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Understanding Workability in Belitic Calcium Sulfoaluminate Concrete Mixtures

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by

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A. INTRODUCTION

Belitic calcium sulfoaluminate (BCSA) cement is a relatively new material in the concrete industry. First developed in the United States in the 1970s due to the work of Professor Alexander Klein at UC Berkeley, BCSA concrete has been used for rapid road, runway, and bridge repairs [1, 2]. BCSA has not been used as a primary structural concrete due to its unknown structural behavior. BCSA has similar hardened properties to portland cement (PC) but can set in under 20 minutes, reach a compressive strength of 4,000 psi in less than 2 hours, and have a maximum compressive strength of around 10,000 psi. Calcium sulfoaluminate cement requires more water than PC to fully hydrate but the addition of belite to calcium sulfoaluminate cements is said to decrease the amount of water needed in the mix [3]. Another study says that BCSA requires 50-85% less CO_2 to produce than PC, which accounted for 7% of the world's CO_2 emissions in 2009 [4, 5]. Considering the combination of the global goal to decrease carbon emissions and the ever-increasing population of the world, the research and development of environmentally sustainable structural materials is needed now more than ever. Before a new material can be used as a PC replacement, designers need to understand the material's properties. This study is part of an effort to create a mix design guide for BCSA cement like design guides for PC such as ACI 211 [6]. The first step is developing guidance for the water content required to achieve a given slump.

B. BACKGROUND

BCSA cement's chemical makeup is different than PC and other cementitious materials. One important aspect of cement chemistry is the oxide composition. In PC, the oxide combination is calcium oxide (CaO), silica (SiO_2), and alumina (Al_2O_3) [3]. BCSA has less silica and calcium oxide than PC and has more alumina and sulfate (SO_3). These appear as ye'elimite, belite, ferrite, and calcium sulfate. The main precipitate of BCSA cement is a crystal called ettringite. In PC concrete, the late formation of ettringite crystals can cause internal tension whenever the crystals expand across a void. This internal tension often causes damage to the concrete. However, in BCSA concrete the formation of ettringite is controlled earlier in the setting process. Ettringite is responsible for the high early strength property of BCSA concrete mixtures.

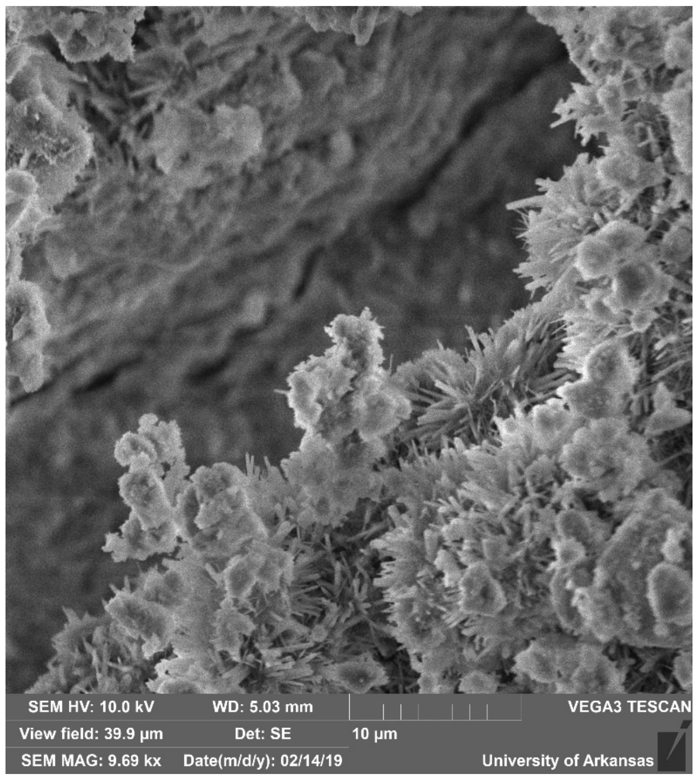

Figure 1. ESM photo of Ettringite and Calcium-Silica-Hydrate (Photo taken by Dr. Gary Prinz at the University of Arkansas, used with permission)

The American Concrete Institute (ACI) has provided ACI 211, which is a design guide for PC based cement mixtures [6]. This standard, first adopted in 1991 and readopted in 2009, provides standard percentages (by weight) of supplementary cementitious materials such as fly ash. The first thing designers choose in ACI 211's design process, Table 6.3.3, is the water content required and expected air content based on their nominal maximum aggregate size and slump [6]. Designers would then go to ACI 211 Table 6.3.4(a) and find their w/c ratio based on their desired 28-day strength. From these two tables a designer has determined the amount of water in their mix and the amount of cement [6]. The standard continues to proportion the amount of coarse and fine aggregates, and to determine the total volume of the mix.

