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MECHANICAL PERFORMANCE OF POST-TENSIONED
RESIDENTIAL FOUNDATION SLABS USING EXPANSIVE BCSA
CEMENTS

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MECHANICAL PERFORMANCE OF POST-TENSIONED
RESIDENTIAL FOUNDATION SLABS USING EXPANSIVE BCSA
CEMENTS

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AND ENVIRONMENTAL SCIENCE

BY THE COMMITTEE CONSISTING OF

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Abstract

Recent research in concrete materials and structural behavior has focused on alternative cements to increase sustainability as cement manufacturing is a leading producer of CO₂ emissions. One promising alternative is calcium sulfoaluminate (CSA) cements. While expansive Type K CSA additives have been used for shrinkage compensating concrete for many years and rapid setting, belitic CSA (BCSA) has found widespread use in pavement repair and precast applications, there has been little research comprehensively analyzing the behavior of CSA cements with both expansive and rapid setting properties.

This research focuses on characterizing the performance of an expansive, rapid setting BCSA cement. This novel cement could be used for post-tensioned slab on grade design that would reducing shrinkage and mitigate prestress losses, resisting the high flexural stresses that result from expansive soil subsurface movements. This can improve the long-term durability and life cycle of these slabs and reduce the magnitude of prestressing forces required for these slabs to resist subsurface movements. Mix designs were developed to provide sufficient workability and working time while achieving sufficient strength at an early age for post-tensioning on the same day, at 6-8 hours after casting. Material properties including elastic modulus, modulus of rupture, restrained and unrestrained expansion, and creep were measured with small scale specimens to establish material properties, and a comparable expansive, non-rapid-setting Type K cement mix was subject to the same tests for comparison. Additional testing was conducted to provide guidance on field curing and retardation procedures.

Finally, large-scale post-tensioned slabs were cast with both mixes alongside a conventional portland cement slab, to assess field performance against predictions from measured properties.

Measured mechanical properties show higher strength than those of the conventional portland cement mix design. Considerable strength increases are observed with the expansive BCSA cement as time of wet curing increases, however subsequent drying can reduce these gains. High sensitivity to temperature was observed, requiring greater attention to retardation admixture dosages. Measured values for long-term prestress losses indicate considerably reduced creep and shrinkage behavior, further offset by concrete expansion. Existing ACI 423 models for creep and shrinkage differed greatly from measured values but yielded more accurate estimates with relatively simple adjustment. The large-scale expansive BCSA slab showed agreement with property characterization, exhibiting lower creep and shrinkage than either the Type K or conventional portland cement concrete slabs.

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1.0 Introduction

1.1 Background

The purpose of the research described in this thesis was to investigate the effects of expansive calcium sulfoaluminate (CSA) cements on reducing shrinkage behavior and prestress losses in post-tensioned slab on grade design, improving the long-term durability and life cycle of these structures and mitigating the magnitude of prestressing forces required for these slabs.

Cracking behavior is a major factor leading to reduced durability in concrete. Most structures are designed to operate in service even after experiencing small stress cracks. Although the ultimate load capacity is not exceeded, the cracking moment, M_{cr} , is often much less than service moments, which opens cracks in the tension zones of concrete elements. Additionally, portland cement concrete experiences significant shrinkage during curing, resulting in additional cracks when movement is restrained. These cracks, while they do not compromise structural integrity, lead to water infiltration and environmental damage that reduces the durability and life expectancy of concrete structures.

Prestressing of concrete has proven to be an effective means of creating high-strength structural elements at smaller sizes and weights than otherwise possible and increasing the durability of structures by minimizing crack formation. Therefore, prestressing has seen widespread usage in the past 50 years, particularly in large-scale, heavy construction such as bridges and to resist intense environmental loads that might

otherwise overstress a structure. However, one aspect of prestressed construction that is still only understood to a limited degree is structural prestress losses. After applying load to initially prestress the strands and transferring that stress to the concrete element, some of that stress is relieved both immediately and over time as the element is in service. These reductions, or losses, in the prestressing force occur for a variety of reasons, including shrinkage during drying and service, elastic shortening due to the application of the prestress, creep during service, strand relaxation, and friction in post-tensioned elements.

Consequently, it is important to predict the degree of losses that will occur in prestressed members accurately to model the element's stress condition during its lifetime. Moreover, overly conservative estimates of prestress losses can be as detrimental as unconservative estimates, adversely affecting the lifetime performance of an element. Therefore, it is crucial to accurately predict losses to establish future behavior, without either over or underestimating them. However, while the causes of many prestress losses are understood, there is still significant difficulty in accurately calculating them. This is particularly true for long-term losses. An immediate loss like elastic shortening can be reasonably predicted using mechanics of materials. Due to material variability, as well as variability in environmental conditions, long-term losses caused by shrinkage and creep can vary significantly and are difficult to predict, even with complex methods.

1.2 Research Question

Calcium Sulfoaluminate (CSA) cements have the potential to reduce prestress losses, particularly those that are time dependent, as many CSA cements exhibit less shrinkage than conventional portland cement or will exhibit expansive behavior during the hydration process. This behavior can reduce the shrinkage losses over time, potentially lead to additional chemically induced prestress, and reduce uncertainty in longer term losses.

In this project, two kinds of expansive CSA cements were explored in comparison to traditional portland cement concrete. Both an expansive Type K cement acting as a supplementary cementitious material added in the proportion of 25% of the cementitious material by volume and a rapid-setting expansive belitic CSA (BCSA) cement used to completely replace conventional portland cement were examined. The goal of both alternatives was reducing total prestress losses and crack formation, which can allow for lowered initial prestressing requirements, and reduce the variability introduced by long term losses.

1.3 Research Objectives

CSA cements are less well characterized than their portland cement counterparts, however among the most promising uses for them is in prestressing applications. Roswurm (2023), Bowser (2020), and Murray et al. (2019) proved their viability in precast prestressing, with an expansive belitic CSA (BCSA) cement allowing for same day prestress transfer for precast beams and reduced long-term prestress losses. This not

only potentially lowers prestress loading requirements but enables multiple elements to be cast in the same day, raising plant efficiency and offsetting higher material costs.

However, there is still insufficient research into the viability of CSA cements for other prestressing operations and the extent of effects on life cycle performance and prestress losses. Little information is available for critical properties such as creep and how expansive behavior affects prestress losses. Moreover, much of the existing literature focus on small scale mixes or mixes under controlled conditions; Frank (2011), for example only mixed small volumes of concrete to establish his retardation curves for set time and only measured initial properties, which ignores the working time requirements for in-field viability. Similarly, the initial property establishment for the proprietary expansive BCSA cement examined was conducted with only small-scale batches and specimens (Bescher 2021), and therefore has limited utility to field applications and meeting requirements for large scale pours. This is a major challenge to field application of rapid setting CSA cement because a crucial evaluation of working time as well as early strength gain is needed for contractors to balance early strength gain with sufficient working time to complete a pour. All of the mixes that set and reach compressive strength requirements in less than 3 hours for example, are infeasible for large field slab pours for example, because they realistically do not have enough working time to pour and finish more than a handful of sections. Therefore, a more comprehensive assessment of temperature effects on set time and workability is needed to supplement an understanding of material properties like strength gain to adjust mix designs to ensure both early strength gain and predictable setting time, with sufficient working time to place concrete in the field.

Therefore, the objectives of this project were to:

- Quantify CSA cement concrete expansion and shrinkage under load.
- Determine the extent of prestress losses in expansive CSA cement concrete post-tensioned slabs.
- Characterize temperature effects on workability of fresh CSA cement concrete mixes and setting time.
- Compare material properties of expansive CSA cements, both Type K and rapid setting belitic variants.
- Characterize the long-term performance and durability of large-scale slabs-on-grade using expansive, rapid setting CSA cement concrete under environmental distresses in the field and compare to solely expansive CSA cement concrete and conventional concrete.
- Assess the overall viability of CSA cements towards post-tensioning operations and field usage.

The general hypothesis of this study is that CSA cement can mostly eliminate stresses and cracking due to drying shrinkage, and associated prestress losses, increasing the durability of slabs on grade and reducing stressing requirements without diminishing long-term performance. Additionally, it is anticipated that rapid setting Belitic CSA cements can have the added advantage of enabling same-day post tensioning and accelerating construction schedules versus conventional concrete or their solely expansive Type K CSA counterparts, which do not experience rapid hardening relative to portland cement concrete.

2.0 Literature Review

2.1 CSA Cements

Calcium Sulfoaluminate (CSA) cements have been an area of recent focus due to their potential high early strength, reduced shrinkage behavior and lower CO₂ emissions as compared to portland cement production. The original principle stems from the idea of removing C₃S from conventional portland cements, which is desirable because of its higher kilning temperature, hardness for grinding, and durability issues it poses. As Bescher (2012, 2016, 2019) explains, the downside to this is that the C₃S phase of cements is where concrete derives its, early strength. Therefore, CSA cements replace this phase with a ye'eliminite phase which is softer and kilns at a lower temperature.

The original work in the development of CSA cements in the 1960s was towards leveraging expansive properties to yield shrinkage compensation in cements, now conventionally referred to as Type K CSA cements, however in the 1960s the work of Professors Alexander Klein and Borje Ost, who through experimentation with the concentrations of a belite phase developed rapid setting CSA cement. (Bescher 2019) This belitic CSA (BCSA) has slowly found widespread use in pavements due to the rapid strength gain and set time enabling quick turnaround of projects.

However, as noted by Bescher (2019), typologies of different CSA cements is a point of confusion in literature, and recommends distinct categories of CSA cements based on their mineralogy, in particular, Type B, or belitic CSA (BCSA) cement is the most common mineralogy responsible for rapid-setting CSA cement behavior while Type K CSA cement reactions are most commonly used to generate expansive behavior. Within

this thesis, the term, Type K, BCSA, and expansive BCSA cements are used to denote cements used with expansive, rapid setting, or both properties, respectively. Table 1 lists the classification of types of CSA cements based on phase concentrations, while Table 2 lists the cements used in this research, terminology used in this study and the classification of these cements according to Bescher (2019).

Table 1: Proposed Classification of CSA Cements by Minerology and Cement Phases. (Bescher 2019a)

	Ye'elemite	Belite	Calcium Sulfate	Other
Type A - Accelerating Additive	35 - 45%	0 - 20%	10 - 30%	5 - 55%
Type B - Belitic Calcium Sulfoaluminate Cement	20 - 30%	40 - 60%	5 - 25%	0 - 35%
Type C - Expansive Additive	10 - 20%	10 - 30%	40 - 60%	0 - 40%
Type K - Shrinkage Compensating Cement	1 - 10%	30 - 50%	1 - 20%	20 - 70%

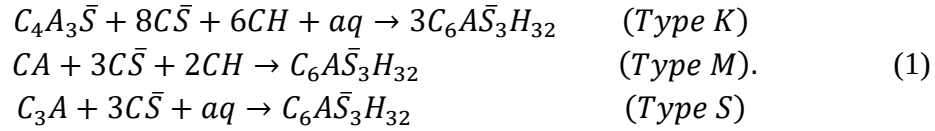
Table 2: Classification of CSA Types and Branded Products used in this Research.

Material	Bescher (2019) Classification	Thesis Terminology	CTS Branded Cement
Type K CSA Cement	Type K	Type K	Komponent®
Belitic CSA Cement	Type B	BCSA, Belitic CSA	RapidSet®
Expansive Belitic CSA Cement	-	Expansive BCSA	ChemStress®

Therefore, depending on their chemistry and intended purpose, CSA cements can be altered to exhibit rapid-setting properties, shrinkage compensation, expansive behavior, or a combination, by varying the concentrations of the belite, ye'eliminate and calcium sulfoaluminate phases. (Bescher 2012, 2019, de Bruyn 2017)

2.1.1 Expansive Behavior

Successive work by Roswurm (2013), and Roswurm (2018) attempted to assess the usefulness of expansive CSA cements. While there are multiple varieties of CSA cements, as characterized by reaction mechanism, the Type K reaction mechanism is most commonly used in commercial products, shown in Equation 1 (Mehta 1986), to resist shrinkage behavior of concrete and mitigate crack formation. Type K cements do not prevent shrinkage from occurring, the principle is that in shrinkage compensating concrete, they can create enough expansion at an early age to offset the eventual shrinkage to prevent crack formation. (Bescher 2021)



S. Roswurm (2013) compared the results of ASTM C157 and C878 specimens to 4 in. diameter x 48 in. long column specimens under different levels of restraint that were instrumented with vibrating wire strain gauges (VSWGs) to establish shrinkage behavior of larger specimens. As wet curing is essential for Type K cement to exhibit expansive behavior, he used cardboard forms with an outer PVC standpipe for wet curing. Initially, at the conclusion of the 7-day wet curing period, he drained the standpipe and intended to leave the cardboard forms on, as shown in Figure 1. However, the procedure was changed to stripping the forms, as the cardboard was found to retain water even after draining the standpipe, prolonging the wet curing period beyond intended. The cardboard was so saturated that it had to be literally scraped off,

which consequently imparted significant physical trauma prior to testing. (Roswurm 2013)



Figure 1: Cardboard Formwork and PVC Casing for Wet Curing (Roswurm 2013)

The findings in this work were that while restraint conditions do inversely affect expansion, it is very small relative to any increase in restraint, and higher percentage replacements of portland cement with Type K cement yield more aggressive expansion and less pronounced shrinkage. Additionally, VWSGs were shown to yield superior results relative to ASTM standard methods such as C157 and C878 in measuring strain development (Roswurm 2013).

Roswurm (2018b) replicated the work of Roswurm (2013) to improve on shortcomings in the testing procedure. He also found that leaving the casings in place was not a feasible strategy as the cardboard remained saturated and prolonged the wet curing beyond its intended period. Consequently, he resorted to stripping off the formwork

after reaching initial set but prior to beginning the wet cure and using misters to wet cure columns during testing, shown in Figure 2.



Figure 2: Close-up of Column Specimen Being Misted (Roswurm 2018)

Use of misters had the disadvantage, however, of drastically raising the relative humidity (RH) in the environmental chamber during the curing process from 50% to 70-80%, affecting all the specimens in the environmental chamber. Roswurm (2018b) generally validated the results of Roswurm (2013); moreover, finding that at ~21% Type K replacement, drying shrinkage can effectively be completely offset. Additionally, he identified that concrete made with Type K cements tends to exhibit more non-linear elastic behavior than its portland cement counterpart.

Shadravan (2015) conducted both small-scale testing with C157, C878, and *shrinkage from zero* specimens and large-scale jointed slab on grade testing. Shrinkage from zero testing was conducted by casting C157 specimens with a single end restrained and mounted to a horizontal gauge, as shown in Figure 3, so that measurement readings could be taken from the start of casting and recorded more consistently.



Figure 3: Mold and Testing Set up for Shrinkage from Zero Testing

In particular, Type K CSA cement vastly outperformed any conventional cement in terms of warping and shrinkage reduction. As shown in Table 3, joint expansion was on the order of 2-4.5x as great in magnitude for all other cement and admixture combinations, with high performance concrete experiencing particularly high shrinkage.

Table 3: Joint Expansion of Slabs at 574 days (82 weeks) (Shadravan 2015)

Mix	Joint Expansion (mm)	Compared to CSA (%)
Type K CSA Cement	1.6	-
Shrinkage Reducing Admixture #1	3.4	231%
Shrinkage Reducing Admixture #2	3.9	244%
Portland Cement Concrete	5.9	367%
High Strength Concrete Mix	7.4	459%

*The shrinkage reducing admixture slabs consisted of the same mix as the portland cement concrete, adding 4.75 oz/cf (4.95L/m³) of admixture.

The authors also found that, in general, shrinkage from zero testing yielded more accurate results that were easier to take and less sensitive to user bias than either C157 or C878 results. However, presumably due to the difference in aspect ratio and the boundary conditions provided by a bed of sand under the slabs that almost always provides moisture, all the methods poorly predicted the large-scale slab on grade expansion behavior. However, what did correlate was that CSA slabs were far more geometrically stable than their portland cement concrete, high-strength concrete, or shrinkage admixture-entrained counterparts (Shadravan 2015).

2.1.2 Rapid Setting Behavior

Adding belite to CSA cements generates another major advantage over traditional portland cement, rapid setting, and strength gain. Belitic CSA cements hydrate faster than portland cements and can be used to accelerate strength gain allowing for increased construction speed due to faster concrete set time (Bescher 2019). One detriment to this however is that belitic CSA cements may have extremely short set times and can potentially flash set, that is, start to harden and set up rapidly while still mixing. Extreme cases of flash setting have a very significant risk of locking up and damaging mixing equipment. Consequently, retarding admixtures generally need to be added to these mixes to extend the workability and set time of mixes.

Roswurm (2018a), developed curves for rapid setting BCSA cement behavior under varying retarding admixtures dosages to predict field dosing requirements. In this study,

CTS Cement Manufacturing Corp. brand RapidSet® fast setting BCSA cement was dosed with varying quantities of granular citric acid and commercial branded liquid retarders, Delvo® and Recover®, to determine target doses to ensure sufficient working time without overdosing the mixes. Overdosing of mixes can lead not only to delayed set, but permanent strength reduction. He found that for RapidSet® BCSA cement, citric acid also has a plasticizing effect, a phenomenon not seen for conventional portland cements. Additionally, citric acid causes a reduction in early age strength gain, while liquid retarders like Delvo® do not. Finally, overdosing mixes with citric acid was shown to increase shrinkage (Roswurm 2018a).

Murray et al. (2019) focused on utilizing rapid setting behavior of CSA cements to accelerate the prestress release of precast beams, assessing the feasibility of multiple pours in the same day and examining the transfer length, development length, prestress loss, and shear behavior of such structural elements. The four beams cast were able to be demolded and have strands cut between 2 and 3 hours after the addition of the cement to the mix, proving the feasibility of same day prestress release. Predicted prestress losses using the AASHTO refined method were more than double the experimentally measured results. Even considering that there was a difference between the volume to surface area (V/SA) ratios of the cylinders used to get a shrinkage estimate (1.2) and the full-scale beam ratio (3.0), the combined shrinkage and creep losses were still overestimated by a factor of over 6, being only 4.3 ksi on average compared to the predicted 26.5ksi, indicating a need for significant adjustment of loss predictions for CSA cements. Transfer length approximations on the other hand appeared to be reasonable (Murray et al. 2019).

Concretes made with CSA cements are extremely temperature sensitive. (Frank 2011, Roswurm 2023) Moreover, the Belitic CSA cements that generate rapid setting behavior are even more reactive to temperature variation than Type K CSA cements used for shrinkage compensating concrete. Therefore, Phillips et al. (1997), notes that due to accelerated set-time behavior, the Ohio Turnpike Commission (OTC) recommended that shrinkage compensating concrete should not be poured if the ambient air temperature is greater than 80°F. The OTC also stated that casting shrinkage compensating concrete at elevated temperatures can result in reduced strength and lower maximum expansion.

Frank (2011) expanded on prior work analyzing the effects of temperature on Type III rapid-setting portland cement, which shows elevated early strength and reduced late strength as curing temperature increases. While the temperature effects on Type III cement, had a moderate amount of literature covering their behavior, similar literature was not available for CSA cements, so Frank (2011) adapted the existing methods from these prior studies to broadly assess temperature effects on CSA cements. He found that curing temperature and mixing temperature primarily impact early strength gain.

Concrete strength guidelines were established based on Oklahoma DOT concrete specifications for Class A concrete, which has a 3 ksi minimum specified strength. The time to achieve this minimum compressive strength was relatively the same at the same temperature range, irrespective of whether a high or low compressive strength mix design was specified. As shown in Table 4, for example, the variation of the mixes' strength gain was only an hour and a half at 100°F, and 2 hours at 80°F. While there was greater variation as temperatures decreased to the lower temperatures of 40 and

60°F, it was highly variable even between specimens that were cured and mixed at the same conditions, such as mix #17 and #18, which set at 11.6h and 3.6h respectively, which implies external factors other than temperature altered the strength gain.

Table 4: High and Low Specified Strength Mixes Sorted by Time to Reach 3000 psi Minimum Specified Strength Based on Curing Temperature (Frank 2011)

Mix #	Strength		Mix Temperature (°F)			Cure Temperature (°F)				3000 PSI Time (Hours)
	High	Low	40	60	80	40	60	80	100	
7		X		X					X	5.0
8	X			X					X	1.7
9		X			X				X	2.6
10	X				X				X	1.1
11		X			X			X		2.6
12	X				X			X		2.0
13		X		X				X		3.9
14	X			X				X		2.1
15		X			X		X			8.8
16	X				X		X			4.6
17		X		X			X			11.6
18	X			X			X			3.9
19		X	X						X	2.3
20	X		X						X	1.4
21		X	X					X		3.0
22	X		X					X		2.4
23		X	X				X			6.2
24	X		X				X			3.6
25		X	X			X				48.6
26	X		X			X				17.9
27		X		X		X				12.4
28	X			X		X				4.8
29		X			X	X				4.9
30	X				X	X				1.6

Mixing temperature on the other hand was found to have some limited impact on overall mix strength gain, with strength gain following banded ranges of increasing time as temperature decreases. Crucially, however, all of Frank's (2011) mixes were small batches of concrete, with workability only being assessed with the initial slump, and set time only considered based on strength gain. Therefore, the results have limited applicability to field mixing at scale.

Only two comprehensive studies on the mechanical behavior of a CSA cements have been identified during this literature review, Bertagnoli et al. (2019) and Roswurm

(2023). Bertagnoli focused on characterizing an additive CSA cement, designed for producing concrete with rapid hardening and strength gain, and reduced shrinkage behavior, while Roswurm used a rapid hardening Belitic CSA cement. Notably, however neither characterization was of a CSA cement exhibiting expansive behavior.

Bertagnoli conducted testing with the goal of providing an exhaustive mechanical characterization of CSA cements, using an additive BCSA cement to replace a portion of the portland cement. The tests run included compression, indirect tension, three-point bending, shrinkage, creep, freeze thaw and fatigue testing, with additional measurements of fracture energy, setting time, stress-strain, semiadiabatic curing and depth of water penetration under pressure. These twelve tests were performed on a total of 173 small-scale specimens that were all cast in a single batch in the span of approximately 50 minutes to ensure consistent material properties. Most significant is the authors' assessment of creep and shrinkage with this additive BCSA cement, comparing the shrinkage behavior compared against the MC2010 empirical model. Additionally, a reference shrinkage measurement was used to back out the true creep behavior.

However, while this characterization was conducted to comprehensively consider numerous variables, including an assessment of creep and shrinkage variation with different curing periods, very little analysis of the results or conclusions were drawn with respect to comparative performance either with traditional portland cement or property prediction and characterization.

That said, a few notable trends can be observed; firstly, while the MC2010 model reasonably predicts the magnitude of longer-term shrinkage, after approximately 60 days, its shape fails to capture the rapid early age shrinkage rate. While in general, creep decreases with increasing loading age as expected with the increase in strength and stiffness with age, the 2-day wet cured specimens actually exhibit the least creep despite being loaded earliest. Thus, there appear to be other factors that may predominate controlling creep magnitude at early age.

On the other hand, the Roswurm (2023) characterization of mechanical performance of non-expansive BCSA cement not only conducts a comprehensive slate of testing including, compression, modulus of elasticity and modulus of rupture, bond pullout and development length. Additionally he conducted in-depth analysis and comparison to existing ACI models and conventional portland cement concrete, culminating in adjusted predictive models accurately predicting material behavior effects for prestressed girders. Roswurm (2023) further studied temperature effects to create retardation dosing guidance based on temperature.

For modulus of rupture data, Roswurm (2023) plotted the ratio of tension strength to the square root of compressive strength, allowing for a more standardized comparison to existing models. It is observed that specimens tend to outperform the ACI predicted ratio of 7.5 in ACI 19.2.3.1 at early ages under 1d, while underperforming at later ages, suggesting that the current ACI prediction underestimates the rate of rupture strength development.

For both the base mix with a 0.53 coarse to fine (C/F) aggregate ratio used for his dissertation, and a second mix with a higher C/F ratio of 0.82., Roswurm (2023) noted a highly linear correlation between compressive strength and elastic modulus. However, Roswurm (2023) chose to provide a square root correlation as shown in Equation 2, because that is the most common relationship currently used in practice.

$$E_c = 50,000\sqrt{f'_c} \quad (2)$$

Additionally, both BCSA mixes show a significantly lower proportionality constant of 44,000 to 50000 versus the currently used ratio of 57000 for normal weight concrete, despite having a consistent unit weight with the common correlation. The two mixes also show an inverse relationship between this correlation and the C/F ratio of a mix, with a 10% reduction between the mixes as the C/F ratio increases from 0.53 to 0.82. While two mixes is too small a data set to draw strong conclusions, this decrease in proportionality with increased coarse aggregate content may suggest BCSA concrete derives stiffness from paste rather than the aggregate matrix.

Creep and shrinkage behavior also show interesting trends. The creep data shows that the magnitude of creep decreases as the age at which loading occurs, however, the creep coefficients are smaller than for conventional portland cement concrete. This is because of the lowered stiffness from MOE testing, which results in higher elastic strains.

Though there is some reduction in absolute creep strains, the creep coefficient exaggerates this reduction because creep strain represents a smaller fraction of the elastic strains. On the other hand, the shrinkage strains, based on both VWSG readings

from the creep column companion shrinkage specimens and C157 readings are significantly reduced relative to portland cement concrete. (Roswurm 2023)

Also of significance in this research is the temperature retardation study that was conducted. While almost all of the large-scale specimens were poured with a dosage of 0.20% citric acid retarder by cement weight, the author recognized the sensitivity of BCSA to temperature posed a challenge to field application and conducted a study of set time for his mix design at three temperature ranges, 50°F, 70°F, and 80°F, with varying dosages of citric acid. He found penetrometer and calorimeter data correlated very well, making both methods a reliable indicator for establishing setting time, however calorimeter data can be taken more easily and more precisely than penetrometer results, and therefore became the preferred method. When compared to the workability data, the calorimeter consistently overshoot the workability data, however this was expected as workability ends at initial set rather than the final set measurements that the calorimeter was assessing. The general trends of both were in agreement, however setting time data showed a knee in the curves that was not present in workability data. (Roswurm 2023)

In general, the results from these tests were comprehensively analyzed, which can provide another baseline for property assessment in this research. Consequently, the work in the Roswurm (2023) study serves as a point of reference for comparison and baseline for drawing conclusions about the wider applicability of analysis of expansive BCSA to non-expansive BCSA as this thesis generally finds deviations from expected behavior not observed in additive type K CSA counterparts.

Finally, while it is not a material property, a point of significant note in the research of Roswurm (2023) is the effect of citric acid retarder dose sequencing. The first large scale beam pour conducted by Roswurm prematurely set, approaching even flash set type behavior, presumably due to a deviation in mixing procedure where the first half of the water added to the mix to wet the aggregates prior to adding any cement was not dosed with any citric acid retarder. This detail led to the rapid slump loss in a self-consolidating mix as shown to the left in Figure 4, versus the expected behavior to the right. As can be seen, not only was all of the slump lost within 20 minutes but the slump cone could not even be properly consolidated.



Figure 4: Slump Taken from Mix FR-1, Which Flash Set (left), and FR-2 (right), Where Citric Acid Retarder was Added to the Water Initially Soaking the Aggregate (Roswurm 2023)

This resulted in the final beam, shown in Figure 5, where only half of the concrete filled the forms and the strands were unloaded by conventional jacking as it was deemed unsafe to even attempt a proper prestress release.



Figure 5: Side View of Flash Set Beam Specimen, B1.

Finally, the work of Bescher (2021) provides initial characterization of properties small specimen testing for the expansive cement used in this research. It is observed that this cement results in a far more aggressive expansion than Type K cements, only matched in magnitude by extremely high levels of Type K replacement, but even then, the expansion occurs slower. In terms of compressive strength gain, this cement appears to gain strength slower than non-expansive BCSA cement, but gains strength much longer, which results in much higher final strengths of 10-11ksi, versus 8-9ksi for non-expansive BCSA. While Bescher (2021) does include data for flexural data and more comprehensive expansion and shrinkage data, little information is provided about testing procedures, such as wet curing, making it difficult to draw any other conclusions.

2.2 Fiber Reinforced Concrete and Chemical Prestressing

The use of fiber reinforced concrete (FRC) has become a common method for passive resistance of cracking and increasing tensile capacity of specimens. In principle, once a concrete element reaches its cracking moment, the fibers, generally steel, engage and bridge the cracks. For elements exhibiting high shrinkage, these fibers can also be engaged by shrinkage strains to reduce cracking due to autogenous or drying shrinkage as well as loading. This both increases the strength capacity of tensile zones after first cracking, and this fiber engagement reduces the crack width and deflected behavior of the element. It also significantly increases the ductility of concrete elements.

The post-cracking behavior of the concrete of FRC is significantly altered by the introduction of fibers. Therefore, accurately modelling this increasingly complex failure mechanism is a major concern—as discussed generally in ACI reports PRC-544.2-544.5, and detailed for specific applications, in publications such as Graybeal (2020), focusing on fiber reinforced ultra-high-performance concrete. In particular, steel fibers can drastically increase the ductility of concrete elements, however because of the inherent random distribution and variability of fiber orientation, the post-cracking behavior becomes highly non-linear. This is further complicated by the continuous support conditions of slabs-on-grade, which have often been modelled as a soil structure interaction (SSI) problem with an elastic Winkler foundation. Barros (2001) created a finite element model to account for nonlinear SSI, using a plane stress shell mesh, and elasto-plastic behavior, and an elastic soil stiffness. This model found good agreement

with testing conducted using hook ended ZX80, and Dramix fibers on an elastic foundation composed of either cork or rubber.

Guimil et al. (2022) experimentally analyzed the effect of fiber orientation on residual flexural capacity of elevated slabs, for vibrated FRC, self-consolidating concrete (SCC), and Fiber Reinforced Self-Consolidating Concrete (FRSCC), using both larger scale slab specimens and prism specimens, tested in accordance with, EN 14561— 3-Point Bending Test Method for Metallic Fibered Concrete, which uses specimens roughly equivalent to ASTM MOR specimens under 3-point loading to assess the flexural capacity of FRC.

However, the authors also recognized that the variation between fiber orientation is not necessarily accurately represented by small scale specimens, as the flow and rheology of SCC will have greater effects with larger scale pours. Therefore, in addition to casting standard flexural testing specimens in accordance with the Eurocode, to account for the difference in size factors between standard EN 14561 flexural tests and full-scale slabs, full slab specimens were also poured and then saw cut into 64 specimens for more accurate field results. The flexural prisms had dimensions of 15cm x 15cm x 62 cm (6''x6''x24''), and the large-scale slab had a 15'' depth and side length equal to four times the long dimension of the prisms or 248 cm (8'), as shown in Figure 6.

