Using belitic calcium sulfoaluminate cement for precast, prestressed concrete beams

Cameron D. Murray, Royce W. Floyd, and Christopher C. E. Ramseyer

- This paper explores the feasibility of using belitic calcium sulfoaluminate (BCSA) cement to produce precast, prestressed concrete beams.
- Four prestressed concrete beams were fabricated using BCSA cement, and the beam fabrication method, prestressing strand transfer length and development length, prestress losses, and flexural and shear behavior were evaluated.
- The results show that BCSA cement can be used in precast, prestressed concrete beams to shorten curing times, reduce prestress losses, and provide durability and sustainability benefits; however, additional research is needed to further investigate flexural and shear behavior.

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Belitic calcium sulfoaluminate (BCSA) cement is a fast-setting, hydraulic cement that can produce concrete with high early strength and excellent durability. While typical precast concrete producers will release prestress at 18 to 24 hours, BCSA cement could allow prestress release in as little as two hours. Releasing prestress this quickly has the potential to improve the speed of producing precast, prestressed concrete members and reduce labor costs. Although this material has been in use for years, there is little to no published information about its structural performance in the United States. This study is an extension of a conference paper[1] and is one of the first documented uses of BCSA cement for precast, prestressed concrete in the United States. More information is needed on the structural performance of members produced with this material, but this work demonstrates the feasibility of BCSA cement in this application. This study focuses on the fabrication of BCSA cement concrete beams at a commercial precast concrete facility and the material properties, transfer length, development length, prestress losses, shear, and flexural performance of these beams.

Background

Fast-setting BCSA cement concrete can achieve the compressive strength required for prestressed concrete construction in less than one-third the time required for conventional concrete. It also provides other benefits related to the durability and sustainability of members made with this material. BCSA 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.[2–6] These differences lead to significant energy savings and reduced carbon dioxide emissions.[4,7,8]

Although BCSA 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, including some precast concrete applications and self-stressed concrete pipes.[2–5,7,9] One major disadvantage of using BCSA cement is the cost, which can be three to four times that of regular cement. However, this disadvantage can be partly overcome by increased speed of construction and production efficiency, and increased demand may lead to lower material costs. BCSA cement clinker is made from limestone, similar to conventional portland cement, but also from 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. BCSA cement is composed primarily of tetracalcium trialuminate sulfate, or ye'elimite ($C_4A_3\overline{S}$) and dicalcium silicate (belite, C_2S).[2–4,6,10] The $C_4A_3\overline{S}$ in BCSA cement reacts quickly to form monosulfate and ettringite in a series of reactions, depending on the combination of the interground materials.[3,4,7] Ettringite is the main resultant product of the cement reaction and produces a strong crystal structure and high compressive strength at early ages.[5,9,11] The setting time depends on the specific composition but typically varies from 30 minutes to 4 hours. The belite in the cement is then available to react and produce C-S-H, which contributes to strength at later ages.[2–4]

The reaction of $C_4A_3\overline{S}$ requires a higher water-cement ratio *w/c* to completely hydrate the BCSA cement, as opposed to the *w/c* required for portland cement.[3,6] Current limitations in the understanding of the material lead to uncertainty regarding the required *w/c* for BCSA 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 BCSA cement concrete not proportioned to produce expansion is negligible.[4] The high early strength development of BCSA cement concrete may reduce creep as well due to a more mature concrete at early ages. Smaller values of creep and shrinkage may reduce prestress losses. Higher compressive strengths have been shown to produce shorter transfer lengths.[12,13] The rapid strength gain and early maturity of the concrete may influence bond behavior of prestressing strands, potentially reducing the transfer length as well.

The advantages of BCSA cement are particularly beneficial to manufacturers of precast, prestressed concrete because it could allow an increase in production with few disadvantages. The main disadvantage is the higher cost, but because the material is so rapid setting, some practice is needed to ensure that the setting times are controlled properly. Prestress release times of 2 to 4 hours for BCSA cement concrete, as opposed to 18 hours for portland cement concrete, could increase production and save on labor costs. There is little published research on the application of BCSA cement in precast, prestressed concrete, and work is needed to determine whether the performance of the material is adequate for this use.

The use of a new cement in prestressed concrete beams partially depends on the ability of the concrete to bond to prestressing strands in a predictable fashion. One objective of this study was to assess prestress transfer and development length in BCSA cement concrete. Prestress transfer in pretensioned, prestressed concrete members is influenced by several factors, including the magnitude of the initial prestress, strand diameter, strand surface condition, concrete compressive strength, and the method of strand release.[14–17] Only nominal strand diameter d_b and effective prestress (stress in the prestressing steel after all losses) f_{pe} are included in the transfer length of the prestressing strand l_t portion of the American Concrete Institute's (ACI)'s *Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-14)*[17] and the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[18] development length equation, given by Eq. (1).

$$l_t = \frac{f_{pe}}{3} d_b \quad (1)$$

ACI 318 and the AASHTO LRFD specifications 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. The development length of prestressing strands is affected by the same factors as prestress transfer. The prediction for development length only includes the stress in the prestressing strand and the nominal strand diameter. The development length l_d is given in ACI 318 as shown in Eq. (2) and in the AASHTO LRFD specifications as shown in Eq. (3):

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

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

where

f_{ps} = stress in the prestressing strand at nominal flexural strength

κ = multiplier for strand development length

The two equations are the same other than the factor κ in the AASHTO LRFD specifications equation, 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. The expression for transfer length of the prestressing strands l_t given in Eq. (1) is not explicitly stated but is included as part of the development length equation given in Eq. (3). The ACI 318 and AASHTO LRFD specifications equations were developed using conventional portland cement concrete. Numerous research projects have focused on transfer and development length of strands cast in specialty concrete types, including high-strength, self-consolidating, lightweight, and ultra-high-performance concretes.[12,13,19–26] No previous work involving strands cast in BCSA cement concrete was noted by the authors in their review.