C. <u>EXPERIMENTAL PROCEDURE</u>

Workability in concrete is said to be "…the effort required to manipulate a freshly mixed quantity of concrete with minimum loss of homogeneity" [7]. It is a qualitative characteristic of wet concrete describing the flowability, and consistency of the mix. It is imperative for concrete contractors to be able to confidently and accurately predict the workability of a mix. Therefore, the slump test was developed as a proxy quantitative measurement for workability. Slump tests are performed per ASTM C143 [8]. Due to the rapid setting nature of BCSA concrete mixtures, a set retarder is necessary for practical use. The retarder used for this study is a food-grade citric acid in powder form mixed at a concentration of 5 lbs of citric acid per gallon of water to create something similar to a typical concrete chemical admixture. Three doses of citric acid were used to identify the admixtures effect on slump: 0, 9, and 18 fl. oz of the admixture solution per 100 lbs of cement (0%, 0.35%, 0.70% of citric acid per cement weight). These dosages are consistent with previous work at the University of Arkansas and are typical for field use of BCSA concrete mixtures: 9 and 18 fl. oz per 100 lbs of cement should provide 45 and 90 minutes of working time, respectively [9].

Apart from citric acid, water content was the other experimental variable. Five water contents were used to test the effect of water content on slump. As seen in

Table 1, each dosage of citric acid had five different water contents that were tested: 275, 300, 325, 350, and 375 lbs per yd^3 of concrete. These water contents were expected to achieve slump measurements in the range of 2-10 inches, representing commonly specified slumps. Consistent with

Table 1, the amount of sand, rock, and cement were kept constant for each mix and the water content and citric acid were variable. Due to how the experiment was set up, the water-to-cement (w/c) ratio was, inadvertently, also variable. As the water content increased in the mic, the cement stayed constant thus increasing the w/c ratio. This is a variable that will be examined in later stages of the research program. Water content is expected to be the primary variable affecting slump.

Figure 2a,b. Mixing setup and slump test being performed by graduate student (Photos taken by author)

Materials for each batch were gathered 3 days prior to mixing. The coarse and fine aggregates were placed in an oven for 24 hours in order to remove any absorbed moisture. Once dry, weights were measured out and an exact amount of water was added to the aggregates to bring the moisture content (MC) to surface saturated dry (SSD). Having the aggregate at SSD ensures that no additional water is either added to or absorbed from the mixing water during the batching. Then the aggregates were placed in the climate-controlled (maintained between 68-71 °F) mixing room along with the cement and water. The materials were placed in the mixing room for 24 hours to reach a consistent temperature before mixing.

Table 1, Proportion of materials per yd^3

Citric Acid Dosage [% of cement weight]	Total Water [lb]	BCSA Cement [lb]	Dry Sand [lb]	Dry Rock [lb]	Sand Water [lb]	w/c
0	275	625	1200	1773	6.6	0.44
	300	625	1200	1773	6.6	0.48
	325	625	1200	1773	6.6	0.52
	350	625	1200	1773	6.6	0.56
	375	625	1200	1773	6.6	0.60
0.35	275	625	1200	1773	6.6	0.44
	300	625	1200	1773	6.6	0.48
	325	625	1200	1773	6.6	0.52
	350	625	1200	1773	6.6	0.56
	375	625	1200	1773	6.6	0.60
0.70	275	625	1200	1773	6.6	0.44
	300	625	1200	1773	6.6	0.48
	325	625	1200	1773	6.6	0.52
	350	625	1200	1773	6.6	0.56
	375	625	1200	1773	6.6	0.60