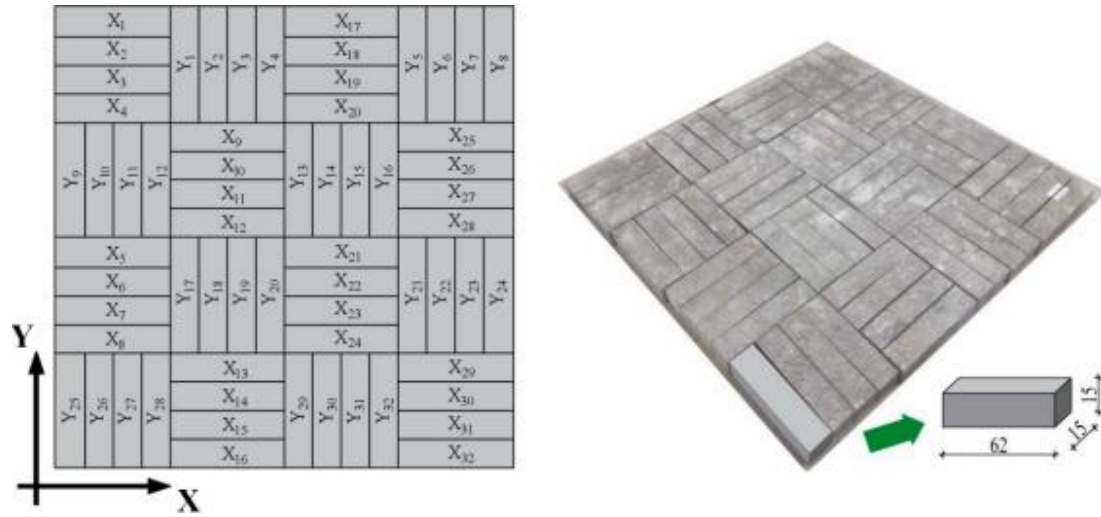


Figure 6: Full Scale Slab Specimen with Orientation and Dimensions of Sawcut EN 14561 Test Specimens (Guimil et al. 2022)

Both a full-scale slab and the sawcut prism sections of a slab were tested for each of the three design mixes. Figure 7 shows the results of the sawcut prism flexural capacities placed in the orientation from which they were cast, normalized and color coded with respect to the full-scale slab capacity to assess the scale effect of prisms relative to a full slab.

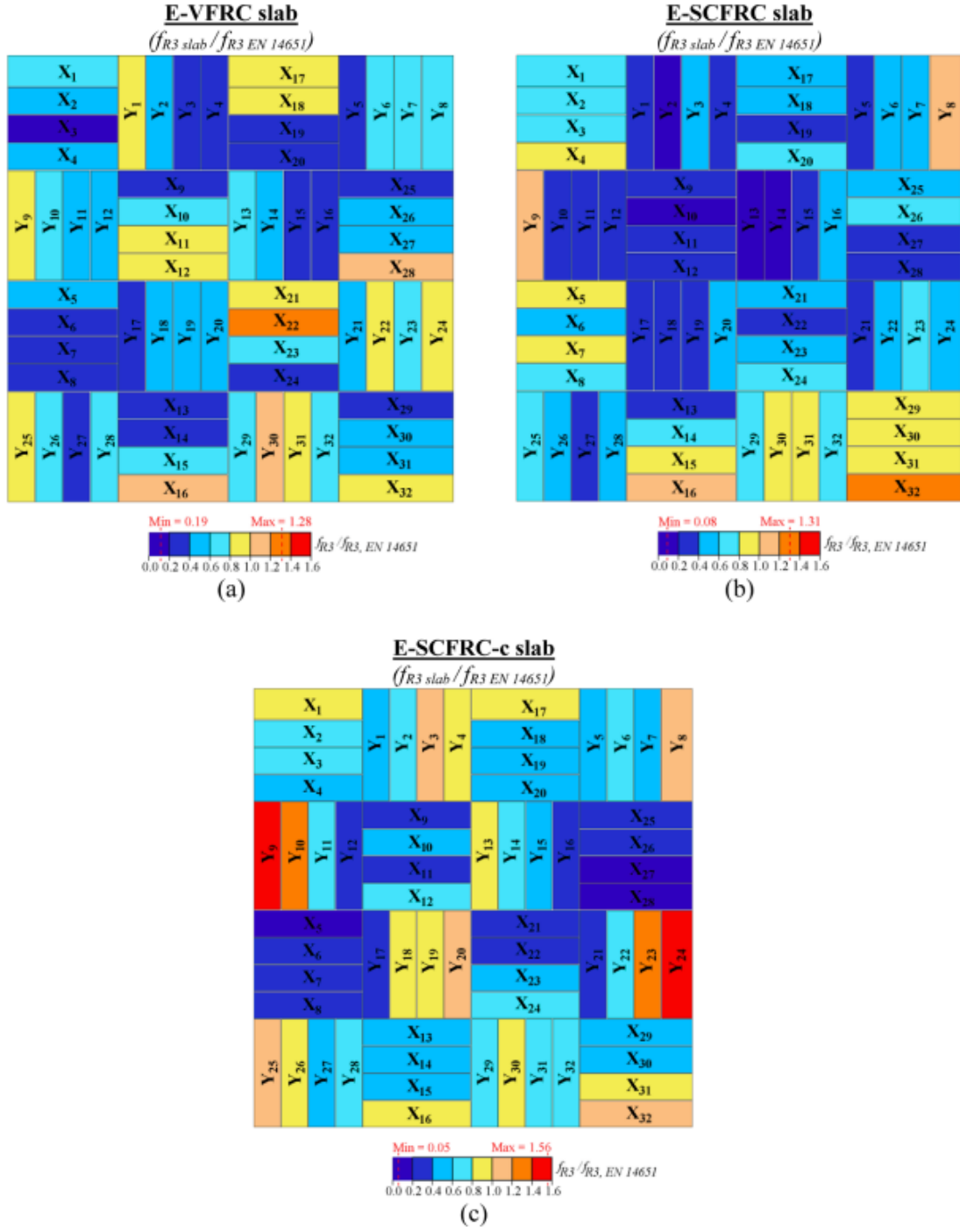


Figure 7: Normalized Comparison Between the Residual Flexural Strength from Slabs and the Mean Value Obtained from EN 14651 tests for E-VFRC (a); E-SCFRC (b); E-SCFRC-c (c).

It was found that the mean values for fiber orientation effects as specimens scaled up from flexural specimens to the full-scale vibrated FRC, SCC and FRSCC mix slabs were 0.64, 0.54, and 0.68 for slab specimens respectively. The authors recommended creating an orientation factor, designated K_o by Eurocode 2 (Annex L), as 0.60 for specimens, to correct results from small scale prism testing to slabs in the field, choosing this as a generic value irrespective of mix design or casting procedure (Guimil et al. 2022). In other words, small scale flexural specimens better align fibers to resist flexural behavior, versus a full-scale flexural specimen, which generally only presents ~60% of the small standard based specimen's measured capacity, which needs to be corrected for when correlating small scale fiber reinforced concrete testing to in-field applications.

Beyond simply using fiber to resist tension, Gennings (2018) examined the use of expansive CSA cements for chemical prestressing of concrete. Chemical prestressing is the principle of using expansive cements with fiber reinforced concrete or prestressing steel, to induce prestress. As the concrete expands and cures, tensile strains are imposed on the fibers or steel, creating additional prestress force within the element. He built on the work of Roswurm (2013) to show that internal restraint of expansion using steel fibers can be used to increase concrete capacity. In particular, he was examining the effect of differing fiber sizes and geometries, show in Figure 8, as well as the fraction of expansive cement on inducing chemical prestressing for field applications. Therefore, his work spanned three phases, testing different cement fractions of Type K cement ranging from 21-29%, characterizing the performance of different fiber types, and then

a comparison of the performance of a large scale chemically prestressed FRC slab to slabs without reinforcement and with conventional rebar reinforcing.

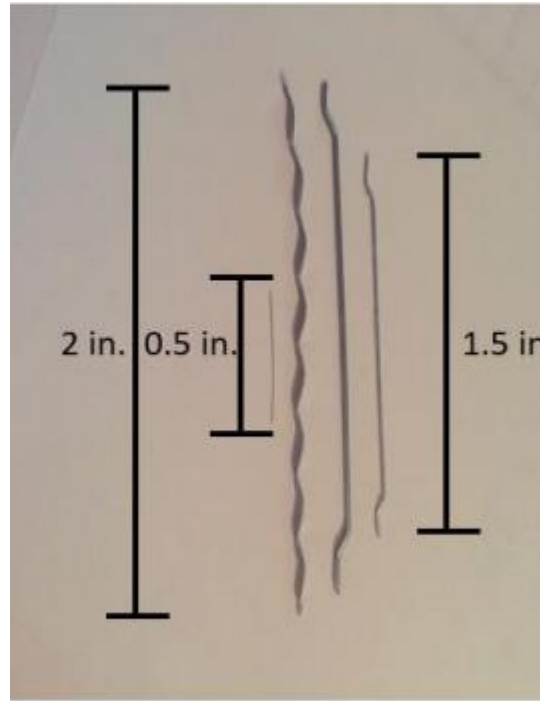


Figure 8: Four Fiber Types tested (left to right, Dramix, Novocon XR, CTS Proprietary, and Novocon 1050he) (Gennings 2018)

Gennings (2018) found that 25% Type K cement yields the minimum required expansion for chemically prestressing fibers in concrete and saw an average compressive strength increase of 1.7 ksi compared to specimens without fibers. He also noted that fiber shape affects chemical prestress capacity, with CTS Cement Manufacturing Corp. propriety fibers providing the greatest strength increase at 28-days (Figure 9) but noticeably less restraint (Figure 10). All the other fibers performing similarly in terms of provided restraint, though there was also notably higher strength provided by the Novocon XR fibers.

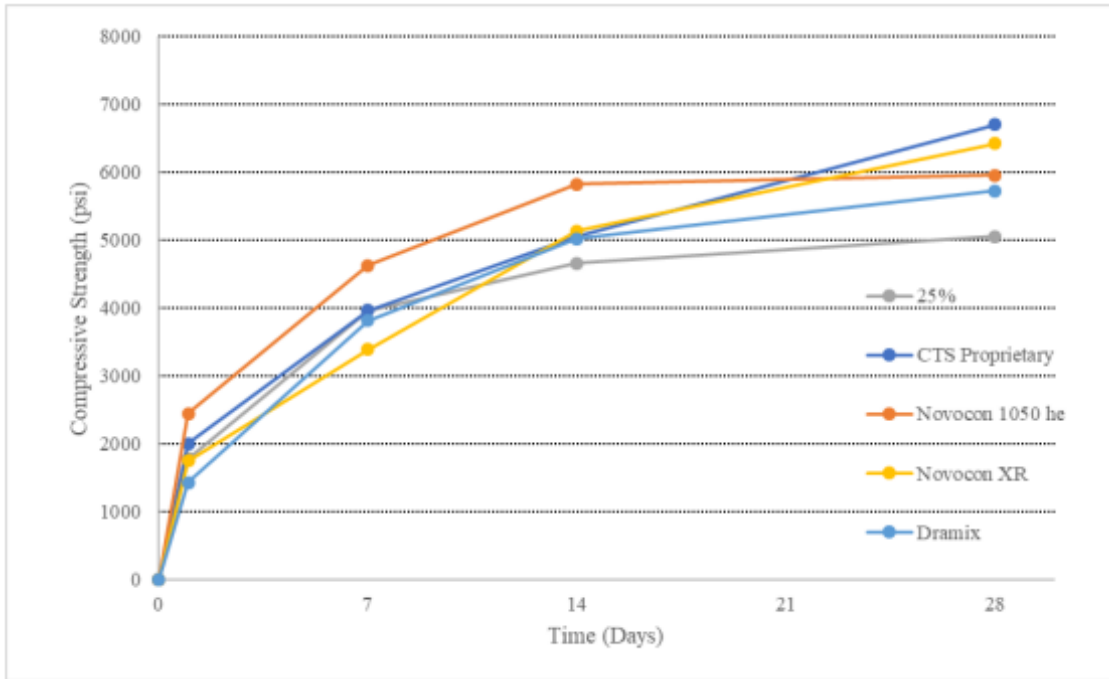


Figure 9: Compressive Strength of All Fiber Types and 25% Type K cement through 28-days (Gennings 2018)

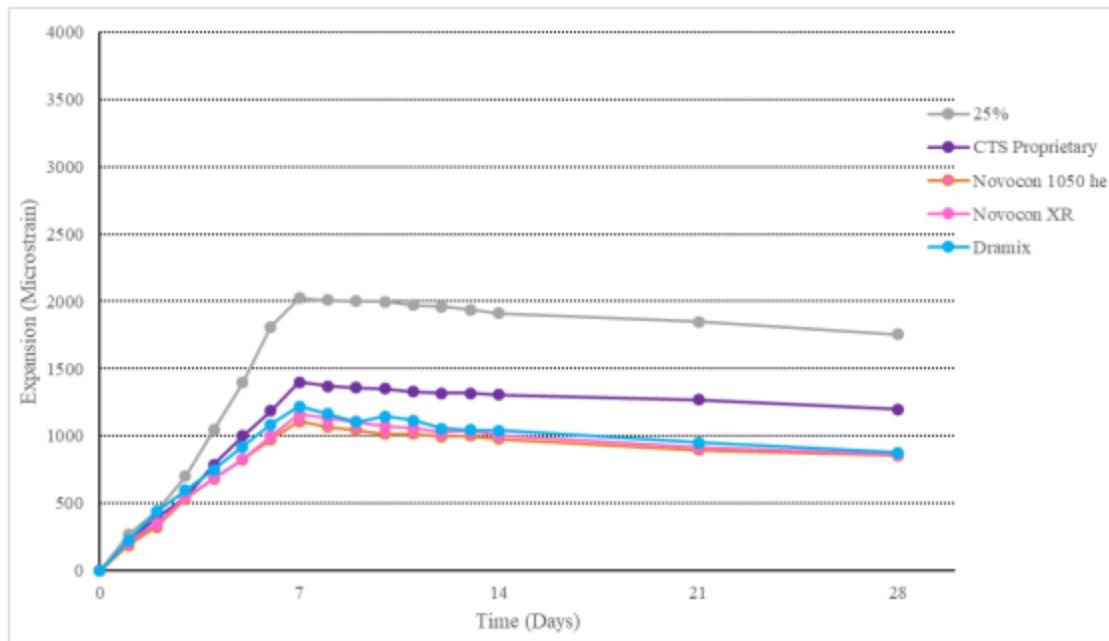


Figure 10: C878 Restrained Expansion of All Fiber Types and 25% Type K cement for 28 days (Gennings 2018)

Additionally, all fiber types except the Novocon 1050he saw at least a 30% increase in flexural capacity, as determined by ASTM C79 modulus of rupture testing, relative to

unreinforced specimens. In terms of large-scale testing however, conclusions were difficult to draw, as the exact amount of restraint placed on the slab and variable humidity affected expansion and shrinkage conditions. Finally, a crucial observation was that there is an inverse relationship between shrinkage compensation, which is dependent on expansion, and chemical prestress which develops by impeding expansion. This observation can be used to guide further research (Gennings 2018).

Wyrzykowski et al. (2018) conducted a mechanical assessment of concrete with a Type K CSA cement substitution ranging from 5-20%, finding that there was comparable mechanical performance to standard portland cement concrete even in the 20% Type K mix. The results of his restrained and unrestrained expansion tests are particularly noteworthy. Wyrzykowski et al. (2018) tested restrained specimens at two separate reinforcement ratios (2.3% and 0.9%) and found that while increasing restraint led to less expansion as expected, the net drying shrinkage and creep did not decrease with the addition of restraint. As a result, the authors inferred that expansion induced stresses are largely elastic, but shrinkage and creep are still plastic and will occur to approximately the same degree irrespective of restraint, as shown in Figure 11. Therefore, while it is expected that prestressing should lead to compressive creep from the restraint, and thus additional shortening, this is mitigated by stress relaxation, so the degree of expansion and restraint need to be balanced against one another. Additionally, the change in restraint due to increased restraint is highly nonlinear.

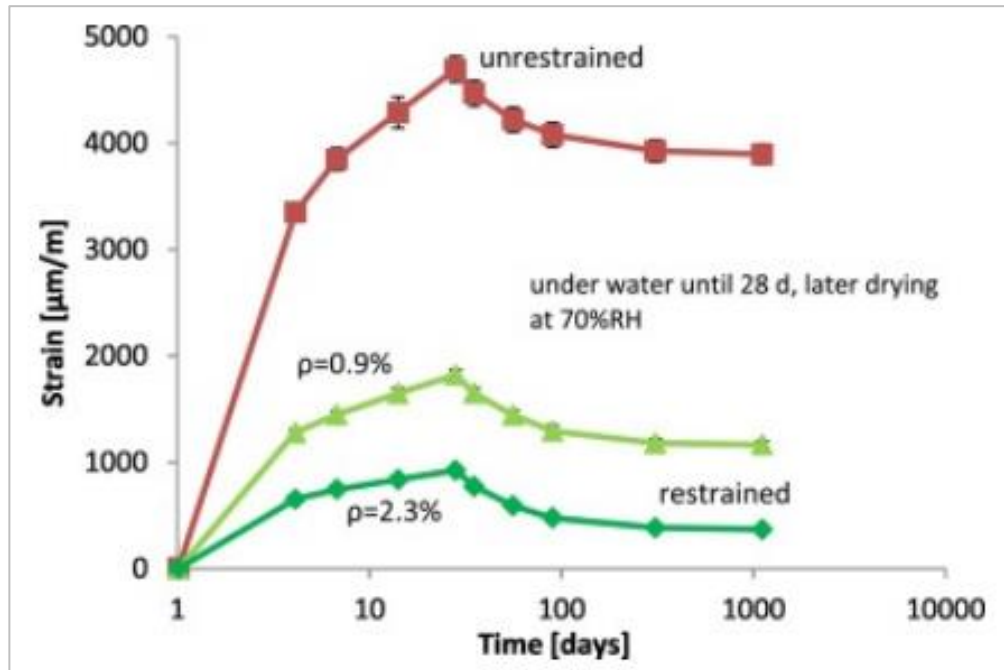


Figure 11: Effect of Expansion Restraint at Two Different Reinforcement Ratios Compared to Unrestrained Expansion (Wyrzykowski 2018)

Additionally, a major point of concern was that specimens that were rewetted after initial expansion showed cracking when allowed to dry again, which posed a potential risk to long term durability. Wyrzykowski (2018) observed that while such cracking was visible, measurements from broken flexural specimens showed that they were only surficial, extending less than 1mm into specimens. This was further validated by freeze-thaw testing, where even these lightly cracked 20% Type K specimens performed comparably to specimens without CSA cement.

3.0 Research Methods and Materials

The scope of this research project spanned three phases. Firstly, as record of characterizing expansive BCSA cements could not be found while conducting the literature review, a baseline mix design had to be established with reasonable strength and workability characteristics for field use at scale, which constituted an initial phase of mix development. Secondly, material characterization of key properties for longer term and overall performance had to be measured to assess the designed expansive BCSA mix, and a similar analysis was conducted for a Type K mix using mix proportions as closely resembling the expansive BCSA design mix as possible, while maintaining the desired field properties. Finally, these mixes were tested at scale, by casting a baseline portland cement post-tensioned slab section alongside slab sections using each of the two expansive cements to compare changes in prestress over time as well as the induced distresses in each slab over their service life.

3.1 Phase 1 – Mix Development

The first phase of this project was based on characterizing the chemical properties of a new proprietary expansive BCSA cement produced by CTS Cement Manufacturing Corp. to develop a mix that would enable high workability and with enough retardation to avoid flash setting, while still achieving early set time and strength for rapid post-tensioning in Phase 3 at 6 hours.

For this phase, the expansive BCSA cement was used to cast mortar cubes per ASTMs C109 and C1437, in the proportions of Table 5. Additionally, a set of non-expansive BCSA cubes were also mixed as a baseline for comparing fresh properties and strength

gain, which had been determined in depth from the prior work of Roswurm (2023). Originally, it was attempted to cast these expansive BCSA mortar cubes without retardation to perfectly follow the mortar test specifications. However, in the initial mixing, the baseline BCSA mortar just began to stiffen as the last of four sets of cubes were being cast, while the expansive BCSA cement began to stiffen while the mortar flow was still being taken and had a crumbly consistency by the end of filling the fourth set of cubes. As a result, only the first two specimens were cohesive enough for use in testing, while the last two sets were honeycombed excessively. Therefore, a second set of specimens was cast using the standard mortar mix with the addition of 0.25% citric acid by cement weight for retardation.

Table 5: ASTM C109 Standard Test Mortar Mix Proportions

Material	Number of Specimens		
	6	9	12
Cement, g	500	740	1060
Sand, g	1375	2035	2915
Water, ml			
Portland or portland-limestone cements	242	359	514
Air entraining portland or portland-limestone cements	230	340	488
Other Cements (to a flow of 110±5)	...	...	...

After establishing a baseline for cement reactivity and strength gain, a variation of the six sack concrete mix proportions from Roswurm (2018a) was used as a baseline mix for a ChemStress cement concrete, shown in Table 6. Roswurm (2018a) used this mix with a non-expansive BCSA cement, and the fresh property and compressive strength results from using expansive BCSA cement at a 1:1 substitution by weight were compared against to the original mix design, to establish admixture adjustments of high-range water reducer and citric acid dosages to achieve acceptable workability, air

content, set time and strength gain for use in later testing. Target properties are shown in Table 7.

Table 6: Expansive BCSA and Type K CSA Concrete Mix Designs

Material	Expansive BCSA		Type K CSA	
	Theoretical Weight (lb)	Volume (cf)	Theoretical Weight (lb)	Volume (cf)
Portland Cement	0.0	0.00	423.0	2.15
Expansive Belitic CSA Cement	564.0	3.03	0.0	0.00
Type K CSA Cement	0.0	0.00	141.0	0.78
Rock	1430.1	8.55	1430.1	8.55
Sand	1715.3	10.45	1715.3	10.45
Water (w/cm = 0.50)	282.0	4.52	282.0	4.52
Entrapped Air (2.0%)	0.0	0.54	0.0	0.54
Total:	3958.1	27.0	3958.1	27.0

Table 7: Target Belitic CSA Mix Design Properties

Mix Property:	Target:	Tolerance
Slump: (in.)	7"	1.5"
Natural Air Content: (%)	4%	2%
Set Time: (h)	6h	0.5h
Early Strength: (ksi)	2.5ksi	@6h
Full Strength: (ksi)	3ksi	

Of particular concern, the expansive BCSA cement was found to be highly sensitive to dosages of high range water reducer, even in comparison to other CSA cements and at low to moderate dosages (4-6 oz/cwt) of Glenium 7920 high range water reducing admixture. Significant air entrainment was found to occur, reaching as high as 12% in some trial mixes. Consequently, a shift to ADVACAST 575 high range water reducing admixture was made, which caused less air entrainment at moderate dosages.

Additionally, relative to the mix designs used by J. Roswurm (2018), the coarse-to-fine aggregate ratio was altered from 55% rock-45% sand to 45% rock-55% sand to reduce

the rapid slump loss and stacking of aggregate during slump testing during the early stages of ettringite formation. This resulted in a final mix design with half a sack smaller than the final concrete mix, developed by Bescher (2021) at 6 sacks, in part because it was originally derived retardation and non-expansive BCSA mix proportioning research of Roswurm (2018a), which was considered the most crucial concern at early stages of mix development. The w/cm ratio was also increased from 0.46 to 0.50, to increase working time and the coarse to fine aggregate ratio was swapped, increasing the aggregate to cementitious material ratio increased from 5.0 to 5.5.

These revisions based on trial mixes led to the final designs in Table 6, which was mixed according to the following procedure:

1. Mixer is wetted down and allowed to turn for 1 minute before being drained.
2. All of the citric acid is added to the mix water and stirred until it dissolves.
3. Rock and Sand are added to the mixer with half of the citric dosed mix water and allowed to turn for 1 minute or until aggregate has been completely soaked.
4. High range water reducing admixture is added to the remaining half of the batch water and stirred in.
5. The cement is added to the mixer with the saturated aggregates, followed by the remaining half of the batch water, poured over 1-2 minutes depending on the size of the pour.
6. The concrete is left to mix, approximately 4 minutes from the addition of cement for smaller batches, or 5-6 minutes for larger batches**

7. Concrete is removed from the mixer as needed with excess not currently being used left in the mixer to turn until the 1-hour mark, or under higher temperatures ($>85^{\circ}\text{F}$)/lower citric dosages ($<0.40\%$ by cwt), the concrete starts to stiffen.

Crucially within these procedures, the citric acid is added to the water prior to addition to the aggregates, so that any water that contacts cement has been dosed with citric acid; this is to prevent any flash set potential as faced by Roswurm (2023) in the first precast beam pour.

Additionally, at step 7, the mix is left in the mixer to improve working time, however it is removed no later than 1 hour after the start of mixing to prevent any premature hardening or buildup that might damage equipment, which is particularly risky at elevated temperatures or lowered dosages of retarder.

For the Type K expansive cement mixes, the same aggregate and water-cement ratio proportions were used, with a mix that had the same volume of cement at a ratio of 75% portland to 25% Type K CSA cement, and a reduction of citric acid to 0.30% by cement weight. These mixes were also mixed using approximately the same procedure, but with looser tolerances on mixing time as the mix did not exhibit rapid setting behavior.

However, to mitigate slump loss at higher temperatures in excess of 80°F , it was found that for Type K mixes, it was necessary to redose the mix with citric acid every 10-15 minutes to prevent excessive loss of workability. These procedures led to an expansive BCSA mix that could reach strength to be post-tensioned in 6-8h after casting, and a Type K mix that could be post-tensioned at $\sim 3\text{d}$.

3.2 Phase 2 – Mix Properties

3.2.1 Hardened Concrete Strength Properties

ASTM testing procedures C39, C78 and C469 were employed to determine the compressive strength, flexural strength, and modulus of elasticity for both the Type K and expansive BCSA mixes. While most properties were established with separate batches, including the C469 and C78 specimens, every mix had at minimum 4 sets of companion C39 cylinders cast and broken at set ages and any testing interval not falling at those testing ages, and at least 2 slump cone measurements taken, an initial reading prior to filling molds, and a reading at ~15 minutes after the initial reading. For the expansive BCSA mixes, a set of companion cylinders were broken at least at 6 hours, 1, 7 and 28 days, with additional breaks potentially done at 3, 10, or 14 days depending on the test, while the Type K mixes had cylinders broken at 3, 7, 10 and 28 days. These maintaining slump within 1 in. of target and compressive strengths within 5% at all ages through these two tests established a minimum baseline for mix reliability in comparing specimens.

After demolding all specimens were wet cured for a 7-day period, which is necessary for the cements to exhibit expansive behavior. These strength properties and baselines for consistency of mixing will aid in later calculations of capacity and losses as well as enable a more comprehensive comparison of these mix designs to a conventional portland cement mix, which by industry standard only has to achieve a full 28-day strength of 3 ksi and can be prestressed at 2.5 ksi. A more comprehensive list of testing done for each mix and the age at which tests were performed is shown in Table 8.

Table 8: Testing Matrix of Mixes with Curing and Loading Ages as Applicable.

Test	Mix Design		
	Expansive BCSA	Type K CSA	ODOT Class A (Reference)
Compressive Cylinders (C39)(ASTM, 2021a)	(6h, 1, 7, 28d)	(3, 7, 14, 28d)	(1,7,28d)
Modulus of Elasticity (C78)(ASTM, 2022)	(6h, 1, 7, 28d)	(3, 7, 14, 28d)	-
Modulus of Rupture (C469)(ASTM, 2014a)	(6h, 1, 7, 28d)	(3, 7, 14, 28d)	-
Unrestrained Expansion (C157) (ASTM, 2017a)	(Continuously Wet Cured, 7d Wet Cured)	(Continuously Wet Cured, 7d Wet Cured)	-
Restrained Expansion (C878)(ASTM, 2014b)	(Continuously Wet Cured)	(Continuously Wet Cured)	-
Creep Columns (based on C512)(ASTM, 2015)	(Loaded at 6h and 7d Wet Cured)	(Loaded at 3d then 7d Wet Cured)	-
Unrestrained Geokon VWSG Shrinkage Companions (with creep columns)	(7d Wet Cured)	(7d Wet Cured)	-
Set Time and Slump Loss Temperature Study (based on C1679, C1753) (ASTM, 2017b, 2021b)	(40-90°F in 10°F ranges; 0.2-0.75% citric dosages)	-	-
Wet Curing Study	Testing Wet Cured ages of 1, 3, 7, 10, 14, 28d	-	-
Post Tensioned Slab-on-Grade (Full-Scale)	(Tensioned at 6h, 7d Wet Cure)	(Tensioned at 3d, 7d Wet Cure)	(Tensioned at 3d, 7d Wet Cure)

The modulus of rupture testing was conducted on the 6 in. x 6 in. x 18 in. specimens under third point loading as shown in Figure 12. The specimens will be marked at the third points for alignment in the loading machine, with the intended failure mode being a rupture plane falling within the middle third and the cross-sectional width and depth of the failure will be measured with a 3-point average across each side of the failure surface to determine the effective cross-section for the rupture modulus load.



Figure 12: Modulus of Rupture Testing Set-up (left) and Failure Mode (right)

The modulus of elasticity will be measured using a Forney to log the time series data of stress and deformation of end-ground 4 in. x 8 in. compressive cylinders, based on linear variable differential transformer (LVDT) readings. The LVDT readings were taken using a ring frame mounted to compressive cylinders as they are loaded to 40% of their compressive strength, shown in Figure 13, as determined by a set of companion compressive strength cylinders loaded to failure.



Figure 13: Set-up for Modulus of Elasticity Testing (left) and Testing Frame (right)

3.2.2 Expansive Properties – Volumetric Expansion/Contraction (C157) and Restrained Expansion (C878)

To assess the expansive behavior of the expansive BCSA cement and Type K cement mixes, both restrained and unrestrained expansion tests were performed. This allowed for predicting later performance both for the creep columns, which had potential to develop additional load due to expansion, and for the full-scale slab design.

The curing conditions were established for both C878 and C157 specimens based on the known behavior of Type K cement, which only displays expansive behavior when subject to wet curing, and similarly observed behavior with expansive Belitic CSA cement during initial testing. A set of three C157 and C878 specimens were each wet cured in a covered water tank indefinitely, and a second set of three C157 specimens were only cured in water for the first 7 days, which were designated as the design wet curing period, with the specimens removed to ambient dry conditions for the remainder

of the testing duration. A picture of the covered and uncovered water tanks is shown in Figure 14.



Figure 14: Plastic Tank Storing Wet Curing C157 and C878 Specimens, with Plexiglas Sheet Used to Cover Tank Behind

Expansive BCSA specimens were initially measured at 6 hours, with further readings being taken at 9 and 12 hours after casting and then daily for the duration of the wet cure period, with weekly measurements taken indefinitely after the end of the wet cure. A similar procedure was utilized for the Type K specimens, with the adjustment that demolding occurred at 3 days, and after the specimens were measured for an initial

reading, only daily measurements were taken through the duration of the wet cure period. Irrespective of the cement, however, weekly readings were taken for the first 3 months after casting and conclusion of the wet cure and then monthly readings beyond 3 months, using the unrestrained and restrained comparator gauges shown in Figure 15.



Figure 15: Comparators for Restrained (left) C878 and Unrestrained (right) C157 Shrinkage Testing

3.2.3 Creep and Shrinkage Behavior

For creep and shrinkage, a set of 6 in. x 12 in. cylinder specimens were instrumented with Geokon® Vibrating Wire Strain Gauges (VWSGs). The VWSGs were centered in five specimen molds, shown in Figure 16.

