12-2018

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Recommended Citation

Cook, Gabriel, "Early Life Flexural Performance and Behavior of Reinforced BCSA Concrete Beams" (2018). *Theses and Dissertations*. 3035.
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Early Life Flexural Performance and Behavior of Reinforced BCSA Concrete Beams

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Civil Engineering

by

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University of Arkansas
Bachelor of Science in Civil Engineering, 2017

December 2018
University of Arkansas

This thesis is approved for recommendation to the Graduate Council.

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Abstract

Belitic calcium sulfoaluminate cement (BCSA) is a hydraulic, rapid setting alternative to ordinary portland cement (OPC) with reduced energy demands and CO_2 emissions. BCSA cement has numerous current and potential applications including transportation repair and precast manufacturing. Currently, limited research exists regarding the structural performance of CSA cements, restricting its potential implementation. Thus, the purpose of this research is to provide insight into the flexural performance and behavior of reinforced BCSA concrete beams. Overall, BCSA concrete had similar cracking and loading behavior to the OPC beams, with increased moment capacity for compression controlled specimens. Furthermore, BCSA concrete showed increased tensile strength and ductility when compared to OPC. Overall, the flexural strength of the BCSA concrete exceeded the predicted flexural strengths, indicating the current flexural strength equations are applicable for BCSA reinforced concrete design.

Keywords: belitic calcium sulfoaluminate cement, CSA, flexural strength, high early strength

Acknowledgements

I would like to thank CTS for donating the BCSA cement used in this research. I would also like to thank my committee (Dr. Murray, Dr. Prinz, and Dr. Hale) for their guidance and patience. Finally, I am grateful to Casey Jones, Caleb Lebow, Remington Reed, Edgar Soriano, and Ahmed Al-Mohammedi for their contributions and encouragement. I couldn’t have done it without you.

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1. Introduction

Belitic calcium sulfoaluminate (BCSA) cement is a hydraulic, rapid hardening alternative to ordinary portland cement (OPC) with reduced environmental impact. Calcium sulfoaluminate cements exhibit different properties depending on their chemical composition but are generally classified as either shrinkage compensating (such as type K cement) or rapid setting/hardening (such as BCSA). BCSA cements have lower energy demands and CO_2 emissions due to decreased kiln temperatures (1250°C vs 1500°C)[1] and lower limestone requirements[1, 2] during the sintering process compared to OPC. Overall, BCSA cements take 25-60%[1, 3, 4] less energy and reduce CO_2 emissions by 20-40%[1, 4, 5] compared to OPC. Moreover, potential increases in dimensional stability and increased fatigue life can improve the sustainability of BCSA concrete systems[1]. The rapid setting behavior of BCSA cements is characterized by an initial setting time of 10-20 minutes. Food-grade citric acid is currently the preferred retarding admixture, allowing for a setting time approaching 1 hour[3]. Even with retardation, BCSA cements can produce concrete with a strength of 4000 psi (27.5 MPa) in 2-4 hours. This rapid strength gain is due to differences in the initial hydration products for BCSA concrete. BCSA concrete develops ettringite crystals rapidly during hydration; these crystals are responsible for the decreased setting time and increased early age strength when compared to OPC concrete[3].

The rapid hardening behavior of BCSA cement creates opportunities for numerous applications. BCSA cement has been incorporated in pavements in the United States since the 1990s and is currently used by 10 state DOTs for patching, highway repair, and bridge repair[6, 7]. However, other potential uses include precast concrete, disaster relief, 3D concrete printing, cold weather concreting, and energy storage[8]. The largest detriment to BCSA implementation is cost; BCSA cement is approximately 4 times more expensive than Type I/II portland cement[3].

However, increased production and demand are likely to reduce the cost in the future[3]. Furthermore, as taxes on CO_2 emissions are enacted or increased, CSA cement becomes a more attractive option[4].

Most of the research on BCSA cements has focused on material characterization, material properties, and durability[9-11]. In order to use it for structural applications, research is needed on its structural properties, behavior, and performance. Specifically, flexural research would help determine the potential viability of BCSA cements for prestressed and precast concrete members as well as whether it is suitable for structural repairs or new construction. The American Concrete Institute (ACI) 318 Building Code Requirements for Structural Concrete[12] provides a strength design methodology to calculate the nominal moment capacity of reinforced concrete beams made with OPC. Therefore, the objective of this research is to investigate the flexural behavior and moment capacity of reinforced concrete beams made with BCSA cement and determine if the ACI flexural strength procedure is appropriate for BCSA cements.

1.1. Research Significance

Cement production currently accounts for approximately 5-10% of the world's total CO_2 emissions[4, 13]. Current estimates show a 30-40%[14, 15] increase in cement consumption by 2050. Incorporating BCSA cements when appropriate can help mitigate concrete's contribution to CO_2 production. This research is intended to begin analyzing CSA cements for use in structural systems, specifically reinforced concrete flexural members.

2. Experimental Procedure

2.1. Materials and Specimens

A commercially available BCSA cement was used in this work. This cement is a standalone complete replacement for OPC. For the control specimens, a type-I OPC was used. The OPC concrete was provided by a local ready-mix company, and the BCSA mixtures were batched in the laboratory. The mix design for the BCSA specimens was devised to roughly match the proportions for the OPC concrete and both mix designs are shown in Table 1. The OPC mix utilized a larger weight of fine aggregate due to the difference between the specific gravities of the cements (2.96 for BCSA cement versus 3.15 for OPC) and a decreased water/cement ratio (w/c) in the OPC mix. BCSA cement requires a higher w/c to ensure complete hydration[9, 16, 17]. A high range water reducer (HRWR) was used to increase the slump of the BCSA cement mixture to facilitate easier placement in the forms, given the shorter working time. Food grade citric acid was implemented as a retarder to increase the set time of the BCSA cement mixes. A solution of 5 lbs. of citric acid per gallon of water was prepared and dosed at a rate of 9 fl. oz. per 100 lb. of cement (oz/cwt). This dosage is equivalent to 0.0035 pounds of citric acid per pound of cement, or 0.35% by weight of cement. The goal of the mix designs was to provide a highly workable concrete with adequate retardation to ensure placement and finishing prior to initial set.

