cast.

The concrete mixture used for the beams was developed by the precast producer and the cement supplier and was tested for necessary behavior in a previous project.[33] The concrete had a targeted compressive strength of 3500 psi (24.1 MPa) at prestress release and a targeted slump flow between 24 and 28 in. (610 and 710 mm). Two batches were required to cast the four beams and were done on consecutive days to work with the plant schedule. The beams cast on day 1 were designated 1 (north beam) and 2 (south beam) with the beams cast on day 2 designated 3 (north) and 4 (south). Each batch was 3 yd^3 (2.3 m^3) to provide enough concrete for two beams and the required fresh property tests. Beams 1 and 2 were cast from the same batch and beams 3 and 4 were cast using the same batch. The mix design is presented in Table 1. The CSA cement had a specific gravity of 2.98, the limestone coarse aggregate had a nominal maximum size of 3/8 in. (9.5 mm) and a specific gravity of 2.71, and the fine aggregate had a specific gravity of 2.60. The *w/c* of 0.48 used for the mixture is near the theoretical minimum required for complete hydration of this CSA cement. A high range water reducer was used to provide the necessary workability and citric acid was added as a set retarder to provide the necessary working time. An additional 88 lb (40 kg) bag of cement was added to the first batch and the citric acid dosage varied between the batches due to the quantity available at the plant. The first batch had a dosage of 0.0025 lb of citric acid to 1 lb of cement (0.25%). The second batch had a dosage of 0.0035 lb/lb (0.35%). The effect of citric acid dosage on working time and concrete placement is described in the results section.

The planned mixing procedure, used for beams 1 and 2, consisted of first adding all the coarse aggregate, all the cement, all the citric acid, 70% of the sand, and 80% of the water to the mixer. The initial addition was followed by adding all the HRWR, the remaining sand, and the remaining water, in that order. The materials were thoroughly mixed before being transported to the formwork. The mixing time was based on the experience of the cement supplier due to the rapid setting characteristics of the mixture. The CSA cement was brought to the precast plant in 88 lb (40 kg) bags and added to the mixer by hand. An error occurred during mixing the batch used for beams 3 and 4 after the initial addition of materials. The final 30% of sand was added before the HRWR which caused the mixture to clump together into a single mass before breaking apart after a few minutes. The remaining water was added after the mixture broke up. The slump of each mixture was measured immediately after discharge from the mixer and within five minutes of the last addition of water to the mixture.

Table 1. Concrete Mix Design

Material	**Quantity**
CSA Cement, lb/yd^3	658
3/8 in. Limestone, lb/yd^3	1782
Sand, lb/yd^3	1188
Water, lb/yd^3	316
HRWR, oz/cwt	24
w/c	0.48

Note: 1 lb = 0.4536 kg, 1 ft = 0.3048 m, and 1 oz = 29.57 mL

Concrete was transported to the prestressing bed using a transfer truck that placed the concrete through a discharge boom, as shown in Figure 2. The concrete was allowed to flow along the length of the beam under its own weight to the extent possible, but the boom was also moved along the beam to facilitate placement. The concrete surface was then screeded and floated to produce the desired surface. The concrete was starting to set by the time finishing of beams 1 and 2 was completed. After final set had occurred (40-50 minutes after addition of water to the mixer) curing water was sprayed onto the tops of the beams. Compressive strength tests were conducted at intervals beginning 105 min after water was added to the mixer for beams 1 and 2. This time interval was shortened to 45 minutes for beams 3 and 4 to better capture strength development. The additional time for beams 1 and 2 was required for placement of end slip measurement devices. Once the required 3500 psi (24.1 MPa) compressive strength was reached and all instrumentation was in place, the strands were flame-cut one at a time at both ends simultaneously. Beams were then removed from the formwork and moved to storage in the yard.