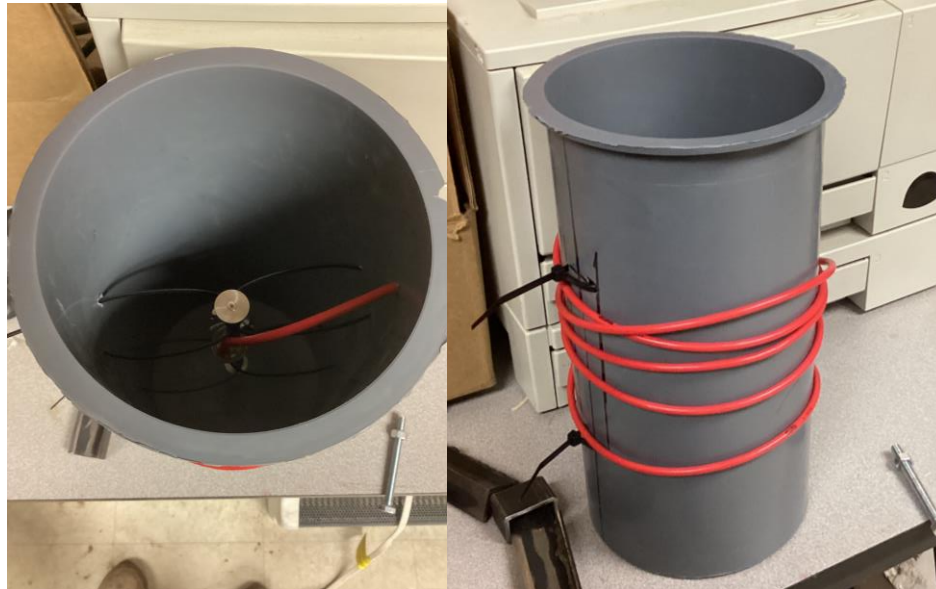


Figure 16: 6" x 12" Cylinder Mold with Suspended VWSG used for creep and Shrinkage Testing

The cylinders were then cast with expansive BCSA or Type K cement concrete, then after demolding, three of the specimens were stacked concentrically in a frame and loaded to 40.5 kips (1.432ksi) for the Type K mix and 62.8 kips (2.221ksi) for the expansive BCSA mix. The selected loads were based on the PTI compressive stress limit of 60% of the equivalent concrete strength for the respective mix at time of loading to measure the creep behavior of the respective mixes when loaded to the maximum allowable stress. The ends of the remaining 2 specimens for each mix were covered to ensure the same volume to exposed surface area as the creep specimens, then allowed to freely expand and shrink without load to correct the total creep

measurements for free expansion or shrinkage of the cylinders while under load.

Additionally, these remaining two shrinkage specimens provide a validating baseline for the free expansion measurements provided by ASTM C157, which can realistically be measured on a consistent basis no more frequently than once a day, whereas VWSGs can provide readings as frequently as 5-minute intervals over the duration of the testing. All specimens were wet cured for 7 days beginning at the time load was applied.

Unlike the work done by Roswurm (2013) and Roswurm (2018b), wet curing under a design load, and not just restraint, was desired to measure expansion behavior while restrained for creep to simulate rapid progression of construction and use after the slab sets. A stack of three 6 in. x 12 in. cylinders and load frames based on ASTM C512, using spring loaded bases shown in Figure 17a-c was used as opposed to the solid plate and rod frames used in these prior works. Also, because the creep frames were being used to monitor creep and expansion under load and wet curing, modifications to the creep frame were made to add a PVC standpipe that could be used for wet curing the specimens and then stripped at the conclusion of the wet cure. Additionally, to ensure a watertight seal the tube had to be mounted and sealed in advance, therefore specimens had to be lowered into the tube prior to loading which created challenges with effectively centering specimens. An aluminum ring was also silicone to the spring-loaded base for centering the first cylinder and the cylinders were stacked using a ratchet strap to lower each cylinder on top of one another. While there was some loss of precision in placing the upper two cylinders, this method ensured a watertight seal at the base and placement of the cylinders with minimal introduction of trauma from alternatives like dropping them in place.

Because creep and expansion would occur under an imposed load, cylinders could only be loaded into the frames once final set occurred and sufficient strength was achieved. For this project, at least 2.5 ksi was defined as the target with an effective cross section prestress of 100 psi. This is just under threshold to post-tension conventional concrete based on ACI compressive strength requirements for slabs standard practice which target 3ksi strength at time of tensioning for a 125-300 psi effective cross-section prestress (ACI 318, Trygestad 2005). Therefore, loading was conducted at roughly 3 days and 6 hours for the Type K and expansive BCSA mix, respectively.



Figure 17a-c: (a) Unloaded Creep Frame with Spring Loaded Base and Centering Ring, (b) Creep Frame with PVC Standpipe in Place, (c) Loaded Creep Column after Draining and Removal of PVC Standpipe.

Consequently, the 7d wet cure for the Type K mix did not begin until 3 days after casting, which may affect the overall expansion behavior. Additionally, the setup for creep testing was modified so that the frames would not corrode due to the wet cure. Specimens were prepared by splitting the standard 6 in. x 12 in. cylinder molds after set and removing them carefully so as to not damage the VWSG wires and grinding the ends plane in preparation for loading. Wet curing was accomplished by placing the cylinders into the creep frame surrounded by an 8 in. diameter PVC standpipe form that was split for removal and sealed back together with and mounted to the base with silicone and hose clamps for a nearly watertight seal during the curing process. The columns were loaded using a hydraulic jack mounted above, with a load cell and secondary plate placed below to monitor stress at early age, and the standpipes were filled with water so that the specimens could be subject to a 7-day wet cure and expand under loaded conditions. After 7 days of wet curing under load, the standpipes were drained, stripped off of the columns and the columns were left to experience creep losses. A set of 2 additional specimens as shown in Figure 18 were cast and wet cured following the same process, but not loaded to factor shrinkage out of the column data. These specimens had their ends capped with wood boards to retain the same exposed V/S ratio as the columns for a 1:1 comparison. This same procedure was repeated for the Type K specimens, the only exception being the timing at which loading and wet cure began was 3 days rather than 6 hours.



Figure 18: Companion Shrinkage Specimens

3.2.4 Temperature Effects on Workability and Set Time

In order to characterize concrete behavior and required modifications due to variation in temperature, an assessment of mix workability and set times with varying citric acid dosages at 6 different temperature ranges—90, 80, 70, 60, 50, $40\pm 3^{\circ}\text{F}$ —will be conducted for expansive BCSA cement. This was considered necessary for feasible usage of expansive BCSA cement due to difficulties observed during testing, where both setting time and working time varied significantly depending on ambient conditions. For this testing, a small 1.2 cubic foot batch was mixed at each temperature interval with the citric dose varying from 0.20% to 0.60% citric acid, in increments of 0.10%, as well as 0.75% citric, the highest dose considered reasonable. The citric acid dosage was based on percentage of total cementitious material weight, while all other mix criteria were held constant. While the targeted slump was 7.5 ± 1.5 inches, the

dosing of water reducing admixture was held constant even if the slump did not reach the targeted range, which occurred for a handful of the extremely high 90°F mixes. For these small batches, a slump cone was taken just after mixing, followed by a reading approximately every 15 minutes after that point. Additionally, to establish setting time, the aggregate was sieved in accordance with ASTM 403 to fill a 4 in. x 8 in. cylinder for use in set time establishment by a Calmetrix I-4000 series isothermal calorimeter, shown in Figure 19. A series of penetrometer measurements of set time for the 80°F increment of measurements was also conducted to correlate the calorimeter results to a more widely established method.



Figure 19: I-4000 Series Calorimeter used for Data Collection

Finally, a general mix naming convention was established 1 or 2 leading letters, denoting the type of cement used, either K for Type K cement or CS for expansive BCSA followed by 2 numbers denoting the citric acid dosage in 100th of a percentage of cement weight and 2 numbers denoting HRWR dosage in oz/yd. For temperature study mixes this was followed by a dash and ambient temperature range of mixing, as shown in Figure 20

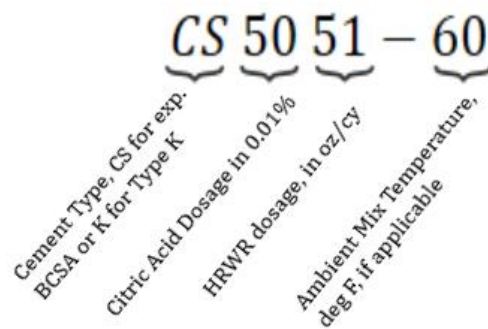


Figure 20: Mix Designation Naming Convention

3.3 Phase 3 – Large Scale Testing

For large scale testing, 5 in. thick, 10.5 ft square slab-on-ground specimens, post-tensioned in both directions at the start of the water curing period, will be cast with each of the non-fiber reinforced mixes for Type K CSA and expansive BCSA. These dimensions were chosen because 5 ft is approximately the minimum distance of moisture variation from the edge to interior of a slab on ground, according to Post-Tensioning Institute (PTI) standard DC10.1-08, and a reasonable approximation for lightly to medium expansive soils. An extra 0.5 ft was added for clear and full moisture development, and 5 in. depth determined based on a stress analysis using the PTI empirical slab equations that ensure uncracked behavior. The design concrete stress was

a 100-psi equivalent stress across the slab section, requiring a post-tensioning force of 63 kips evenly split between three Gr. 270- 1/2-inch strands, and a set of #4 backer bars placed above and below the strand to control against bursting stresses in the local zones of each anchorage, in accordance with ACI 25.9.4.4.6 for detailing of post-tensioned anchorage reinforcing. These backer bars were cut as single 9.5-foot bars to extend 6 inches beyond the edges of the anchors of the extreme strands in each direction, while the strands were left with an additional 1.5 feet overhanging beyond the slab for subsequent post tensioning. Use of the PTI equations yielded the slab design shown in Figure 21, with strands denoted by the thick dashed lines and #4 backer bars marked by the thinner dashed lines. (PTI 2008)

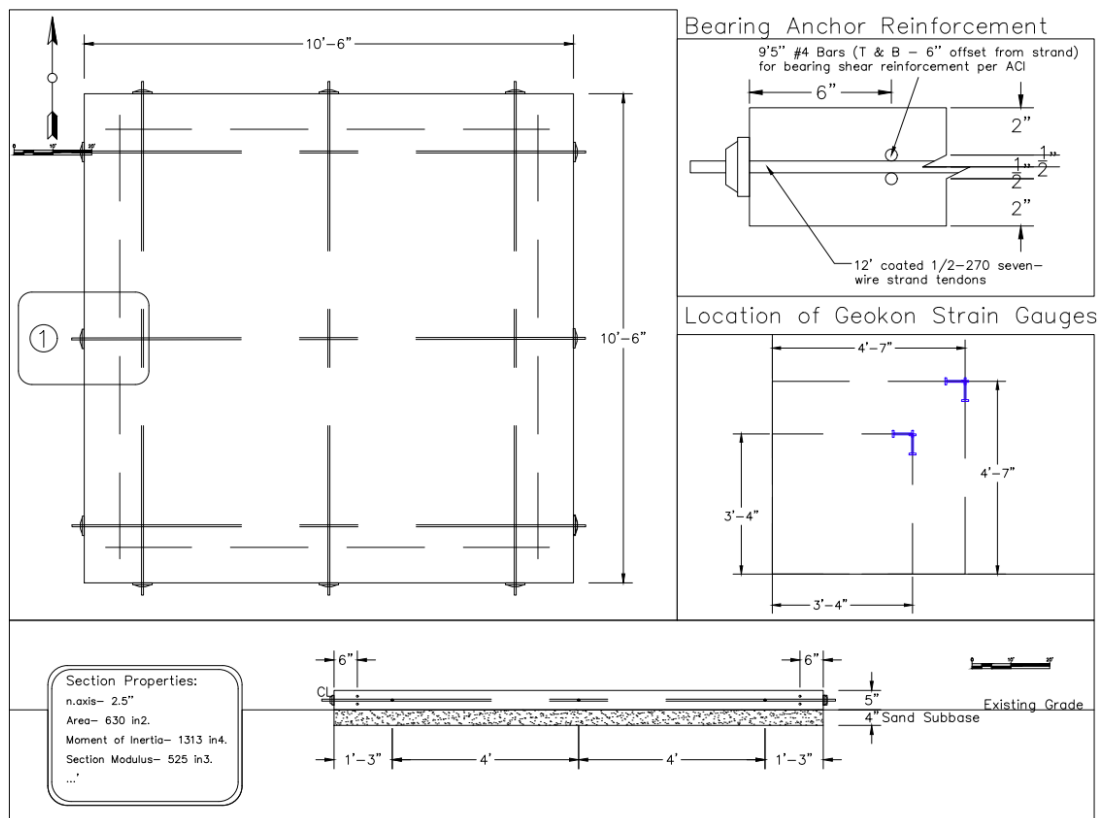


Figure 21: Plan and Profile for Full-Scale Slab Design

In addition to the type K and expansive BCSA slabs, a standard reinforced concrete mix was used for a third control specimen to benchmark the difference in prestress losses between the expansive slabs and a standard slab construction. Two VSWGs were placed within each slab oriented in each direction at 55 inches, approximately just within the predicted edge moisture variation zone where moment demand should level out, and two more were placed at the β -distance of 40 inches, where according to PTI, the maximum moment demand occurs in slab on grade construction. These gauges were intended to measure the strain changes due to creep and shrinkage over time. The gauges in each pair were zip-tied to a tree of rebar and set perpendicular to each other at the midline of the slab's depth as shown in Figure 22.



Figure 22: Rebar Tree used to Place and Mount VSWG Gauges Instrumenting the Slabs

The VWSG measurements were used to assess to what extent the expansive behavior of the concrete during the water curing period offsets shrinkage and potentially chemically prestresses the concrete to mitigate prestress losses. The site for each slab was first leveled to 9 inches below final grade (-9") as staked out by a transit. And then embankments were built around the slab edges back up to an elevation 5" below final grade (-5"), the final depth of the bottom of the slab as shown in Figure 23.



Figure 23: Site Graded to -9" with Embankments Around the Edges Added to -5"

The area inside the embankments was filled with #67 coarse aggregate to provide a 4" base below the slab and compacted to the -5" grade for each slab as show in Figures 24-26. A vapor barrier was placed down on this aggregate base to reduce friction losses and moisture infiltration, and the wooden 2x6 forms were set around the edges of the

subgrade. The forms, which fastened to the anchors, were then used to pull to unbonded strand taut during casting, and the slabs were poured and screeded.



Figure 24: Compaction of the #67 Coarse Aggregate Base



Figure 25: Final Compacted Site Material



Figure 26: Final Site Preparation with Formwork and Vapor Barrier Laid Out.

For the conventional concrete and 25% Type K concrete slabs the strands were planned to be post-tensioned at 3d after casting as that was the approximate period for full set and sufficient strength gain of the concrete, while the expansive BCSA concrete was planned for post-tensioning on the same day, approximately 6-8h after casting, as trial batches and small-scale testing showed sufficient strength at approximately the point offset.

To avoid potential cracking due to overstressing in one direction before stressing in the other, or creating excessive moment about one corner the slabs were stressed in order according to the numbers in Figure 27.

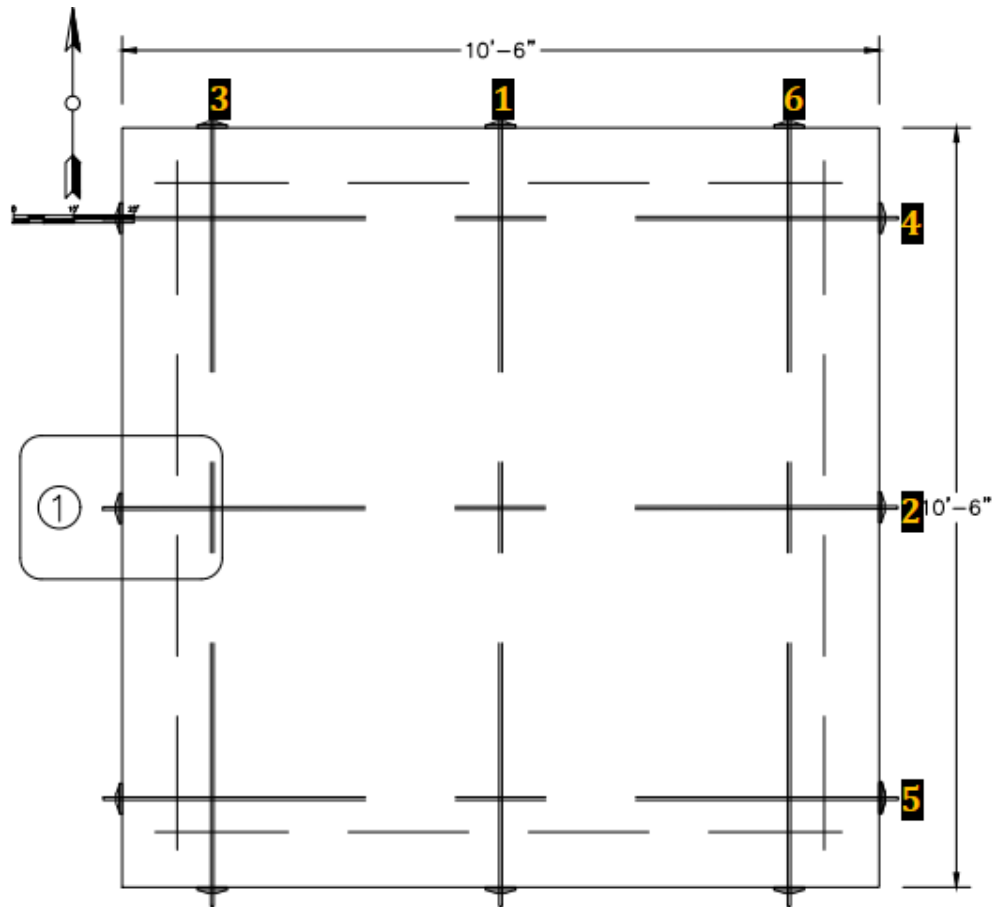


Figure 27: Strand Prestressing Order for Full Scale Slabs

Moreover, to monitor prestress losses in the strands more directly during the wet curing and early stages of each slab drying, the middle strand in each direction was fitted with a double anchorage, shown in Figure 28, so that a load cell could be connected. The original intent was to be able to torch cut the strand between the load cell bearing plate and the primary anchor, circled in red, which would result in additional anchor seating losses, but safely transfer stress without the need for additional jacking of the strand.



1. Secondary Anchor
2. Guide Plate for bearing on load cell
3. Load cell
4. Bearing Plate for load transfer from load cell to primary anchor
5. Primary Anchorage

Figure 28: Double Anchor and Guide Plate for Loading/Unloading Strand with a Load Cell.

However, the short length of the slab made the anchor seating losses excessive, and it was deemed unreasonable to incur additional such losses with this method. Therefore, a jacking frame, shown in Figure 29, was constructed to go around the double anchorage to allow for unloading of the strand to remove the load cells. Once the load cell was removed, the strands were re-tensioned using the same methods as for the other strands.



Figure 29: Post-Tensioning Jack Bearing Against Unloading Frame Used to Remove Load Cell

For all other anchors and reloading of strands initially double anchored after load cell removal, post-tensioning was conducted normally by bearing directly against the anchorage as in Figure 30, with a target load of 21 kips per strand that was over tensioned to 23 kips, to compensate for immediate losses. This 2-kip overage was considered the maximum to safely over-tension at early age without cracking the concrete, but was still insufficient due to short lengths of the slab even using a jack with power seating of anchors to reduce seating loss.



Figure 30: Post-Tensioning of Standard Single Anchorages

After post-tensioning, the slabs were immediately covered with wet burlap and a sheet of plastic to retain moisture for wet curing. For the reference slab, burlap was left on for the duration of the wet curing period, however, as CSA cements gain strength faster than their conventional portland cement counterparts, and a major goal of this study was achieving early strength for more rapid post tensioning and service usage, this wet burlap was replaced within a day by a ~1'' bed of wet sand though it was still covered by the plastic. This wet sand was used to both better store and retain moisture during the wet curing period, as well as to simulate the design dead load expected for the slab on grade.

At the end of the wet curing period, the CSA slabs were uncovered so that the sand could dry out. While it was considered that this might extend the wet curing beyond the

design 7d period, the decision was made to allow the sand to dry naturally, because slabs on grade will be exposed to weather generally during field construction, and the weather forecast predicted rain the day after the end of the wet curing period anyway. Moreover, the exposed bed of sand drying and wetting based on ambient conditions could also simulate variable live loading of the slabs. For consistency, the reference slab was considered to be put into service with an equivalent 1” bed of sand, at field moisture conditions applied 14 days after the end of curing. Table 9 generally lists both the intended and actual timeline for each slab, which changed for some actions based on environmental conditions and strength gain.

Table 9: Intended and Actual Timeline for Slab Curing after Casting

Event	Reference Slab		Expansive BCSA		25% Type K CSA	
	Intended	Actual	Intended	Actual	Intended	Actual
Slab Demolded	2d	2d	6h	7h	2d	3d
Slab Post-Tensioned	3d	7d	6-8h	20h	3d	3d
Wet Burlap Applied	3d	7d	6-8h	20h	3d	3d
Sand Applied	14d	14d	1d	2d	14d	14d
Slab Uncovered to dry cure	11d	14d	7d	8d	11d	11d
Load Cells Removed	18d	21d	14d	14d	18d	18d

4.0 Results and Analysis

The scope of this research project spans three phases. Firstly, as record of characterizing expansive BCSA cements could not be found while conducting the literature review, a baseline mix design had to be established with reasonable strength and workability characteristics for field use at scale, which constituted an initial phase of mix development. Secondly, material characterization of key properties for longer term and overall performance had to be measured to assess the designed expansive BCSA mix,

and a similar analysis was conducted for a Type K mix using mix proportions as closely resembling the expansive BCSA design mix as possible, while maintaining the desired strength and workability. Finally, these mixes were tested at scale, by casting a baseline portland cement post-tensioned slab alongside slabs using each of the two expansive cements to compare changes in prestress over time as well as the induced distresses in each slab over their service life.

4.1 Phase 1 – Mix Development

Based on the work of Roswurm (2023) characterizing non-expansive BCSA cements and retardation requirements, mortar cubes were cast in accordance with ASTMs C109 and C1437 (See Table 8) to approximate the variation in reactivity for the expansive BCSA cement from its non-BCSA counterpart, with the results shown in Table 10 and Figure 31.

Table 10: Average Compressive Strength of 3 Mortar Cubes for Non-expansive and Expansive BCSA Cements

Test Age	Non-expansive BCSA cement	Expansive BCSA cement
3h	2160	3050
6h	3500	3450
1d	4830	4320
9d	6070	8840
28d	-	9000



Figure 31: Series of Expansive BCSA Mortar Cubes Dosed with 0.2% Citric and Tested at 9 Days

Based on these results, the reactivity of the cement was confirmed, as it hydrated more aggressively than the non-expansive BSCA but was still affected by dosing with citric acid retarder. The series 1 trial mixes were then compared using the 6.5 sack BCSA mix from Roswurm (2018a) as a baseline and adjusting the admixture dosages to achieve the desired properties of the mix as discussed in Table 7. A problem that was encountered was that BASF MasterGlenium 7920 HRWR admixture was also found to behave as an air entraining admixture with the expansive BCSA cement. Even at low dosages of 4-5oz/cwt, air contents of 6-7% were measured while at higher dosages of 9oz/cwt air contents spiked to as high as 11.5% air. Consequently, the HRWR admixture was changed to GCP Applied Technologies ADVACAST 575, which showed some air entraining at high dosages in excess of ~15oz/cwt but was relatively stable below this point. Additionally, a particularly concerning result of the mix was the rapid slump loss that occurred, even at more moderate temperatures in the upper 60°F and low 70°F ranges, where 3 inches of slump could be lost in 10-15 minutes, (12in./h), which would yield working times of only 30-45 minutes for larger scale pours. The series 1 trial mixes and properties are listed in Tables 11 and 12, using the baseline mix in Table 6

and making the stepwise adjustments of citric acid, HRWR, and water cement (w/c) ratio.

Table 11: Expansive BCSA Series 1 Trial Mix Matrix with Varied Properties and Rationale

Mix	w/c	Citric Dosage	High Range Water Reducer			Notes
			Admixture	oz/cy	oz/cwt	
#1	0.47	0.50%	Glenium 7920	35	6.2	Baseline, using Roswurm (2018a)
#2	0.47	0.30%	Glenium 7920	30	5.3	Reduce HRWR for lower slump
#3	0.47	0.20%	Glenium 7920	25	4.4	Reduce citric and HRWR
#4	0.47	0.20%	ADVACAST 575	25	4.4	Change HRWR

Table 12: Properties of Expansive BCSA Series 1 Trial Mixes

Mix	Compressive Strength (psi)						Slump		Air Temp (°F)	RH (%)	Conc. Temp (°F)	% Air
	3h	6h	1d	3d	7d	28d	Initial	15 min.				
#1	2510	2530	4300	5890	6390	8310	16*		51.3	55	53	11
#2	-	2090	2950	4030	4500	-	9		71.2	45	59.5	10.5
#3	2510	2540	4300	5890	6390	-	6.5		-	97	63.6	6.0
#4	3260	3740	4030	6500	7670	9490	3.5		79.5	80	73.6	2.9
MOR	3000	-	5260	-	8070	9120	6	3	79.2	70	73.5	2.9
MOE	-		5770	-			2	0	89.2	50	81.3	3.3
EXP1	3590	-	6100	-	-	10110	4		75.4	85	67.2	3.4
EXP2	3520	-	3770	-	7290	8690	3.5	1.5	85.8	59	73	4.4

The initial mix was based on the research of Roswurm (2018a), swapping the non-expansive BCSA used for the expansive BCSA of interest in this research.

Problematically, the mix both achieved SCC conditions, registering a 16-inch average spread flow on a conventional slump cone, and excessively high air content of 11%.

The next mixes, #2 and #3, lowered the citric and HRWR admixtures to bring slump to a non-self-consolidating state and reduce the air entrained in the mix, however even at less than 4.5oz/cwt, the mix showed an air content as high as 6%. Mix #4 swapped the Glenium 7920 HRWR admixture for an alternative, ADVACAST 575, but in the same

dosage, which resolved the air entrainment properties. This shows that Glenium 7920 acts as an auxiliary air entraining admixture with this expansive BCSA chemistry.

At this point, mix design #4 was used to establish material properties in 4 subsequent batches, casting specimens in mixes modulus of rupture, modulus of elasticity and two sets of expansion/shrinkage prisms. A problem was noticed; the mixes could not maintain slump effectively, and this increased with increasing temperature. The original mix development was conducted in the spring, and by the time these property mixes were poured, daily ambient temperatures had risen significantly, reaching as much as 10°F hotter than the trial batches even during early mornings. Therefore, this mix was considered infeasible for practical use in the field. A secondary series of trial mixes (Series 2), listed in Table 13, with properties in Tables 14 and 15, were developed to achieve more reasonable slump loss targets.

Table 13: Expansive BSCA Series 2 Trial Mix Matrix with Varied Properties and Rationale

Mix	w/c	Citric Dosage	High Range Water Reducer			Notes
			Admixture	oz/cy	oz/cwt	
#5	0.47	0.20%	ADVACAST 575	25	4.4	
#6	0.47	0.30%	ADVACAST 575	35	6.2	Increase citric to 0.30%
#7	0.47	0.50%	ADVACAST 575	35	6.2	Increase citric to 0.50%
#8	0.47	0.50%	ADVACAST 575	35	6.2	Replace #67 with Rounded River Rock
#9	0.47	0.75%	ADVACAST 575	35	6.2	Increase citric dosage to 0.75%
#10	0.47	0.75%	ADVACAST 575	35	6.2	Try 3:7 coarse to fine aggregate proportions
#11	0.47	0.75%	ADVACAST 575	35	6.2	Try 4:6 coarse to fine aggregate proportion
#12	0.47	0.75%	ADVACAST 575	35	6.2	Repeat #12 replacing #67 with $\frac{5}{8}$ nominal limestone aggregate
#13	0.47	0.75%	ADVACAST 575	95	16.8	Increase ADVACAST 575 dose to 95 oz/cy
#14	0.47	0.75%	ADVACAST 575	100	17.7	Increase ADVACAST 575 dose to 100 oz/cy
#15	0.52	0.75%	ADVACAST 575	51	9.0	Increase w/c ratio to 0.52 and ADVACAST 575 to 51 oz/cy
#16	0.5	1.00%	ADVACAST 575	51	9.0	Repeat #15 increasing citric acid to 1.0% citric per cement weight
#17	0.5	0.75%	ADVACAST 575	51	9.0	Lower w/c to 0.50.

Mixes #5, #6 and #7 focused on adjusting citric acid to increase working time, which was found to have minimal impact on the slump loss rate. Mixes #8-#12 focused on adjusting aggregate proportions and types to create a more flowable gradation and paste matrix, however, this too had limited impact. Mixes #13-#16 adjusted the w/c ratio and HRWR dosage to produce better flowability and reduce slump in the mix and was by far the most effective method tested. Increasing the HRWR dosage was among the last methods considered due to concerns about potentially triggering air entrainment or a significant jump in flow and segregation potential through these methods, because of how the Glenium 7920 behaved at low dosages. However, this did not appear to be a problem. Both increasing the w/c ratio and HRWR dosage were extremely effective at increasing workability, with increased w/c ratio slightly outperforming the increase in

admixture dosage. This may be attributable to the relatively modest dosage increase, relative to w/c ratio increase. Regardless of the method, the absolute rate of slump loss did not change significantly with approximately 3-4 in./hour, holding as a lower bound, and a significant increase in slump loss rate was consistently observed at the 60–75-minute mark. Consequently, a higher initial slump is necessary to extend workability even at reasonably high w/c ratios or HRWR dosages. The only exception was mix #14 which ran a 0.55 w/c ratio to keep paste workability, however this was deemed excessively high for field usage. Because strengths significantly exceeded ACI code minimums of 3-4ksi for slab and post-tensioned concrete, w/c ratio increase was the preferred method of increasing working time, within limits, as 0.50 is a common upper bound of DOTs, including ODOT for w/c ratio in structural concrete (ODOT 2019). The final result, mix #17, therefore balanced the improvements of mixes #15 and #16, raising the w/c ratio to 0.50—the highest considered reasonable for field concrete applications—using a HRWR dosage of 51 oz/cy, equivalent to 9 oz/cwt in the mix, to achieve the required workability. Similar to Series 1 material properties 4 subsequent mixes were used for property testing of Mix #17 after selecting it, labelled MOE, MOR, EXP, and Creep, with their respective strengths, fresh properties and ambient casting conditions listed as well.

Table 14: Compressive Strengths of Expansive BCSA Series 2 Trial Mixes

Mix	Compressive Strength (psi)					
	3h	6h	1d	3d	7d	28d
#5	3250	-	5730	-	7930	10830
#6	-	3200	5480	-	7290	9050
#7	-	3520	5590	-	7690	8920
#8	-	3370	4950	-	6980	8820
#9	-	3530	4500	-	6350	9500
#10	-	-	3670	-	-	-
#11	-	2900	3690	-	6650	9430
#12	-	2870	3700	-	6790	8880
#13	-	2860	3540	-	6500	10720
#14	-	-	3120	-	6560	-
#15	-	2790	4140	-	6620	8420
#16	-	3390	4010	-	7400	9060
#17						
MOE	-	3430	5320	7200	8140	13060
MOR	-	3060	3570	-	9070	13560
EXP	-	3550	5130	-	10650	13730
Creep	-	3740	5140	-	10070	14270

Table 15: Slump and Environmental Conditions of Expansive BCSA Series 2 Trial Mixes

Mix	Slump (in.)						Air Temp.	RH	Conc. Temp	% Air
	Initial	15 min	30 min	45 min	60 min	75 min				
#5	6.25	3.5	1.5	0.5			83.4	40	76.4	2.5%
#6	6	2	1.5				83	-	76.2	-
#7	7	3	1.25	1			79.5	65	74.3	-
#8	7	4	2	1.25			82	57	78.2	-
#9	5.75	3.75	1.5	0.5			78.4	56	73.5	-
#10	1.5						85.6	46	74.4	-
#11	7	5.5	4	3.25	2	1.25	85	50	76.2	-
#12	4	2.5					89.1	49	78.2	-
#13	8.5	8	7.75	7.25	6.5	3.5	82	72	79.5	-
#14	9.5		9		8		95	-	89	-
#15	9.25	8.5	8.5	6.75	3.5	2.5	87.3	41	81.1	-
#16	6.5	6.5	5.5	2.5	1.25		81.5	63	77	3.0%
#17	-	-	-	-	-	-				-
MOE	7.5	6.5	-	-	-	-	93	-	-	2.7%
MOR	8	6.5	-	-	-	-	90.9	48	83.1	-
EXP	7	-	-	-	-	-	87.8	35	74.6	-
Creep	7.5	-	-	-	-	-	78.4	82	-	-

A similar mixing study was conducted for the 25% type K mix design, however this had the added objective of attempting to keep the mix as close as possible to the design of mix #17 used for the subsequent expansive BCSA testing. Consequently, other than substituting the expansive BCSA cement for a 25% Type K-75% portland cement blend by volume, admixture dosages were the only change from the baseline mix in Table 6. As with the Expansive BCSA Series 2 Trials, mixes and adjustments are listed in Table 16, while properties are in Tables 17 and 18, with the properties of the 3 subsequent mixes used to cast MOE and expansion/shrinkage specimens, MOR specimens, and creep columns listed below the original trial mix.

