5-2019

Tension Splitting Strength of BCSA Concrete Cylinders

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ABSTRACT

The focus of this research was to compare the tension splitting strength (TSS) of belitic calcium sufloaluminate (BCSA) cement concrete to tensile strength predicted by the American Concrete Institute (ACI) and to similarly proportioned portland cement (PC) concrete. BCSA is a rapid-setting cement with higher early strength, higher ettringite content, and lower calcium silicate hydrate (C-S-H) content than PC. PC and BCSA cement concrete cylinders were broken at different ages in both uniaxial compression and TSS. It was found that BCSA had a similar TSS to both the ACI prediction and PC TSS, but the results require further testing for application.

Keywords: BCSA cement, tension splitting strength (TSS), ettringite, C-S-H.

INTRODUCTION

Belitic calcium sufloaluminate (BCSA) cement is a rapid-setting cement with the potential to achieve 4,000 psi compressive strength within 2-hours after mixing. BCSA is a potential alternative to portland cement (PC) concrete for structural concrete, including structural repairs or construction of roadways, buildings, and other concrete structures. It has multiple other advantages to PC, including lower CO_2 emissions and a lower clinkering temperature than PC (Thomas, et. al., 2018), which could reduce the environmental impact of concrete construction. BCSA has also shown considerably higher dimensional stability, i.e., shrinkage, and creep (Bowser, Murray, & Floyd, 2018). On the other hand, BCSA is more expensive than PC, but this could be partially attributed to the lower demand for BCSA; BCSA is emerging in more research but has very little publicity as of now.

The chemical composition of hydrated BCSA differs from portland cement. BCSA cement products include a higher amount of ettringite than C-S-H, whereas PC has a higher calcium silicate hydrate (C-S-H) percentage (Thomas, et. al., 2018). Ettringite forms much more quickly and has a more crystalline structure than C-S-H, which results in a higher early strength than PC. Ettringite begins to form within ten minutes of mixing, but citric acid can be added to retard the setting time to 1-2 hours or more. (Bowser, Murray, & Floyd, 2018). BCSA also requires a higher water-to-cement (w/c) ratio compared to PC to ensure adequate hydration, but the BCSA hydration reaction uses water faster than PC, which results in lower porosity and shrinkage (Thomas, et. al., 2018).

RESEARCH SIGNIFICANCE

BCSA concrete is a potential construction material that has a faster set time, lower shrinkage, and higher durability compared to PC concrete. Few tests have been performed on the hardened properties of BCSA concrete. To encourage further use of the material it is essential to catalogue the hardened properties and compare them to existing models developed for portland cement. Research has been conducted throughout different topics with BCSA, from prestressed strand bond testing (Bowser, Murray, & Floyd, 2018), nuclear and radioactive encapsulation (Zhou, Milestone, & Hayes, 2006), and heavy metal immobilization (Giergiczny & Król, 2008).

As discussed before, BCSA cement primarily forms ettringite, rather than C-S-H. Because of this, BCSA could have a higher tension splitting strength (TSS) than PC. ACI 318-14 expresses TSS in relation to the compressive strength of PC in equation 1, per ACI 318-14 R19.2.4 (American Concrete Institute, 2014).

$$f_t = 6.7 * \lambda * \sqrt{f'_c} \quad \text{(equation 1)}$$

f_t Tensile Splitting Strength
λ Concrete Weight Coefficient
f'_c Concrete Compressive Strength

If BCSA does show a higher TSS than PC, this increased strength could be utilized in structural design. A higher tensile strength would benefit flexural members, pavements, bridge decks, etc. Structural repairs or new construction would benefit from BCSA's set time and durability.

EXPERIMENTAL PROCEDURE

To compare the TSS of BCSA concrete to PC concrete, as well as the ACI TSS equation, two batches of concrete were prepared. Concrete cylinder specimens were cast in accordance with ASTM C192 (ASTM, 2018). 42 Cylinders were made from both BCSA cement concrete and PC concrete. The specimens were 4" by 8" cylinders for both tension splitting and compressive strength tests. Tests were performed at the ages shown in Table 1. Six specimens were tested at each age, three compression and three splitting tension.