Strand transfer length is typically determined experimentally using concrete surface strain or strand end slip along with the theoretical expression given in Eq. (4).[14,16,19,27–30]

$$l_t = \alpha \Delta_s \left(\frac{E_{ps}}{f_{si}} \right) \quad (4)$$

where

α = factor accounting for the bond stress distribution

Δ_s = strand end slip

E_{ps} = modulus of elasticity of the prestressing steel

f_{si} = stress in the prestressing strand immediately after prestress release

Values for α between 2.0 and 3.0, corresponding to a constant and linear variation of bond stress, respectively, have been proposed by previous researchers.[27–31] Transfer length measurements have been attempted using strain gauges bonded to the prestressing strands, but these are often damaged during prestress transfer or by moisture within the concrete, making them unreliable.[27] Vibrating-wire strain gauges embedded at the level of the prestressing strands are a promising alternative to traditional methods of measuring transfer length and have been shown to be more reliable than surface measurements for long-term strain monitoring.[32]

Prestress losses are affected by the elastic shortening of the prestressed concrete member at prestress release, concrete creep, concrete shrinkage, and relaxation of the prestressing steel.[33,34] Each of these components is considered separately in the detailed methods for predicting prestress losses, and factors are included to account for variable conditions. Prestress loss predictions are based on studies of conventional concrete and conventional high-strength concrete, and no factors are included to quantify the effects of reduced creep or shrinkage related to cement type.[33,34] A change in concrete behavior for any one of the major prestress loss components will affect the overall prestress losses and the accuracy of the prediction.

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

Procedures

The experimental program was designed to determine whether multiple beams could be produced in one day from a given prestressing bed and to examine the transfer length, development length, prestress loss, and shear behavior of the specimens. Four 8 in. × 24 in. × 25 ft (200 mm × 610 mm × 7.6 m) rectangular beams were cast at a prestressing plant in Oklahoma City, Okla., using BCSA cement concrete over the course of two days in the summer. The temperature at the time of batching was about 80°F (26.7°C). 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. (13.2 mm) diameter special prestressing strands. Three strands were located 2 in.

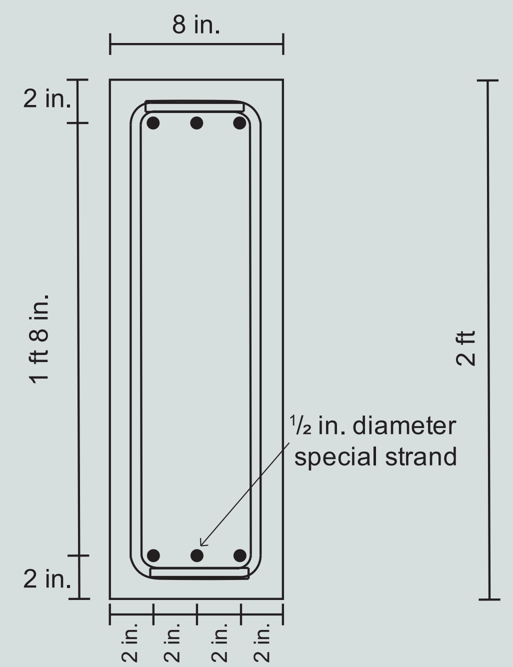

Figure 1. Beam cross section. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

(50 mm) from the bottom of the section, and three strands were located 2 in. from the top of the section. One double-leg stirrup was provided at each end to resist bursting stresses and cracking during prestress release. **Figure 1** shows the beam cross section.

The concrete used for the beams was developed by the precast concrete producer and the cement supplier and was tested for necessary behavior in a previous project.[35] 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 of concrete were required to cast the four beams and were mixed on consecutive days to work with the plant schedule. The beams cast on the first day were designated 1 (north beam) and 2 (south beam); the beams cast on the second day were designated 3 (north beam) and 4 (south beam). Each concrete 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 from the same batch.

Table 1 presents the basic mixture proportions used for both sets of beams. The BCSA 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 concrete is near the theoretical minimum required for complete hydration of this BCSA cement. A high-range water-reducing admixture (HRWRA) was used to provide the necessary workability, and citric acid was added as a set retarder to provide the necessary working time. A self-consolidating concrete (SCC) with a spread flow between 24 and 28 in. (610 and 710 mm) was desired by the precast concrete producer.

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. Citric acid is a commonly used set retarder for BCSA cement. The first batch had a dosage of 0.0025 lb (0.0011 kg) of citric acid to 1 lb (0.45 kg) of cement (0.25%). The second batch had a dosage of 0.0035 lb/lb (0.0035 kg/kg) (0.35%). The effect of citric acid dosage on working time and concrete placement is described in the results section.

Table 1. Concrete mixture proportions

Material	Quantity
Belitic calcium sulfoaluminate cement, lb/yd^3	658
$^3/_8$ in. limestone, lb/yd^3	1782
Sand, lb/yd^3	1188
Water, lb/yd^3	316
High-range water-reducing admixture, oz/100 lb cement	24
Water-cement ratio	0.48

Note: 1 in. = 25.4 mm; 1 lb/yd^3 = 0.5926 kg/m^3; 1 oz/100 lb = 1 mL/1.5352 kg.

