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Evaluating the Effects of Curing Methods on BCSA Cement Concrete

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Background and Introduction

Belitic calcium sulfoaluminate (BCSA) concrete is an existing alternative to portland cement (PC) concrete, and recently it has been piquing researchers' interests. The main advantages of BCSA concrete are its fast strength gain and high later-age strength (Bescher, 2020). Typical concrete contains PC as the binder and takes about 4 hours for PC concrete to set. Concrete with PC is often designed to reach a full strength of 4000 psi in 28 days. Comparatively, BCSA concrete takes 20 minutes to set and reaches a strength of 5000 psi in 6 hours (Péra and Ambroise, 2004). This rapid setting time makes BCSA cement a great option for structural repairs or other applications where structural-strength concrete is needed quickly.

Correctly curing and utilizing BCSA concrete can be a powerful technique due to the widespread use of concrete in infrastructure and how much of this infrastructure is aging. One idea to utilize BCSA concrete consists of quick repairs of failing infrastructure due to its rapid setting nature. For example, repairing a damaged bridge deck so traffic flow can continue is integral to a city and state's transportation. Effective bridge repair, and therefore traffic flow, prevents drivers from using detours, and causes fewer disruptions to citizens and the economy. Drivers can reach their destinations quicker, saving their employers' money. PC is also responsible for around 7% of global CO2 emissions. These emissions could be reduced by utilizing alternative cements – such as BCSA cement. The process of making BCSA cement produces less CO_2 than PC, making it a more environmentally friendly option (Becker and Malits, 2019). Another difference between the BCSA and PC cement binders is that PC mostly forms calcium silicate hydrate (CSH) in the presence of water. Like PC, BCSA hydrates or reacts in the presence of water, but it primarily forms ettringite, a needle-like compound that gives the resulting concrete its strength; therefore, the hydration of PC and BCSA are fundamentally different (Juenger, et al, 2010).

Because the hydration of BCSA cement concrete is different than the hydration of PC concrete, and because hydration is a key factor in concrete curing, researchers are curious about the outcome of various curing methods of BCSA cement concrete. Concrete curing is defined as "an action taken to maintain moisture and temperature conditions in a freshly placed cementitious mixture to allow hydraulic cement hydration" (ACI Committee 308, 2016, p.2). Curing should maximize the concrete's quality by promoting full hydration of the cement. The best curing conditions for PC are well established, but because BCSA primarily forms ettringite rather than CSH during hydration, these curing conditions may differ for BCSA concrete. There is also a difference found in short- and longer-term curing of concrete specimens. Most PC concrete seems to have a higher compressive strength at 28 days, but with BCSA concrete setting much quicker than PC concrete, the time that BCSA concrete reaches its highest compressive strength may vary as well (Whiting, 2003).

Curing cylinders is different than curing specimens going into the field, but the idea is to match the cylinder curing conditions to what the interior of a concrete placement would be exposed to in terms of temperature and moisture. The curing of compressive strength cylinders is highly regulated to ensure that the curing conditions are not adversely or overly beneficial to the strength. The specific purpose of this research is to establish curing criteria for BCSA cement concrete cylinders and finding any possible correlation between curing conditions and compressive strength.

This study was broken up into two stages, or batches. In the beginning of this study, Batch 1, 48 concrete cylinders made of BCSA cement were prepared in order to investigate differences in strength from curing conditions for the short-term. For the second stage, Batch 2, 33 BCSA cement concrete cylinders were prepared in fewer curing conditions to study the longer-term effects of curing. Each curing condition is further explained in the *Curing Procedures* section of the paper.

Procedure and Methods

The purpose of this study was to investigate the effect of curing conditions on BCSA cement compressive strength samples over the course of 6 months. The following sections discuss the mixture design, mixing procedures, and curing conditions used for all of the test samples.