Table 1: Concrete Cylinder Break Day

BCSA	PC
2 hour	-
24 hour	24 hour
1 day	1 day
7 day	7 day
14 day	14 day
28 day	28 day
56 day	56 day

Compression cylinders were tested according to ASTM C39 (ASTM, 2018), with a load rate of 35 psi/s and an initial load of 10% of the predicted strength. The compressive strength was taken as the average of three cylinder breaks for a given testing time. TSS was measured according to ASTM C496 (ASTM, 2017), with a loading rate of 2 psi/s and an initial load at 5% of the predicted capacity. Both the tension and compression test were completed in a Forney F-400F-LC1. The first set of BCSA concrete cylinders were broken at the earliest possible break time -

when the concrete was sufficiently set. The PC was broken following the ASTM C39 break schedule, while BCSA had an additional break at its earliest strength to analyze the rapid strength growth of BCSA in both compression and tension (ASTM, 2018).

Tables 2 and 3 display the mix designs for the BCSA and the PC concrete, respectively. Different amounts of material and additional admixtures were used to create a sufficiently comparable early compressive strength material. BCSA requires more water than PC for hydration, therefore a higher w/c was used. BCSA cement also has a lower specific gravity than PC. These two factors meant that extra sand was required in the BCSA mixture for a given cubic yard mix. Apart from these deviations, the amount of cement and amount of limestone aggregate was close to the same in each mixture. The mix designs were intended to create a similar long-term strength (roughly 8000 psi). High range water reducer was used at a rate of 18 fl. oz. per 100 lb cement for the BCSA mixture and 4 fl. oz. per 100 lb cement for the PC mixture. Citric acid set retarder was used at a dosage of 6 fl. oz. per 100 lb cement for the BCSA concrete to extend the working time to around 1 hour.

Table 2: BCSA concrete mix design for 1 cubic yard

Field Mix	**Weight (lb)**	**Volume (ft^3)**
Cement	658	3.56
River Sand	1164	7.04
3/4” Crushed Limestone	1782	10.93
Water	316	5.06
Air	0	0.41
Total	3920	27.00

Table 3: PC concrete mix design for 1 cubic yard

Field Mix	**Weight (lb)**	**Volume (ft^3)**
Cement	660	3.36
River Sand	1343	8.12
3/4” Crushed Limestone	1775	10.89
Water	264	4.23
Air	0	0.41
Total	4042	27.00

RESULTS AND DISCUSSION

Concrete Properties

Both mixes were completed on the same day and the fresh properties of the concrete and ambient temperature at that time are shown in Table 4. The BCSA concrete’s slump was 10 inches. The PC concrete had a slump of 7 inches. The temperature and weather conditions were 66-67 (°F), with clear weather.

Table 4: Concrete Fresh Properties

Mix	PC concrete	BCSA concrete
Slump (in)	7	10
Ambient Temperature (°F)	67	66
Concrete Temperature (°F)	71	70

The PC concrete achieved an average 1-day compressive strength of 3,544 psi, and a 28-day strength of 8,080 psi. All compressive strengths achieved at or above the predicted values of the mix design. One of the 28-day cylinders was contained a large piece of vegetation and the break was significantly lower than corresponding day breaks and previous two week breaks and was removed from the average. More breaks were unable to be completed because of time constraint for that day. BCSA concrete achieved a 2-hour compressive strength (f'c) break of 2,970 psi and a 28-day strength of 7430 psi.

Table 5: Average Compressive Strength of Concrete Specimens

Break Date	BCSA concrete f'c (psi)	PC concrete f'c (psi)
2-hour	2970	-
1-day	6290	3540
7-day	7360	6920
14-day	7620	7560
28-day	7430	8080
56-day	7380	7940

Figure 1 shows the compressive strength (f'_c) of the BCSA and PC concrete as a variable of time. As predicted, the BCSA shows considerably higher early strength, but the PC meets and passes the BCSA near the 14-day break.