Table 1: Mix Design Criteria

	BCSA	**Portland Cement**	
Cement	658	660	**lbs/CY**
Coarse Aggregate	1782	1775	**lbs/CY**
Fine Aggregate	1156	1340	**lbs/CY**
Water Reducer	18*	4	**oz/cwt**
Citric Acid	9	-	**oz/cwt**
W/C Ratio	0.48	0.40	

**The first BCSA mix (BCSA TD1) used 12 oz/cwt of HRWR*

Grade 60 rebar was used in this study. Two tension tests on samples of the rebar were performed, as shown in Figure 1. The steel samples exceeded their nominal yield strength of 60 ksi, with an average yield strength of 71 ksi. The modulus of elasticity, E, varied between tests and was estimated to be 26000 ksi and 29700 ksi.

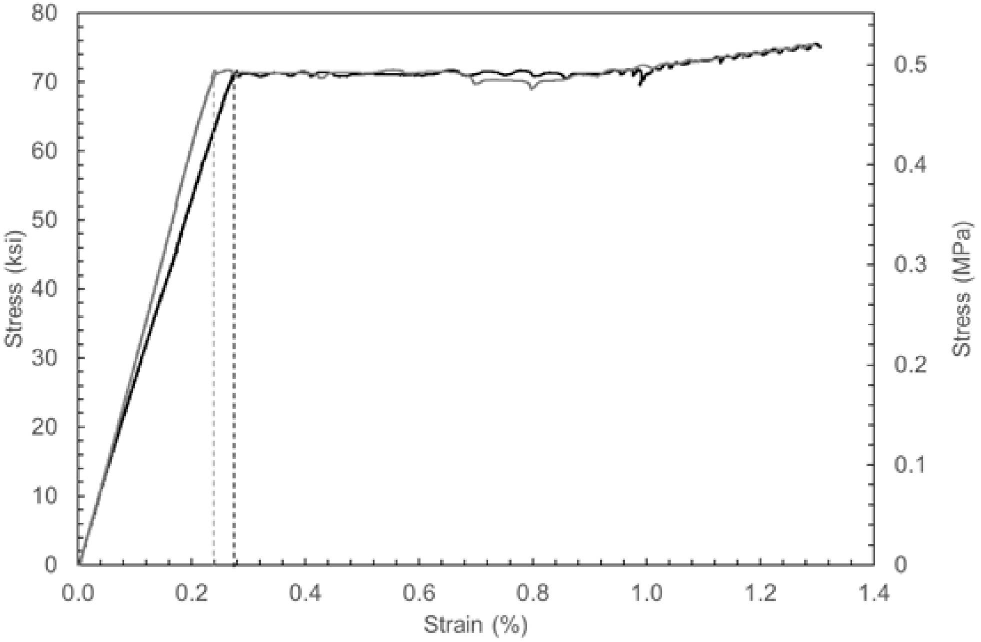

Figure 1: Stress-strain relationship of reinforcing steel

A total of 12 reinforced concrete beams were cast, 4 were cast with OPC and 8 were cast with BCSA concrete. All 4 OPC concrete beams were poured from the same batch and flexural strength tests were performed at 35 days of age. The 8 BCSA beams were batched individually at the University of Arkansas Engineering Research Center using a tilting drum mixer. Flexural strength tests for the BCSA beams were performed at either 1 day of age or 2-5 hours after concrete placement to determine the effects, if any, of age of the BCSA cement concrete on its flexural performance. The 2-5 hour flexural tests were performed as soon as the concrete strength allowed the beams to be demolded and placed in the testing frame.

The flexural reinforcement was designed to provide tension controlled or compression controlled behavior. Two compression controlled and two tension controlled beams were cast for each test case (OPC, 2-5 hour BCSA, and 1-day BCSA). The naming convention denotes the type of cement used, tension or compression controlled, time of test, and specimen number. For example, BCSA TD1 is the first BCSA tension controlled 1-day break. Each beam was 12 ft. long, 12 in. deep, and 6 in. wide. The tension controlled beams consisted of a single layer of two #6 bars placed approximately 1.5 in. from the bottom of the beam resulting in a reinforcement ratio of 0.0140. The compression controlled beams contained four #7 bars placed in two layers, the first layer at approximately 1.5 in. and the second at 3.3 in. from the bottom. The compression controlled beams had a reinforcement ratio of 0.0418. Both beam designs included compression steel, consisting of two #3 bars located approximately 9 in. above the lowest layer of steel. The shear reinforcement consisted of #3 shear stirrups. Stirrup spacing was 4 in. except for the middle sixth of the beam, in which stirrup spacing was 8 in. The shear reinforcement was designed to force a compression controlled or tension controlled flexural failure. The reinforcement layout and beam cross sections are shown in Figure 2 and Figure 3.