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 HRWRA, 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 fast-setting characteristics of the concrete. The BCSA cement was brought to the precast concrete plant in 88 lb (40 kg) bags and added to the mixer by hand. An error occurred while mixing the batch used for beams 3 and 4, after the initial addition of materials. The final 30% of sand was added before the HRWRA, which caused the mixture to clump together into a single mass before becoming fluid again after a few minutes. The remaining water was added after the mixture became fluid. The slump of each concrete was measured immediately after discharge from the mixer and within five minutes of the last addition of water to the mixture.

Concrete was transported to the prestressing bed (located in a covered warehouse) using a transfer truck that placed the concrete through a discharge boom. 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. After final set had occurred (40 to 50 minutes after addition of water to the mixer), curing water was sprayed onto the tops of the beams. Concrete compressive strength tests were conducted at intervals beginning 105 minutes 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) concrete compressive strength was reached and all instrumentation was in place, the strands were flame cut one at a time (at both ends simultaneously). The beams were then removed from the formwork and moved to storage in the yard.

Transfer length measurements

A total of 15 vibrating-wire strain gauges were attached to the bottom middle strand throughout the length of each beam. **Figure 2** shows an example of gauge placement. Gauges were placed before strand tensioning. Four vibrating-wire strain gauges were placed at one end of each beam and spaced approximately 18 in. (460 mm) on center, with the first gauge placed 6 in. (150 mm) from the beam end. One gauge was placed directly at the centerline of each beam, and the remaining 10 were placed at the opposite end of the beam and spaced 8 to 10 in. (200 to 250 mm) on center, with the first gauge

Figure 2. Vibrating-wire strain gauge placement.

located 6 in. from the beam end. These locations are approximate because the gauges shifted during strand tensioning. The exact gauge locations were determined after testing, and these locations were used in the data analysis. An additional vibrating-wire strain gauge was cast inside a 6 × 12 in. (150 × 300 mm) cylinder kept with each beam to monitor free shrinkage. All strain gauges were connected to a mobile datalogger before the concrete was cast.

The transfer length was determined from the vibrating-wire strain gauge measurements by plotting the measured strain along the length of the beams and taking the location where the strains reached 95% of the constant value as the transfer length, similar to previous research.[27] 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 end slip. Transfer length was determined using the strand end-slip measurements and Eq. (4). Both the AASHTO LRFD specifications and ACI 318 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 for transfer length. A value of 2.6, based on a maximum likelihood method determination of the bond stress distribution from previous work, was also considered.[36]

Determining prestress losses

Prestress losses were determined using the measured strains from the vibrating-wire strain gauges at the bottom row of prestressing strands and the known modulus of elasticity of the prestressing strands over a period of up to three years. The measured strains beginning at the location where the strains reach 95% of the constant value were averaged to obtain an average strain. The difference between this value at prestress release and the initial prestress was taken as the elastic shortening loss and the change in value over time after elastic shortening was taken as the creep and shrinkage losses. A free 6 × 12 in. (150 × 300 mm) cylinder was cast with a vibrating-wire strain gauge inside for each beam to estimate shrinkage losses. Relaxation losses cannot be measured using strain in the concrete or strands and were considered an addition to the total measured losses. Relaxation losses were, therefore, not included in the comparison of measured to predicted prestress losses. When evaluating prestress losses at the time of testing for use in analysis, the detailed method described in the AASHTO LRFD specifications[18] section C5.9.5.4.2c was used to estimate relaxation losses. The measured creep and shrinkage were used in this equation to determine the most accurate relaxation estimate. Measured prestress losses were compared with the estimated prestress losses calculated by the AASHTO LRFD specifications section 5.9.5.4 (refined method).[18] Recent research suggests that internal strain measurement (by vibrating-wire strain gauge) is the most accurate way to account for long-term prestress losses.[32]

Description of development length tests

A single point load was applied near one end of each beam to evaluate the development of the prestressing strands. The load point was chosen based on the estimated development length of the ½ in. (13.2 mm) diameter special prestressing strands. A simple span of 23 ft (7.0 m) with a 1 ft (0.3 m) overhang on each end was used, with steel rollers as the supports. A 100 kip (445 kN) capacity load cell was used to monitor load. Load was applied in 5 kip (22 kN) increments up to the cracking load, after which 2.5 kip (11 kN) increments were used. Cracks were marked on the beams with a permanent marker between load increments. Deflection was measured manually using a laser level and steel ruler and with two wire potentiometers under the load point. Strand slip was measured using linear variable displacement transducers on the bottom three strands and the top center strand. Beams 1 through 4 are referred to as B1, B2, B3, and B4 in this paper. Specimens B1 and B4 were tested in November 2014 at an age of roughly one year and four months. Specimens B2 and B3 were tested in June 2016 at an age of roughly three years. The difference in test times was chosen to obtain longer-term prestress loss data.

Results and discussion

The concrete slump was 9 in. (230 mm) for beams 1 and 2 and 8 in. (200 mm) for beams 3 and 4. The SCC spread flow for beams 1 and 2 was 16.5 in. (420 mm). Spread flow was not measured for beams 3 and 4 because the concrete did not flow as expected. The measured spread flow was less than the targeted 24 to 28 in. (610 to 710 mm) for both mixtures, but the concrete filled the forms without issue. The concrete exhibited excellent cohesion throughout the casting process with no evidence of segregation. The finished beams had an excellent surface condition with a limited number of small bugholes. The HRWRA demand for the BCSA cement concrete 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 in an active plant environment with new mixture proportions. The concrete for the first set of beams reached initial set by the time the finishing process was completed. Adjustments were made to task assignments for project personnel to allow for immediate screeding and finishing, and the second set of beams was cast much more efficiently and without difficulty.