Transfer length was determined from the VWSG measurements by plotting the measured strain along the length of the beams and taking the location where the strains reach 95% of the constant value as the transfer length similarly to previous research.[26] The values measured for each end were then averaged to obtain an overall transfer length for each specimen. Steel block clamps were attached to selected prestressing strands and the offset from the beam ends was measured before and after release of prestress to determine strand draw-in. End slip measurements are shown in Figure 3. Transfer length was determined using the strand draw-in measurements and Equation 3. AASHTO LRFD and the ACI 318 building code assume a linear variation of stress in the strands, and corresponding constant bond stress, throughout the transfer length. Based on the assumption that the actual bond stress distribution is between the two extremes of constant and linear, an α of 3.0 was used to obtain conservative values.

After the beams were allowed to cure in the prestressing yard for 28 days to simulate storage between prestress release and transport to a construction site, they were brought to Fears Structural Engineering lab at the University of Oklahoma for monitoring and flexural testing.

Figure 3. Measurement of strand end slip using steel block clamped to strand and depth micrometer

Two beams were tested to evaluate development length and the remaining two beams were placed in storage within the lab in order to continue monitoring prestress losses over time.

A single flexural test was conducted on the end of the beam containing the larger density of VWSGs. A single point load was applied at an embedment length chosen based on the calculated development length for the ½ in. special prestressing strands. Steel rollers placed 12 in. (305 mm) from each end of the beams were used to create a 23 ft (7 m) simply supported span. The loading configuration is shown in Figure 4. Load was monitored using a 100 kip (445 kN) capacity load cell. Load was applied in 5 kip (22 kN) increments until cracks were observed and 2.5 kip (11 kN) increments after cracking. Visible cracks were marked after each load increment. Deflection was monitored with both a single wire potentiometer (pot) at the load point and manual deflection measurements made after each increment using a laser attached to the load frame, a line scribed on the beam, and a steel rule. End slip was monitored using linear voltage differential transformers (LVDTs) attached to the bottom three exposed prestressing strands and the center top prestressing strand. Instrumentation used is shown in Figure 5. Both specimens were loaded until they could no longer support additional load.

Figure 4. Loading configuration showing single point load and roller supports

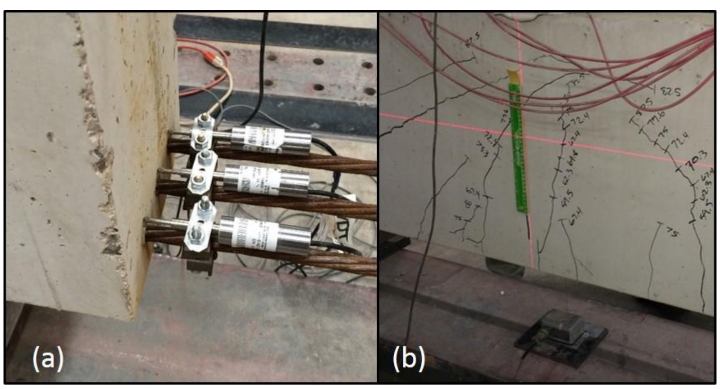

Figure 5. Instrumentation for flexural test including (a) LVDTs used to monitor strand slip and (b) wire pot and laser used for manual deflection measurements

Prestress losses were determined using the measured strains from the VWSGs at the level of the bottom prestressing strands and the known modulus of elasticity of the prestressing strands. The measured strains within the constant region described in the transfer length section were averaged in order to obtain an average strain. The change in this value before and after prestress release and over time were taken as the elastic shortening loss and creep and shrinkage losses respectively. Relaxation losses cannot be measured using strain in the concrete or strands and were considered as an addition to the total measured losses. Relaxation losses were, therefore, not included in the comparison of measured to predicted prestress losses, but a value of 1.2 ksi (8.3 MPa), taken from AASHTO LRFD section 5.9.5.4.2c, was included as a loss in determination of effective prestress for service stress, flexure, and shear calculations

RESULTS AND DISCUSSION

The slump for the concrete used for beams 1 and 2 was 9 in. (230 mm) and for beams 3 and 4 was 8 in. (200 mm). The SCC spread flow was also measured for beams 1 and 2 and was 16.5 in. (420 mm). Spread flow was not measured for beams 3 and 4 due to the poor flow. The measured spread flow was less than the targeted 24 in. to 28 in. (610 mm to 710 mm), but the concrete flowed into the forms without issue. The mixture exhibited excellent cohesion throughout the casting process with no evidence of segregation. The finished beams had an excellent surface condition with only a limited number of small bug holes. The high range water reducer demand was much higher than for conventional concrete and determining the proper dosage of citric acid retarder to obtain the desired flow properties and time of set was challenging. The first set of beams had nearly set by the time the finishing process was completed. Adjustments were made to task assignments to project personnel to allow for instant screeding and finishing, and the second set of beams was cast without difficulty.