Table 16: 25% Type K Trial Mix Matrix with Varied Properties and Rationale

Mix	w/c	Citric Dosage	High Range Water Reducer			Notes
			Admixture	oz/cy	oz/cwt	
#18	0.5	0.75%	ADVACAST 575	51	9.0	Baseline, using #17 with Type K
#19	0.5	0.30%	ADVACAST 575	51	9.0	Reduced citric acid dosage, with periodic redosing to maintain workability
#20	0.5	0.50%	ADVACAST 575	51	9.0	Periodic redosing, with higher citric content to see effect on working time.

Table 17: Compressive Strengths of 25% Type K Trial Mixes

Mix	Compressive Strength (psi)				
	6h	1d	3d	7d	28d
#18	2630	-	-	-	-
#19	1840	-	3930	-	-
	-	-	-	-	5530
	-	-	3540	5130	7170
	-	-	2390	-	-
#20	-	-	-	3400	-

Table 18: Slump and Environmental Conditions of 25% Type K Trial Mixes

Mix	Slump (in.)						Air Temp.	RH	Conc. Temp	% Air
	Initial	15 min	30 min	45 min	60 min	75 min				
#18	7.5	4	1.5	0.75			86.2	50	79.3	-
#19	8	7	6.25	5.5	2	1	82.2	52	78.9	-
MOE/EXP	9	9	8.5	-	-	-	101.8	32	90	1.6%
MOR	8.5	7.5	-	-	-	-	98.4	50	85	2.6%
Creep	7	-	-	-	-	-	83.8	62	82.7	3.0%
#20	8	6.5	3	2			84.2	52	78.8	2.3%

For the Type K mixes, a lower citric acid dosage could be considered as the cement does not exhibit rapid setting behavior. It was found that mixes show better working time however, with a lowered initial dosage of citric acid and periodic redosing of the mix, rather than adding all of the citric acid retarder at the beginning. While such a modification may not be necessary for smaller batches, it is an important consideration for large mix volumes. Finally, mix #20 was discarded in favor of mix #19 because the high dosage combined with periodic redosing of mix #20 led to not only an extension of time to set and initial strength, but a permanently reduced strength,

In adjusting the w/c ratio up from 0.47 to 0.50, these mixes changed the coarse to fine aggregate ratio from 55%/45% by volume to 45%/55%, as some stacking of aggregate was still observed in slump cone measurements. Despite these changes, expansive BCSA still exhibits higher slump loss than conventional concrete. Even at low temperatures, and citric dosages as high as 0.75%—the highest dosage considered reasonable—these cement concretes exhibited a slump loss rate of ~2in/h. This was only achieved at temperatures below 80°F, however; for mixes above 80°F slump loss was 5-6in/h, and >8in/h above 90°F. The only case in which lower slump loss rates than

these were observed was for w/c ratios exceeding 0.50, which was also considered excessive for field use.

While these results showed some challenges with mixing at high temperatures, they were at least reasonable enough to confidently proceed with large scale batches for test specimens. This yielded the final mix, denoted as CS5051, used for the rest of the research, and for a fair comparison, the 25% Type K CSA mix was conducted using the same proportions, but with the expansive BCSA replaced with 75% portland cement and 25% Type K CSA cement by volume, and reducing the citric acid dosage to 0.30%.

4.2 Phase 2 – Mix Properties

The alternative chemistry of both an additive Type K CSA cement and an expansive BCSA cement requires the addition of a retarder to ensure sufficient working time for the mix and to avoid flash setting of the concrete either while still mixing in the mixer, or prior to placement. Additionally, the sensitivity of mixes to retardation can significantly affect setting time and strength gain which has significant implications for the timeline of post-tensioning or other similar processes. As a result, for both concrete mixes, it was important to study not just full-strength properties or a single early strength measurement of properties but the progression and development of properties over time. This section presents the results of fresh and hardened material properties conducted over time.

4.2.1 Hardened Concrete Strength Properties

The compressive strength behavior of expansive BCSA cement concrete exhibits not only rapid hardening, but also rapid strength gain. As a result, the concrete exceeds the minimum foundation strength requirements set forth in ACI section 19.2.1.1, shown in Table 19.

Table 19: ACI Table 19.2.1.1, Minimum Compressive Strengths Based on Application.

Application	Minimum f'_c , psi
General	2500
Foundations for structures assigned to SDC A, B, or C	2500
Foundations for Residential and Utility use and occupancy classification with stud bearing wall construction two stories or less assigned to SDC D, E, or F	2500
Foundations for structures assigned to SDC D, E, or F other than Residential and Utility use and occupancy classification with stud bearing wall construction two stories or less	3000
Special moment frames	3000
Special structural walls with Grade 60 or 80 reinforcement	3000
Special structural walls with Grade 100 reinforcement	5000
Precast-nonprestressed driven piles Drilled shafts	4000
Precast-prestressed driven piles	5000

Post-tensioning is allowed at 2/3 of the required maximum strength, therefore this strength gain effectively allows for post-tensioning at any point after set for any application specifying a minimum strength of 5000 psi or less. However, the initial 6h strength gain of the expansive BCSA concrete represents only about $\frac{1}{3}$ to $\frac{1}{4}$ of the total compressive strength gain, shown in Figure 32.

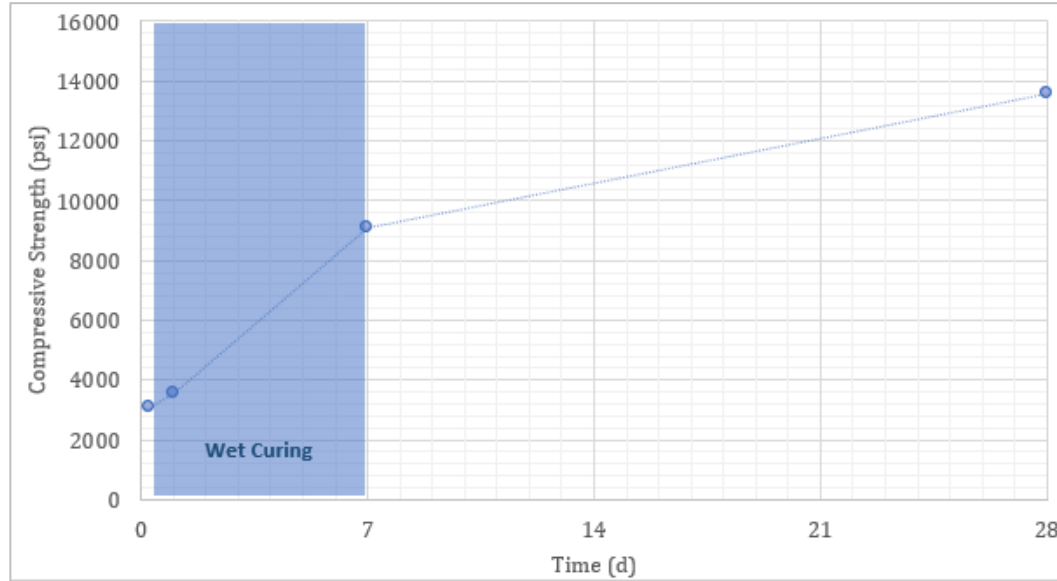


Figure 32: Expansive BCSA Concrete Compressive Strength Gain (from MOR Mix)

Expansive BCSA cement must be wet cured to exhibit expansive properties, therefore all specimens experienced a 7-day wet curing period, occurring between the initial 6h and 7d compressive strength testing, and denoted by the blue highlighted box in Figure 32. Additionally, the strength gain has also been shown to be significantly affected by the length of the wet curing period, therefore Figure 33 shows the difference in strength gain from varying the wet curing period, with specimens removed from the wet cure at each testing interval and dry cured for the remaining period until 28d.

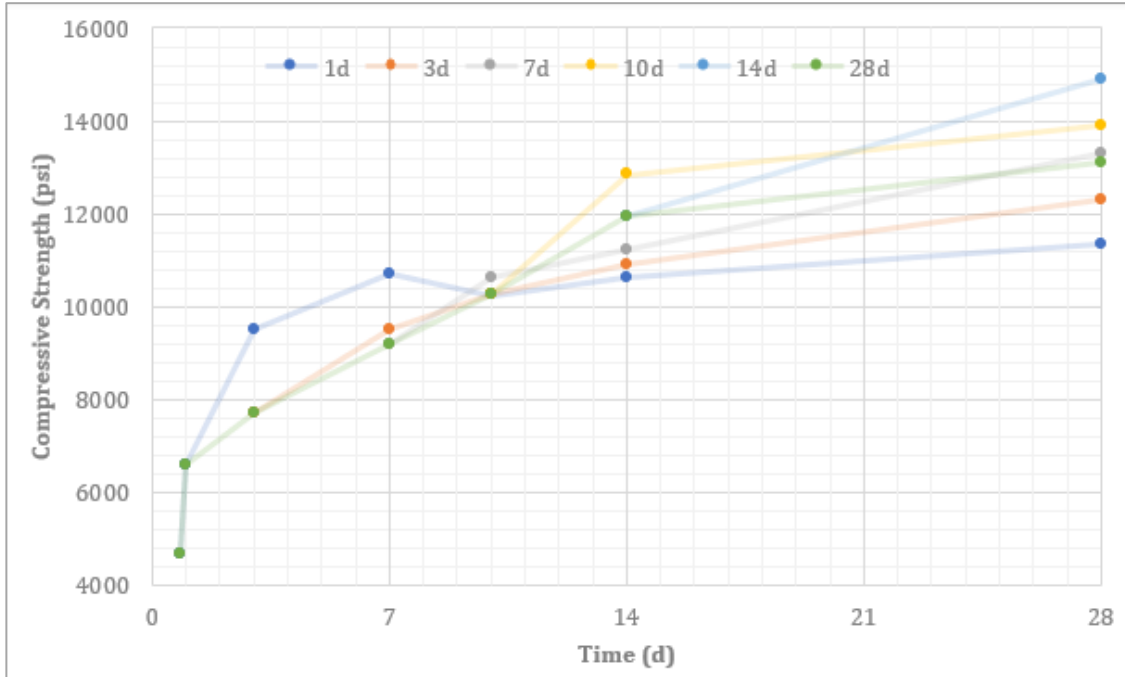


Figure 33: Wet Cure Effects on Compressive Strength

Wet curing leads to a significant variation in the final compressive strength, with most of the specimens seeing an almost 1 ksi increase between curing intervals, at 28d. The one exception to this is the 28d cured specimens which only reached a strength of 13.1ksi, which is comparable to the specimens cured for only 7d at 13.3ksi. However, this actually highlights an interesting trend within the data, where wet curing appears to suppress strength gain relative to dry curing specimens of preceding intervals. All of the specimens show a lower compressive strength at the immediate end of the wet cure relative to at least one specimen of a shorter wet cure that is currently dry curing, before surpassing them in subsequent tests. This seems to suggest that wet curing leads to slower but prolonged strength gain, with specimens experiencing a final rapid burst of strength gain, before levelling off after being removed from wet curing conditions. Finally, though it is not represented in the data, the longer wet curing times led to

greater cracking potential in the specimens, as wet curing expansion does not eliminate shrinkage, it only compensates for it. Therefore, it appears that greater strengths of the cylinders at the time of removal from wet curing, led to observations of more aggressive the cracking due to nonreversible shrinkage, as shown in Figure 34. This cracking appeared to be only surficial and had no apparent impact on compressive strength.



Figure 34: Shrinkage Cracking on Wet Cure Duration Compressive Specimens

The compressive strength gain of the 25% Type K mix with portland cement follows much more conventional behavior. As shown in Figure 35, the concrete achieved ~40% of its full strength at 3d and 60% at 7d. Additionally, there does not appear to be nearly as significant an effect due to wet curing, where as little as 3d increase in wet curing increased the final strength by over 1000 psi.

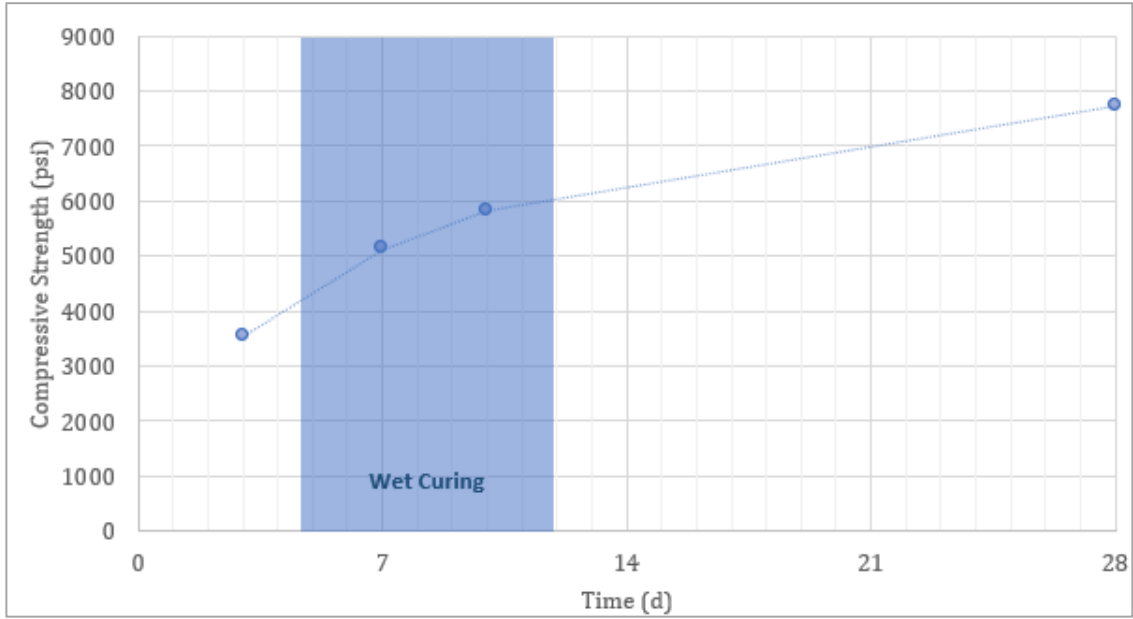


Figure 35: Compressive Strength Gain of 25% Type K Cement (from MOR Companion Specimens)

4.2.1.1 Flexural Strength

The flexural strength of the expansive BCSA cement concrete was determined in accordance with ASTM C78. As specimens broke in the middle third of the third point loading test, the stress at failure was determined according to Equation 3, using calipers to take accurate cross-sectional dimensions across the failure plane.

$$f_r = \frac{Pl}{bd^2} \quad (3)$$

Interestingly as shown in Figure 36, the results show a peaking during the wet cure period with a decline between 7d and 28d after dry curing. Based on the results of the wet cure study, this appears to suggest that while shrinkage micro-fracturing in the concrete after wet curing does not appear to affect the concrete in compression, it may have an effect in flexure.

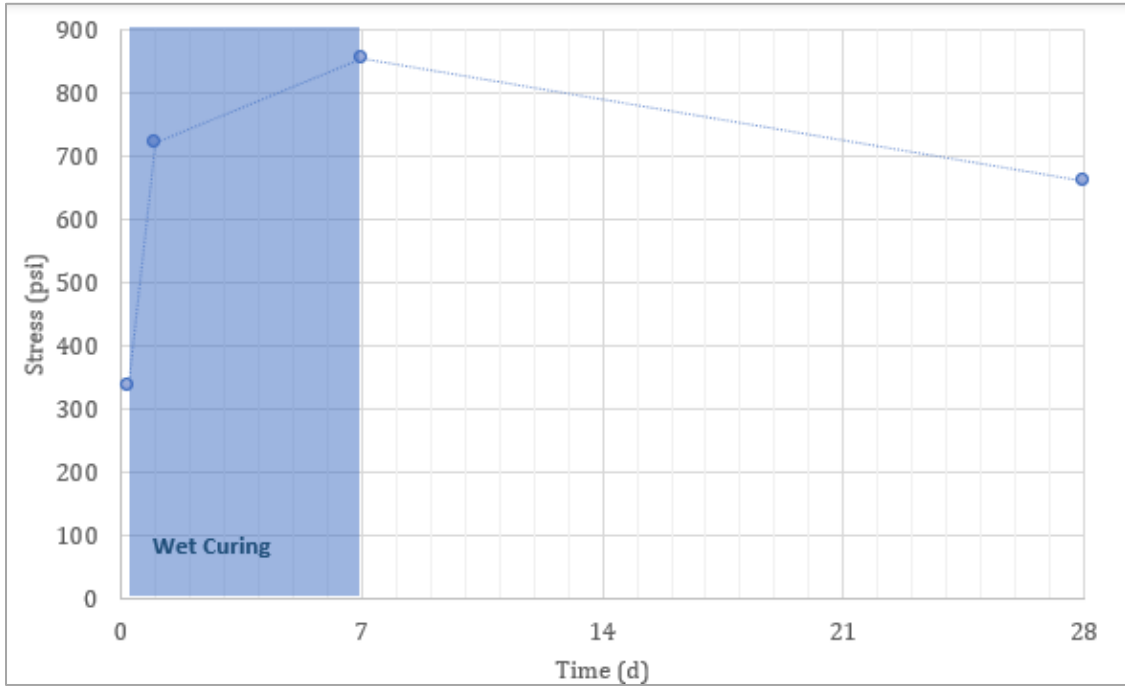


Figure 36: Modulus of Rupture for Expansive BCSA Cement

This also shows a departure from expected behavior according to ACI, which predicts modulus of rupture to follow compressive strength according to Equation 4. However, to assess to what extent this is a function of the differing cement chemistry or shrinkage it is necessary to compare against modulus of rupture results without wet curing the specimens, shown in Figure 37.

$$f_r = 7.5\lambda\sqrt{f'_c} \quad (4)$$

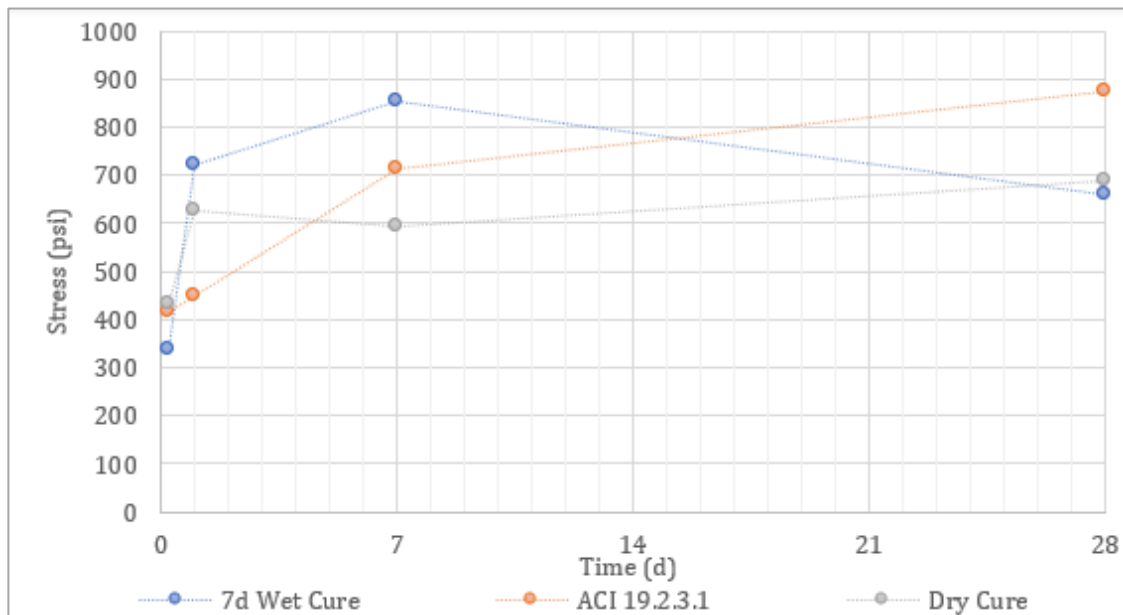


Figure 37: Wet Cured Expansive BCSA Modulus of Rupture, as Compared to ACI 19.2.3.1 Predictions and Dry Cured Modulus

This shows that the departure from the prediction may be attributable to both the differing chemistry and the wet curing. Neither the ACI compressive strength correlation, nor the dry curing modulus show any decrease overtime, therefore it is possible that those micro-fractures observed after wet curing are the cause of the decline in the flexural tension strength of the wet cured specimens. Nevertheless, cement BCSA cement chemistry appears to deviate significantly from the ACI correlation with flexural tension strength gaining and levelling off occurring far faster than the approximation based on square root of compressive strength. Rather the trend shows some degree of direct linearity.

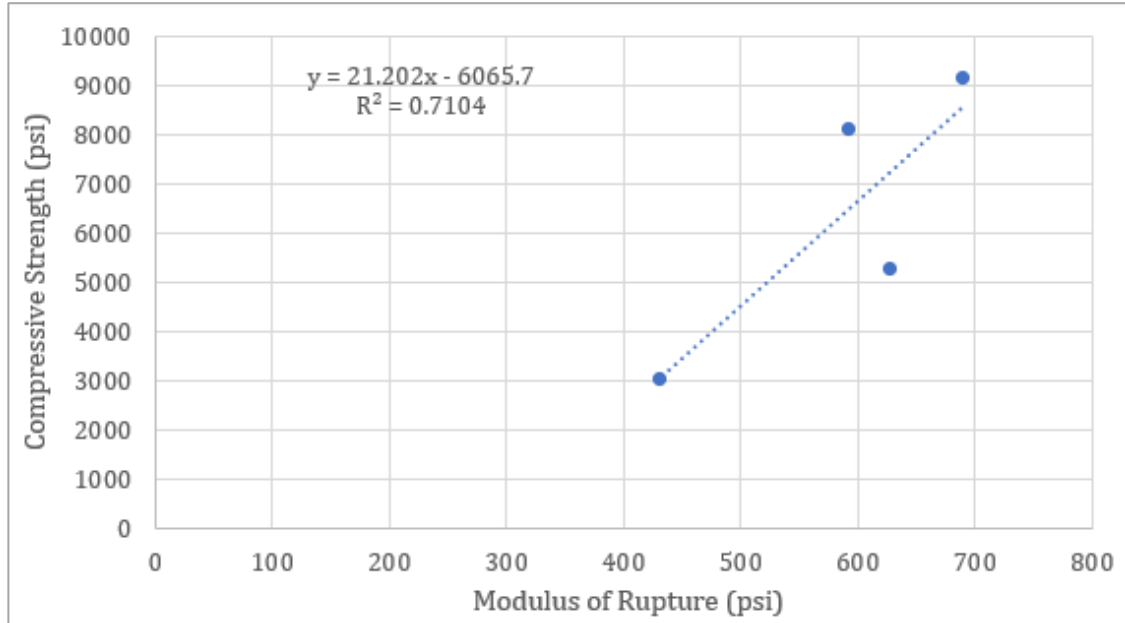


Figure 38: Expansive BCSA Modulus of Rupture versus Compressive Strength

Even the Type K specimens exhibit similar behavior during the drying period following the end of wet curing in Figure 35. Though the initial tension strength gain is more significant than the ACI correlation predicts, shown by Figure 39 the rate of gain follows the correlation reasonably well. The slightly greater gain initially compensates for the decrease in the modulus of rupture after removal from the water.

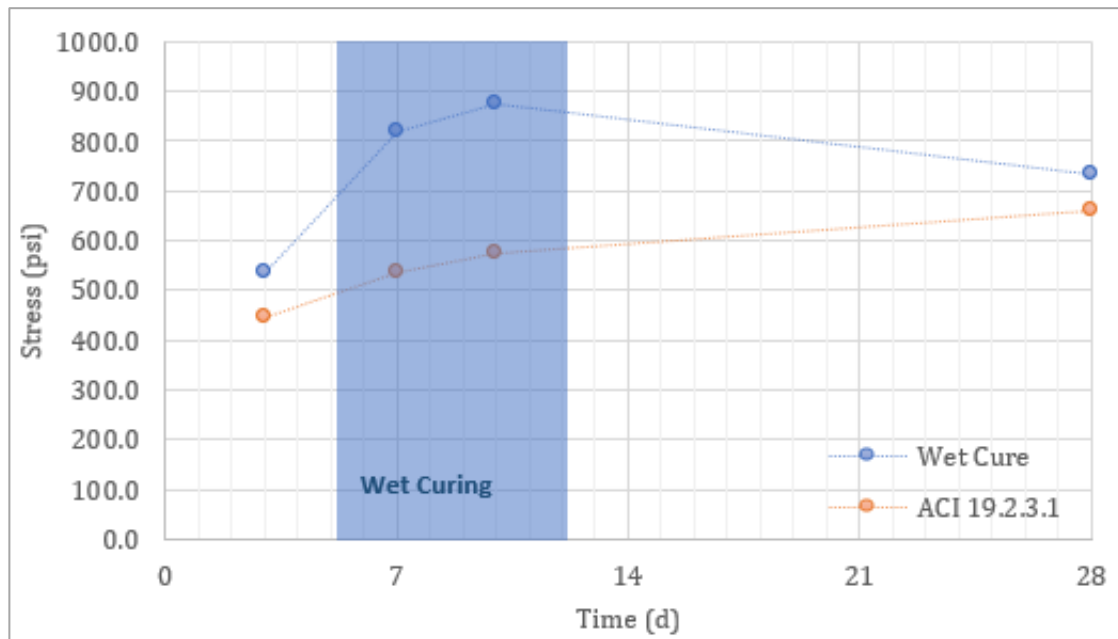


Figure 39: Modulus of Rupture Development for Wet Cured Specimens vs. ACI 19.2.3.1 Predictions

However, based on the observed reductions at 28 days and cracking in the cylinder used for the wet curing study of compressive strength, there were concerns about potential for aggressive drying shrinkage after the end of wet curing to permanently compromise flexural strength, particularly for the expansive BCSA specimens as the cement is far less understood. Therefore, a second set of BCSA MOR specimens were cast for breaking at 7 days and 28 days. One set was left to air cure for the entire period, one set of MORs was wet cured for 7 days and then left to air cure and one set was wet cured for the entirety of the 28-day period. Additionally, as there were an extra 2 specimens, a single specimen was broken at 14 and 28 days each, simulating a 14-day wet cure for an estimation of how the duration of wet curing affects shrinkage cracking reduction of flexural modulus behavior. These results are graphed in Figure 40. As measurements were not taken until 7 days the exact timing of flexural tension strength gain is not

visible, as early age specimens were not tested, but based on Figure 37, it presumably occurs in the first 24 hours.

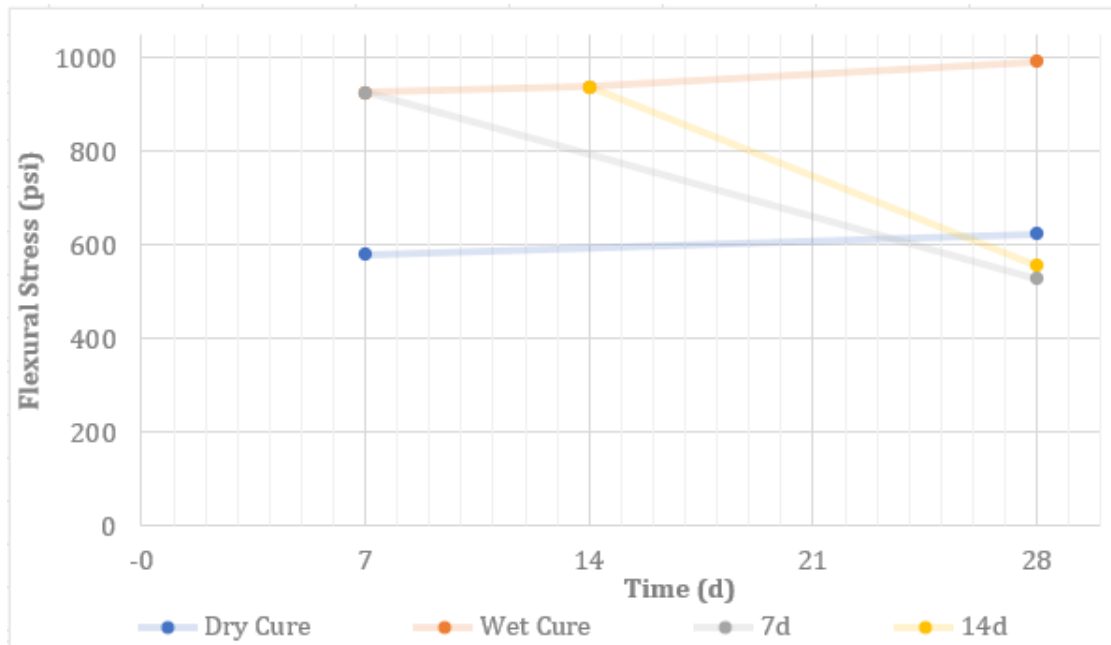


Figure 40: Effect of Duration of Wet Cure and Recovery Shrinkage on Flexural Modulus

These results show a more than 30% increase in the modulus of rupture of the expansive BCSA specimens under wet curing conditions, but there is a nearly 40% reduction in modulus after drying and plastic shrinkage occurs. Likely, the surficial cracking behaviors observed during the compressive cylinder wet curing study (Figure 34) led to a reduced effective cross section under flexure, which may contribute to compromising strength for modulus of rupture, but does not inhibit compressive strength. This also means that the current ACI model for shrinkage is still reasonable; even if expansive specimens significantly exceed projects due to gains during wet cure, such gains are only temporary and projected modulus of rupture returns to approximately the range predicted in the long-term after drying.