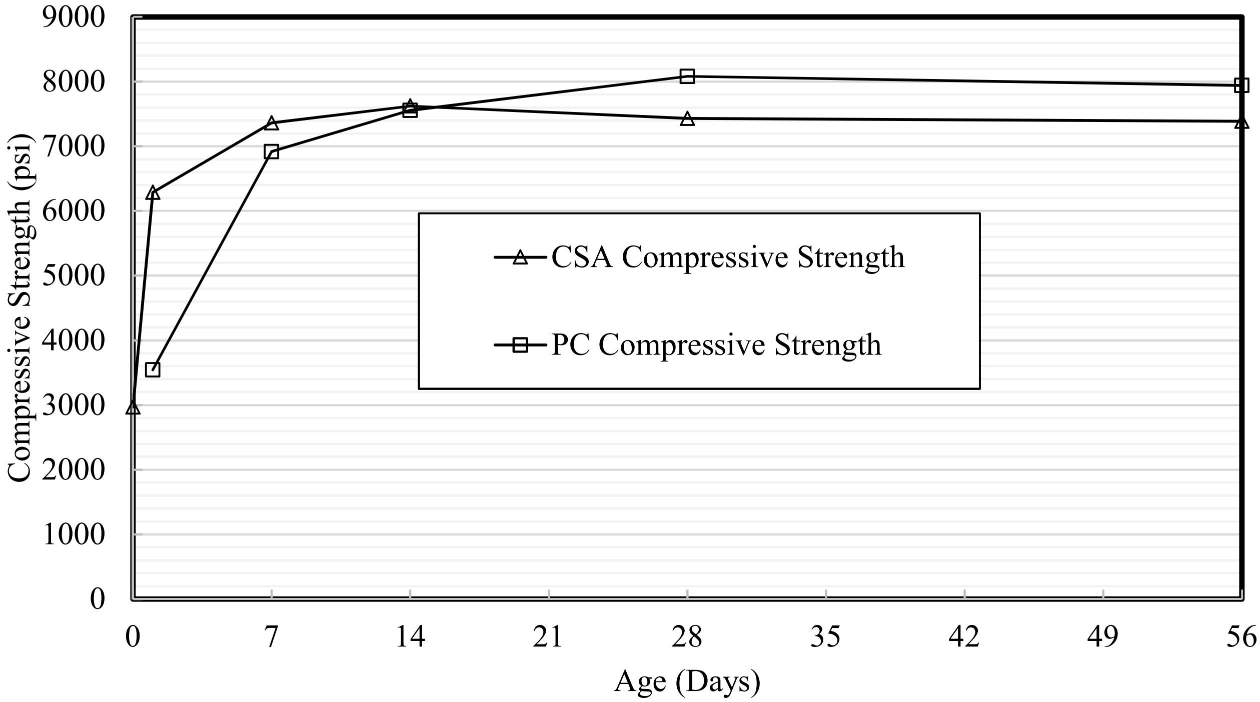

Figure 1: Compressive Strength of BCSA and PC concrete

Tension Splitting Strength

Table 6 displays the TSS from the BCSA and PC (f_t). The TSS is displayed along with the coefficient of variation and standard deviation of the three breaks. Figure 2 displays the TSS (f_t) as a variable of time. As in the compressive strength, the BCSA shows a higher early strength but there is a sudden drop in strength towards the 14-day break for both materials, and then rises for the 28-day strength. The average coefficient of variation in the PC concrete (9.1%) is more in line with the expected values from ASTM C39 (7.0%) (ASTM, 2018). The average coefficient of variation of the BCSA concrete (11.1%). The higher coefficient and variation of the BCSA was a result of the 1-day and 28-day breaks which had a significant variation.

Table 6: Tension Splitting Strength (TSS) Data

Material	BCSA concrete			PC concrete		
Break Day	TSS - f'_c (psi)	Standard Deviation	Coefficient Variation (%)	TSS - f'_c (psi)	Standard Deviation	Coefficient Variation (%)
2-hour	432	26	6.12%	-	-	-
1-day	519	113	21.70%	397	40	10.07%
7-day	581	29	4.93%	561	72	12.82%
14-day	557	51	9.22%	513	56	10.84%
28-day	565	99	17.61%	606	38	6.21%
56-day	568	40	7.01%	599	34	5.64%