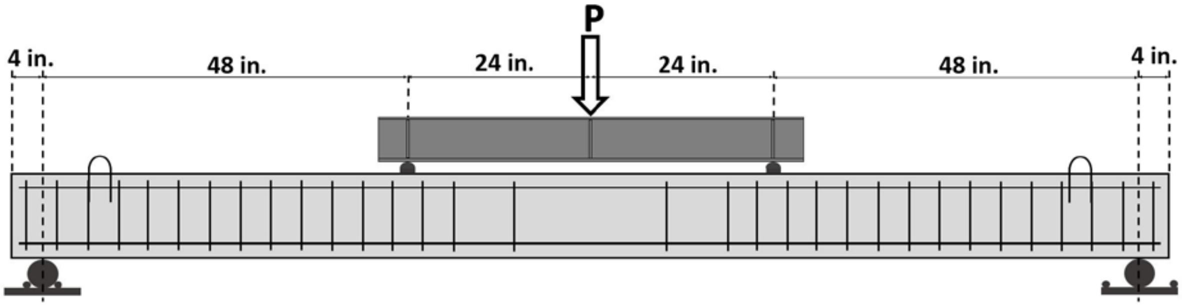

Figure 2: Beam loading and reinforcement layout

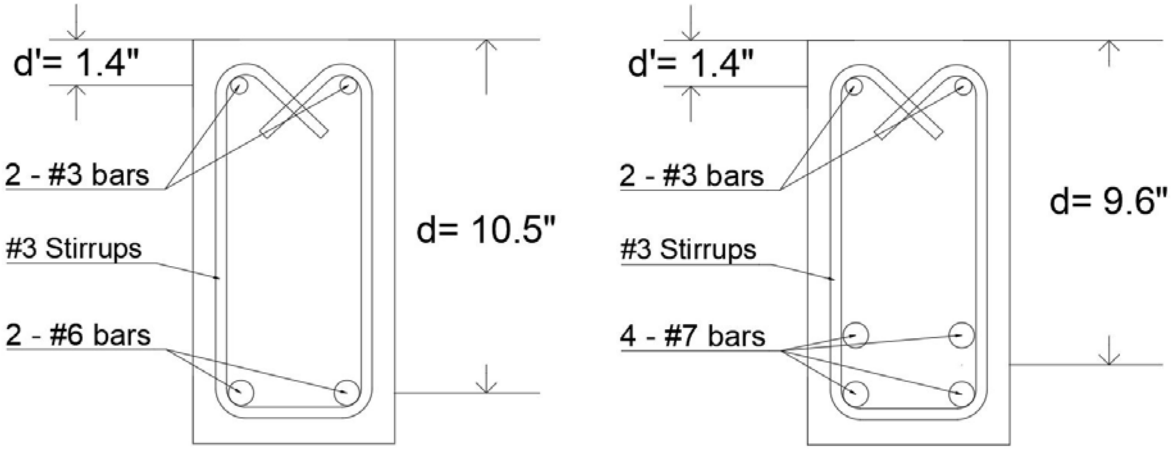

Figure 3: Beam cross section for the tension controlled beams (left) and the compression controlled beams (right)

Flexural testing was conducted using third point loading shown in Figure 2. This loading produced a constant maximum moment in the middle third of the span with zero shear between load points. This load arrangement was selected to encourage flexural failures in the middle portion of the span. A hydraulic ram applied load onto a calibrated load cell atop a steel spreader beam. Leather strips atop semi-circular load points were used to evenly apply load across the width of the beams. Beams were loaded until failure, defined as crushing of the concrete. Linear Variable Differential Transformers (LVDTs) were placed on either side of the beam at both load points to continuously measure deflections throughout the test.

3. Results

3.1. Compressive Strength and Slump

The slump, compressive strength, and temperature of each concrete mixture is shown in Table 2. Due to the limited capacity of the mixer, each CSA specimen was composed of two concrete batches. Three cylinders were tested per batch and the 6 cylinders were averaged to determine the overall compressive strength of the specimen, *f'c*. Slump was also tested for both batches and was typically between 7-11 inches. The second slump test was consistently higher, this is assumed to be due to additional moisture and coating of the mixer. Concrete temperature was measured for the first batch and compared to ambient temperature. The setting time of the BCSA cement mixture was sensitive to ambient and concrete temperature, so ice was added to the mixing water, and care was taken to avoid batching concrete during hot times of the day. The time of testing indicates the period between concrete placement and the beginning of loading.

Table 2: Concrete properties for all specimens

Beam	**Slump (in)**		**Concrete Strength, *f'c* (ksi)**	**Concrete Temperature (°F)**	**Ambient Temperature (°F)**	**Time of Testing**
PC	6.75		6.64	77	67	35 days
BCSA TH1	9.00	9.50	4.35*	N/A	84	5 hours
BCSA TH2	8.50	9.00	3.96	70	77	3 hours
BCSA TD1	4.00**		7.91	68	73	1 day
BCSA TD2	7.25	9.50	6.70	66	75	1 day
BCSA CH1	7.50	9.25	3.85	62	73	2.25 hours
BCSA CH2	9.00	9.50	3.83	68	73	2.5 hours
BCSA CD1	8.50	10.50	6.49	68	74	1 day
BCSA CD2	9.75	10.25	5.85	62	76	1 day

**BCSA TH1 contained additional retarder in the first layer of the beam, therefore the layers were averaged for compressive strength*

***BCSA TD1 contained less HRWR than the rest of the beams*

3.2. Cracking diagrams

Cracks were marked on the beam surface throughout loading and at the conclusion of the tests. Afterwards, cracks were retraced from photos of the tests to compare the crack patterns. These results are shown in Figure 4 for the tension controlled beams and Figure 5 for the compression controlled beams. The BCSA and OPC beams appeared to have similar crack spacings and crack heights. Additionally, most cracks in the beams were flexural or flexural shear cracks. Flexural-shear cracking primarily occurred for compression controlled specimens, where the shear forces were higher due to a larger moment capacity. None of the tests resulted in a shear failure. Black shaded areas indicate where concrete crushing occurred. For all beams, the test was ended when crushing occurred, and the concrete always crushed between the load points, indicated by arrows. This seems to indicate that the failures were indeed flexural failures.