Table 2 shows a detailed timeline of beam production. **Table 3** shows the concrete compressive strengths measured at time of release and at three years of age for the two sets of beams. 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. Even with the extra instrumentation required for these beams, only two hours were required from the beginning of the concrete mixing to prestressing strand release (Table 2). The concrete for both sets of beams reached the desired compressive strength of 3500 psi (24.1 MPa) within 1.75 hours from the time of the addition of the initial water to the mixture.

Table 2. Beam construction timeline (in minutes, beginning with addition of water)

Item	Beams 1 and 2	Beams 3 and 4
Water added to mixer	0	0
Slump/spread flow test	5	8
Beams finished	37	28
Curing water initiated	50	39
First cylinder tested	105	43
Second cylinder tested	130	70
Third cylinder tested	n/a	85
Fourth cylinder tested	n/a	92
Strands cut	165	101
Beams removed from molds	175	121
Total time	2 hours 55 minutes	2 hours 1 minute

Note: n/a = not applicable.

Table 3. Concrete compressive strength test results

Batch	At release, psi	At approximately three years of age, psi
1 (B1, B2)	4520 (at 130 minutes)	11,340
2 (B3, B4)	3870 (at 92 minutes)	11,440

Note: 1 psi = 6.895 kPa.

Transfer length results

Table 4 gives a summary of measured transfer lengths determined by the 95% average maximum strain method.[27] The average transfer length measured using the internal vibrating-wire strain gauges for B1 was 28.6 in. (726 mm) before flexural testing at one year and four months of age. This was 9% less than the 31.4 in. (798 mm) average transfer length measured in the first 28 days. One end of B1 had an unusually small transfer length at the time of testing, which may be an

Table 4. Summary of transfer lengths

Age	Transfer length, in.							
	B1		B2		B3		B4	
	End with 4 VWSGs	End with 10 VWSGs	End with 4 VWSGs	End with 10 VWSGs	End with 4 VWSGs	End with 10 VWSGs	End with 4 VWSGs	End with 10 VWSGs
Release	30.91	31.46	31.49	27.29	27.98	26.01	25.38	30.00
1 day	31.82	31.71	30.87	27.21	27.84	25.85	25.98	29.63
7 days	30.92	31.52	29.54	26.95	28.21	25.87	26.56	29.92
28 days	31.18	31.72	31.33	27.28	28.31	25.95	26.75	30.16
16 months	26.68	30.59	n/a	n/a	n/a	n/a	26.60	31.18
3 years	n/a	n/a	31.18	30.61	28.62	27.79	n/a	n/a

Note: n/a = not applicable; VWSG = vibrating-wire strain gauge. 1 in. = 25.4 mm.

outlier because the transfer length decreased only for this single final measurement. The average measured transfer length using both ends of B2 was 30.9 in. (785 mm) at the time of flexural testing and exhibited an increase of roughly 1 in. (25 mm) (5%) between release of prestress and three years of age. The transfer length at both ends was approximately the same (within 2%) at 3 years of age. Some data from B2 were rendered unusable because of faulty vibrating-wire strain gauges. In these cases, adjacent strain gauges were averaged to provide continuous data along the beam's length. The average measured transfer length using both ends of B3 was 28.2 in. (716 mm) at three years of age. The transfer length at the ends differed by roughly 2 in. (50 mm) at prestress release, though they differed by less than 1 in. at three years of age. The average transfer length for both ends of B4 was 28.9 in (734 mm) at one year four months of age. In this case, the end with fewer vibrating-wire strain gauges had a shorter transfer length than the other end by 4 in. (100 mm). The transfer lengths for this beam increased approximately 1 in. over the course of the beam's life. **Figure 3** shows the internal strains at the beam ends over time for all specimens. Strand end-slip measurements did not provide transfer lengths comparable to those measured by the vibrating-wire strain gauges. These measurements were not initially planned and could only be taken on strands that were accessible. Positioning of the forms also made the measurements unreliable; therefore, these results are not included in this paper. **Figure 4** compares the predicted and measured transfer lengths.

Prestress losses

Prestress losses were calculated from measured strain data and predicted using the AASHTO LRFD specifications[18] refined method at prestress release, 1 day, 7 days, 28 days, and at time of final testing for each beam. **Figure 5** gives a summary of the predicted and measured prestress losses at time of final testing. The prestress losses measured for B1 at one year and four months of age totaled 14.4 ksi (99 MPa), excluding relaxation losses. The prestress losses for B2 at three years of age totaled 13.7 ksi (94 MPa), excluding relaxation. The predicted prestress losses were roughly equal for B1/B2 and B3/B4, even when the difference in age at time of testing is accounted for, because the concrete was the same for each set of beams. The predicted prestress losses for B1 and B2 (using the AASHTO LRFD specifications refined method) were approximately 33 ksi (228 MPa), roughly two times the measured prestress losses. Measured prestress losses for B3 and B4 were 14.7 and 13.4 ksi (101 and 92 MPa) at