A drum mixer was used for each batch, and a ventilation system was used to reduce the amount of suspended cement in the air. Prior to mixing, an ambient room and water temperature were taken, and the citric acid dose was added to the water. Through trial and error, it was found that the optimal mix procedure was ½ coarse aggregate, followed by the fine aggregate, BCSA cement, water, and finished with the last half coarse aggregate. Adding half of the coarse aggregate last broke up any agglomerated sand or cement at the back of the mixer and created a more homogenous mix. All materials were added to the mixer as quickly as possible and then allowed to mix for 3 minutes. During the 3-minute mixing phase, the slump cone, tray, and all utensils such as scoops, were wetted down and prepared for testing. When the 3 minutes of mixing was complete, the mixer was turned off and the slump test started immediately per ASTM C143. Once performed it is imperative to add water to the concrete remaining in the mixer and start mixing. This extra water helps to break up the already setting concrete and make cleanup as easy as possible. The mixer and all utensils were then cleaned out and prepared for the next batch.

C. RESULTS AND ANALYSIS

There was found to be a positive relationship between water content and slump for BCSA concrete mixtures, Figure 3. Although each citric acid dosage showed an increase in slump as water content increased, the 0% and 0.35% of cement weight dosage showed more consistent results over a two-trial average when compared to the 0.70% dose.

When looking at slump variation and w/c ratio groupings, Figure 4, it is found that the extreme w/c ratios of 0.44 and 0.6 provided less variability in slump with ranges of 1.88 in and 2.75 in, respectively. The intermediate w/c ratios had increased variability contrary to our initial expectations.

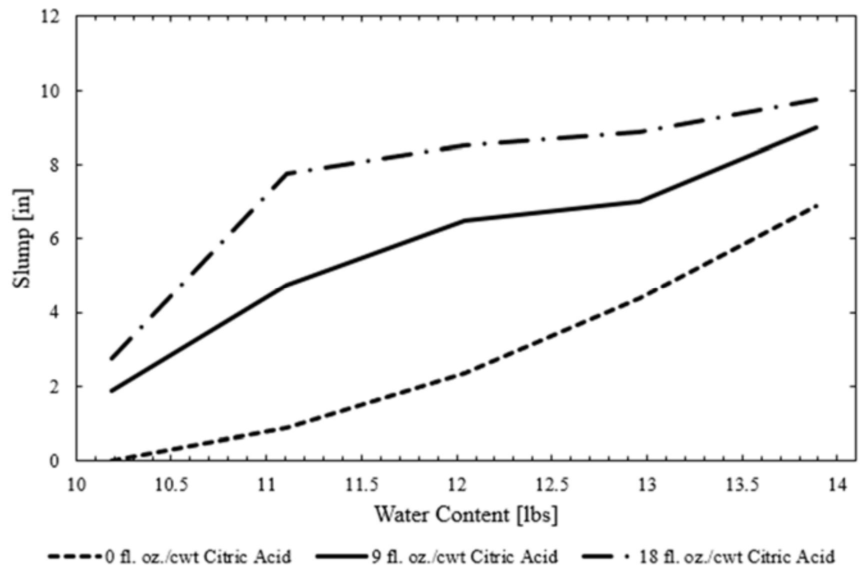

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Figure 3. Combined citric acid slump at varying water contents