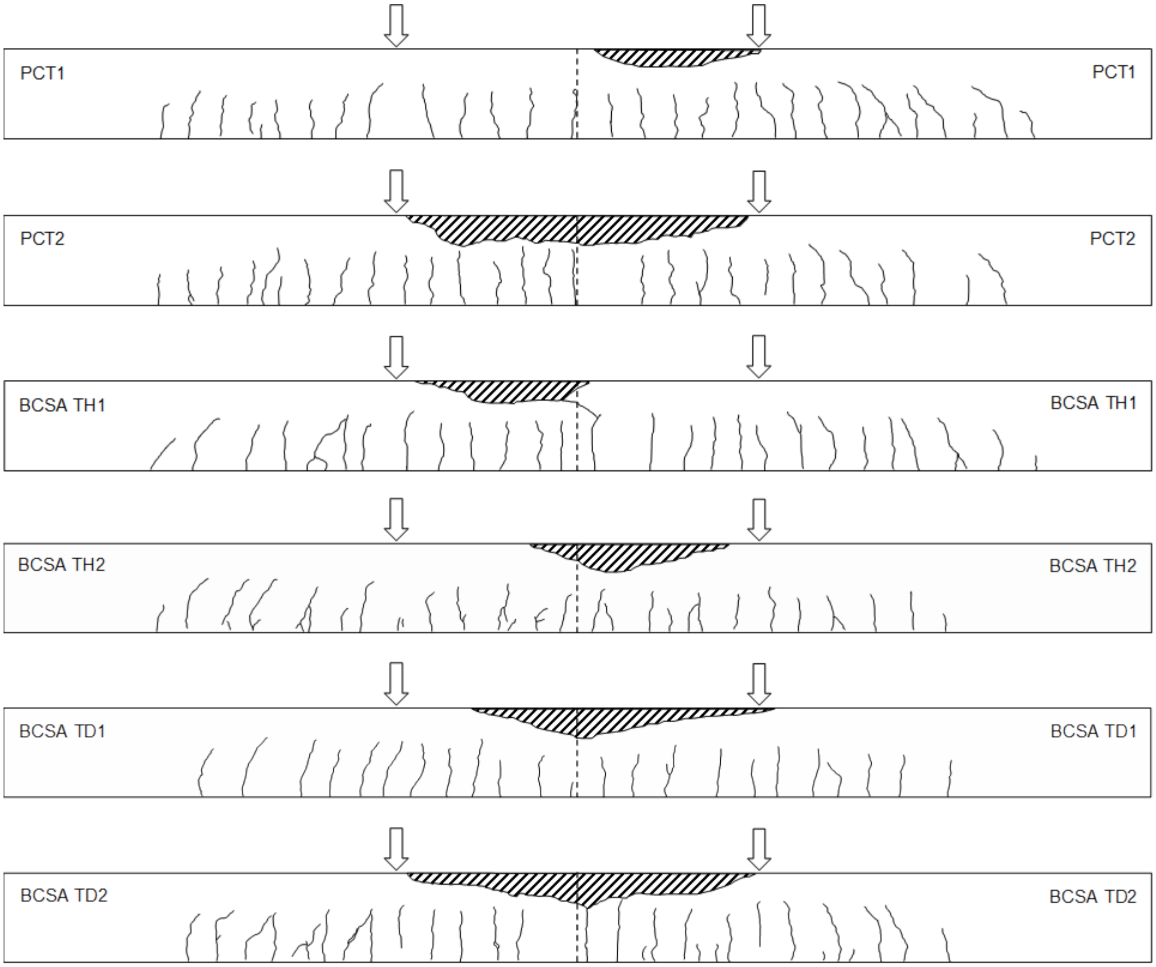

Figure 4: Cracking diagram for tension controlled beams

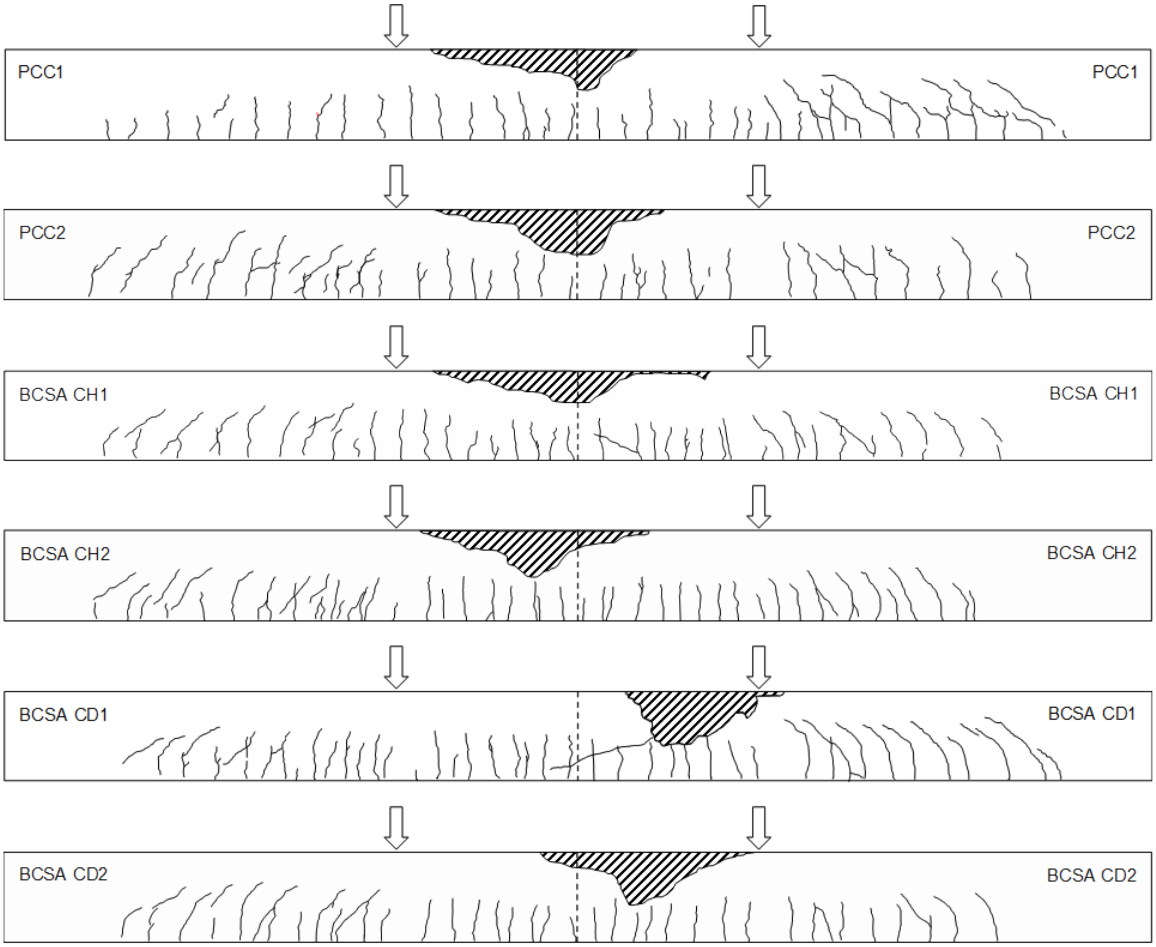

Figure 5: Cracking diagram for compression controlled beams

3.3. Load-deflection Relationships

Load-deflection graphs were plotted to examine the behavior of the beams throughout testing. The graphs were used to estimate the cracking load, yield strength, ultimate strength, yield deflection, and ultimate deflection. Figure 6 shows the load-deflection curves for the tension controlled beams. The tension controlled beams exhibited similar elastic behavior (indicated by the linear portion of the curve prior to yielding), indicating similarities in stiffness between OPC and BCSA specimens. The load at yielding for all tension controlled beams were within 10% of each other and the ultimate load reached was within 12%, despite the varying compressive strengths between beams.