Mixture Design

The mixture design and mixing process used in this work corresponded to a mixture used in past research on BCSA cement (Cook and Murray, 2020). The mixture proportions are shown in Table 1 in the Data and Analysis section. Four days prior to mixing, these materials were roughly batched out in 5-gallon buckets, covered with lids, and left in the lab. This procedure allowed the materials to reach the same temperature prior to mixing. Because the aggregate stockpiles are stored outside, hot summer temperatures can affect the mixture if the aggregate is not allowed to cool before mixing. When batching the materials, moisture contents of the rock and sand were measured in order to adjust the actual mixture proportions to allow for water trapped in the rock and sand.

The materials and their qualities as used in this study are as follows. The rock was a #57 crushed limestone, 1-inch nominal maximum size aggregate (NMSA), quarried in Springdale, Arkansas. The sand was a river sand from Van Buren, Arkansas, and it had a fineness modulus of 2.50. The cement was RapidSet manufactured by CTS Cement Manufacturing Corporation. The water used was potable tap water. Citric acid was also used as an admixture to delay the setting time of the concrete. The admixture solution was made of 5 lb powdered citric acid per gallon of water. It was made into a liquid admixture to make it easier to dose in concrete. 18 fl oz of this admixture is equivalent to 0.35% powder citric acid by weight of cement. This dosage has been shown to provide about 40 minutes of working time before the concrete set (Burris, et al). The desired water-to-cement (w/c) ratio was 0.48.

Mixing Procedure

Both of the mixing days for each batch began with measuring out the exact weight of each material followed by lab set up. Lab set up consisted of preparing a bucket of water for the tools and spraying each mold generously with WD-40 as a form release solution so the cylinders would not get stuck inside their molds. Prior to mixing, the ambient temperature and mixing water temperature were taken and can be found in the data section in Table 1. Shortly after mixing, the temperature of the fresh concrete was measured as seen in Figure 01.

Figure 01. Fresh concrete temperature being measured immediately after mixing

The mixing order was to add all the rock, add all the sand, turn on the mixer, then add all cement, and add all the water. The materials were mixed for 3 minutes after the water was added, then discharged into two wheelbarrows. The mixing time was kept short because of the short working time of the mixture. One researcher performed a standard slump test (following ASTM C143), three researchers made compressive strength cylinders (following ASTM C192 and one researcher is shown in Figure 02), one researcher cleaned, and a final researcher took pictures throughout the entire mixing process (ASTM C143, 2020; ASTM C192, 2020). Although the citric acid provides extra workability time, it is recommended to move quickly in order to complete all specimens before the concrete loses slump.