A detailed timeline of beam production is shown in Table 2. The compressive strengths measured at each time increment for the two sets of beams are shown in Tables 3 and 4. The difference in time for the first compression test for beams 1 and 2 was due to delays in attaching instrumentation after concrete placement was completed. The concrete for both sets of beams reached the desired compressive strength of 3500 psi (24.1 MPa) within 1.75 hr from addition of the initial water to the mix. Even with the extra instrumentation required for these beams, it is clear from Table 2 that only two hours were required from initiation of the concrete mixing to prestressing strand release.

Transfer lengths determined from the plots of strain measured along the length of each member using the VWSGs and the values predicted using Equation 1, the ACI $50d_b$, and the AASHTO $60d_b$ expressions are shown in Figure 6. The values from specimen B1 are not included due to incorrect output format from the datalogger. This loss of data from one specimen reduced what was at first a small data set even further, which only allows for preliminary conclusions to be drawn. It was not possible to make an accurate assessment of variability in the measurements of transfer length using either method. The average transfer length for all specimens of 29.0 in. (737 mm) was 13.9% less than the value calculated using Equation 1, 10.3% greater than the ACI $50d_b$ value, and 7.7% less than the AASHTO $60d_b$ value.

Table 2: Beam Construction Timeline (time, in minutes, from initial water addition)

Item	Beams 1 and 2	Beams 3 and 4
Water added to mixer	0	0
Slump/spread flow test	5	8
Beam casting begins	5	10
Beams finished	37	28
Curing water initiated	50	39
First cylinder tested	105	43
Second cylinder tested	130	70
Third cylinder tested	NA	85
Fourth cylinder tested	NA	92
Strands cut	165	101
Beams removed from molds	175	121
Total Time	2 hr 55 min	2 hr 1 min

Table 3: Compression Test Results for Beams 1 and 2

Time from initial water (min)	Compressive Strength, f_c (psi)
105	4370
130	4520

Note: 1 psi = 0.00689 MPa

Table 4: Compression Test Results for Beams 3 and 4

Time from initial water (min)	Compressive Strength, f_c (psi)
43	50
70	2130
85	3360
92	3870

Note: 1 psi = 0.00689 MPa

Equation 1 includes effective prestress, but the larger effective prestress resulting from the smaller prestress losses described later in this paper may have contributed to transfer lengths greater than predicted by the ACI $50d_b$ expression. The transfer lengths for the end of the beams with more VSWGs were greater than the opposite end for beams B4 and B3 while the end with more VSWGs had a smaller transfer length for specimen B2.

The transfer lengths determined from the measured strand draw-in for each beam are presented in Table 5. These measurements were not planned with the initial test setup and were added in order to compare to the internal strain gage measurements. Only a limited data set could be collected due to restrictions on access to the prestressing strands in the formwork. The strands are identified using the beam number, cardinal direction of the end, vertical location, and horizontal location. For example, the designation 1NTW refers to beam 1, north end, top strand on the west side. The formwork was not initially set up to facilitate end slip measurements, so values were only collected from selected strands with adequate access. Considering the entire data set, at least one data point was collected from each potential strand location. The beam end plates also had a relatively rough surface at some locations which resulted in poor data.