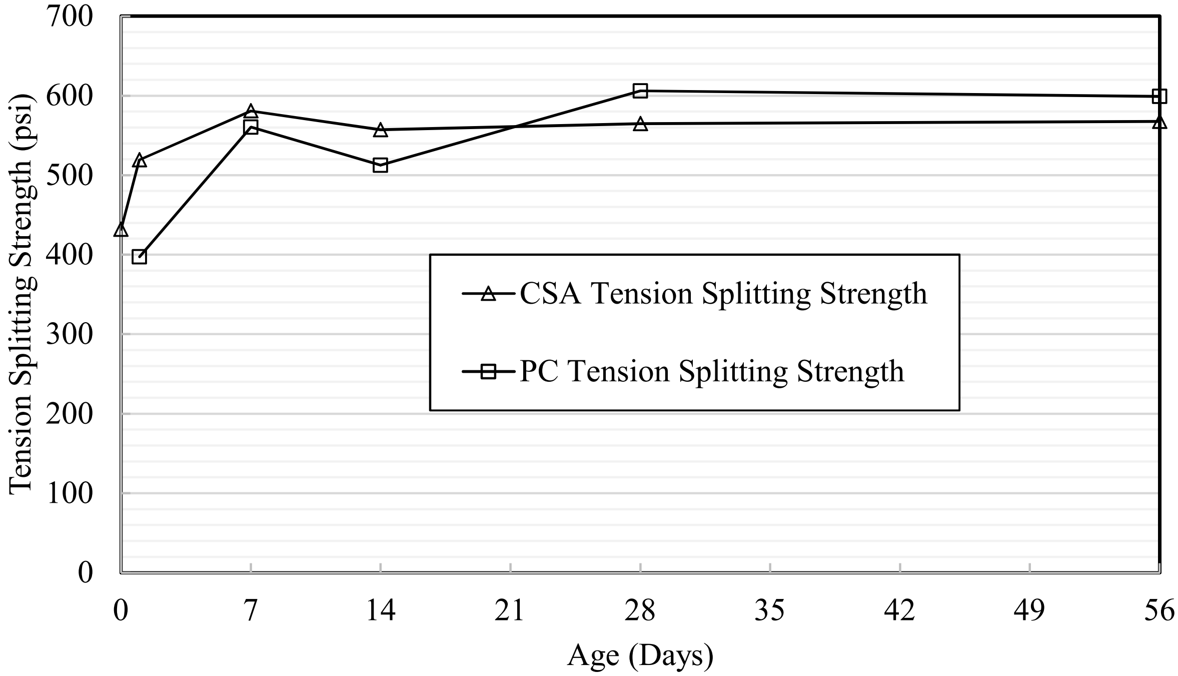

Figure 2: Tension Splitting Strength (TSS) of BCSA and PC concrete

Figure 3 compares the average tensile strength data from the BCSA and PC TSS to the square root of the compressive strengths. The figure shows the average BCSA TSS is similarly proportional to compressive strength as both PC and the ACI predicted TSS. The average lines of TSS for BCSA, PC, and ACI predicted values, shown on Figure 3, are very closely spaced. Based on this result, the ACI predicted TSS is sufficient to predict the TSS of CSA concrete.

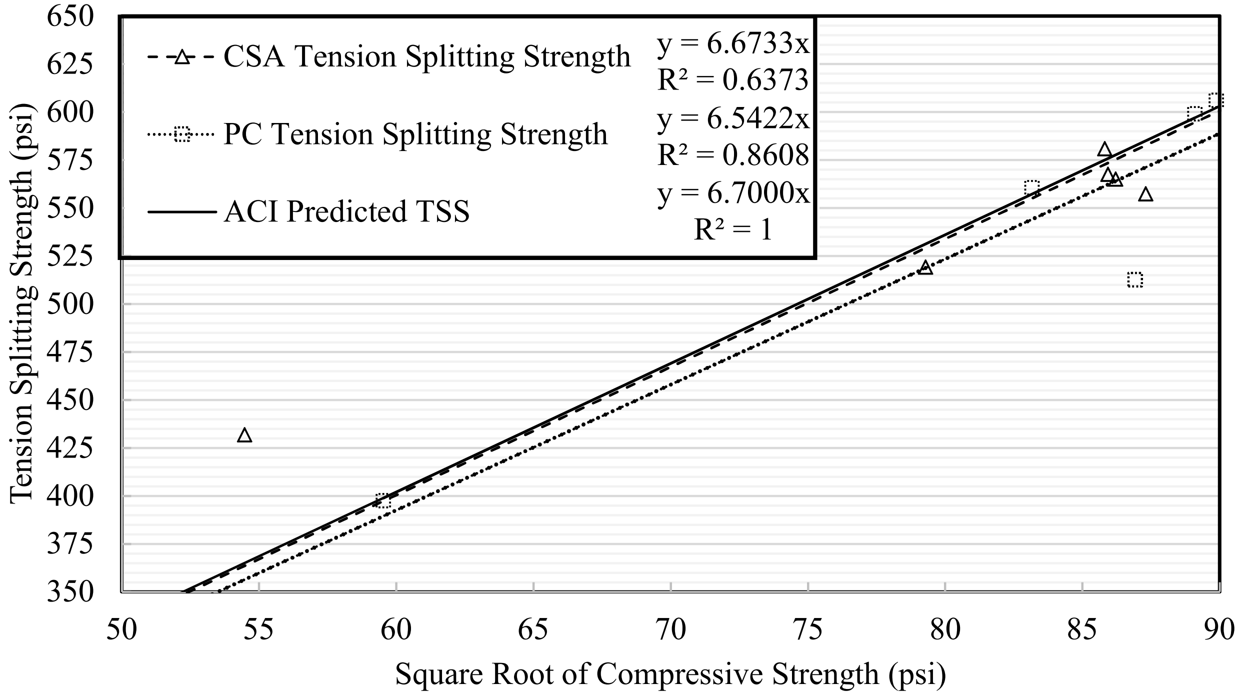

Figure 3: Average Tension Splitting Strength (TSS) related to Compression Strength