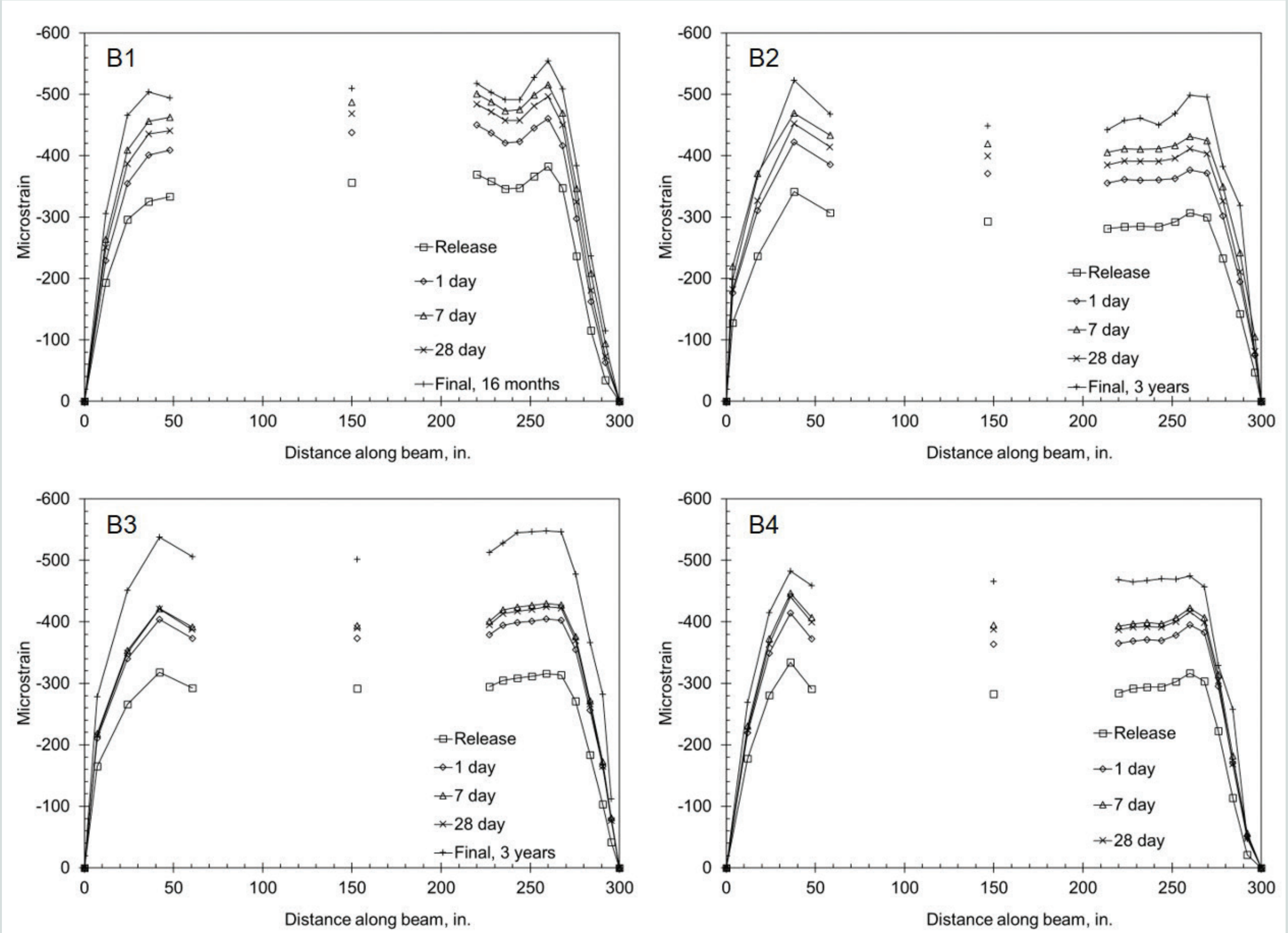

Figure 3. Internal strain profiles used for transfer length determination. Note: 1 in. = 25.4 mm.

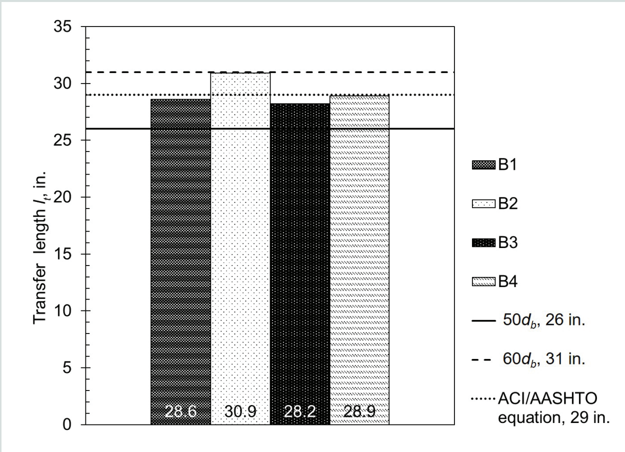

Figure 4. Average measured transfer lengths for each specimen at the time of flexural testing compared with predicted transfer lengths. Note: ACI/AASHTO = American Concrete Institute's *Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-14)* and the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*; d_b = nominal strand diameter. 1 in. = 25.4 mm.

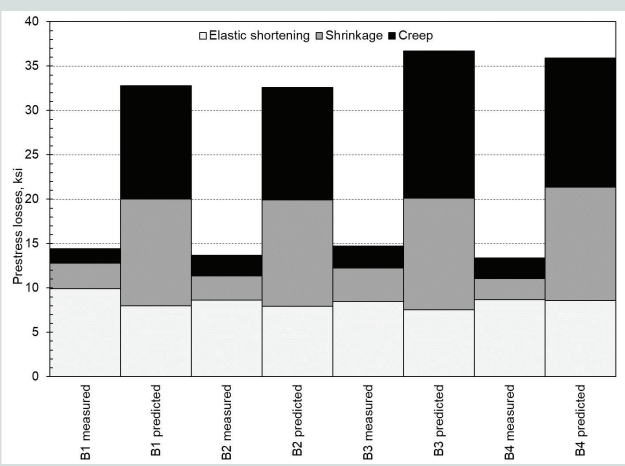

Figure 5. Comparison of measured and predicted prestress losses showing contribution of each loss component except relaxation. Note: 1 ksi = 6.895 MPa.