4.2.1.2 Static Elastic Modulus

The modulus of elasticity for the expansive BCSA concrete specimens was also determined, based on general accordance with ASTM C469. Initially, three companion cylinders were tested to failure according to C39 compressive strength procedures. Three cylinders were then loaded to 40% of that average failure stress three times each with the modulus of elasticity taken as the slope of the line of best fit from 50 μ strain to that at 40% of f'_c . Based on the average of those readings, the static elastic modulus is plotted in Figure 41, along with the estimation of elastic modulus according to Equation 5 from ACI 318 19.2.2.1, based on the compressive strength, and measured mix unit weight, 143.4pcf.

$$E_c = 33w_c^{1.5}\sqrt{f'_c} \quad (5)$$

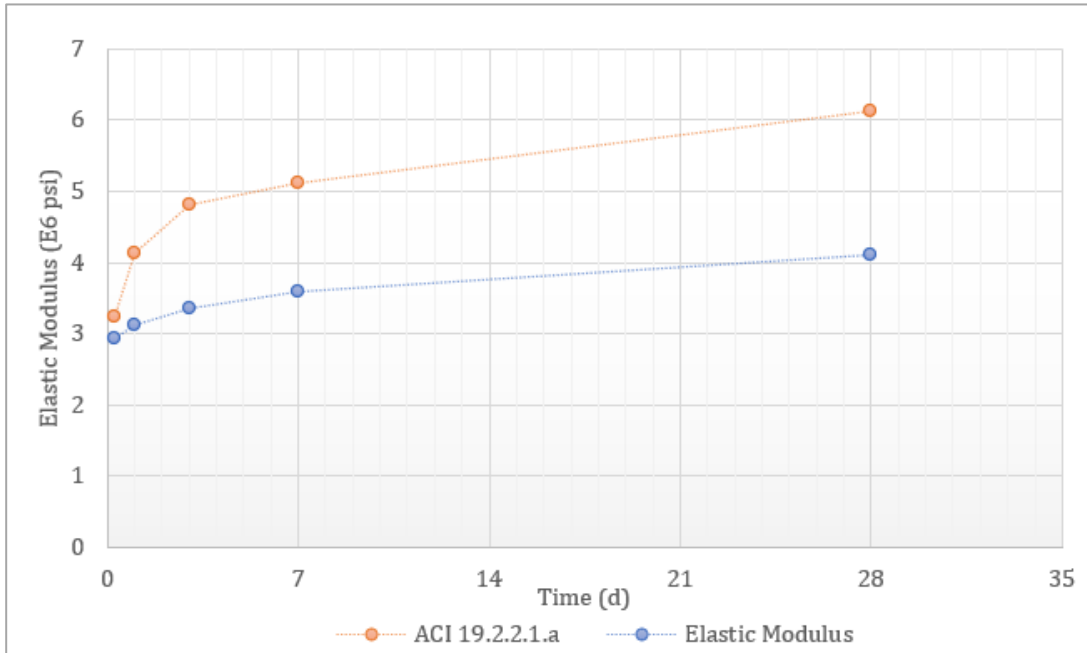


Figure 41: Elastic Modulus of Expansive BCSA Concrete, Experimental vs. ACI 19.2.2.1.a Predictions

Similar to the modulus of rupture, rather than being a function of the square root of the compressive strength the correlation between the elastic modulus and compressive strength appears linear. As shown in Figure 42, this correlation appears far more strongly than for modulus of rupture.

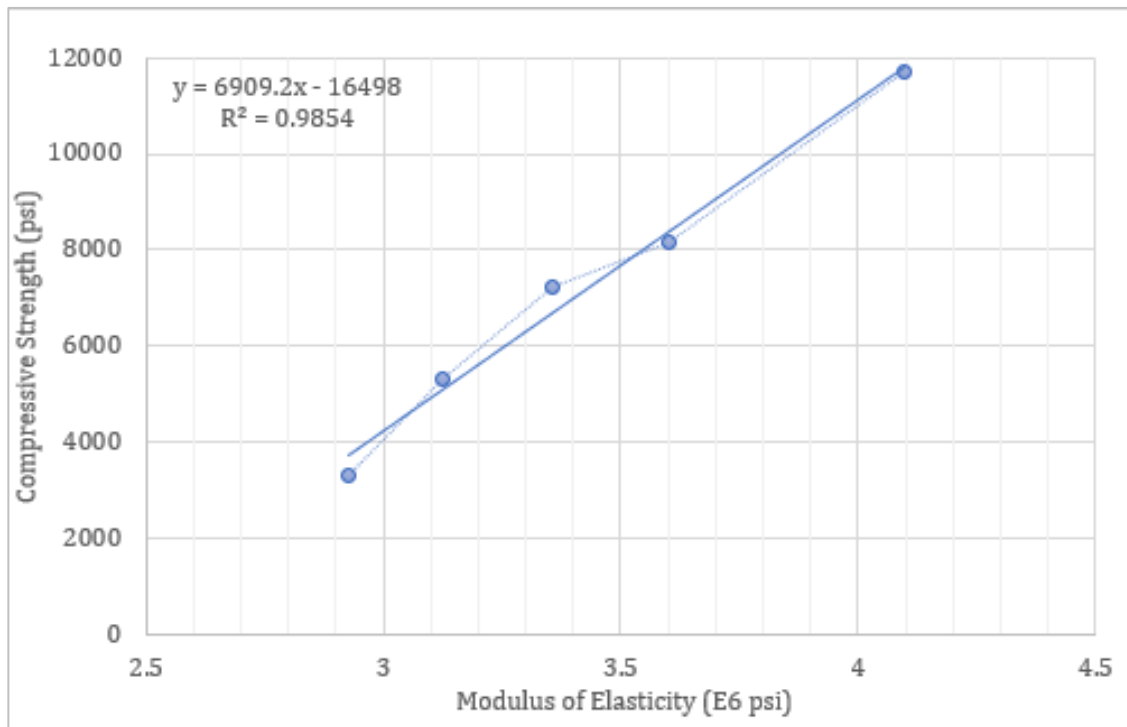


Figure 42: Elastic Modulus vs. Compressive Strength for Expansive BCSA Cement

Notably, a strong direct linear correlation between compressive strength and modulus was also noted by Roswurm (2023) for non-expansive BCSA cement. However, a square root correlation was still chosen to present elastic modulus behavior as it is currently the common method used.

The ACI correlation of modulus and compressive strength consistently overestimates by ~40% for the Type K mix despite having a reasonably standard mix proportions and

unit weight of 148 pcf, as shown in Figure 43. This consistent overestimation implies there may be a need to adjust the factor of 33 included in Equation 5, but the correlation still holds reasonably. A new correlation for expansive BCSA cement. However, for similar reasons as Roswurm (2023), while BCSA cements both in this research and Roswurm (2023) appear to have a linear correlation, the following square root correlation is proposed in Equation 6 for the purpose of comparison against the work of Roswurm (2023) with non-expansive BCSA, even though the correlation accuracy is particularly low at early (<1d) ages, when it is most desirable to use this concrete.

$$E_c = 41,000\sqrt{f'_c} \quad (6)$$

This correlation includes a coefficient lower than Equation 2 proposed by Roswurm (2023), by approximately 20%. The Type K CSA mix modulus is also consistently lower than ACI predictions in Figure 43. Thus, the expansion of both type K CSA and expansive BCSA appears to lead to lower stiffness.

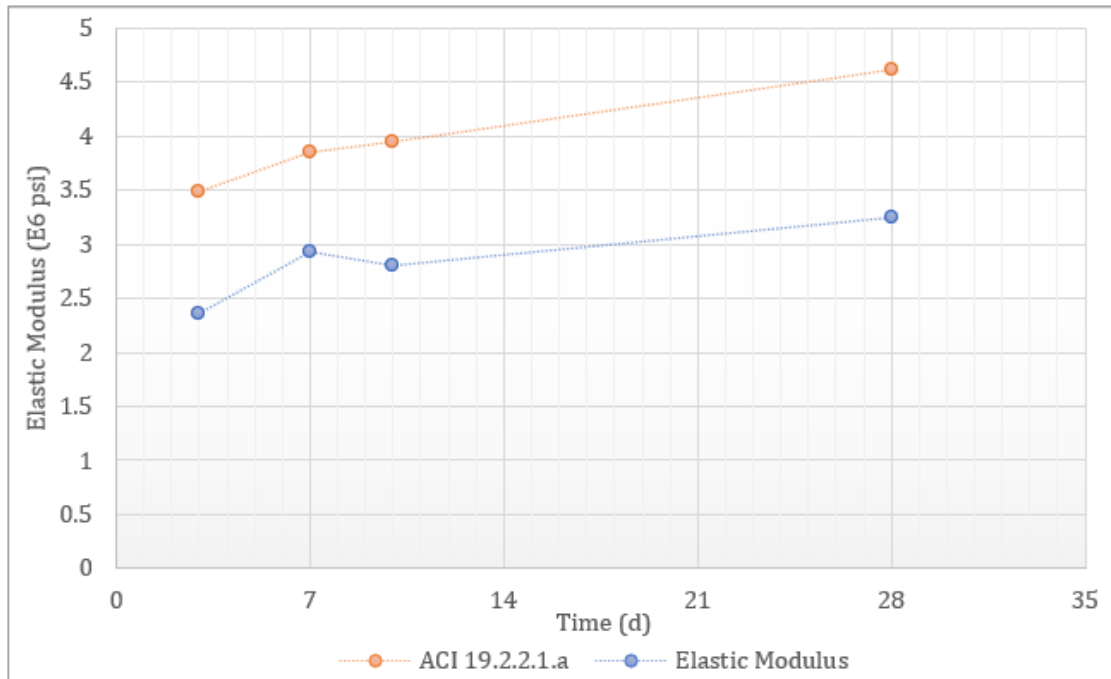


Figure 43: Elastic Modulus of 25% Type K CSA Concrete, Experimental vs. ACI 19.2.2.1.a Predictions

While additive CSA cements, such as the Type K mix in this research, do not fundamentally change the chemistry of concrete and current ACI correlations to compressive strength are still of relatively reasonable order, this was not true for the fully CSA mix. The expansive BCSA cement shows near linear correlation between compressive strength and related mechanical properties like elastic modulus and modulus of rupture, rather than the current ACI square root correlations. Whether using a BCSA or a conventional portland cement mix however, expansive counterparts clearly exhibit a reduced elastic modulus relative to strength gain behavior, potentially because the expansion reduces the matrix density of the paste and aggregate, resulting in reduced stiffness. Conversely, this is also somewhat exacerbated by the rapid strength gain and heightened pure compressive strength. So, it may simply be that ettringite

results in higher compressive strengths, given the same paste content and accompanying stiffness.

4.2.2 Expansive Properties – Volumetric Expansion/Contraction (C157) and Restrained Expansion (C878)

Type K expansive cement is known to only exhibit expansion under wet curing conditions, and expansive BCSA cement exhibits similar behavior, requiring a wet cure to show any expansion. Therefore, both the C878 specimens shown in Figure 44 and C157 specimens shown in Figure 45 were wet cured throughout the monitoring period. Significantly, the expansive behavior occurs primarily during the first four months of the wet cure with very little change beyond this point.

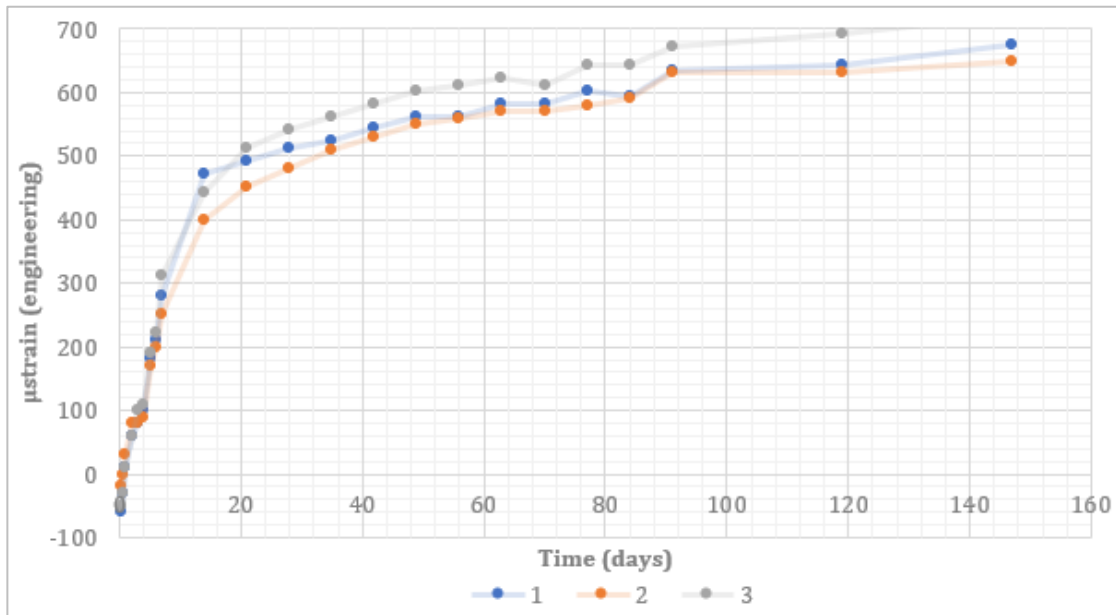


Figure 44: C878 Restrained Expansion of Fully Wet Cured Expansive BCSA Concrete

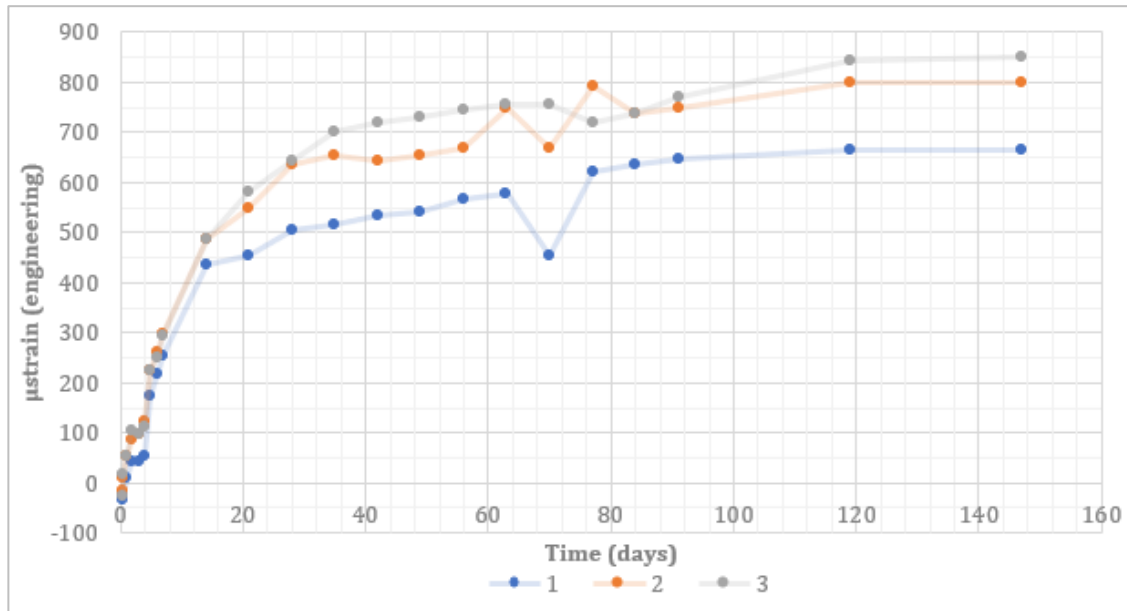


Figure 45: C157 Unrestrained Expansion of Fully Wet Cured Expansive BCSA Concrete

Additionally, the extent of drying shrinkage that will recover after removal from wet curing needs to be accounted for. Accordingly, an additional set of C157 specimens shown in Figure 46 were tested with a wet curing period of only 7d, comparable to the duration of wet curing expected in the field and used on the large-scale slab specimens.

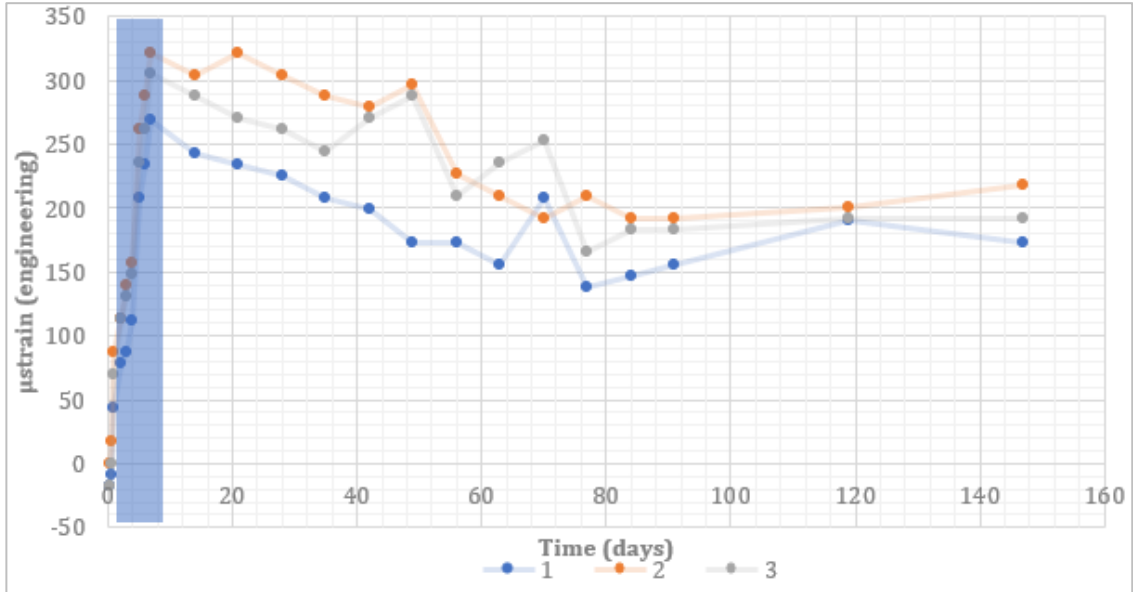


Figure 46: C157 Unrestrained Expansion of Expansive BCSA Concrete with 7d Wet-Cure Highlighted Blue

All three cases have relatively low variation between specimens. The average shrinkage and expansion from these three cases, shown in Figure 47, shows that not only is there very little irreversible shrinkage—only on the order of 100 μ strain over 2 months from the end of wet curing—but the expansion is aggressive enough to not only fully counter this shrinkage, but to also only see slight reduction under restraint, which only takes effect after the majority of the expansion is induced over the first two weeks. Moreover, the reduction due to restraint during later stages of expansion is limited. The final magnitude of this was minimal and corresponded to only ~ 100 μ strain difference between restrained C878 and unrestrained C157 testing.

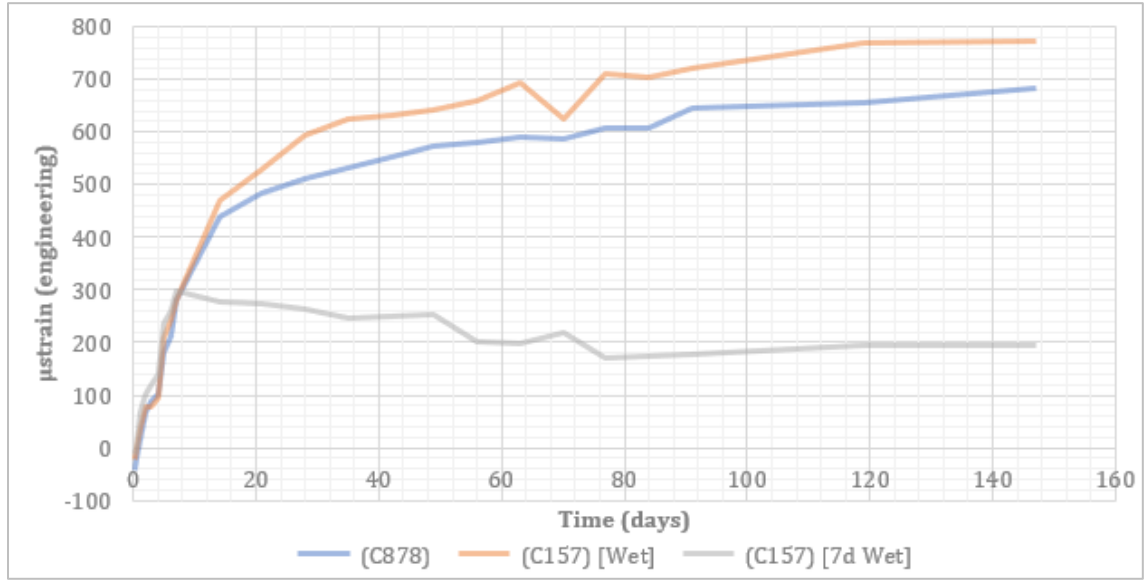


Figure 47: Average Expansion of Expansive BCSA concrete under Fully Wet Cured Restrained and Unrestrained Conditions and a 7d Unrestrained Wet Cure

Conversely, the Type K specimens show far less expansion, both in the restrained case shown in Figure 48 and the unrestrained case shown in Figure 49. Additionally, the variation in expansion between specimens is far more significant, due to the additive nature of the cement, versus the extremely close results from the expansive BCSA cement. This is further compounded by a handful of apparent fluctuations in the measurements of some specimens that distort the data, most notably at 35d and 49d for C878 specimens 1 and 3, 63d for the fully wet cured C157s and 70d for the 7d wet cured C157s.

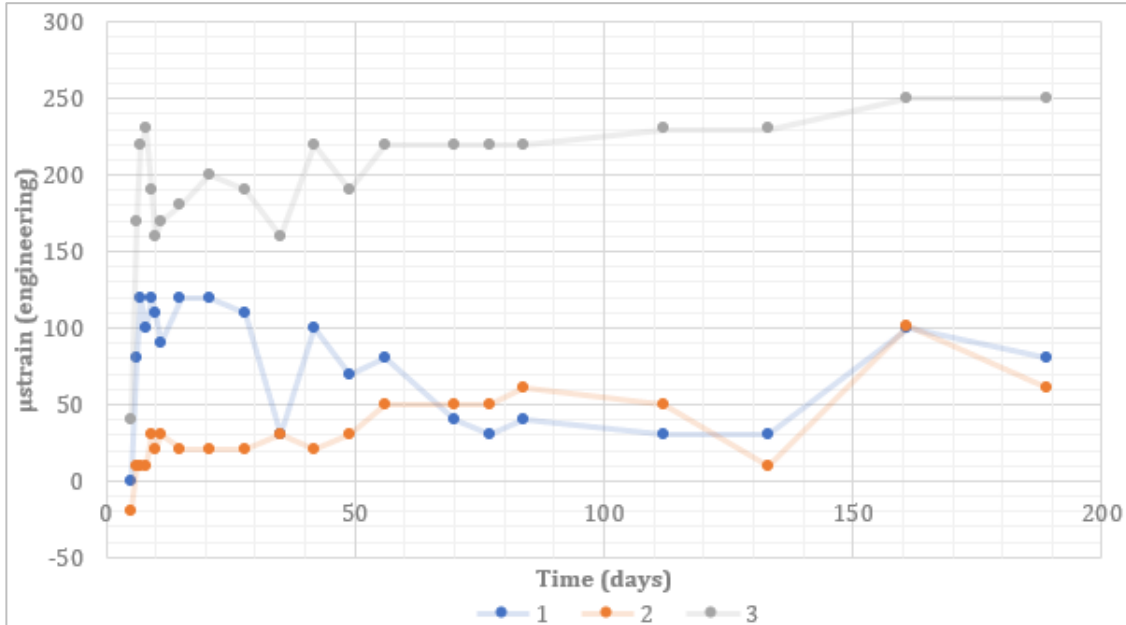


Figure 48: C878 Restrained Expansion of Fully Wet Cured 25% Type K CSA Concrete

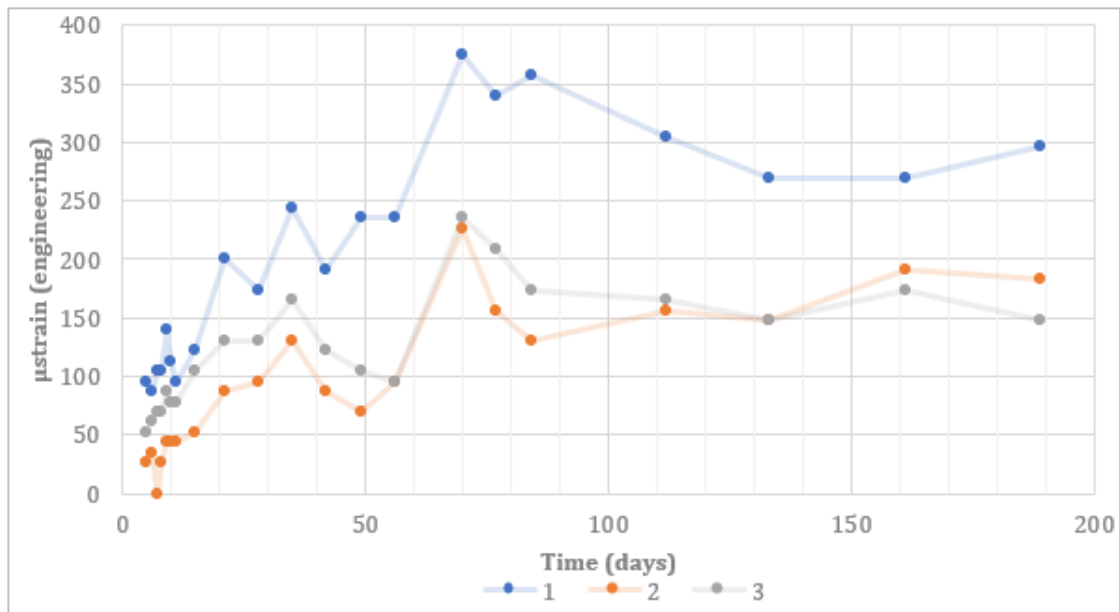


Figure 49: C157 Unrestrained Expansion of Fully Wet Cured 25% Type K CSA Concrete

Notably, as an additive cement rather than a replacement of conventional portland cement, Figure 50 shows that Type K cement also does not see reduction in the overall

shrinkage of the concrete. Rather the expansion of the Type K cement additive is only counteracting some of the natural shrinkage that would be seen with conventional portland cement concrete, which is why it is more accurately termed as a shrinkage compensating concrete rather than a non-shrink or expansive concrete, as described by Bescher (2022).

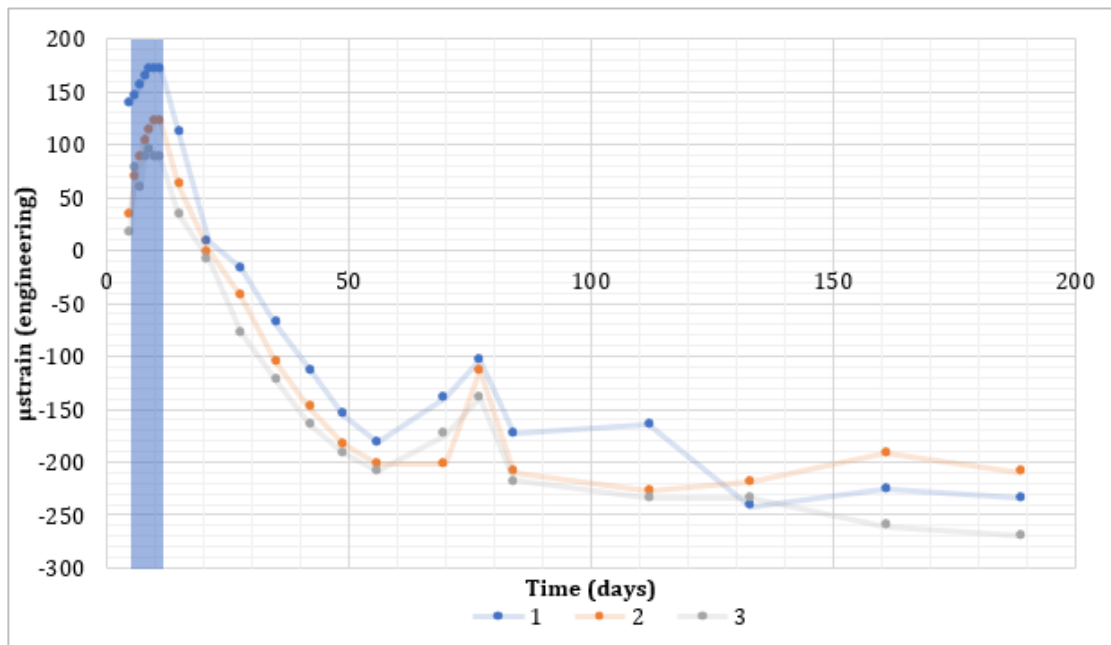


Figure 50: C157 Unrestrained Expansion of 25% Type K CSA Concrete Wet-Cured for 7d

Finally, the average expansion from these three trials for a 25% Type K cement are shown in Figure 51. Despite the Type K CSA cement exhibiting far less aggressive expansion, the effect of restraint on inhibiting expansion is similar to that of the expansive BCSA cement, on the order of 100 μ strain. Conversely, there is significantly more embodied shrinkage; from end of wet curing to 90d, there is more than 330 μ strain, more than 3x the strain of the expansive BCSA cement.

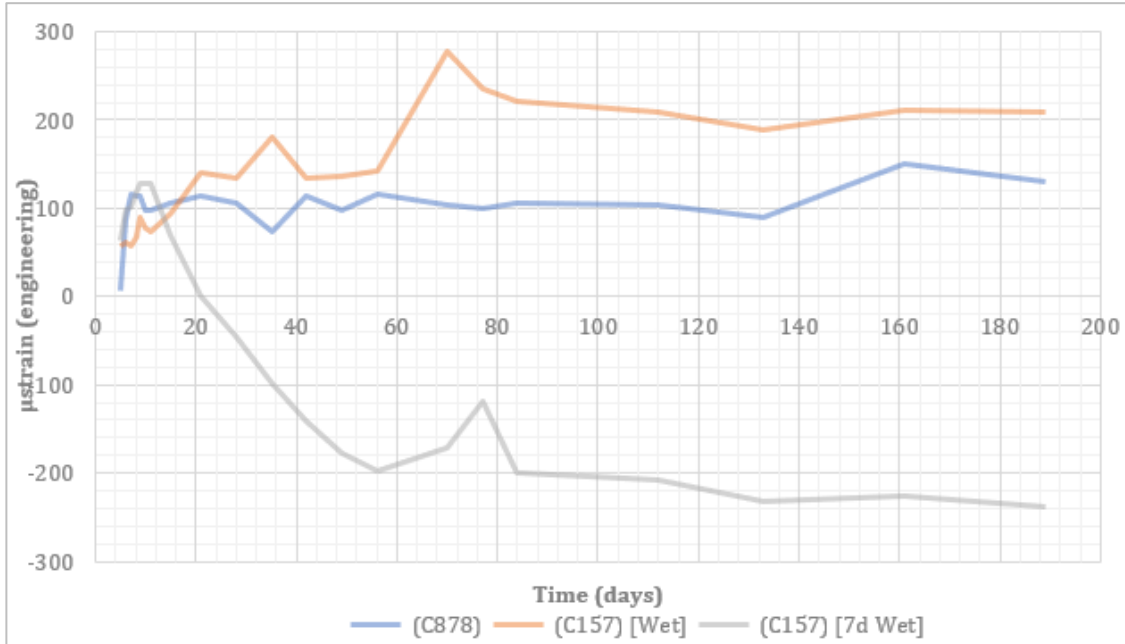


Figure 51: Average Expansion of 25% Type K CSA Concrete under Fully Wet Cured Restrained and Unrestrained Conditions and a 7d Unrestrained Wet Cure

Unfortunately, during the middle stages of data collection for the Type K specimens, the thermostat in the environmental chamber began to malfunction, where the chamber would at times reach as high as the upper 90 degrees Fahrenheit. As this was not fixed until over 2 months later, there are significant fluctuations in the data even when averaged out below, between 21 and 77 days. These fluctuations persist even after attempting to manually correct for thermal effects by backing out additional expansion in the standard rods.

4.2.3 Creep and Shrinkage Behavior

Creep represents a crucial property for the determination of prestress losses and was measured with vibrating wire strain gauges (VWSGs) under the planned loading

conditions of the full-scale slabs, beginning at the initiation of the wet cure.

Furthermore, to isolate the creep effects from shrinkage and expansion, a pair of unloaded control specimens were also cast with VWSGs. Results from these companion specimens can also validate the observed trends from the C157 7-day wet curing specimens. Figure 52 shows the raw results from the expansive BCSA concrete, with measurements taken at 5-minute intervals for the first 2 weeks and 30-minute intervals afterwards.