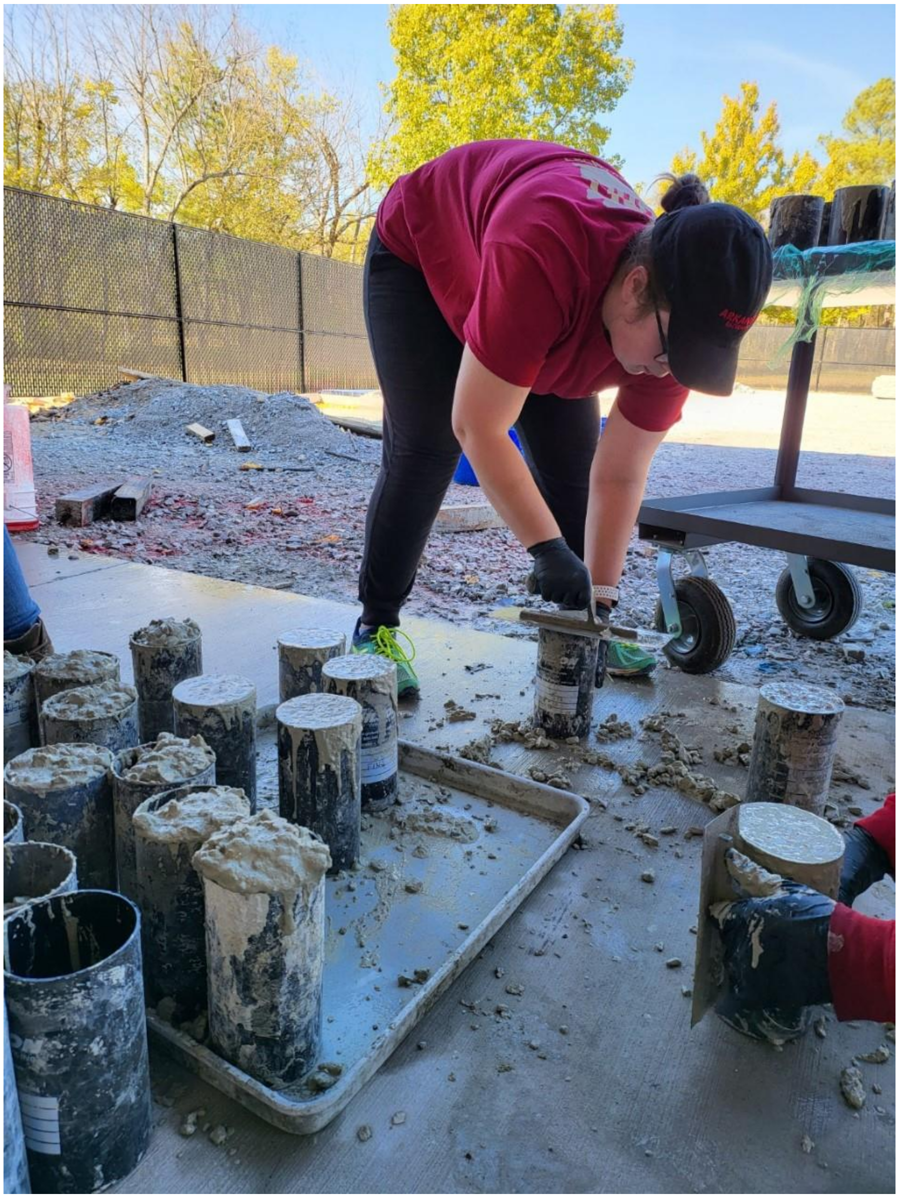


Figure 02. Primary researcher preparing BCSA concrete cylinders

Curing Procedures

The first 48 BCSA concrete cylinders were left in a “no-curing” (NC) condition for the first 3 hours until they initially hardened as shown in Figure 03. (“No-curing” refers to situation in which concrete is not placed in any special curing condition. In this study, “no-curing” specifically referred to the cylinders being placed in the open lab area where the humidity was not controlled as in the chamber.) After hardening (usually 3-4 hours), they were all de-molded and placed into their respective curing conditions. Nine of the cylinders were kept in the NC condition, nine cylinders were placed in a water bath (WB), nine cylinders in the environmental (moisture) chamber at 72 degrees and 50% humidity (EC), and nine cylinders were placed in a lime bath (LB). The LB was prepared following ASTM C511 which calls for 136.08 g of lime to be placed in every 100 lbs of water (ASTM C511, 2013). During the beginning phase of research, the LB water was not replenished, nor any extra lime added. For Batch 2, the LB2 water was replenished once after 45 days, and no extra lime was added (both lime bath curing conditions were set up in the environmental chamber that was regulated at 50% humidity). Lime has been proven to have an effect on the formation of ettringite, so it was integrated into this study to determine if it had any effect on BCSA cement concrete (Metha, 1973). To examine the effect (if any) of "mixed curing" in Batch 1, six cylinders were placed in the moisture chamber for the first 24 hours and then were moved into the water bath for the remaining tests. These were labeled as EC+W. Three cylinders were tested at 3 hours of age (after demolding) and the remaining three cylinders were kept as extras. The latter part of this study, or Batch 2, consisted of 33 concrete cylinders that were placed into the NC conditions for 3 hours and then placed into two different curing conditions: a moisture chamber at 100% humidity (wet room – WR) and another lime bath (second lime bath – LB2). Twelve of the cylinders were placed in the WR (as shown in Figure 04), twelve of the cylinders were placed in LB2, six of the cylinders were placed in the wet room but were marked to be moved into the regular moisture chamber at 72 degrees humidity at the 3-month mark, and three extra cylinders. The cylinders that were not tested at 7 days or 3 months will be used in a continuation of this study by another researcher.