485 and 1095 days, respectively. For B3 and B4, the prestress losses predicted by the AASHTO LRFD specifications refined method were approximately 36 ksi (248 MPa), again more than two times the measured prestress losses. The prestress losses shown do not include measured or predicted strand relaxation losses.

Elastic shortening losses were similar to the estimates from the AASHTO LRFD specifications[18] refined method, but the shrinkage and creep estimates were inaccurate. The contribution of shrinkage to total losses was estimated using the 6 × 12 in. (150 × 300 mm) cylinder that monitored free shrinkage with a vibrating-wire strain gauge. Creep was determined by subtracting the measured free shrinkage of the cylinder from the total strain after elastic shortening. The accuracy of the shrinkage measurements therefore affected the creep estimate. Because the cylinder had a volume–to–surface area ratio of 1.2, compared with 3.0 for the beams, it is likely that shrinkage losses were overestimated by the cylinders. Despite this, the combined creep and shrinkage losses for all beams at the time of final testing were on average 4.3 ksi (30 MPa), compared with an average of 26.5 ksi (183 MPa) predicted by the AASHTO LRFD specifications refined method. Long-term losses predicted by the AASHTO LRFD specifications must be modified when using BCSA cement concrete, but currently no published creep or shrinkage relationships are available. The average effective prestress for the beams was 187 ksi (1289 MPa), compared with an estimated effective prestress of 166.5 ksi (1148 MPa). The difference in effective prestress (approximately 12%) could reduce the required number of prestressing strands for a specific prestress force in service. The results indicate that the beams produced in this study reduce long-term prestress losses, making BCSA cement appealing for use in prestressed concrete. Relaxation losses were calculated with both measured and estimated creep and shrinkage values, and there was little difference between the two calculated relaxation losses.

Development length test results

Specimen B1 was tested at an embedment length of 72 in. (1.8 m), or approximately 97% of the development length predicted using the ACI 318 and AASHTO LRFD specifications equation. Flexural cracking occurred at a load of 36 kip (160 kN), which corresponds to an applied moment of 141 kip-ft (191 kN-m). The specimen continued to carry load until crushing of the compression zone occurred at a load of approximately 59.2 kip (263 kN). The maximum moment of 241 kip-ft (327 kN-m) was 5.2% 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 46.4 kip (206 kN) was approximately 12% less than the ACI 318 simplified shear capacity, but the specimen failure was primarily controlled by flexure. Measured strand slip of less than 0.005 in. (0.127 mm) was observed for one of the bottom strands with no appreciable strand slip measured for the others. This minor measured slip on only one strand indicated that the embedment length of 72 in. was adequate to develop the design strength of the strand. **Figure 6** gives the moment-deflection curve for specimen B1.

The next beam tested was B4 at an embedment length of 48 in. (1.2 m), or approximately 65% of the development length predicted using the ACI 318 and AASHTO LRFD specifications equation. Flexural cracking began for specimen B4 at a load of approximately 59.5 kip (265 kN), which corresponds to an applied moment of 161 kip-ft (218 kN-m). The maximum applied load was 82.6 kip (367 kN), corresponding to an applied moment of 221 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 (**Fig. 7**). This crack was accompanied by strand slip greater than 0.07 in. (1.8 mm) for all three bottom strands, indicating a probable bond-shear failure.