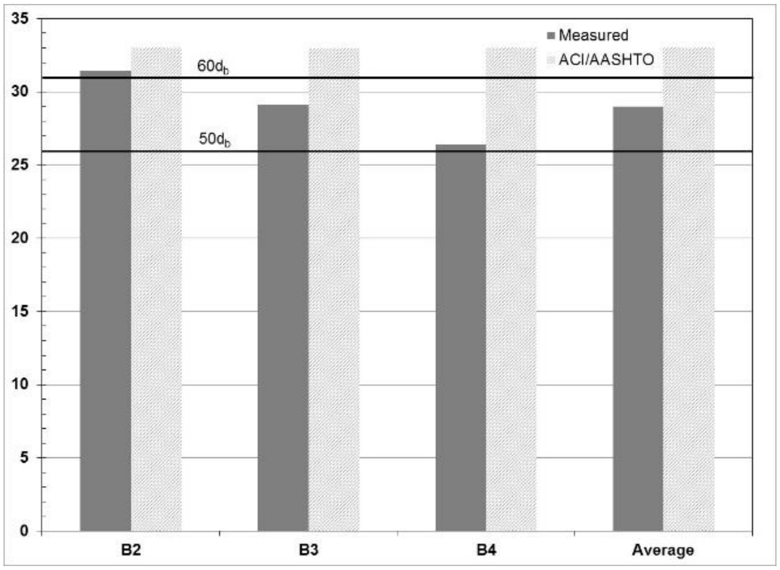

Figure 6. Measured and predicted transfer lengths at 28 days.

These data were not included with those presented in Table 5. The average transfer length of all specimen ends determined using strand slip was 15.1 in. (384 mm), but a standard deviation of 7.8 indicated high variability within the data set. However, only two values indicated a transfer length greater than the code estimation of $50d_b$, or 26 in. (660 mm). These two BM strands were in locations where the largest number of vibrating wire strain gages (VWSG) were attached, which may have interfered with the bonding of the strand to the concrete and caused additional strand slip. The foam blocks used to support the VWSG's may be acting similarly to the plastic sheathing used for debonded tendons. These longer transfer lengths were corroborated by the internal strain gage data. The BM ends with fewer gages exhibited behavior more typical of the other strand locations. While not enough data were collected to make a definite conclusion, no evidence of poorer strand bond for top strands was observed. The reduction, or elimination, in bleed water when using CSA cement would reduce the contribution of this mechanism to bond behavior for strands with more than 12 in. (305 mm) of concrete below.

Table 5. Transfer length determined from strand end slip using $\alpha = 3.0$ (all values in inches)

Beam End	TW	TM	TE	BW	BM	BE
1N	--	5.3	--	--	--	--
1S	11.8	13.0	8.3	--	31.9	14.9
2N	--	--	--	--	--	--
2S	15.6	16.0	18.9	--	9.8	--
3N	17.8	--	--	--	--	--
3S	--	6.5	--	--	34.04	--
4N	12.7	19.5	19.5	--	--	--
4S	--	--	8.1	22.3	6.7	10.2
Average	14.5	12.1	13.7	22.3	20.6	12.5

Note: 1 in. = 25.4 mm

Measured and predicted average prestress losses for each set of two beams are presented in Table 6. Average measured elastic shortening losses were approximately 7.5% greater than the values calculated using the modulus of elasticity predicted with the ACI equation using the compressive strength at prestress release. Previous work by the authors[33] indicated that the ACI equation provided an accurate prediction of elastic modulus for the mix design used in this project, but typical variation in the concrete compressive strength could explain the small differences. Predicted creep and shrinkage losses at 28 days were approximately 11 times greater than the measured values. A reduction in shrinkage losses was expected due to the known low shrinkage of CSA cement concrete. The reduction in creep may be due to the increased maturity of the concrete at prestress release, but further testing is needed to isolate the cause of this behavior and to develop accurate models of creep and shrinkage behavior for use in prestress loss prediction.