Figure 03. 48 BCSA concrete cement cylinders (Batch 1) in molds before placed in respective curing conditions

Figure 04. Batch 2 BCSA concrete cylinders placed inside the WR curing condition

Results and Discussion

From the mix design spreadsheet, the weights of each material needed were calculated for a batch size of 4.33 cubic feet for Batch 1 and 2.66 cubic feet for Batch 2. During each mix, the ambient temperature, water temperature, and mixture temperature were taken as well as the slump. All of these measurements can be found below in Table 1.

Table 1. Field batch proportions, temperatures, and slumps

	BATCH 1	BATCH 2
Cement, lbs	105.51	64.92
Coarse Aggregate, lbs	282.78	174.52
Fine Aggregate, lbs	187.62	116.91
Water, lbs	51.31	29.55
Ambient Temperature, °F	49.8	68.0
Water Temperature, °F	69.6	56.2
Mixture Temperature, °F	67.1	59.5
Slump, in	9	10

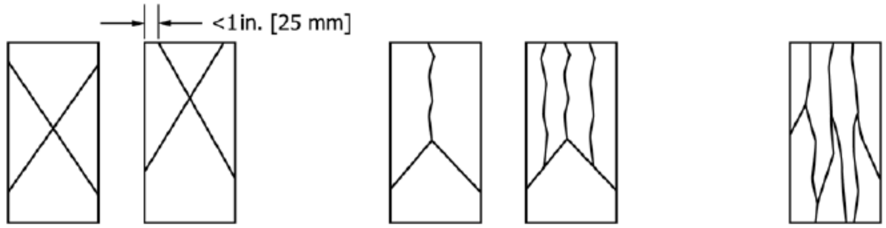
The measured slump in both batches was higher than expected from the trial batches. During trial batches the measured slump was only 3 in. The concrete was extremely workable and easy to scoop into the cylinder molds; however, the high slump made for cylinders that had not hardened completely at the 3-hour mark, delaying their setting. Even though the actual slump differed from the trial batches, the consistency of Batch 1 and Batch 2 allows for good comparison between the batches. As shown in Figure 05, the consistency of the mixtures, despite the high slumps, was good and there was no segregation or bleeding observed.

Figure 05. Concrete slump being measured after a slump test

Before each break, all cylinders were placed into an end grinder in order to smooth out the ends so they could be placed directly in the compression machine without using rubber pads or capping compound (see Figure 06). They were then tested following ASTM C39 (ASTM C39, 2021). Each cylinder had been marked with upward arrows to denote which direction was the top of the cylinder as-cast to place in the compression testing machine. Grinding the cylinders ensured the ends were flat and plane and there were no protrusions or irregularities in the surfaces that could have affected the compressive strength.

Figure 06. 3 cylinders in an end grinder with already-ground ends facing viewer

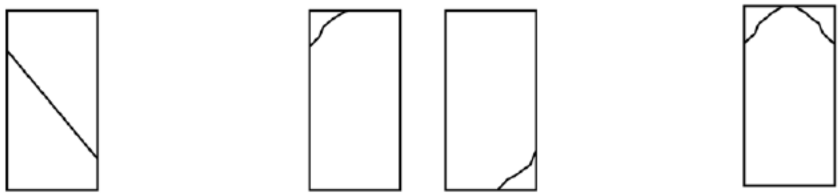
To crush the cylinders and get their compressive strengths, the cylinders were placed individually in a Forney compression testing machine with a capacity of 400,000 lbs. Each specimen was preloaded with 5000 lb force to begin the test and after that initial loading, the load was applied at 35 psi/min (± 7 psi/min). The force which caused the cylinders to break was recorded and converted to psi by dividing by the cross-sectional area of the cylinder. While crushing, one observation was that the cylinders that were cured in any kind of bath made a loud popping noise when they broke. Most of the specimens resembled Type 2 and 3 cracking as shown below by Figure 07 from ASTM C39. Figures 08 and 09 show two of the broken cylinders from the study.