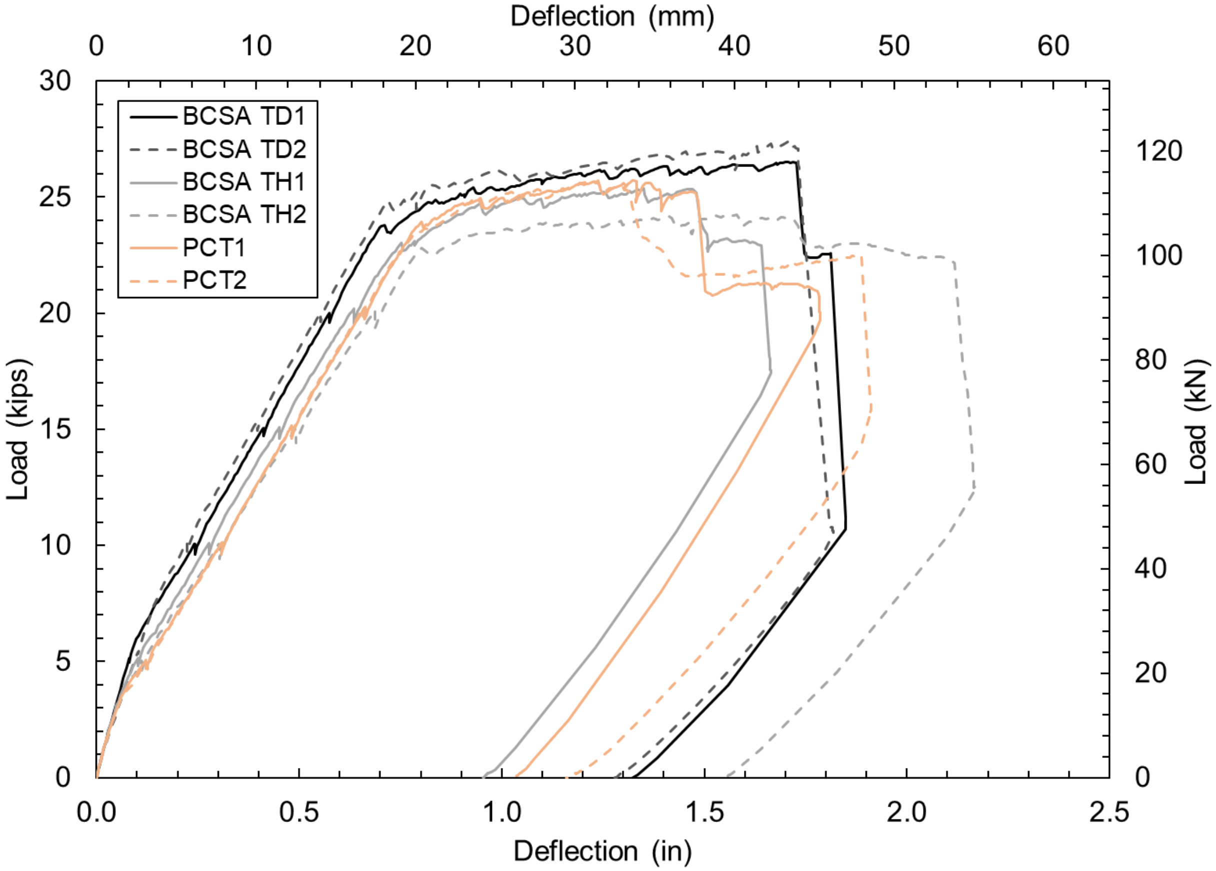

Figure 6: Load-deflection for tension controlled reinforced beams

Figure 7 displays the compression controlled load-deflection behavior. The cracking loads and slopes of the elastic portion of the compression controlled beams were less similar between specimens, indicating a higher influence of the concrete compressive strength on the behavior of the beams. This is further corroborated by the ultimate strengths, as the multi-hour BCSA beams displayed just over a 20% reduction in ultimate strength compared to the BCSA 1 day beams. Conversely, the BCSA specimens tested at 1 day of age had lower compressive strengths compared to the OPC beams but had approximately 11% higher flexural strengths. While this result is based on the limited tests reported here, it does seem to suggest there is a difference in the flexural strength of BCSA beams compared to OPC beams. When combined with the comparisons to nominal moment capacities and ductility indices (described in the following sections), this may indicate BCSA beams provide a greater ultimate strength for a given compressive strength.