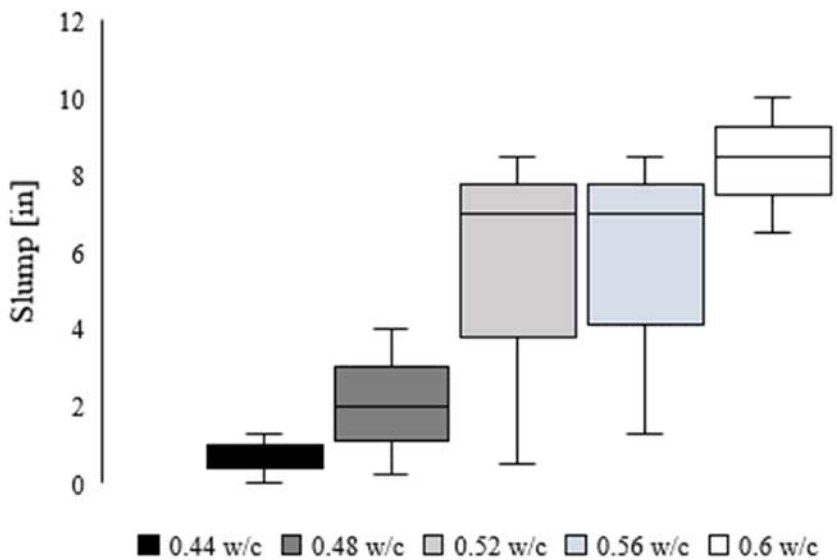

Figure 4. Slump variability between water-cement ratios

Table 2, Slump achieved at each water content and citric acid dosage

Water [lb]	Slump [in]								
	0% Citric Acid			0.35% Citric Acid			0.7% Citric Acid		
10.19	0	0	-	1.25	2.5	2.5	0.75	0.5	4.75
11.11	0.25	1.5	-	4	5.5	6	2	7.5	8
12.04	0.5	9.5	4.25	7	6	8	8.5	9	8.5
12.96	1.25	7.5	6	7	7	8.5	8.5	9.25	-
13.89	6.5	7.5	7.25	8.5	10	9.5	10	9.5	-

Table 3, Temperature for 0.0% citric acid trials

Water [lb]		1st Measure	2nd Measure	3rd Measure
10.19	Ambient [F]	74.1	68.4	-
	Water [F]	71	60	-
	Mix [F]	77	63	-
11.11	Ambient [F]	74.1	66.7	-
	Water [F]	71	56	-
	Mix [F]	76	61	-
12.04	Ambient [F]	74.1	68.5	70.3
	Water [F]	71	56	65
	Mix [F]	76	63	68
12.96	Ambient [F]	74.5	68.7	69.4
	Water [F]	72	59	64
	Mix [F]	75	62	65
13.89	Ambient [F]	74.5	68.4	69.3
	Water [F]	70	68	66
	Mix [F]	75	62	66

Table 4, Temperature for 0.35% citric acid trials

Water [lb]		1st Measure	2nd Measure	3rd Measure
10.19	Ambient [F]	69.8	69.8	70.2
	Water [F]	66	59	69.1
	Mix [F]	69	59	73.1
11.11	Ambient [F]	69.6	70	70.3
	Water [F]	66	68.9	70.3
	Mix [F]	70	70.9	73.4
12.04	Ambient [F]	70	70	70
	Water [F]	67	68.9	70.3
	Mix [F]	72	72	70.3
12.96	Ambient [F]	70.5	70.5	72.3
	Water [F]	65	65	70
	Mix [F]	70	70	70.2
13.89	Ambient [F]	70.2	69.4	68.7
	Water [F]	67	60	69.8
	Mix [F]	71	59	70.2

Table 5, Temperature for 0.70% citric acid trials

Water [lb]		1st Measure	2nd Measure	3rd Measure
10.19	Ambient [F]	71.6	70	70.2
	Water [F]	69	65	60
	Mix [F]	72	66	63
11.11	Ambient [F]	72.7	70	69.6
	Water [F]	69	64	60
	Mix [F]	73	69	64
12.04	Ambient [F]	73	70	69.6
	Water [F]	69	65	70
	Mix [F]	72	64	70.9
12.96	Ambient [F]	73.6	70	-
	Water [F]	70	66	-
	Mix [F]	73	65	-
13.89	Ambient [F]	73.9	70	-
	Water [F]	66	65	-
	Mix [F]	68	64	-

D. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions based on the work performed in this study:

a. There is a positive relationship between water content and slump in BCSA concrete mixtures.

b. The addition of citric acid into a mix increases the slump at each water content and therefore workability of the mixture.

c. Due to setting time and reduced workability, a citric acid dose of at least 0.35% of cement weight is recommended for a usable mix.

d. A citric acid dose of 0.35% of cement weight produces a more consistent mix with adequate working time.

More research is required to verify the results achieved in this study. This paper reveals some basic relationships between citric acid dosage, water content, and slump in BCSA concrete mixtures to be used in future research. Future research could improve on this work by doing the following:

a. Perform more trial batches to reduce error. A sample of at least 3 data points is recommended.

b. Ensure that one person is running the slump test to reduce variability.

c. Set up the mix designs so that the water-cement ratio is held constant.

E. REFERENCES

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