Type 1
Reasonably well-formed cones on both ends, less than 1 in. [25 mm] of cracking through caps

Type 2
Well-formed cone on one end, vertical cracks running through caps, no well-defined cone on other end

Type 3
Columnar vertical cracking through both ends, no well-formed cones



Type 4
Diagonal fracture with no cracking through ends; tap with hammer to distinguish from Type 1

Type 5
Side fractures at top or bottom (occur commonly with unbonded caps)

Type 6
Similar to Type 5 but end of cylinder is pointed

Figure 07. ASTM C39 typical cylinder fracture patterns (ASTM C39, 2021)

Figure 08. Batch 1 cylinder from WB curing condition on day 7

Figure 09. Batch 2 cylinder from WC curing condition on day 94.

The final results for the Batch 1 resulted in the EC+W cylinders and the LB cylinders having the highest compressive strengths at 28 days on average as shown in Table 2 and Figure 10 below. This led to the idea for the creation of the WR condition and the LB2 conditions tested for a longer duration of time (Batch 2). The results for these 7-day and 3-month (84 days) conditions, the LB2 resulted in higher compressive strength as shown in Table 3 and Figure 11 below.

Table 2. Batch 1 BCSA Concrete Cylinder Compressive Strengths

Testing Time	Cylinder No.	NC	WB	EC	EC+W	LB
3 hours	1	2220	2220	2220	2220	2220
	2	2430	2430	2430	2430	2430
	3	2720	2720	2720	2720	2720
	Average:	2460	2460	2460	2460	2460
1 day	1	5700	5470	5620	5620	5510
	2	5910	5670	5850	5850	5790
	3	5590	5660	5880	5880	5700
	Average:	5740	5600	5780	5780	5670
7 days	1	6490	7170	6880	7570	7110
	2	6490	7320	6230	7340	7100
	3	6640	7290	6250	7060	7140
	Average:	6540	7260	6450	7330	7120
28 days	1	6690	7410	6620	7890	8030
	2	7120	7860	6500	8060	7610
	3	6760	7210	6960	7300	7390
	Average:	6850	7500	6700	7750	7680

Table 3. Batch 2 Cylinder Strengths

Testing Time	Cylinder No.	LB2	WR
7 days	1	5200	5380
	2	5280	4990
	3	6060	5660
	Average:	5510	5340
3 months	1	9240	7460
	2	9580	7580
	3	8580	8270
	Average:	9130	7770