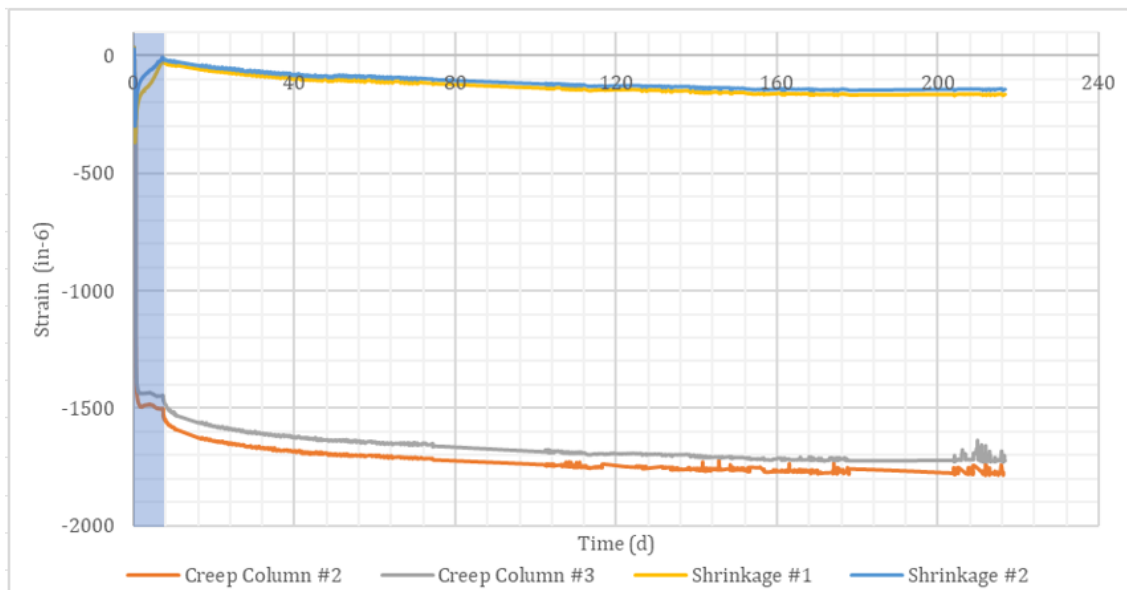


Figure 52: Raw Creep Column and Companion Shrinkage Specimens of Expansive BCSA concrete Measured with VWSGs.

Unfortunately, one of the three VWSGs in the creep column specimens malfunctioned under loading and wet cure and had to be discarded from the data. However, the remaining two VWSGs yielded enough data for comparison. Despite this flaw, this sampling method is particularly useful as it allows for data collection from time zero, that is, the initial concrete pour, which allows for observations of trends that cannot

otherwise be captured. After backing out the elastic strain behavior, the exact magnitude of the combined creep and shrinkage can be recorded beside the reference shrinkage specimens shown in Figure 53.

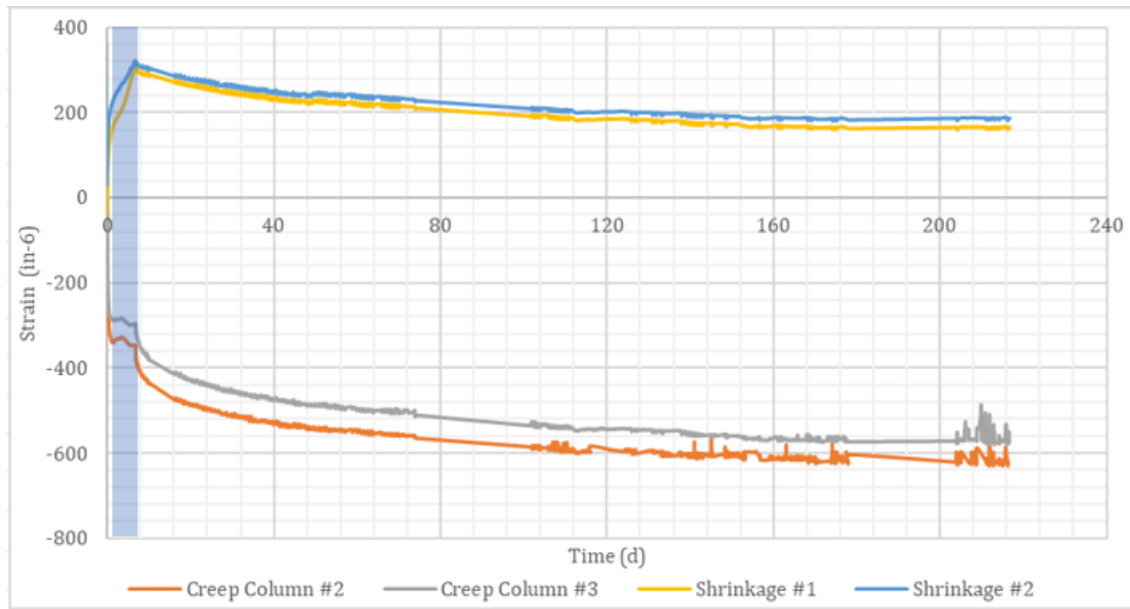


Figure 53: Creep Column Specimens and Companion Shrinkage of Expansive BCSA after Backing Out Elastic Shortening.

Additionally, the setting of these specimens was closely tracked to load them as close to set and making strength as possible and there is a clear jump in apparent compressive strain. In fact, due to high humidity and rainy weather the day of casting, the setting of the specimens was delayed beyond the expected 6-8h. These specimens did not make strength to be loaded until ~10.5-11h after casting, with actual loading occurring at the 12-hour mark. Based on this, apparent shrinkage of ~330 μ strain occurs prior to set, however, this should induce no internal stresses because the concrete has not fully hardened when this autogenous shrinkage occurs. Moreover, unrestrained C157 shrinkage measurements validate this behavior, as measurements were taken almost

immediately after final set and are effectively equivalent to the VWSG readings without this autogenous shrinkage strain occurring. Consequently, an additional correction has been made to make this the true zero-point from which subsequent stress inducing compressive and tensile strains are measured.

Of further consideration is the rapid rate at which creep strains occur. Figure 54 shows the average readings from the creep column specimens and reference shrinkage specimens for the first four weeks after loading, with time of loading set as the zero-point. The pure shrinkage of these reference specimens was then subtracted from the total creep and shrinkage, to resolve the true creep behavior. This figure only shows the data only out to 28d because of difficulty in seeing the knee (point of slope change) for the creep curve at extended periods. Beyond this point the data tends to appear almost bilinear, as in Figure 55.

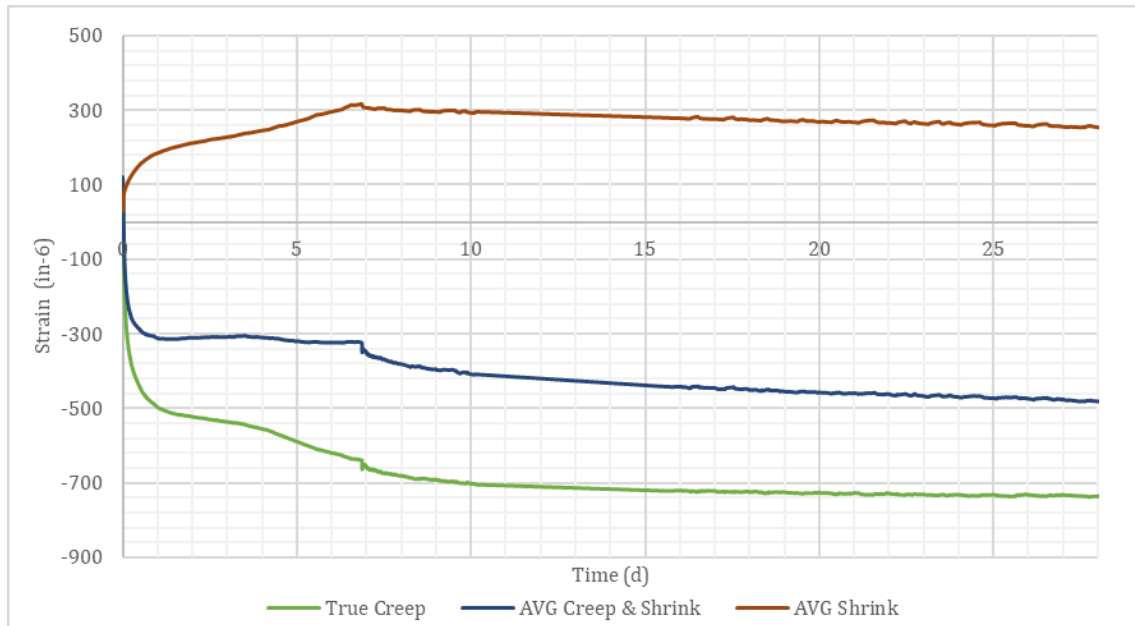


Figure 54: Average of Combined Creep and Shrinkage, Companion Shrinkage, and Net Creep in Creep Column Specimen to 28 days.

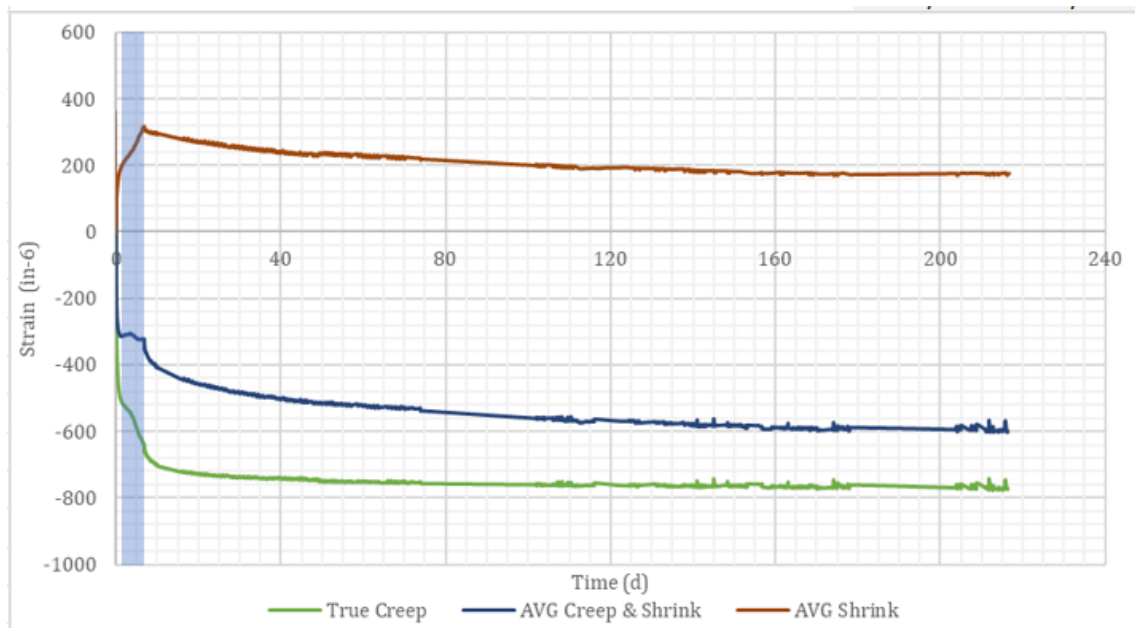


Figure 55: Complete Timeline of Total Creep and Shrinkage, Companion Shrinkage, and Net Creep in Creep Column Specimen after Backing Out Elastic Shortening.

Almost 500 μ strain of creep, representing more than 60% of the ultimate creep strain, occurs in less than 12 hours. This rate is so close to immediate that without backing out elastic strain behavior, it becomes difficult to fully differentiate it, even at a sampling rate of every 5 minutes. Moreover, the creep column achieves more than 90% of the ultimate creep during the wet curing period, even considering that the imposed initial stresses are particularly high, at the ACI limit of $0.60f'_c$ at time of loading.

Moreover, after this “immediate creep”, the increase in strain is essentially completely counteracted by the expansive strains from wet curing, resulting in the net strain change in the specimens from ~1d to the end of wet curing holding constant, and only slightly increasing after this point. In fact, after the end of wet curing, both shrinkage and the residual long-term creep are only slightly more than 100 μ strain each, with the net effect of 300 μ strain of expansion countering more than 1/3 of the total combined creep and shrinkage, with the majority of the uncompensated creep coming from the immediate creep component. Moreover, Roswurm (2023) found that the magnitude of the immediate creep in non-expansive BCSA cement concrete was inversely proportional to the age at loading, so this could potentially be further mitigated by loading at later ages. Conversely, the 25% Type K CSA concrete shows far more creep and shrinkage, without the immediate shrinkage observed in the expansive BCSA cement concrete. Figure 56 shows the raw data, while Figure 57 adjusts the data by removing the elastic strains, and backs out the setting shrinkage behavior to zero out the strains with respect to the setting time and only analyze the true creep and shrinkage induced strains after loading. Notably, the setting shrinkage follows a more gradual trend than expansive

BCSA concrete. Rather, the slight decrease prior to loading in Figure 56 is more gradual and in line with autogenous and drying shrinkage after set.

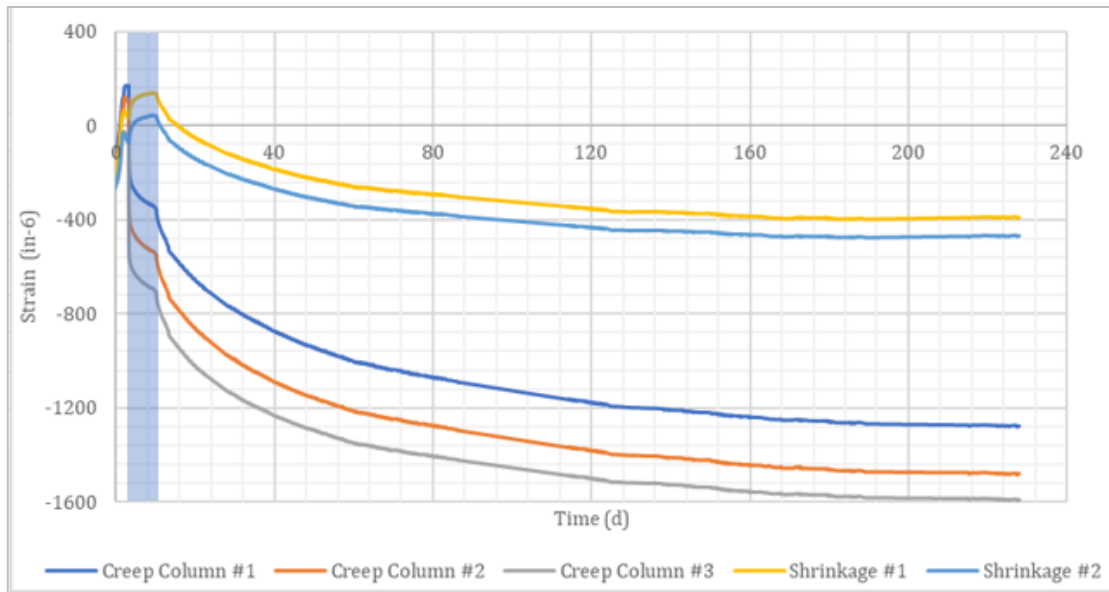


Figure 56: Raw Creep Column and Companion Shrinkage Specimens of 25% Type K CSA concrete Measured with VWSGs.

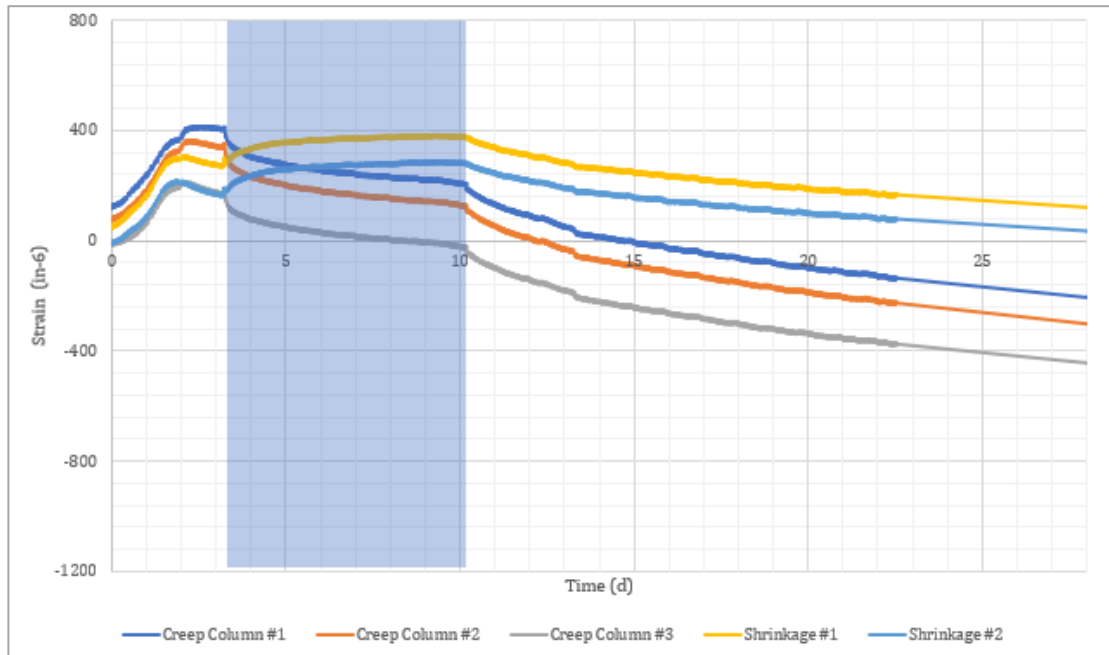


Figure 57: Creep Column Specimens and Companion Shrinkage of 25% Type K CSA to 28d after Backing Out Elastic Shortening.

Additionally, because the effect of expansion is far less aggressive than the expansive BCSA as evidenced by the C157 and C878 results, the effect of the wet curing expansion can only reduce overall creep rather than offset it. The magnitudes and rates for both creep and shrinkage are more comparable to conventional portland cement concrete as the type K cement is additive, rather than a completely different cement. Thus, when analyzing the average creep and shrinkage to determine the true creep shown in Figure 58, the creep component of strain takes far longer to level off as compared to the expansive BCSA specimens.

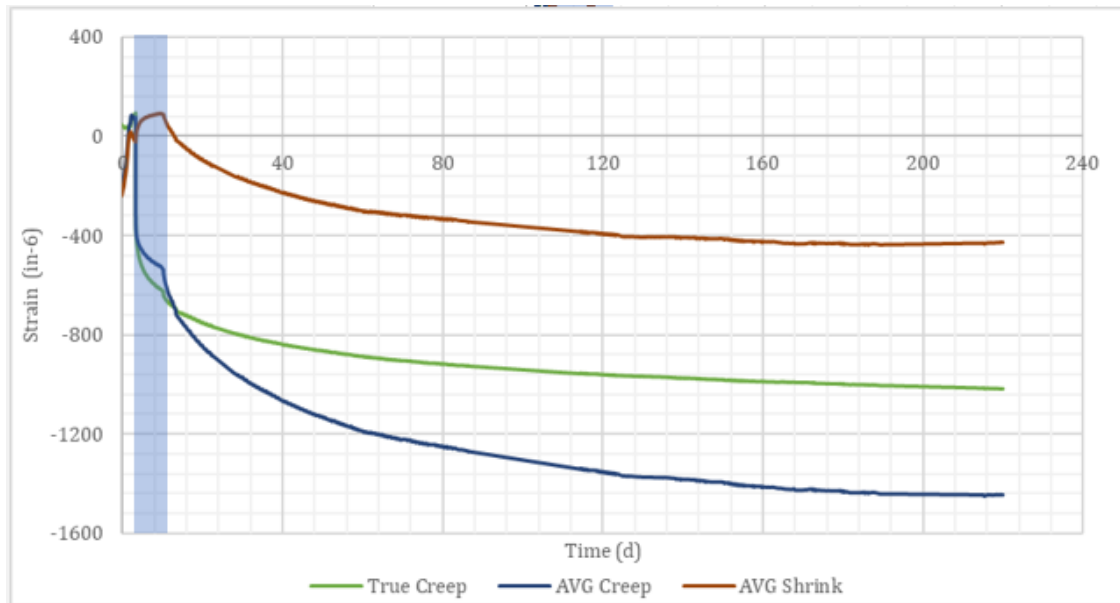


Figure 58: Average Shrinkage and Creep Column readings of 25% Type K CSA concrete for Determination of True Creep.

In terms of property prediction, with conventional models a major limitation is the prolonged strength gain of the expansive BCSA cement. While it does not achieve the same early strength as its non-expansive counterpart, it does gain significantly more as it achieves full 28-day strength, which ultimately exceeds the allowable limits for most creep and shrinkage models. For the purpose of this research both the AASHTO model and all five models described in ACI 209 for creep are presented in Figure 59, out to 40 days so that the initial shapes can be compared. The same models for shrinkage in the expansive BCSA concrete are presented in Figure 60, as compared against the experimental results from the VWSGs in the creep column companion shrinkage specimens. It should be noted that there is an additional model for shrinkage, as the 1999 revision to the MC90 model which refined the shrinkage model, but not the creep model. The results from the C157 and C878 testing are not included as an experimental

curve for shrinkage as there was general agreement between the VSWG results and the ASTM C157 results, but the ASTM results faced environmental instability and user errors, as well as a far coarser sampling rate, making it harder to map against model predictions.

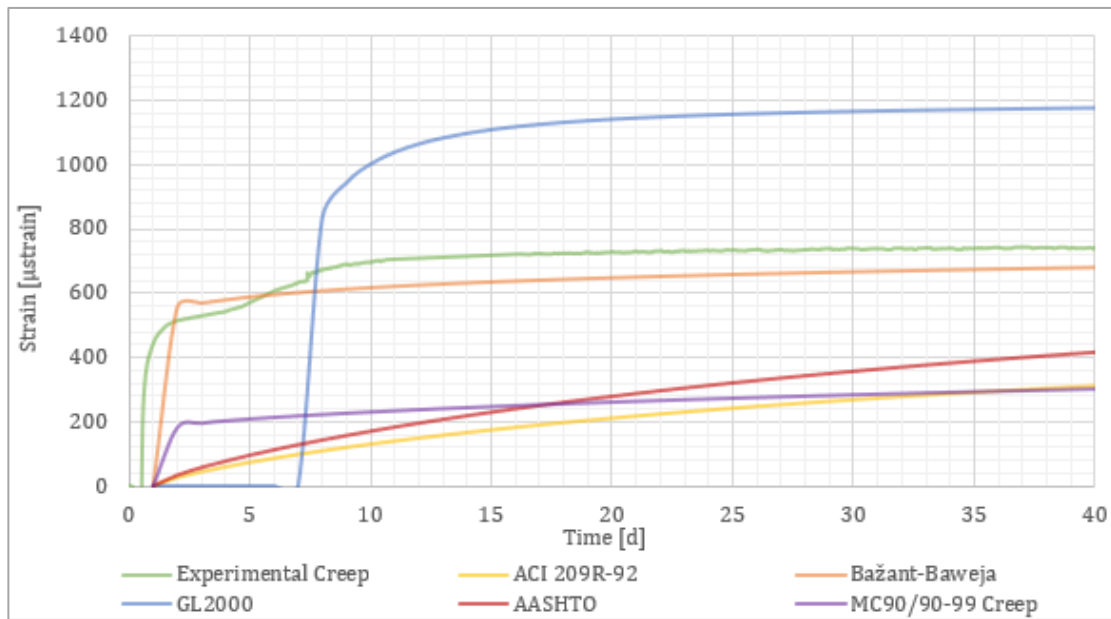


Figure 59: Expansive BCSA Experimental Creep Column Results vs. AASHTO and ACI 209 Model Predictions to 40 days

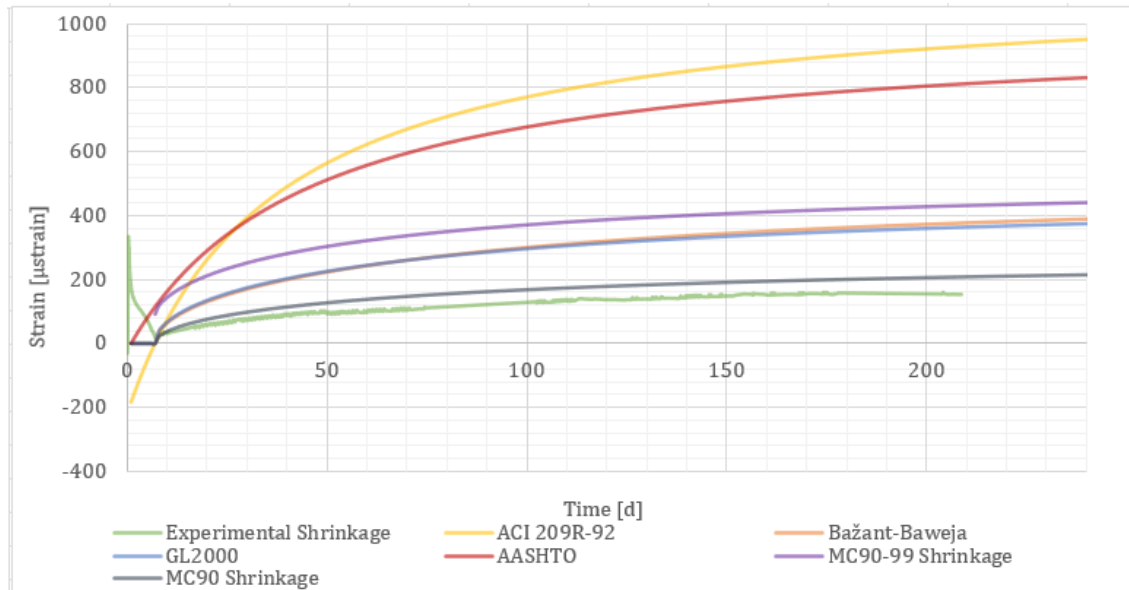


Figure 60: Expansive BCSA Experimental Companion Shrinkage Results vs. AASHTO and ACI 209 Model Predictions to 250 days

The high strength and chemistry of CSA cement do not fit well with most of the restrictions built into these models. There was insufficient data collected in this research for a unique CSA model to be developed so the best alternative was to map results to these existing models. Moreover, as the length of the wet curing regime increases strength, it further pushes the limits of these models with the increased strength gain, only fully meeting the 15ksi limit for the AASHTO model, and just exceeding the limits for the GL2000 (11.9ksi) and CEB MC90 (11.6ksi) models at 7-days. Additionally, all of these models define the times of load application and the end of curing as critical points for assessing the rate of strain development with respect to set time of zero. However, all of the models appear to have at least the implicit assumption of loading at or after the end of wet curing, without the consideration for wet curing continuing after load application to compensate for creep and shrinkage losses as intended here. Most

significantly, this is explicit within the GL2000 model, which only allows for creep and shrinkage prediction after the end of wet curing. All of these points account for the poor predictive results of these models to the experimental data.

That said, Roswurm (2023) found that existing model predictions could be reasonably utilized for CSA cements irrespective of limitations due to alternative chemistry if the equivalent ultimate creep and shrinkage values were adjusted for their reduced values with CSA cements. Therefore, Figures 61 and 62 depict the models, respectively, with ultimate value for shrinkage and creep adjusted to the values at 240 days, which is the approximate amount of experimental data collected, while Figures 63 and 64 show the model predictions out to 5 years, for the adjusted ultimate strains at 240 days to provide a better sense of overall shape and anticipated ultimate strains.

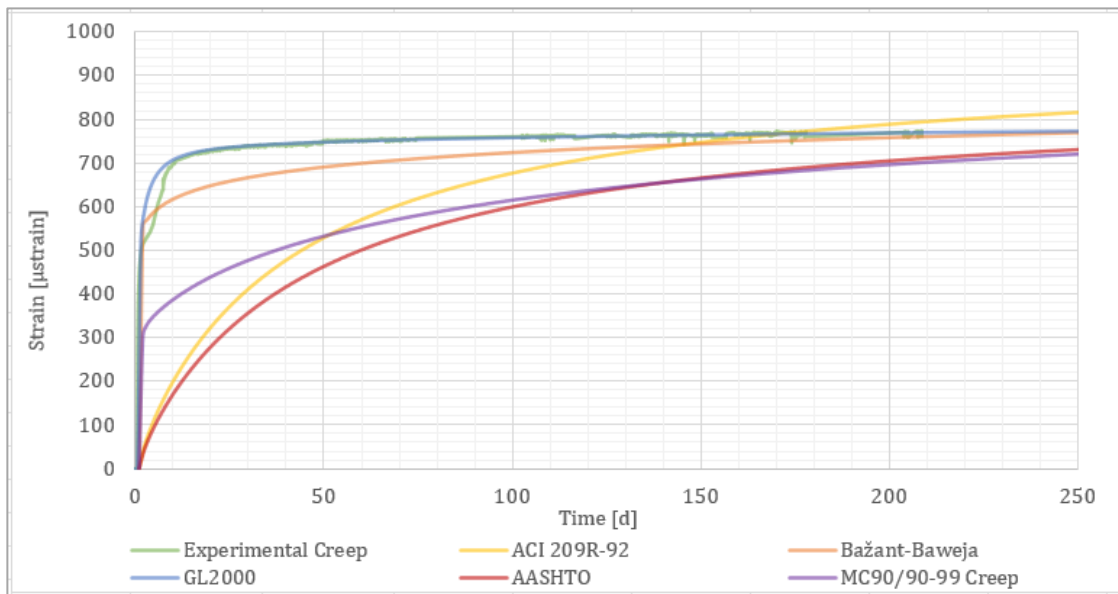


Figure 61: Expansive BCSA Experimental Creep Data vs. ACI 209 and AASHTO Models Using Adjusted Ultimate Values Out to 250 days.