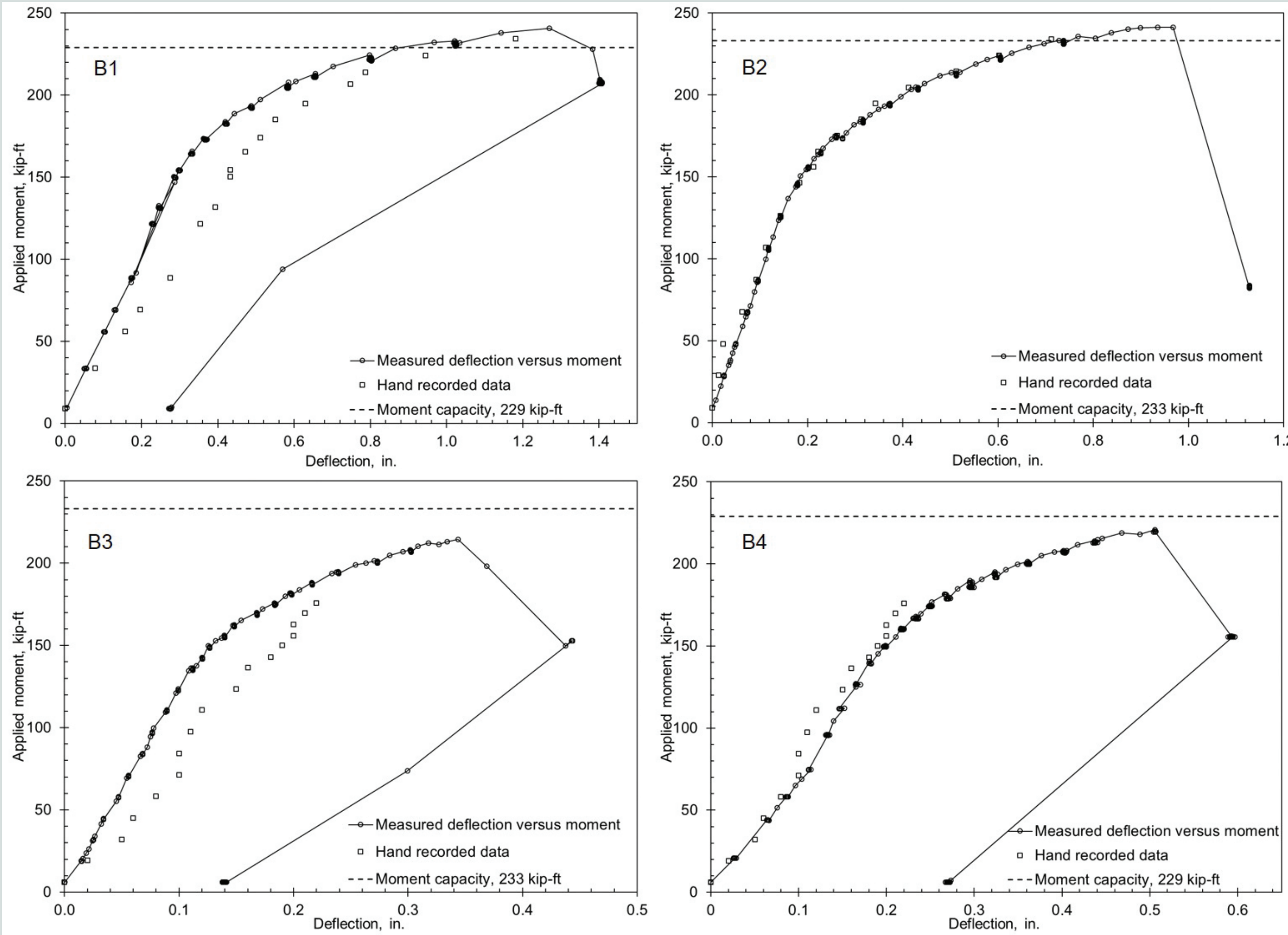

Figure 6. Deflection versus applied moment curves for all specimens. Note: 1 in. = 25.4 mm; 1 kip-ft = 1.356 kN-m.

The maximum applied shear of 71.8 kip (319 kN) was approximately 5.3% greater than the ACI 318 simplified shear capacity of 68.2 kip (303 kN). The beam specimens were not designed with shear reinforcement, only with a single stirrup at each end 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. Figure 6 gives the moment-deflection curve for specimen B4. Because the applied shear exceeded the shear capacity, the development of the prestressing strands appears to be adequate for the failure mechanism at this load location.

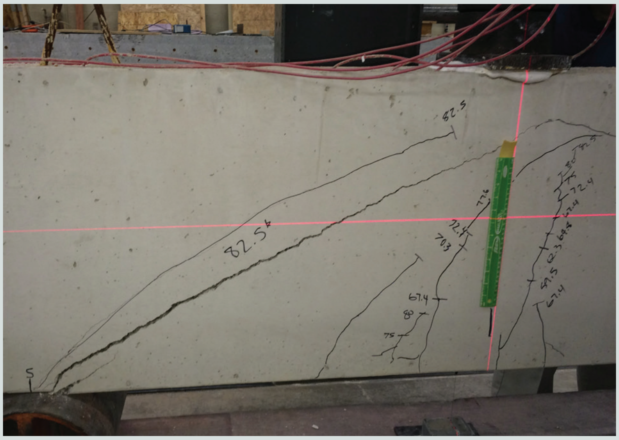

Figure 7. Shear cracking at failure for specimen B4.

Specimen B2 was tested at an embedment length of 72 in. (1.8 m), or approximately 95% of the development length predicted using the ACI 318 and AASHTO LRFD specifications equation. Flexural cracking was observed at a load of 35 kip (156 kN), corresponding to an applied moment of 146 kip-ft (198 kN-m). The maximum applied load was 59.4 kip (264 kN), corresponding to an applied moment of 241 kip-ft (327 kN-m). This applied moment was approximately 3.4% greater than the calculated flexural capacity of 233 kip-ft (316 kN-m). A large flexure-shear crack grew as the load approached the capacity of the beam and led to horizontal cracking along the bottom strands. As the beam reached the failure load, strand slip greater than 0.14 in. (3.6 mm) was immediately observed in all of the bottom strands. The beam exceeded its nominal capacity before any slip was measured. The maximum applied shear of 46.5 kip (207 kN) was approximately 17% less than the shear capacity predicted by the ACI 318 simplified method. The failure appeared to be controlled by shear because there was a large diagonal crack

Beam	Embedment, in.	Predicted l_d, in.	M_n, kip-ft	V_n, kip	P_{max}, kip	M_{max}, kip-ft	V_{max}, kip	Strand slip, in.
B1	72.0	74.3	229.0	52.9	59.2	240.8	46.4	~0
B2	72.0	74.0	233.0	56.0	59.4	241.4	46.5	0.16
B3	48.0	73.6	233.0	86.3	79.9	214.5	69.5	0.03
B4	48.0	74.0	229.0	68.2	82.6	221.4	71.8	0.09

Table 5. Development length testing summary

Note: l_d = development length of prestressing strand; M_{max} = maximum applied moment; M_n = nominal moment capacity; P_{max} = maximum applied load; V_{max} = maximum applied shear; V_n = nominal shear capacity. 1 in. = 25.4 mm; 1 kip = 4.448 kN; 1 kip-ft = 1.356 kN-m.

that formed after loss of prestress. Again, there was no shear reinforcing steel in the beam. In spite of the large flexure-shear crack and strand slip, the beam reached its nominal moment capacity, indicating adequate strand development. Figure 6 gives the moment-deflection curve for specimen B2.