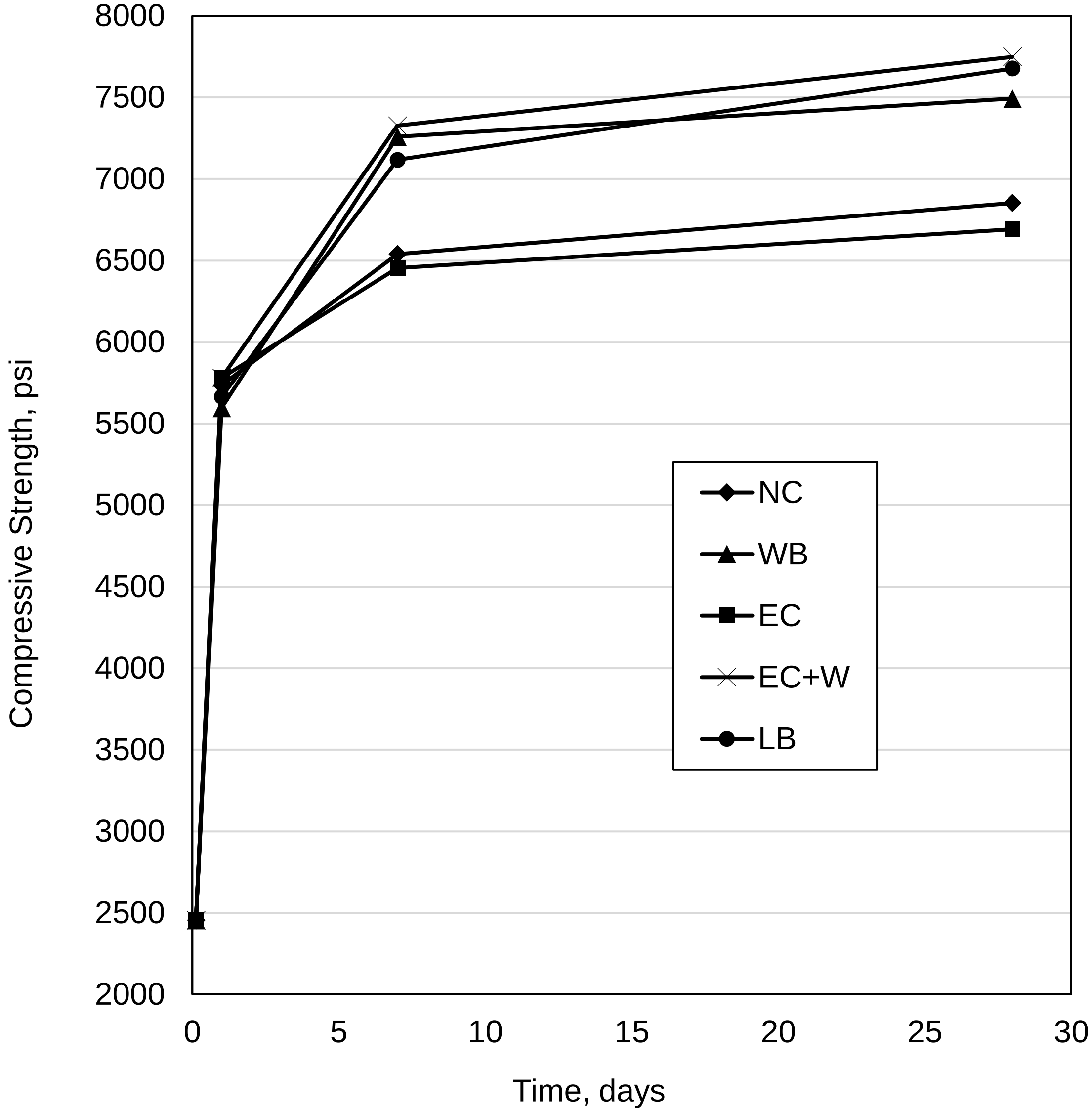


Figure 10. Batch 1 Compressive Strength Results

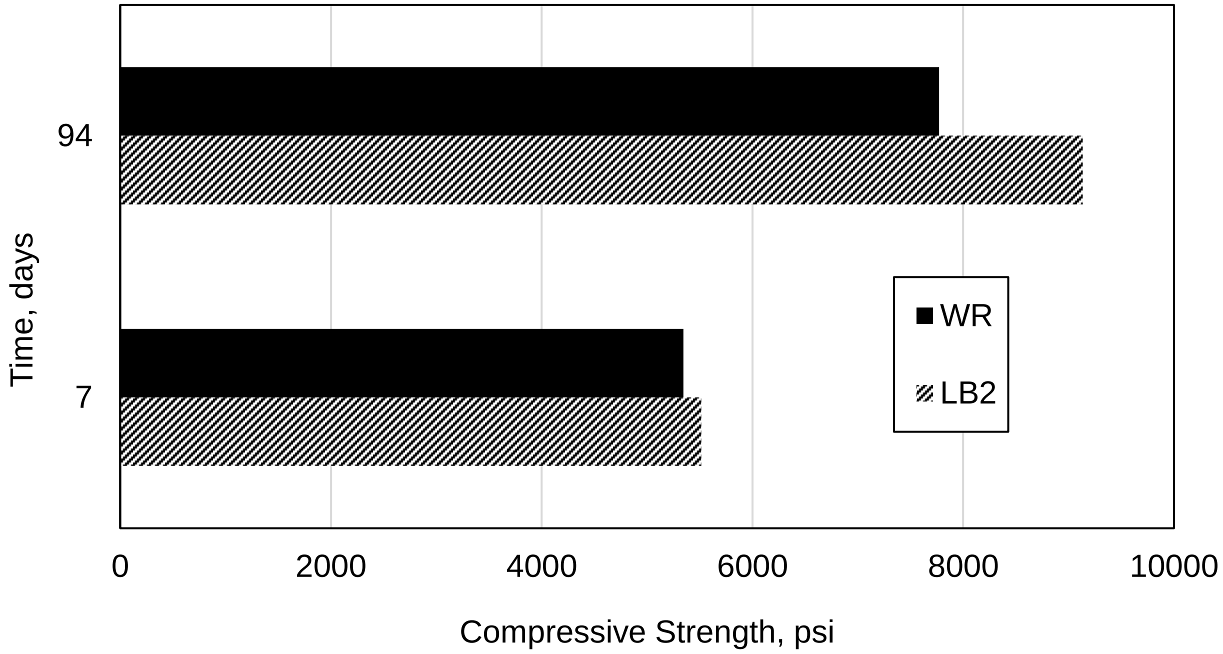


Figure 11. Batch 2 Compressive Strength Results

Batch 1 Analysis

The compressive strength results from the EC condition were interesting because those cylinders were predicted to have a higher strength than the cylinders in the NC condition. A reason for this could be because the cylinders in the NC condition were exposed to regular, out-doors humidity when the doors of the lab were left open. Humidity is often high in Arkansas, especially during the warmer months when this study was conducted. Another interesting correlation is that of the WB condition and the EC+W condition. The WB compressive strength results were about 500 psi lower, on average, than that of the EC+W condition at 28 days. The only difference between these two conditions is the EC+W cylinders were left in the environmental chamber for 27 hours before being placed into the WB while the WB cylinders were placed into the WB after 3 hours. Even though BCSA cement concrete sets up relatively quickly, perhaps the extra setting time helps it to gain strength before it is submerged in water. However, further analysis would be required for this theory because the day 1 compressive strengths for all curing conditions are similar.

Batch 2 Analysis

The strength results of Batch 2 were about as expected, but it was intriguing how, on average, the LB2 condition results were 18% higher than the WR strengths. This idea supports Metha's article on lime's positive effect on the hydration of calcium sulfoaluminates, and it is something that should be studied further (Metha, 1973).

Batch 1 vs. Batch 2 Analysis

Batch 1's LB compressive strengths at 7 days were, on average, 5665 psi, while Batch 2's LB2 compressive strengths at 7 days were, on average, 5513 psi. The difference is only 3%, and this could be due to minor differences in mixing and curing condition set up. Even though everything was kept as constant as possible in this study, concrete is highly variable and will not result in the exact same strengths every time.