Table 6. Measured and calculated prestress losses at 28 Days

Beam	f'_{ci} (psi)	ACI E_c (ksi)	Meas. ES (ksi)	Calc. ES (ksi)	Meas. CR+SH (ksi)	Calc. CR+SH (ksi)
1 and 2	4520	3832	7.99	7.53	1.48	12.30
3 and 4	3870	3546	8.63	8.11	1.05	14.36
Average	--	--	8.42	7.82	1.19	13.33

Note: 1 psi = 0.00689 MPa, f'_{ci} indicates compressive strength at prestress release, ES = elastic shortening loss, CR = creep loss, and SH = shrinkage loss

Specimens B1 and B4 were tested in flexure with embedment lengths of 72 in. and 48 in. (1.83 m and 1.22 m) respectively. These values were 95% and 58% of the development length calculated using Equation 2 for those specimens and were chosen to represent cases of critical loading at and within the development length. The total applied moment (including self-weight) and resulting deflection for each test are shown in Figure 7 with the calculated moment capacity indicated. Moment capacity was calculated using the principles of strain compatibility and a rectangular stress block. The effective prestress used in these calculations was based on losses calculated using the AASHTO refined method. The stress in both the bottom and top strands at failure was based on the strain calculated using a linear distribution and an assumed value of neutral axis location. The location of the neutral axis was iterated until the compression and tension forces reached equilibrium.

Specimen B1 exhibited first flexural cracking at a load of approximately 36 kips (160 kN), which corresponds to an applied moment of 141 kip-ft (191 kN-m). A large flexure-shear crack, shown in Figure 8, was observed at a load of approximately 55 kips (245 kN) and corresponding total moment of 224 kip-ft (304 kN-m). The specimen continued to carry load until crushing of the compression zone occurred at a load of approximately 59.5 kips (265 kN). The maximum moment of 242 k-ft (328 kN-m) was 5.5% greater than the moment capacity of 229 kip-ft (310 kN-m) calculated using the principles of strain compatibility. The maximum applied shear force of 47.9 kips (213 kN) was approximately 9% less than the ACI simplified shear capacity, but the specimen failure was primarily controlled by a flexure mechanism. Measured strand slip of less than 0.005 in. (0.13 mm) was observed for one of the bottom

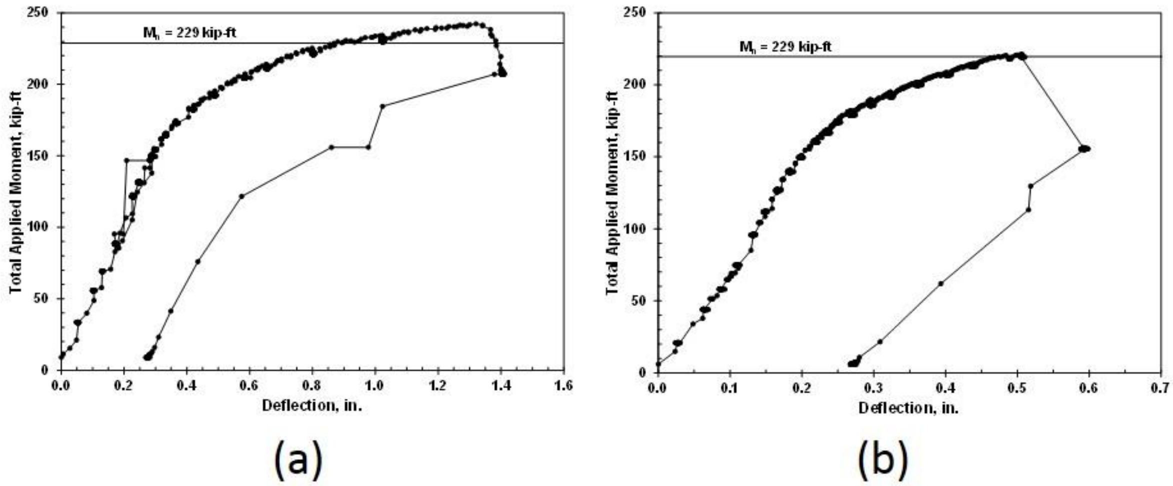

Figure 7. Total applied moment vs deflection for specimen (a) B1 and (b) B4.