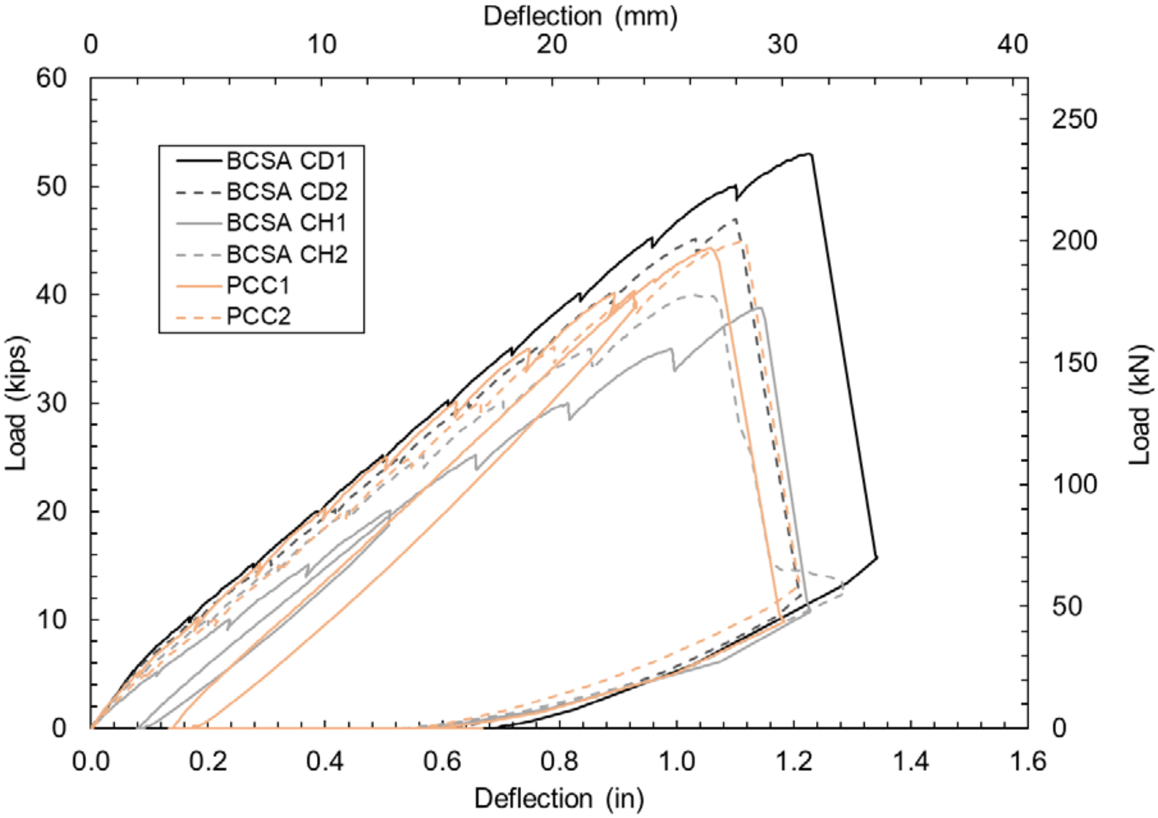

Figure 7:Load-deflection for compression controlled reinforced beams

Table 3 shows the information obtained from the load versus deflection graphs. Cracking load was estimated from the graphs (indicated by the first change in slope) and was used to calculate a cracking moment for each beam. This was compared to the predicted cracking moment using the ACI modulus of rupture equation (7.5*($f'c)^{0.5}$) in Section 19.2.3.1 of ACI 318-14. The 7.5 coefficient in this equation is based on historical testing on OPC concrete. Overall, the predicted cracking moment correlated well with the actual cracking moment for the OPC beams but consistently underestimated the cracking moment of the BCSA beams. In Table 4 the coefficient for the modulus of rupture equation is estimated based on the measured cracking moment. All the CSA beams had a corresponding coefficient of 7.79 or higher, and the coefficient increased with compressive strength. This indicates a potentially higher tensile strength for BCSA concrete compared to OPC concrete. More work is needed to characterize this behavior, but it is theorized that the ettringite in hardened BCSA cement concrete may contribute to a higher tensile strength compared to OPC which gains most of its strength from other hydration products.

Table 3: Cracking, yield, and ultimate strength estimates

Beam	**Concrete Strength, f'c (ksi)**	**Cracking Load (kips)**	**Cracking Moment (k-in)**	**Predicted Cracking Moment [based on 7.5(f'c)$^{0.5}$] (k-in)**	**Yield Load (kips)**	**Yield Deflection (in)**	**Ultimate Load (kips)**	**Ultimate Deflection (in)**
PCT1	6.64	3.80	91.20	88.01	23.87	0.81	25.68	1.23
PCT2	6.64	3.50	84.00	88.01	23.34	0.78	25.65	1.22
BCSA TH1	4.35	3.10	74.40	64.75	22.83	0.74	25.19	1.48
BCSA TH2	3.96	3.50	84.00	67.92	22.64	0.79	24.27	1.56
BCSA TD1	7.91	6.00	144.00	96.07	23.77	0.70	26.51	1.72
BCSA TD2	6.70	7.00	168.00	88.37	24.85	0.72	27.13	1.71
PCC1	6.64	3.90	93.60	88.01	N/A	N/A	44.10	1.06
PCC2	6.64	4.10	98.40	88.01	N/A	N/A	44.92	1.11
BCSA CH1	3.85	2.90	69.60	67.03	N/A	N/A	38.74	1.15
BCSA CH2	3.83	3.30	79.20	66.86	N/A	N/A	39.95	1.03
BCSA CD1	6.49	5.20	124.80	87.03	N/A	N/A	53.07	1.23
BCSA CD2	5.85	4.80	115.20	82.63	N/A	N/A	46.97	1.10

Table 4: Modulus of rupture coefficient calculation

Beam	Concrete Strength, f'c (ksi)	Cracking Moment (kips)	fr (psi)	Coefficient	Average
PCT1	6.64	91.2	633.33	7.77	7.47
PCT2	6.64	84	583.33	7.16	
BCSA TH1	3.60	74.4	516.67	8.62	8.95
BCSA TH2	3.96	84	583.33	9.28	
BCSA TD1	7.91	144	1000.00	11.24	12.75
BCSA TD2	6.70	168	1166.67	14.26	
PCC1	6.64	93.6	650.00	7.98	8.18
PCC2	6.64	98.4	683.33	8.39	
BCSA CH1	3.85	69.6	483.33	7.79	8.34
BCSA CH2	3.83	79.2	550.00	8.88	
BCSA CD1	6.49	124.8	866.67	10.75	10.61
BCSA CD2	5.85	115.2	800.00	10.46	

3.4. Comparisons to Nominal Moment Capacity

Nominal moment capacities for all beams were calculated using the ACI strength design procedures outlined in section 22.3 of ACI 318-14 and compared to the actual moment capacities determined from flexural testing. Nominal moment capacities were calculated using measured concrete strengths and measured steel yield strength. Strength reduction factors were not included in this analysis. Figure 8 compares the results for the tension controlled beams. The tension controlled beams showed consistent results between the two beams tested for each case, and all beams failed at loads 21-28% higher than those predicted by the nominal moment capacity. The nominal moment capacities gave conservative capacities for all test cases, and the ACI equations appear to be adequate for predicting the strength of BCSA reinforced beams.