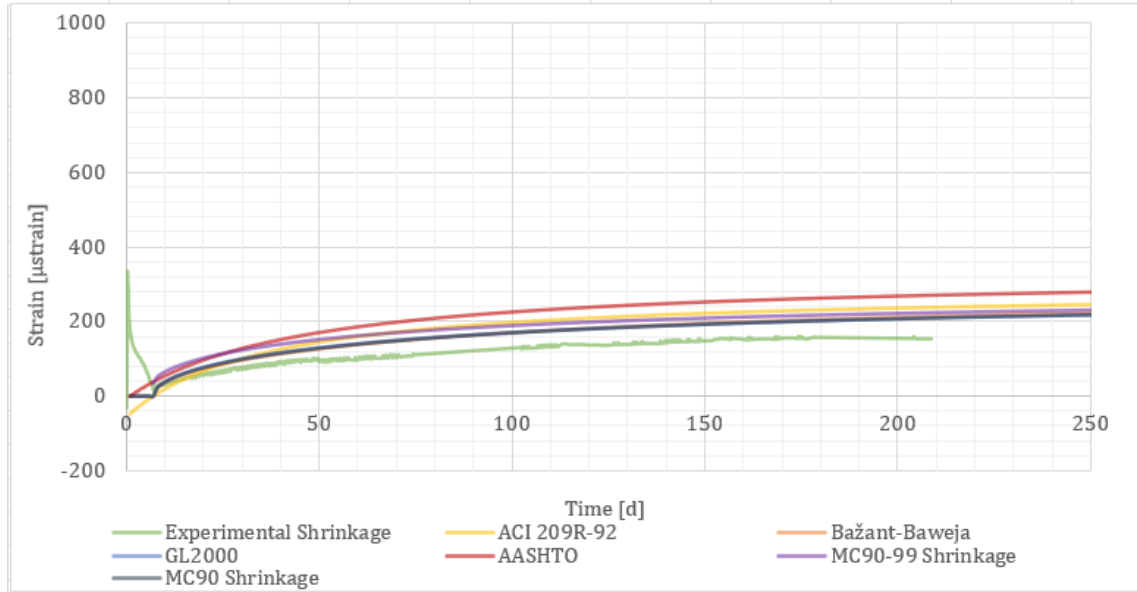


Figure 62: Expansive BCSA Experimental Shrinkage Data vs. ACI 209 and AASHTO Models Using Adjusted Ultimate Values Out to 240 Days

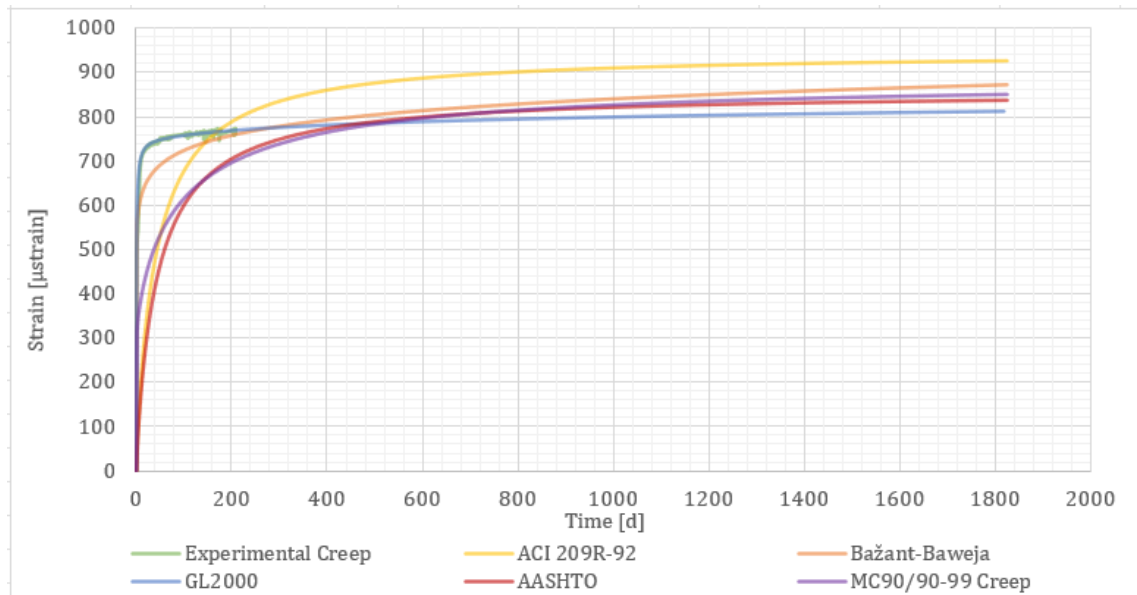


Figure 63: Expansive BCSA Experimental Creep Data vs. ACI 209 and AASHTO Models Using Adjusted Ultimate Values Out to 5 years.

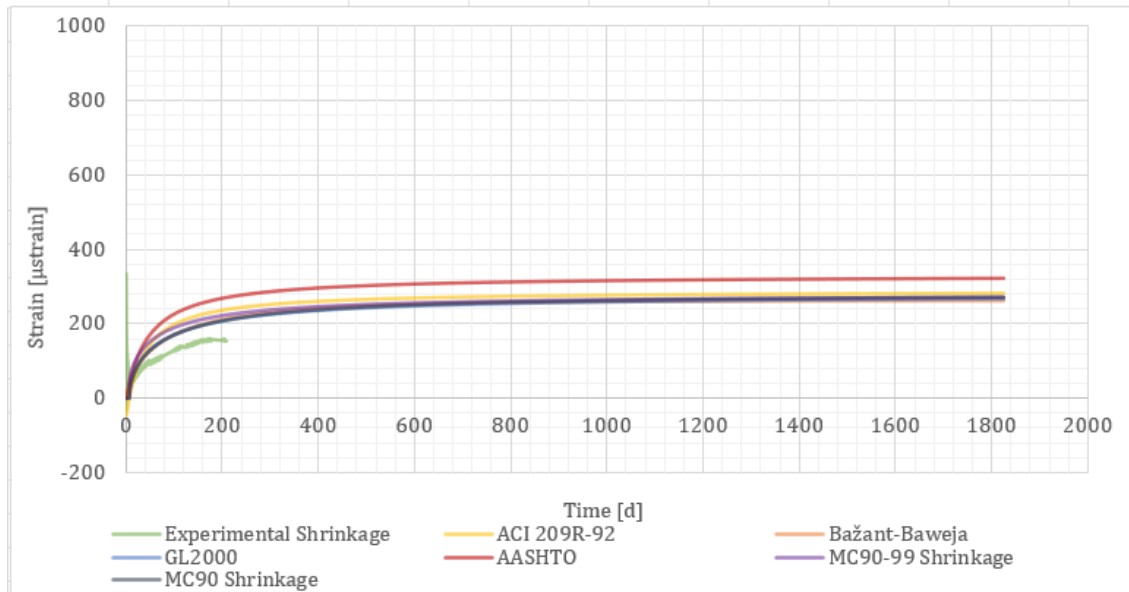


Figure 64: Expansive BCSA Experimental Shrinkage Data vs. ACI 209 and AASHTO Models Using Adjusted Ultimate Values Out to 5 years.

No model effectively accounts for expansion potential of cements and are intended to only predict shrinkage. However, the shrinkage models are recalibrated, taking the final value after initial expansion as a zero point, the models generally yield reasonable results, though they all do still provide an overestimate. For the expansive BCSA, the MC90 model yields a reasonable approximation whether adjusted for ultimate values or not, while adjusting for ultimate values yields similarly reasonable approximations of the shrinkage curve for both the GL2000 and Bazant B3 models. On the other hand, the creep behavior is not realistically predicted by any model; most models appear to implicitly consider loading to only occur after the end of wet curing. This neglects some prestressing applications, and particularly the ability to predict creep behavior in expansive cements used for chemical prestressing. In fact, the most visually accurate curve in shape is the GL2000 model, however it is the most explicit about this

assumption, suffering from the limitation that the suggested creep coefficient function does not have a defined case for loading prior to the end of wet curing. Therefore, while all other models are only adjusted by changing the ultimate strain value or coefficient, in the GLI2000 model this is overcome by an additional adjustment, translating the curve to the load time as well as adjusting the ultimate creep values. In fact, these two adjustments combine to yield a curve with accurate predictions of the measured data. However, this second adjustment really represents a fundamental reworking of how the GLI2000 model assesses creep.

Similarly, Figures 65 and 66 depict the model predictions for creep and shrinkage of 25% Type K cement concrete based on measured mechanical properties.

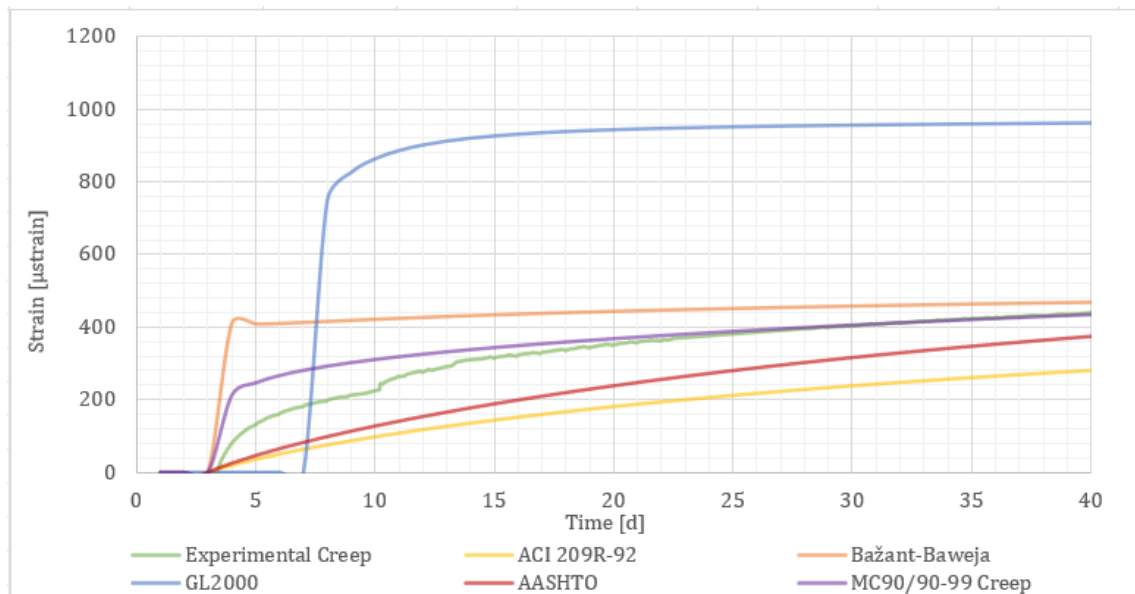


Figure 65: 25% Type K CSA Experimental Creep Column Results vs. AASHTO and ACI 209 Model Predictions to 40 days

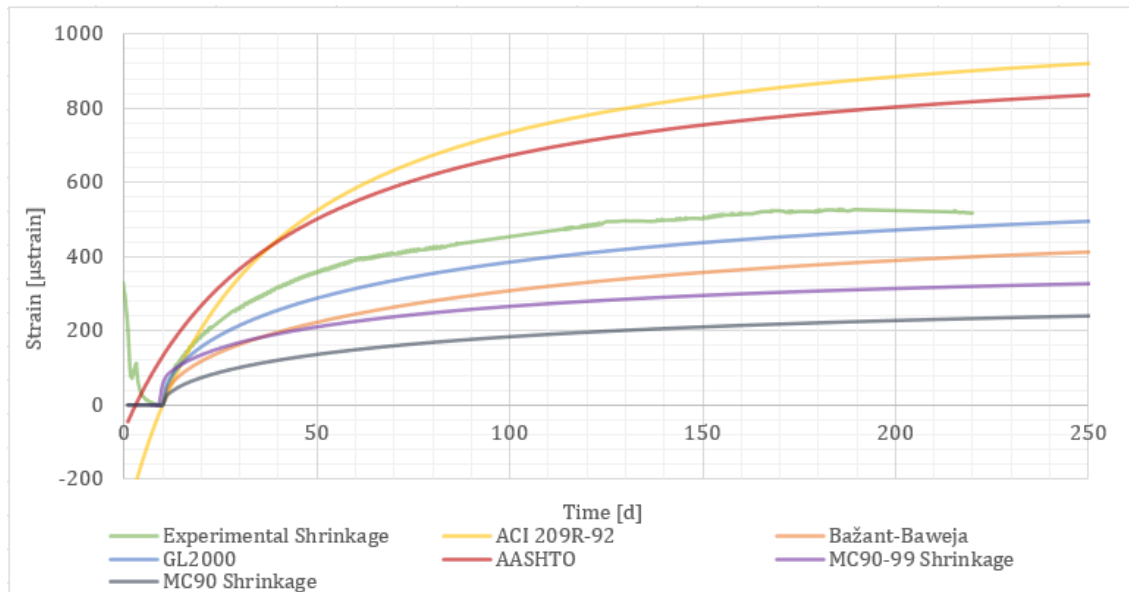


Figure 66: 25% Type K CSA Experimental Companion Shrinkage Results vs. AASHTO and ACI 209 Model Predictions to 250 days

For the Type K cement concrete, both the shrinkage and creep models yield results of reasonably accurate magnitude. Experimental results fall squarely between the predictions of the majority of the models, which is realistic considering variations in assessing the time progression of creep and shrinkage behavior. Moreover, after the end of the expansion period, the curvature and shape of almost all of the shrinkage models are reasonably similar to the experimental shrinkage behavior over time, though experimental shrinkage does appear to level off slightly faster than models predict. The creep curve shape does not follow any of the models particularly well in the short term, despite the models effectively bounding the magnitude of creep strain development, however beyond full strength development at 28 days the creep development follows the MC90 model almost exactly, as seen in Figure 67.

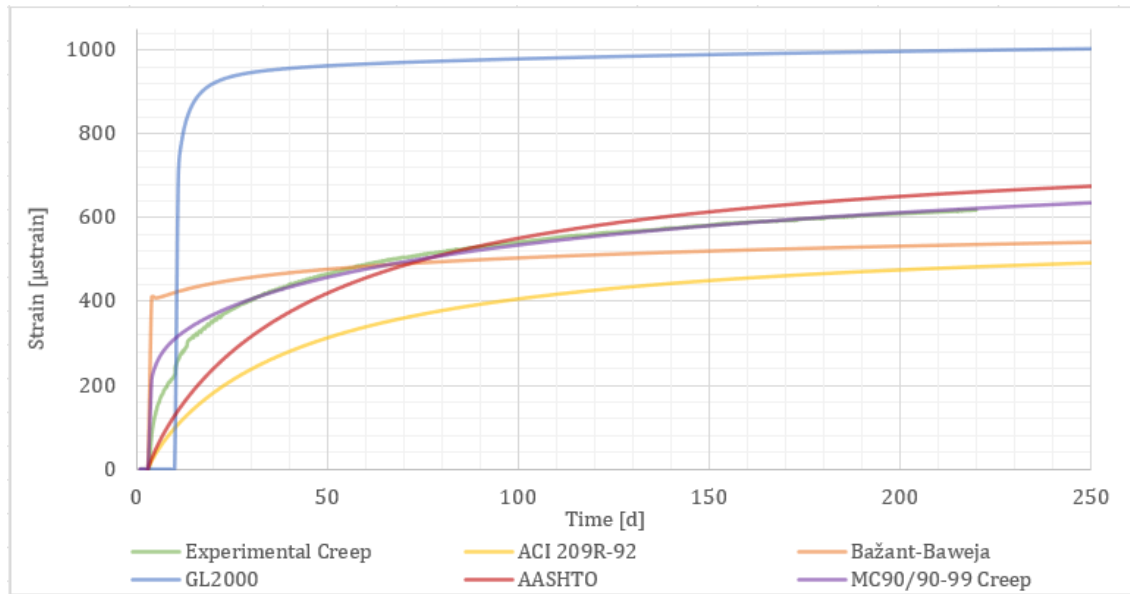


Figure 67: 25% Type K CSA Experimental Creep Column Results vs. AASHTO and ACI 209 Model Predictions to 250 days

Therefore, in general, the shrinkage models do not account for the effects of expansion during wet curing but have a reasonable shape for the rate of shrinkage strain development afterwards. For the Type K additive cement, the magnitude of predictions is fairly accurate, while for the BCSA, which exhibits far less shrinkage than portland cement concretes, the approximate magnitude can be adjusted for by using more suitable ultimate strain values or coefficients.

On the other hand, creep behavior shows far more deviation from model predictions which fail to capture either shape of development or magnitude for expansive BCSA and fail to capture the initial shape for the type K additive cement. While correcting ultimate strains can better control the magnitude of strain predictions, capturing shape, particularly early on, is difficult.

4.2.4 Temperature Effects on Slump Loss and Workability

It is notable that CSA cements are more temperature sensitive than conventional portland cements and have shorter working times. The manufacturer of the Type K cement used in this study for example suggests retardation at higher temperatures and recommends not placing any concrete more than 90 minutes after mixing. Similar to the research by Roswurm (2023) with non-expansive BCSA cements, a temperature study was crucial to assessing sensitivity to retardation and temperature changes on workability and set time to characterize the expansive BCSA cement sufficiently for large scale and field applications. Moreover, during the mechanical property evaluation, it was seen that the expansive BCSA cement was more sensitive than either its solely rapid setting BCSA or solely expansive Type K counterparts. The creep column specimen using expansive BCSA for example was cast on a rainy day while most prior mixes had been cast during drier, warmer weather. Even though one previous trial had been done at a similar, albeit warmer, temperature range, and a 20% reduction in citric acid dosage was made to approximate less extreme setting conditions, the creep specimens still took an additional 2.5 hours to gain sufficient strength to be ground and loaded. Therefore, the expansive BCSA concrete was tested at 10°F intervals, with a 3.5°F tolerance across the range of 40 to 90°F. The results of slump loss testing, taken at 15 minute intervals for the various temperature increments, is shown in Figures 68-73.

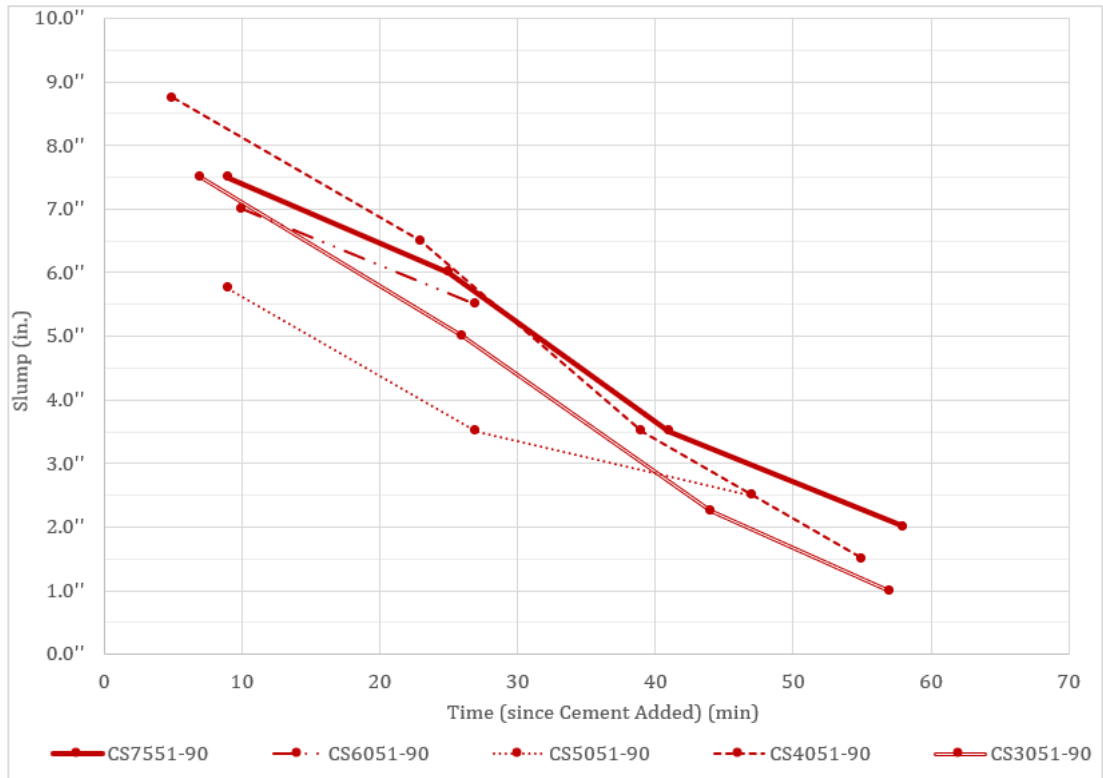


Figure 68: Expansive BCSA Slump Loss at 90°F

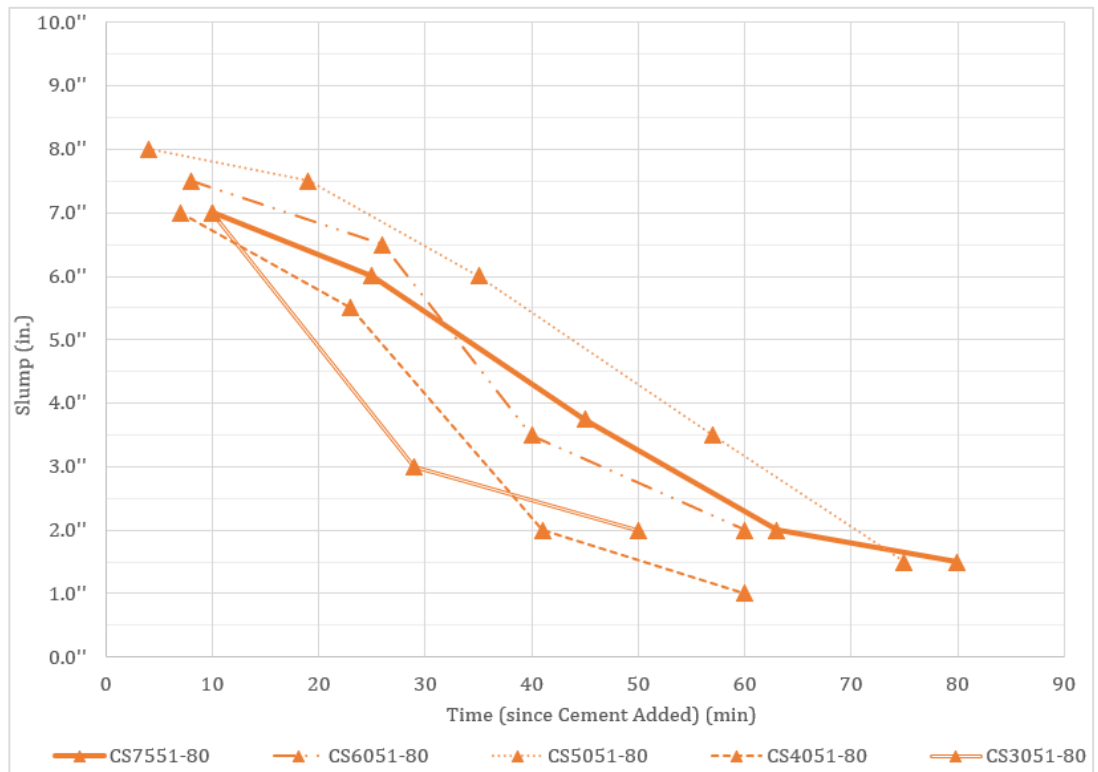


Figure 69: Expansive BCSA Slump Loss at 80°F

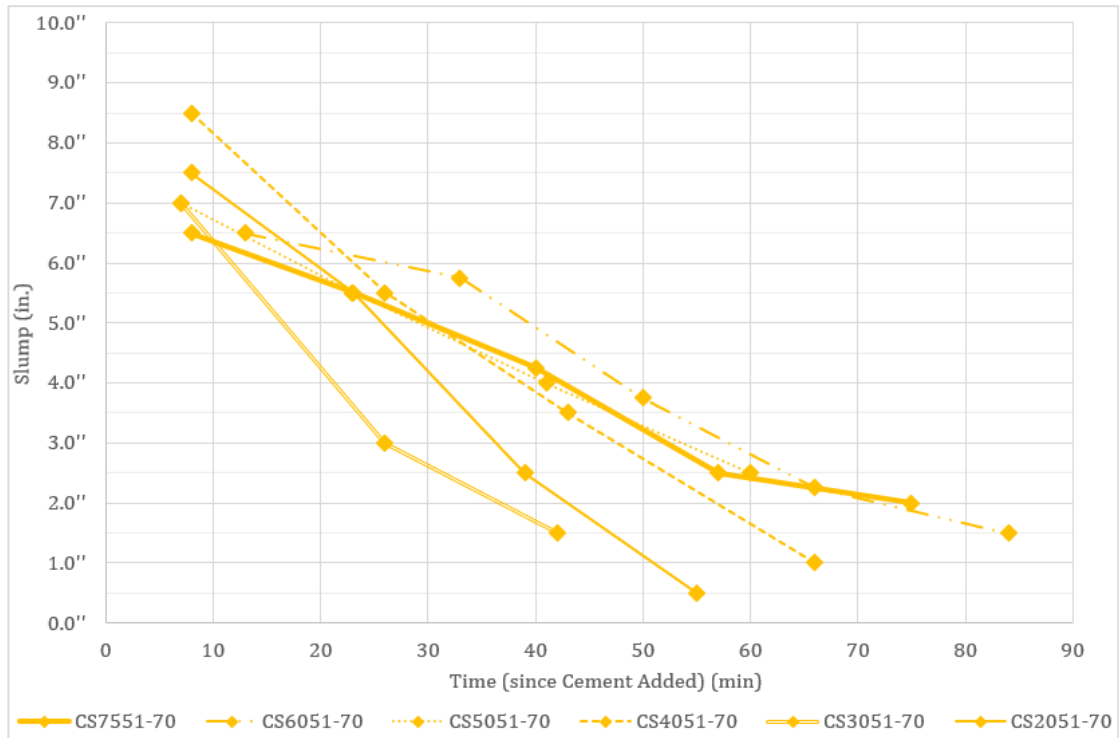


Figure 70: Expansive BCSA Slump Loss at 70°F

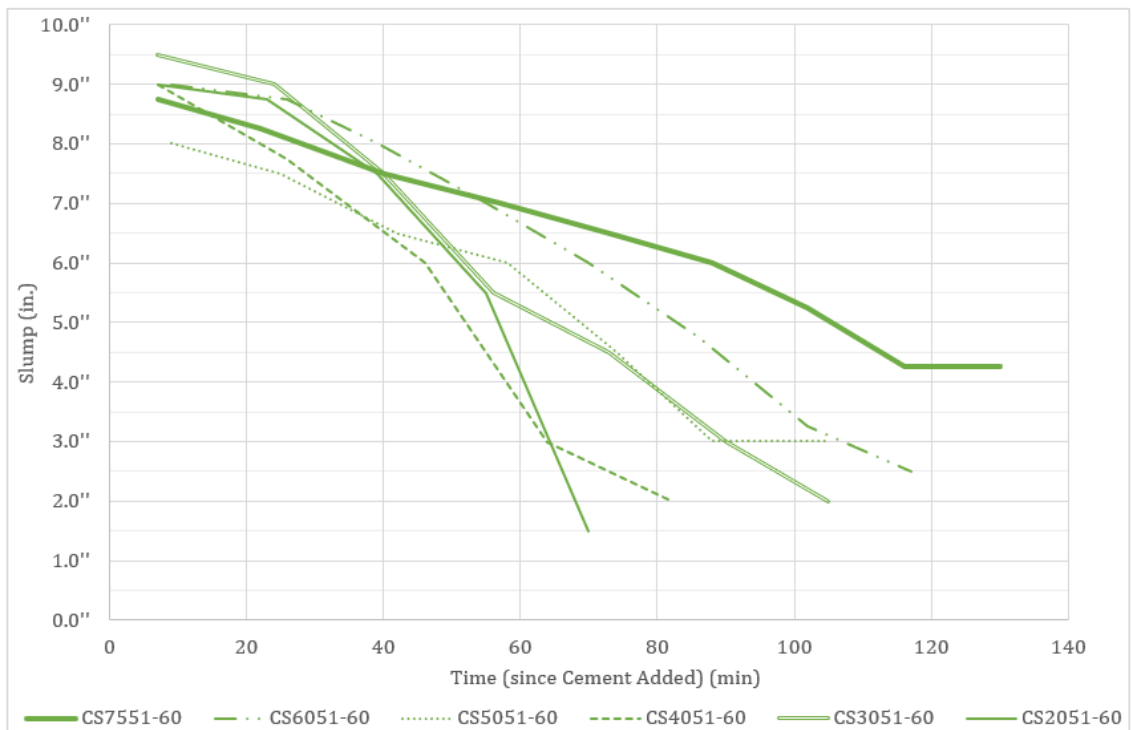


Figure 71: Expansive BCSA Slump Loss at 60°F

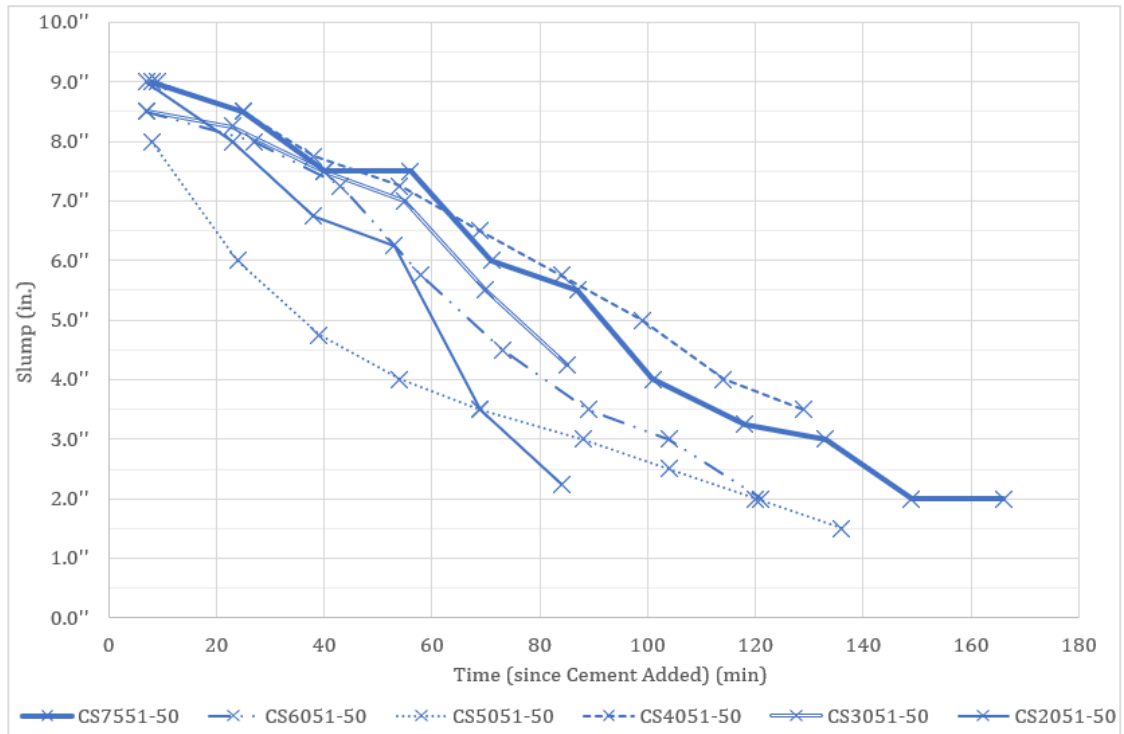


Figure 72: Expansive BCSA Slump Loss at 50°F

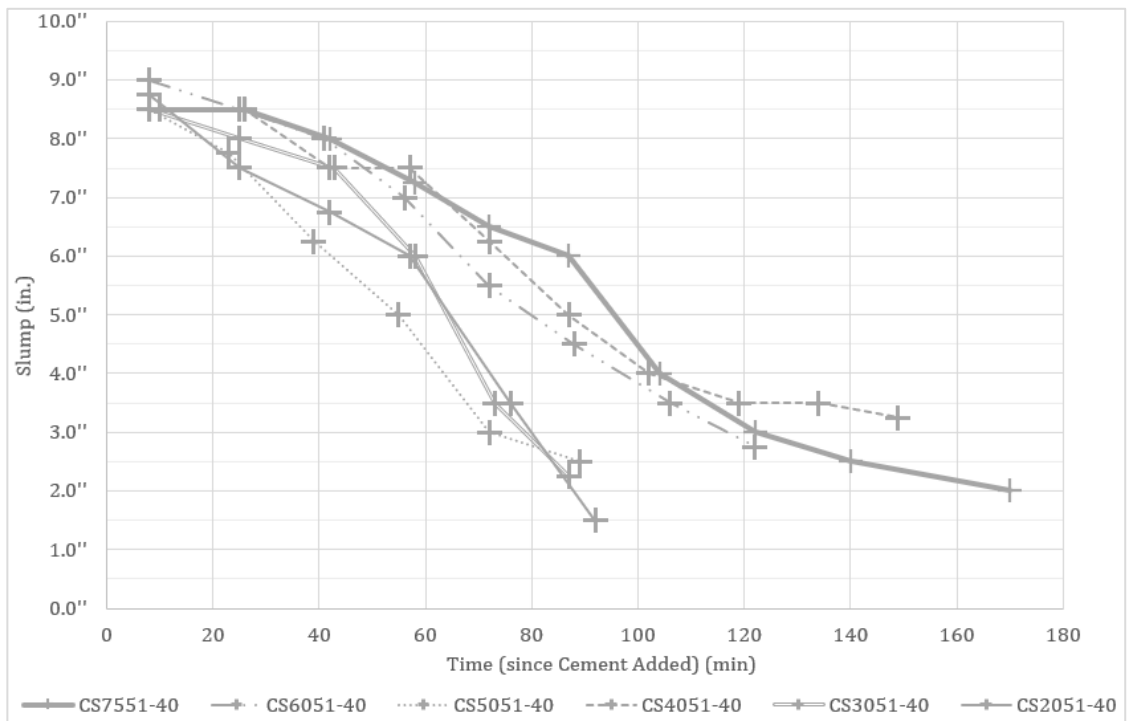


Figure 73: Expansive BCSA Slump Loss at 40°F

As these mixes were conducted in ambient outside conditions for a more realistic assessment of field conditions, additional factors such as cloud cover or humidity and rainy condition were not accounted for, solely the shade temperature was used to characterize environmental condition ranges. Thus, there is some variation in initial slump, however it is still generally within the target of 7.5 ± 1.5 inches. Therefore, the working time estimates are still reasonable, and rates of slump loss are relatively consistent. In particular, most mixes in the 70°F range and below were conducted in the morning while temperatures were rising so some of the latter increments greater than 90 minutes or so after casting may have been taken at temperatures exceeding the intended temperature range.