Figure 4 instead shows all three break values per day of TSS for another representation of the results. The figure shows the variability of each break value towards the weaker compressive strength days, but towards the later ages, the TSS seems to converge

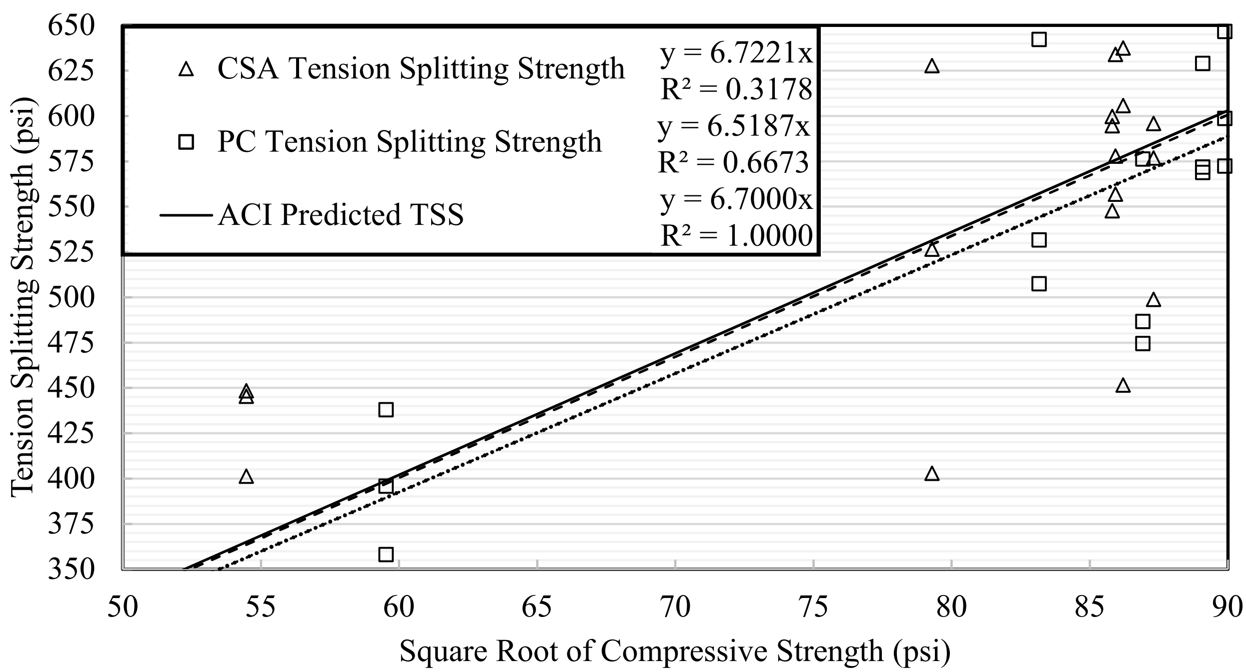

Figure 4: Raw Tension Splitting Strength (TSS) to Compression Strength inc. all break data

CONCLUSIONS

A comparison of the TSS of BCSA and PC concrete cylinders was performed and compared to ACI 318-14 code prediction of TSS. Several different concrete ages were tested, based on the ASTM C39 break schedule (ASTM, 2018) and on testing the BCSA at sufficient set.

The main conclusions were:

- the ACI TSS equation (equation 1) is sufficiently appropriate to approximate the TSS based on the compressive strength of BCSA concrete
- the BCSA TSS is higher at early ages than PC TSS but over time the values converge with PC TSS being slightly higher
- BCSA and PC have a similar correlation of compressive strength to TSS

Further research into the early strength variability of TSS of BCSA concrete would be useful. The coefficients of variability for both PC and BCSA is comparable, but the 1-day strength for BCSA caused an almost 3% increase in the average variability. Whether this is an isolated case or common among BCSA might be a topic of future research. A larger selection of breaks would be more appropriate due to the variability of the splitting tension test. In conclusion, BCSA does have a very similar relationship of compressive strength to TSS, which matches with equation 1.

ACKNOWLEDGEMENTS

The author would like to thank Dr. Cameron Murray of the University of Arkansas for his guidance and assistance for this project. As well as Edgar Somarriba for helping with the testing and equipment set-up. Materials included were provided by CTS Cement Manufacturing Corporation.

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