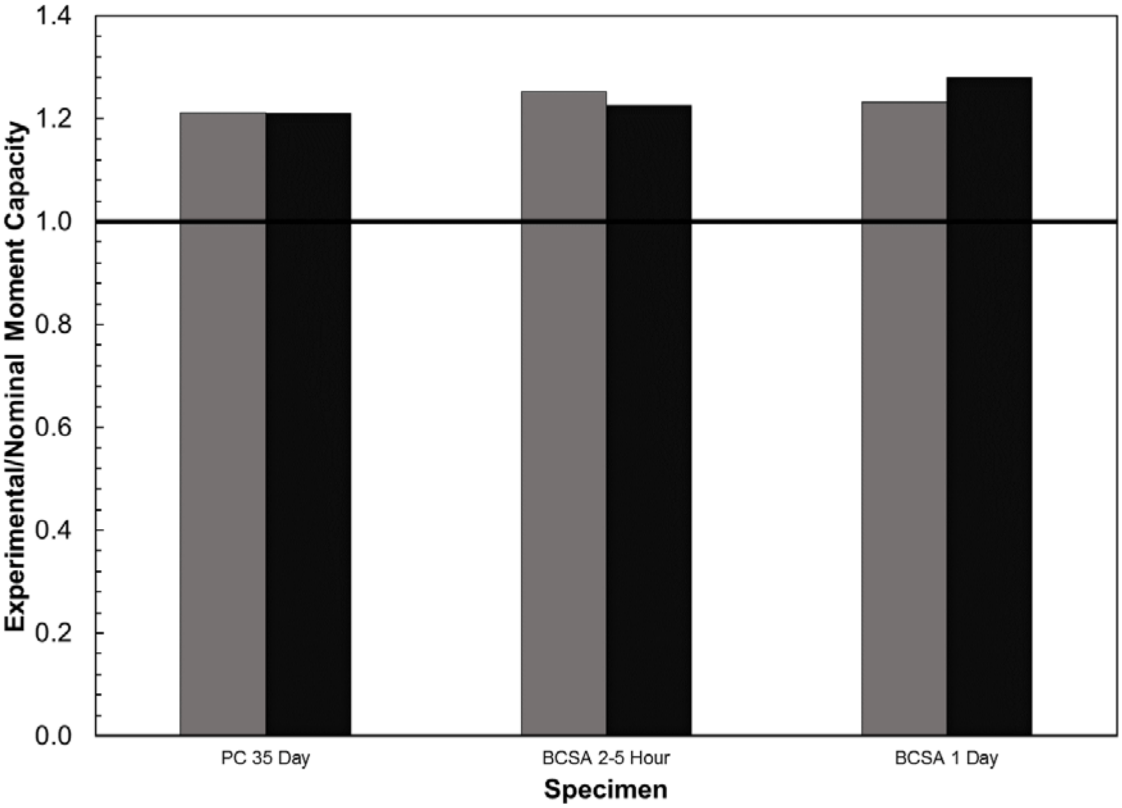

Figure 8: Ratio of ultimate to nominal moment capacity for tension controlled beams

The results for the compression controlled beams are displayed in Figure 9 and are more variable. The ratio of experimental capacity to nominal capacity for the OPC specimens averaged 5% higher than the predicted capacity but lower than the OPC tension specimens. The compression controlled BCSA specimens failed at moments 16-27% above the predicted capacity with an average of 23%. This could be explained by an increased maximum compressive strain of for BCSA concrete compared to the estimated 0.003 ultimate compressive strain for OPC recommended in ACI 318-14 section 22.2.2.1. If the maximum compression strain for BCSA is higher, it would result in a larger moment capacity in compression controlled members, as observed in this study. More research is needed to corroborate this finding, but it is possible that the ettringite formed in the BCSA concrete results in a more ductile structure at early ages. As more reaction products are formed in the BCSA cement matrix this compression behavior may change and more closely align with that of OPC. All beams still failed at a moment higher than the predicted capacity, exhibiting the conservative nature of the ACI 318-14 nominal moment capacity procedures.

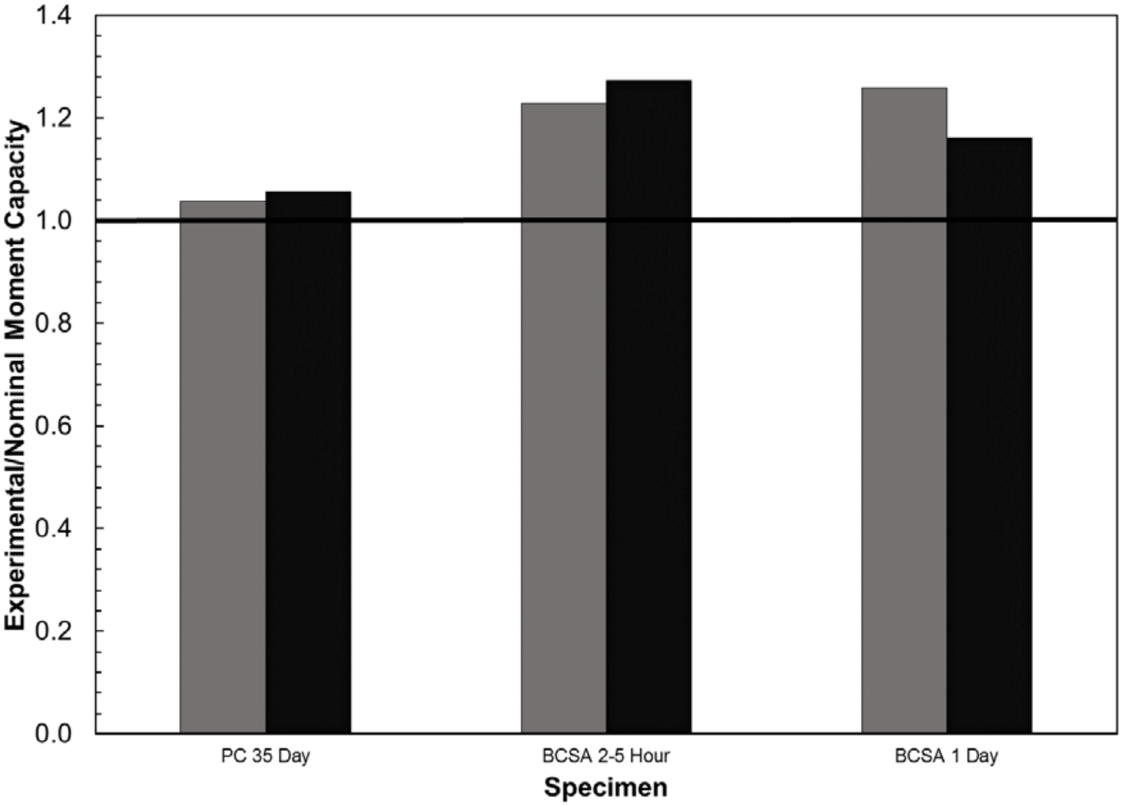

Figure 9: Ratio of ultimate to nominal moment capacity for compression controlled beams