The WR condition from Batch 2 was created as a way to blend the EC+W condition from Batch 1 while also adding in some more variability to the curing conditions. At 7 days, the average compression strength results from the WR condition were 8% lower than the results from EC+W. Further research and testing would need to be conducted to determine longer-term strengths of the EC+W condition, but it seems to be an ideal curing condition for BCSA cement concrete during the short-term. The ideal short- and long-term curing condition for BCSA based on this study seems to be a lime bath curing condition.

Conclusion

Throughout this whole study, a total of 81 BCSA cement concrete cylinders were placed into different curing conditions for various lengths of time. Compressive strengths were taken, recorded, and analyzed to make comparisons between curing conditions.

Some conclusions that can be drawn from the testing reported in this thesis are:

1. The curing condition that resulted in highest compressive strengths at 28 days were the EC+W condition and the LB condition. The EC+W condition average strength was only 0.9% stronger than the LB condition average strength.
2. The curing condition that resulted in lowest compressive strengths at 28 days was the EC condition. It was 16% lower than the EC+W condition.
3. The curing condition that resulted in highest compressive strengths at 3 months was the LB2 condition. It was 18% higher than the WR condition.

Potential avenues for future research could include maintaining the same mix design and procedures and focusing more specifically on 1-3 curing conditions at a time. Additionally, another potential study would be to make a larger batch of concrete (perhaps 7 cubic feet to make about 100 cylinders) and place the cylinders in the highest-strength conditions found in this study without any interruptions between the lengths of time. The difference would allow for better consistency since the cylinders would be in 1 large batch rather than being broken up into 2 batches. Along with making and testing only 1 batch of concrete, a compressive strength study could be conducted on large beams or slabs by testing the in-place strengths of cores to compare to the cylinder strengths. Another study idea would be to test different properties, such as density and flexural strength, to determine the effects of curing conditions on those properties that differ from compressive strength.

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