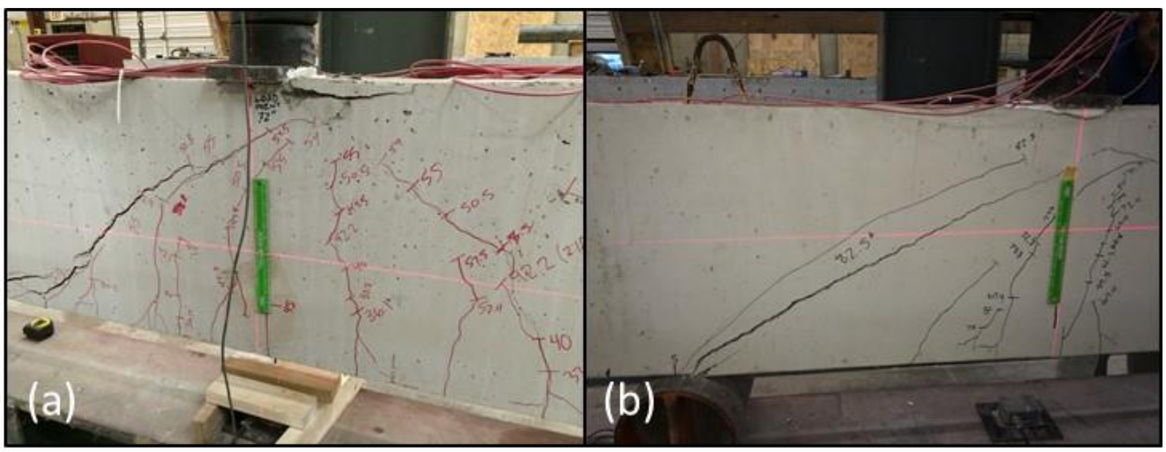

Figure 8. Cracking pattern at failure for specimen B1 (a) and B4 (b).

strands with no appreciable strand slip measured for the others. This minor measured slip on only one strand indicated that the embedment length was adequate to develop the design strength of the strand. Specimen B4 exhibited first flexural cracking at a load of approximately 59.5 kips (265 kN) which corresponds to an applied moment of 161 kip-ft (218 kN-m). The maximum applied load was 82.6 kips (367 kN), corresponding to an applied moment of 221.5 kip-ft (300 kN-m). This value was approximately 3% less than the calculated moment capacity of 229 kip-ft (310 kN-m). A large shear crack appeared while under sustained maximum load, as shown in Figure 8. This crack was accompanied by slip in excess of 0.07 in. (1.8 mm) for all three bottom strands indicating bond shear failure. The maximum applied shear of 73.5 kips (327 kN) was approximately 8% greater than the ACI simplified shear capacity of 68.2 kips (303 kN). It should be noted that the beam specimens were not designed with shear reinforcement, only with a single stirrup to resist bursting stress. This lack of transverse reinforcement significantly affected the observed performance and failure mechanisms including the large shear cracks and measured strand slip.

CONCLUSION

The results of this testing program show that it is feasible to use CSA cement concrete for prestressed members and that the prestress can be released for such members in as little as two hours. As long as the logistics are properly managed, this material has the potential to significantly increase the speed of precast member production. Difficulties were encountered in selecting the proper dosage of high range water reducer and citric acid set retarder that should be solved through production experience using the material. It is possible that this material could be used without the need for these admixtures if a higher *w/c* was used and casting occurred at a lower temperature. More investigation of this possibility is needed, however. Mixing procedures may also need modification for compatibility with the specific equipment available at a given precast plant. The fast set time requires careful planning of all activities, and care should be taken to reduce any delay between mixing, placing and finishing the concrete. Measured strand slip and transfer lengths were within the range of those measured for typical portland cement concrete members and were less than the ACI code prediction. Transfer lengths measured using embedded vibrating wire strain gage were consistently greater than the ACI $50d_b$ used for shear capacity calculations, and less than the AASHTO $60d_b$ expression. Measured time dependent prestress losses were significantly less than the predicted values indicating the need for CSA cement concrete specific prestress loss predictions. Limited development length testing indicated that the development length predicted using the ACI/AASHTO equation is adequate for strands cast in CSA cement concrete with early prestress release. However, further research is necessary to verify the performance of CSA cement concrete members for both short term performance and long term behavior.

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