3.5. Ductility Index

Ductility index is defined as the ratio of the deflection at ultimate load or moment and the deflection at the yield load or moment. Ductility index provides an indication to the amount of bending or warning before beam failure. Therefore, a higher ductility index is preferable. Figure 10 shows the ductility indices of all tension controlled beam specimens. The OPC beams had the lowest ductility indices, achieving an average ductility index of 1.55. In comparison, the average ductility index for the BCSA 2-5 hour beams and BCSA 1 day beams were 1.98 and 2.41, respectively. Compression controlled beams were not included in this analysis as there was no yielding before failure. Generally, a higher compressive strength should produce a higher ductility index, because the concrete will take more load to crush for a given beam cross section. However, the BCSA 2-5 hour beams were able to outperform the OPC beams with a compressive strength approximately 2000 psi lower than the OPC specimens. This may be due to the theorized increase in maximum compressive strain for BCSA concrete postulated in the previous section. The larger ductility indices in the tension controlled beams and increased moment capacity in compression controlled beams can both be explained by this rationale. More testing is needed to determine if this is true, and it is possible that this behavior may change at later ages, as the microstructure of the initially ettringite dominated BCSA matrix is filled in with different reaction products at later ages.

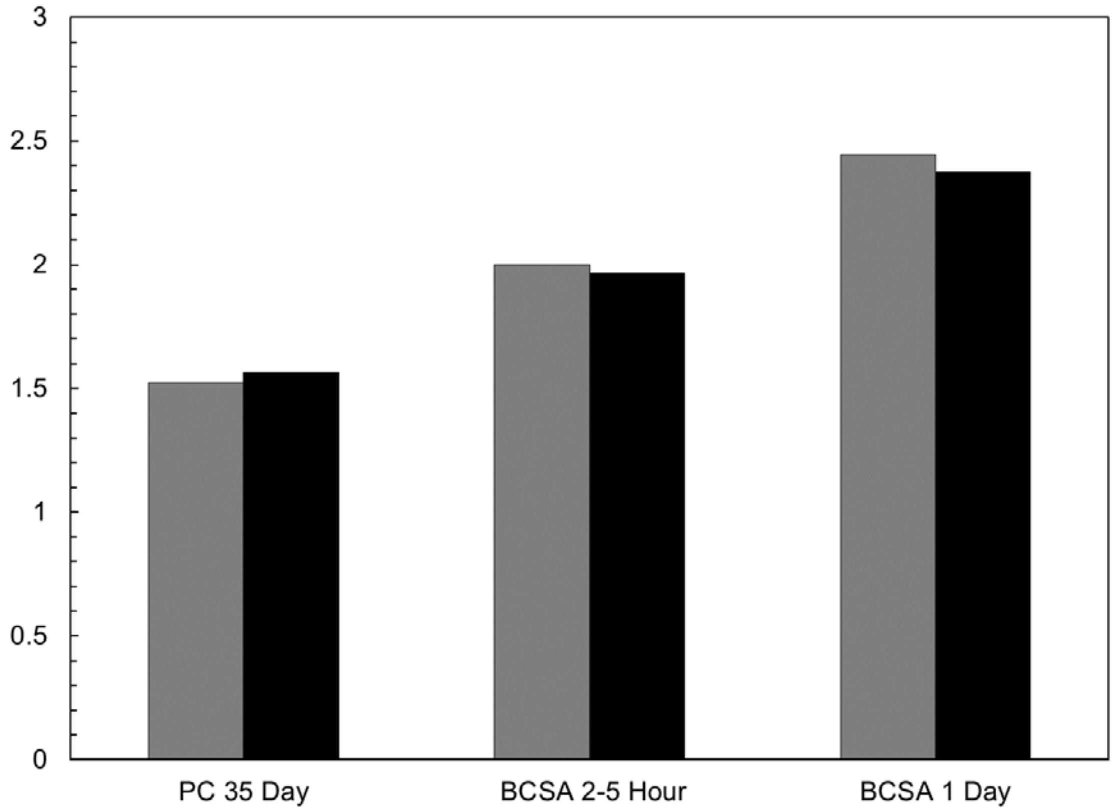

Figure 10: Ductility index for portland cement, BCSA 2-5 hour, and BCSA 1 day tests

4. Conclusions

This study compared the flexural performance of tension controlled and compression controlled beams made with OPC and BCSA concrete. Early age strength of the BCSA was compared to the later age strength of OPC.

1) Overall, cracking behavior and performance during testing was similar between CSA and OPC concrete beams. The extent and distribution of cracking was similar for OPC and BCSA.
2) The ratio of experimental and nominal flexural strength was similar for tension controlled BCSA and tension controlled OPC beams, indicating that the flexural strength procedures from the ACI 318-14 code are adequate for BCSA cement. These ratios for the compression controlled beams differed between OPC and BCSA, with BCSA beams outperforming the ACI 318-14 estimates. This may be due to an increased ultimate compression strain for BCSA concrete at early ages. It is hypothesized that the microstructure of BCSA cement, being dominated by ettringite, may deform more than would be expected for OPC. As BCSA concrete ages this behavior may change, and more testing is needed to observe this phenomenon.
3) The cracking moment for BCSA specimens appeared to be generally greater than for the OPC beams. It is hypothesized that the ettringite in the hardened BCSA cement matrix contributes to a slightly higher tensile strength compared to OPC. More work is needed to characterize this behavior, but based on the work presented here, the modulus of rupture of the BCSA beams varied between 7.79 and 14.26 times the square of the compressive strength.

4) BCSA concrete beams had higher ductility indices compared to the OPC concrete beams, including when the compressive strengths were lower. This is theorized to be caused by an increased maximum compressive strain of BCSA concrete compared to the 0.003 strain given by ACI 318-14 section 22.2.2.1 for OPC concrete. Further research is needed to confirm and estimate the maximum compressive strain of CSA concrete. It is possible that this maximum strain capacity changes with age as the ettringite microstructure of BCSA concrete is filled in with other hydration products over time.
5) Overall BCSA cement performed at least as well as OPC in terms of its flexural strength for the beams tested in this study. The ACI 318-14 flexural strength procedures in section 22.3 appear to be applicable to BCSA concrete.

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