Specimen B3 was tested at an embedment length of 48 in. (1.2 m), or approximately 57% of the development length predicted by the ACI 318 and AASHTO LRFD specifications equation. Flexural cracking occurred at an applied load of 50 kip (222 kN), corresponding to an applied moment of 136 kip-ft (184 kN-m). The maximum load was 79.9 kip (355 kN), which corresponds to a moment of 214 kip-ft (290 kN-m). The applied moment was approximately 8% less than the calculated moment capacity of 233 kip-ft (316 kN-m). The applied shear at failure was 69.5 kip (309 kN), 19.5% less than the shear capacity of the section predicted by the ACI 318 simplified method (86 kip [383 kN]). A flexure-shear crack formed at an applied load of 75 kip (334 kN) and ultimately led to the failure of the beam. This crack was accompanied by horizontal cracking along the level of the prestressing strands. Strand slip in the bottom strands ranged from 0.01 to nearly 0.03 in. (0.25 to 0.76 mm). The failure can be characterized as a bond-shear failure, and the beam failed to reach its nominal shear and moment capacities. Figure 6 gives the moment-deflection for specimen B3.

Table 5 summarizes the results of all beam tests. The values are nominal and do not include strength-reduction factors. The nominal shear capacity was determined using the ACI 318 simplified method, and the nominal moment capacity was calculated using the principles of strain compatibility.

Strand bond was compromised to some degree in the tests of B2, B3, and B4. The lack of transverse reinforcement meant that large shear cracks formed and entered the transfer zone. These cracks reduced the ability of the strands to bond to the concrete. All tests were performed at an embedment length less than the predicted development length, and the test of B1 resulted primarily in a flexural failure. During the tests of B2, B3, and B4, a horizontal crack began at the tip of the initiating failure crack along the length of the girder. The compression force imparted by the top strands and the lack of shear reinforcing steel in the member caused the crack. The unusual prestress forces present in the beams, coupled with the lack of transverse reinforcing steel, no doubt affected the failure of the members. Based on the development length testing, the beams seem to provide adequate anchorage for prestressing strands at the predicted development length. Because this study focused primarily on the feasibility of casting prestressed concrete members with BCSA cement concrete, more work should be done to evaluate the flexural and shear performance of BCSA cement concrete members with typical cross sections and reinforcing details.

Conclusion

The results of the study described in this paper indicate that casting prestressed concrete beams at a commercial facility using BCSA cement is feasible and can result in shorter required curing times before removing beams from the prestressing bed. Transfer lengths do not appear to be affected by the early-age strength gain and prestress transfer and can be estimated using traditional methods. Initial losses due to elastic shortening compare favorably with those predicted using current methods. Time-dependent prestress losses for BCSA cement concrete are minimal compared with portland cement concrete, making BCSA cement an appealing alternative for prestressed concrete. However, prestress loss prediction methods developed for portland cement concrete are inaccurate for BCSA cement concrete and more work is needed to develop relationships for creep and shrinkage for BCSA cement concrete. Load tests performed in this research indicated reasonable agreement with the predicted strengths; however, more testing should be done to validate the development length for strands embedded in this material and to further study flexural and shear behavior for more-typical beam configurations. This study also indicates that vibrating-wire strain gauges are a simple and accurate method for measuring transfer lengths and prestress losses.

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Notation

d_b = nominal strand diameter

E_{ps} = modulus of elasticity of prestressing steel

f_{pe} = stress in prestressing steel after all losses

f_{ps} = stress in the prestressing strand at nominal flexural strength

f_{si} = stress in the prestressing strand immediately after prestress release

l_d = development length of prestressing strand

l_t = transfer length of prestressing strand

M_{max} = maximum applied moment

M_n = nominal moment capacity

P_{max} = maximum applied load

V_{max} = maximum applied shear

V_n = nominal shear capacity

w/c = water-cement ratio

α = factor accounting for bond stress distribution

Δ_s = strand end slip

κ = multiplier for strand development length

About the authors

Cameron D. Murray, PhD, is an assistant professor in the Department of Civil Engineering at the University of Arkansas in Fayetteville. His research interests include prestressed concrete, alkali-silica reaction, and rapid-setting concrete.

Royce W. Floyd, PhD, PE, is an associate professor in the School of Civil Engineering and Environmental Science at the University of Oklahoma in Norman. His research interests include prestressed concrete, lightweight self-consolidating concrete, and rapid-setting concrete.

Chris C. E. Ramseyer, PhD, PE, is an associate professor in the School of Civil Engineering and Environmental Science at the University of Oklahoma.

Abstract

Belitic calcium sulfoaluminate (BCSA) cement is a fast-setting, hydraulic cement that can produce concrete with high early strength and excellent durability. Its fast setting time makes it a promising material for precast, prestressed concrete applications. Although this material has been in use in China for years, there is little to no published information about its structural performance in the United States. This study is one of the first published papers on the use of BCSA cement for prestressed concrete in the United States. More information is needed on the structural performance of members cast with this material, but this work demonstrates that BCSA cement can produce prestressed concrete beams in as little as two hours in an industrial facility. The results also show that prestressed concrete beams produced with BCSA cement have very low prestress losses compared with the equations in the American Concrete Institute's (ACI's) *Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-14)* and the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*, and that bond lengths can be reasonably predicted using current design methods.

Keywords

Belitic calcium sulfoaluminate cement, calcium sulfoaluminate cement, development length, prestress losses, rapid-setting concrete, transfer length.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process.

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