Nonetheless, there is a clear trend that temperature significantly affects the working time as measured by slump loss. For the temperature ranges of 40°F and 50°F, the working time approaches three hours for higher dosages of citric acid. Whereas for the upper extremes of the temperature study, in the 90°F range, loss of workability occurred in under an hour even at the highest dosage of 0.75% citric acid by cement weight. Collectively, the final working time as measured by slump loss and approximate slump loss rate, measured in inches per hour, are listed in Table 20. However, this does not fully explain the inconsistency in variation of slump loss, that is seen by superimposing the curves from each of the temperature ranges, as shown in Figure 74.

Table 20: Working Time and Slump Loss Rate with Varying Temperature and Citric Acid Dosages

			Temperature Range					
			90°F	80°F	70°F	60°F	50°F	40°F
Citric Acid Dosage (% cwt)	0.75%	Working Time (min)	58	63	75	130	133	140
		Slump Loss Rate (in/h)	-6.73	-4.71	-4.03	-2.20	-2.88	-2.74
	0.60%	Working Time (min)	43	60	66	117	121	122
		Slump Loss Rate (in/h)	-5.29	-6.35	-4.23	-3.61	-3.42	-3.29
	0.50%	Working Time (min)	47	65	60	82	120	89
		Slump Loss Rate (in/h)	-9.08	-5.49	-5.09	-3.13	-3.05	-4.44
	0.40%	Working Time (min)	47	41	54	82	134	154
		Slump Loss Rate (in/h)	-8.70	-6.79	-7.76	-5.60	-2.75	-2.27
	0.30%	Working Time (min)	44	50	35	105	100	87
		Slump Loss Rate (in/h)	-7.80	-7.50	-9.43	-4.59	-3.27	-4.75
	0.20%	Working Time (min)	---	---	39	65	84	84
		Slump Loss Rate (in/h)	---	---	-8.94	-7.14	-5.26	-5.18

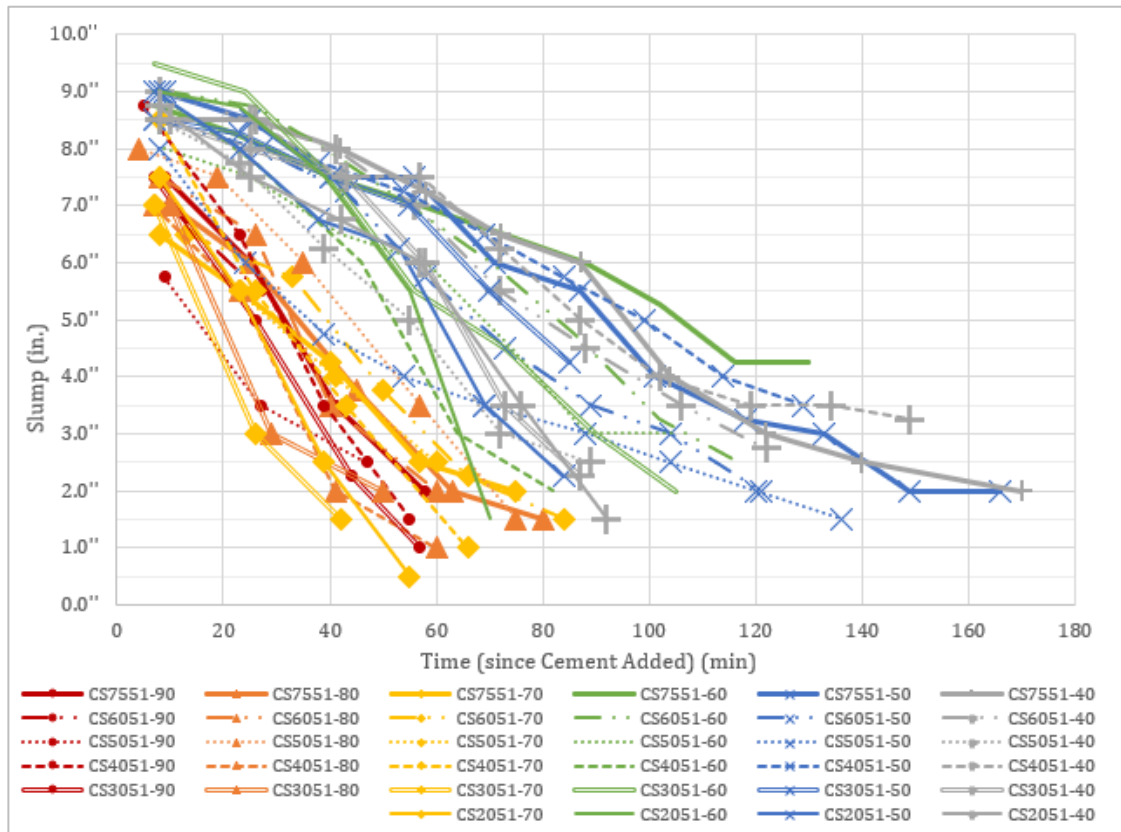


Figure 74: Superposition of Expansive BCSA Temperature Range Variation Curves

While there is some increase in working time as temperature decreases between 90°F and 70°F, it is small relative to the variation in working time over the ranges, or the change in working time from 70°F to 60°F or 60°F to 50°F. Rather than a function of ambient temperature, the temperature effects on working time far more closely correlate to internal temperature. When the temperature curves are color-coded instead by internal concrete temperature, as in Figure 75, the clustering of data becomes far more apparent.

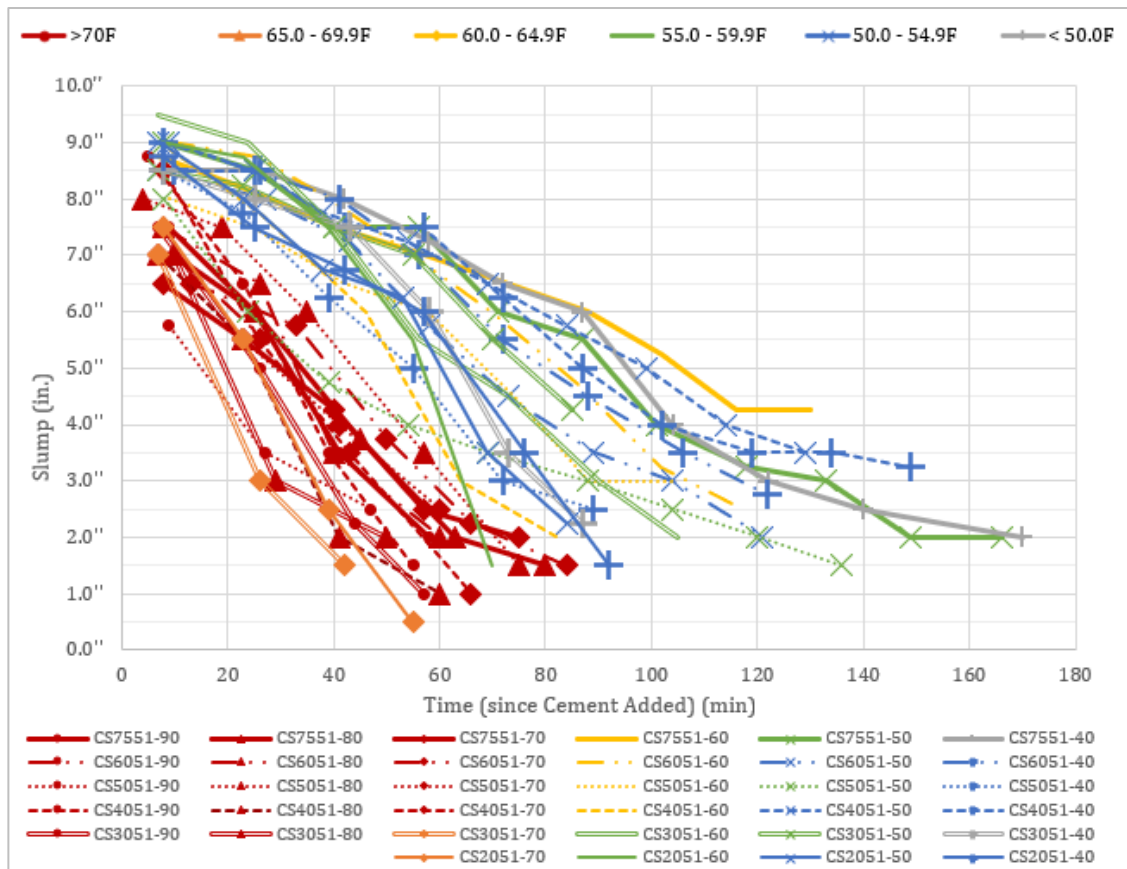


Figure 75: Expansive BCSA Temperature Range Variation Curves Color-Coded Based on Internal Temperature

In fact, the effect of internal temperature is even more significant than the amount of retardation; above an internal temperature of $\sim 65^{\circ}\text{F}$, working time even under the most extreme retardation cases can only extend working time to a maximum of 90 minutes under the best circumstances after the addition of cement, while mixes with low amounts of retardation having working times as short as 45 minutes. Below this threshold temperature, however, even the mixes with the lowest dosage of citric acid approach 90 minutes of working time, with the shortest recorded measurement being 75 minutes. Mixes with high doses of citric acid retarder consistently holding for at least two hours before falling below 2 in. of slump, with the most extreme cases holding for 2.5 to almost 3 hours. Most indicative of this behavior is the variation within the set of mixes at 60°F where the mix with a 0.20% citric dosage performs worse than some of the mixes with temperatures above the 65°F threshold, while the 0.75% mix outperforms all other mixes. This was further validated by adding ice to a mix at the 90°F temperature range to suppress the internal mix temperature, shown by the ice-blue line in Figure 76.

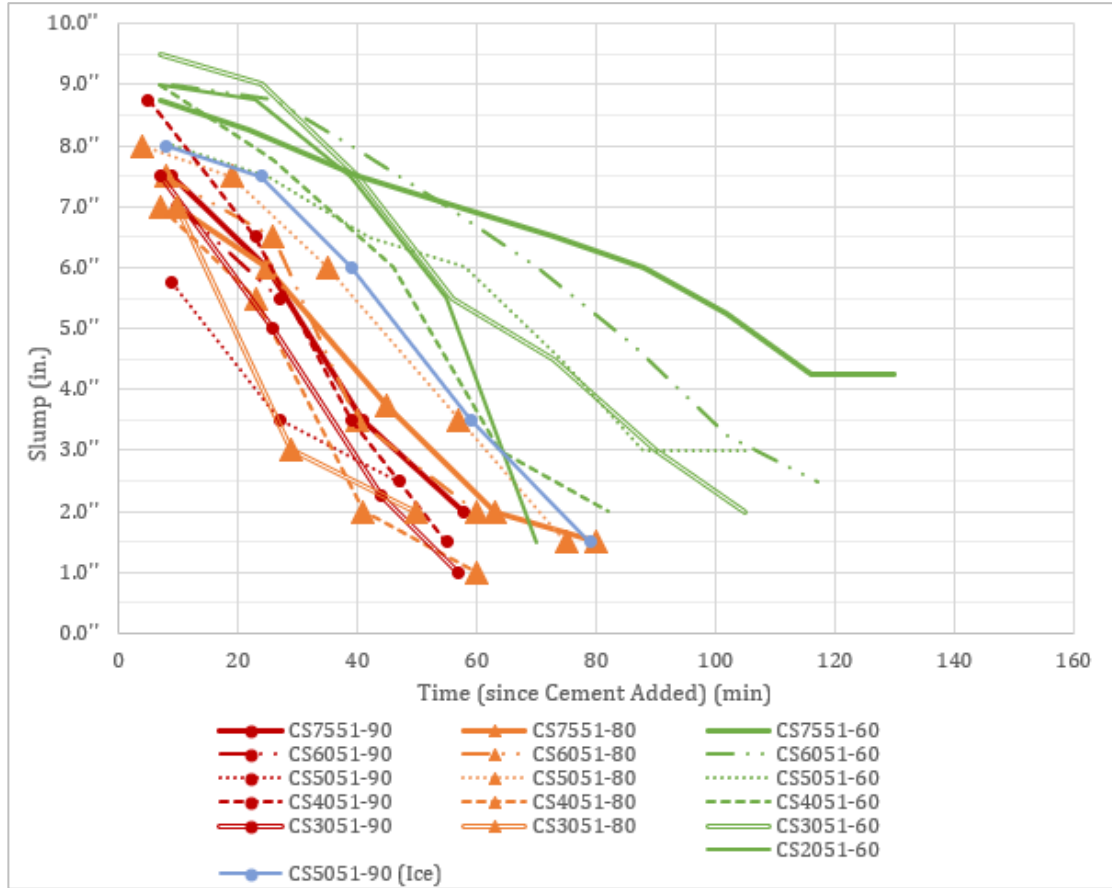


Figure 76: 90°F Expansive BCSA Cement Mix, with 0.50% Citric Acid, Suppressed to Internal Temperature of 65.5°F, Compared to 90, 80 and 60°F Temperature Ranges.

This mix outperforms every mix not only within its own 90°F range, but within the 80°F range despite having only two-thirds of the maximum citric dosage at 0.50%. In fact, based on slump loss rates, it initially follows closely with the 0.50% mix at 60°F before diverging and accelerating, ostensibly due to the ambient temperature effects. Despite this, it is still basically comparable to the 0.40% at 60°F mix in terms of working time.

Conversely, temperature elevation has little to no impact on working time. Figure 77 shows two 0.50% citric mixes, one at 49°F, heated with 88°F mix water, and one at 37°F heated with 115°F mix water.

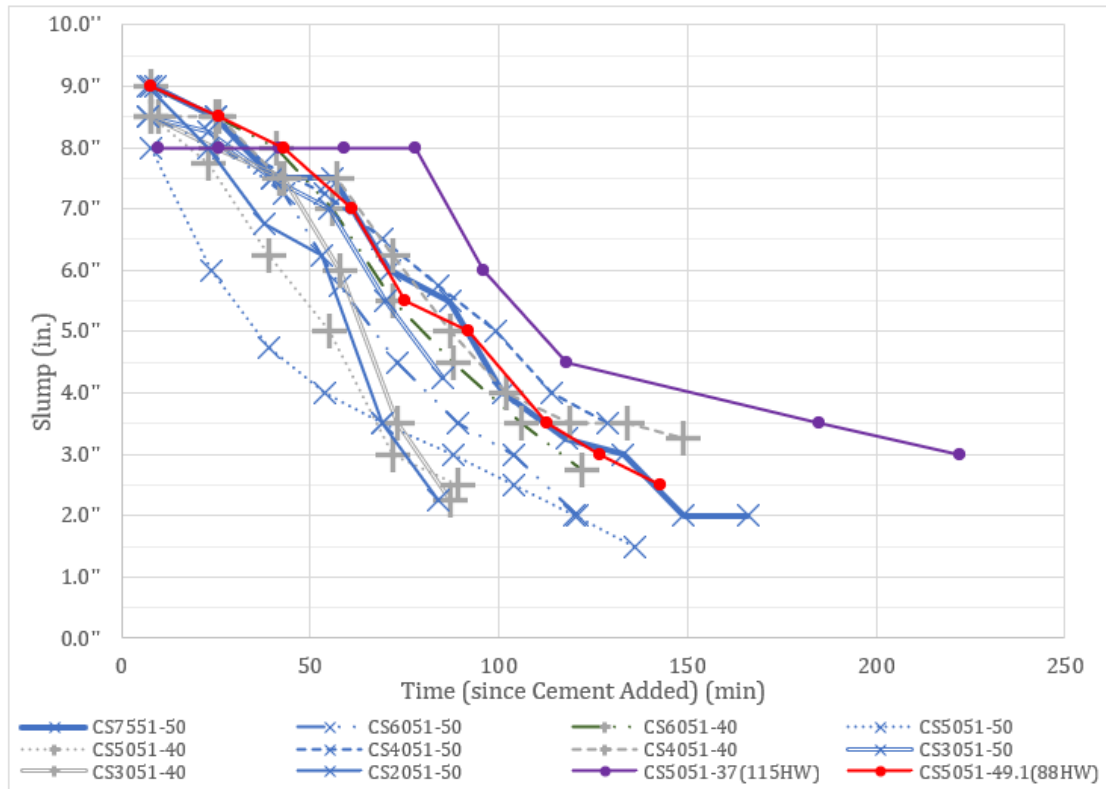


Figure 77: 0.50% Citric Acid, 49°F Expansive BCSA Cement Mix, Heated with 88°F Hot Water, and 37°F Expansive BCSA Cement Mix, Heated with 115°F Hot Water Compared with 40 and 50°F Temperature Ranges.

Additionally, the 40°F and 50°F temperature increments are shown, and the results of heating led to little reduction in workability relative to unheated mixes at similar conditions. The 37°F mix represents the most extreme condition tested, as 40°F and rising is generally considered the minimum temperature for mixing. As expected, it demonstrates far greater working time relative to any of the conventional ranges, which is beneficial for placement, but may also inhibit set.

Slump data alone is a rather inaccurate assessment of working time as the expansive BCSA cement was observed to exhibit highly thixotropic behavior even compared to conventional concrete. Even after slump loss reaches 2 in. or less, by adding energy to vibrate the concrete, the concrete can maintain workability for as much as an hour at the lowest temperature ranges of 40 and 50°F. Figure 78, for example shows a slump cone from one such mix approximately 2h after mixing; while the concrete in the cone only registered a 2 in. slump, the concrete in the scoop, having been vibrated has returned to a more workable state than that slump implies.



Figure 78: 2" Slump of Expansive BCSA Concrete at 2h after Cement Addition, vs Vibrated Scoop of Concrete.

Moreover, while this effect decreases with increasing temperature, vibration still has an impact of 20-30 minutes at higher temperature range of 80°F. Only the 90°F range

shows no effect because the loss of slump at extremes of high temperature ranges is accompanied by initial set.

Finally, based on observations of during the trial mix stage that increasing w/c ratio over 0.50 vastly decreased slump loss, with one mix at a w/c ratio of 0.52 holding 9 in. slump for an hour and a half at 100°F, a set of mixes were conducted varying the dosage of HRWR. To assess this, the 0.60% citric acid mix at 60°F was chosen as a mix with sufficient retardation and a low enough temperature that effects from changing the dose should predominate any variation. These results are plotted in Figure 79, with the other mixes in the 60°F range placed for reference.

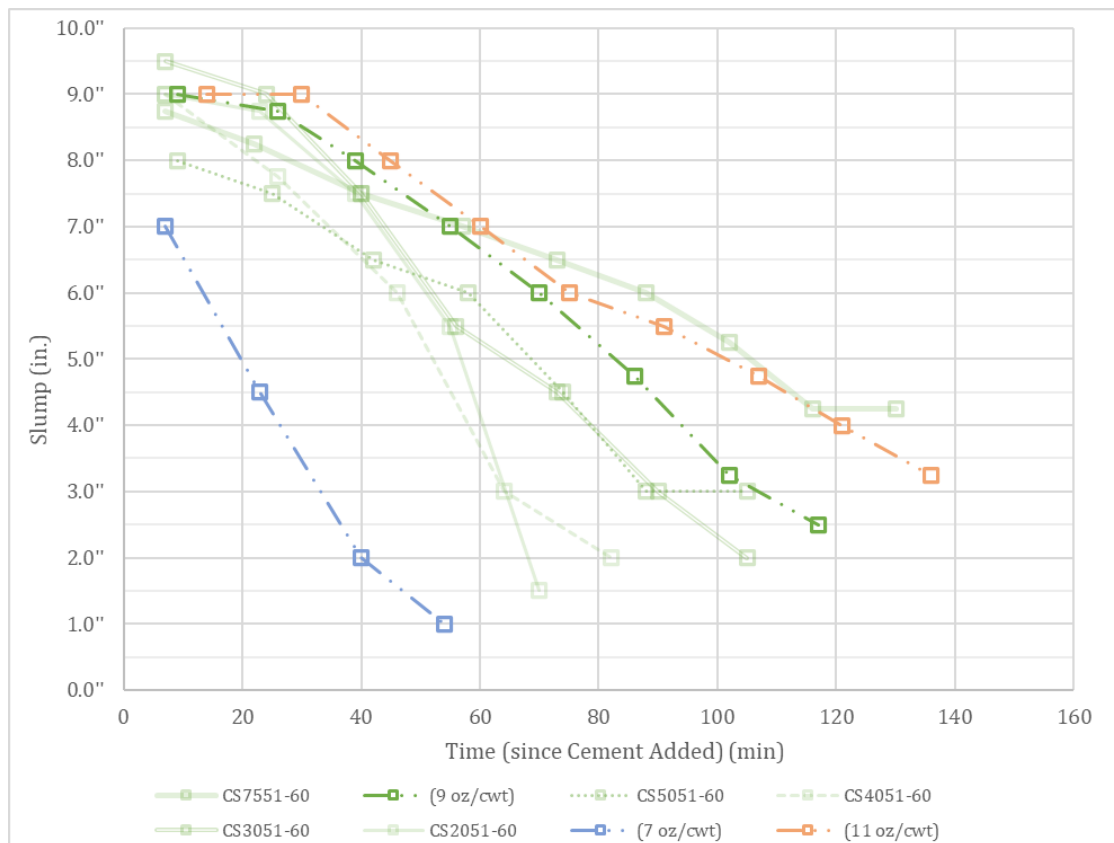


Figure 79: Effect of Varying HRWR Admixture on Slump Loss and Working Time

The dosage of HRWR has a significant effect on working time. The addition of 2 oz/cwt shows an increase in working time of over 30 minutes extending the time taken to go from 3-¼ in. of slump from 102 minutes for the 9 oz/cwt baseline to 136 minutes for the 11oz/cwt dosage. But even more pronounced is the reduction of HRWR. A value of 9oz/cwt was originally chosen because it was the lowest dosage that provided sufficient workability, so it is not surprising that there is lower slump at the lowered 7oz/cwt increment. What is surprising, however is that not only is the initial slump much lower, but the slump loss rate, sharply increases, taking only 40 minutes to reach 2-inch slump versus 120 minutes for the 9oz/cwt mix. Even considering the lowered starting slump, this represents an increase in the slump loss rate of 113%, from 3.6 in/h to 7.7 in/h. Furthermore, the sensitivity to vibration is significantly more pronounced as well; directly after completing the last slump test at the 140-minute mark, there is an even more marked difference in the consistency of the concrete after being vibrated, as shown in Figure 80. The 11oz/cwt mix on the left has returned to an almost liquid state, whereas, the 9 oz/cwt mix does recover workability, but only partially returns to a gelatinous state.



Figure 80: Consistency of Mixes with 11oz HRWR (left) and 9oz HRWR (right) after Final Slump Cone 3" Measurement and Being Vibrated.

4.2.5 Temperature Effects on Set Time

The slump loss mix matrix was also used to assess set time, with both calorimetry and ASTM C403 testing by penetration resistance performed for the 80°F range, and solely calorimetry performed at other temperatures due to ease of use, and ability to sample more frequently. Penetrometer readings were taken every 15 minutes to yield before interpolating to yield the curves in Figure 81 and values in Table 21. Additionally, the 90°F, 0.50% citric mix with ice was also tested by penetrometer and calorimeter to determine effects of temperature suppression on set time.

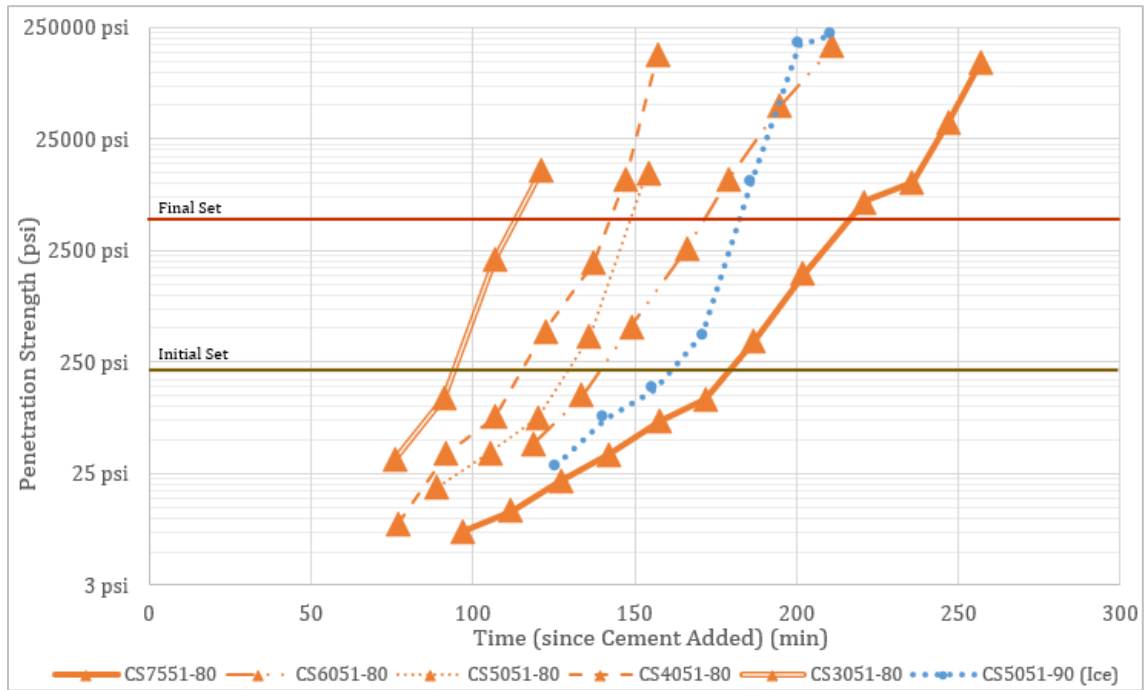


Figure 81: Set Time Curves of 80°F Specimens by Penetrometer, and 90°F Specimen with Temperature Suppressed Using Ice.

Table 21: Set Time of 80°F Expansive BCSA Mixes Based on Penetrometer.

80°F Citric Dosage	Initial Set (min)	Final Set (min)
0.75%	177	214
0.60%	137	170
0.50%	126	143
0.40%	112	141
0.30%	92	111
0.50% with Ice	161	176

As can be seen above, while dosing with citric acid showed limited effect on slump loss, it shows a significant effect on extending set time. Excluding the interval from 0.40% to 0.50%, every successive increment of citric acid dosage adds 15-20 minutes to

the initial set and 30 minutes to the final setting time, while the mix that had its internal temperature suppressed performed between 1 and 2 dose increments better.

However, penetrometer-based setting values were found to not accurately assess the specimen set time. Penetrometer specimens were demolded within 10 minutes of measured final set by inverting the bucket used to cast the specimen and lightly tapping the bottom to get the specimens to release from the greased bucket. Using this procedure, stress cracks were consistently observed around the circumference as shown in Figures 82-84, marking a division between concrete that had hardened at the surface and concrete still setting up at the bottom of the bucket. This was noted to increase in depth with decreasing citric acid dosage. In the most extreme case, the unset bottom portion actually split apart, shown in Figure 85.



Figure 82: Angled View of Demolded Penetrometer Specimen Cracks



Figure 83: Damage to Bottom of Partially Set Demolded Penetrometer Specimens

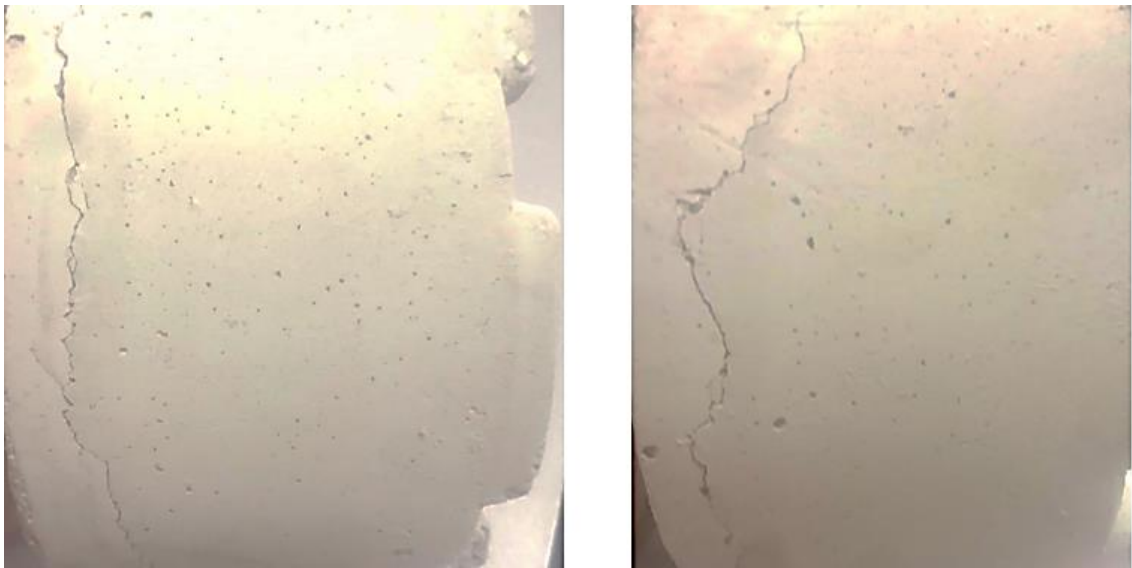


Figure 84: a, b: Side Views of Cracking of Penetrometer Specimens during Demolding



Figure 85: Splitting of Partially Set Bottom Portion of 0.30% Penetrometer Specimen

Therefore, while the penetrometer results generally plotted onto the calorimeter heat gain curve at the inflection point where heat gain began to spike, the point of actual set was known to be later. Calmetrix (2014), who manufactured the calorimeter used for this research recommends taking 1/3 of the peak heat generation from the dormancy period (relatively flat initial slope) to the peak heat generation as the set point, in accordance with ASTM C1753 Appendix X1.4 procedures. This is further corroborated based on observations of one set of penetrometer specimens that were not fully set at demolding and could be visibly seen heating up significantly over about 40 minutes while hardening. Based on this method for identifying the final set of the calorimeter specimens from their heat gain curves, the set time curve series in Figures 86-91, were developed. Because internal temperatures variations exceeded 20°F, and ambient temperature in the calorimeter fluctuated, initial set values varied over a more than 30°F range. For more effective analysis these curves were all zeroed to the starting

temperature after the internal calorimeter temperature stabilized, i.e. the plots show temperature change from this initial value. Raw data for each set of curves without this correction is available in Appendix 1: Raw Calorimetry .

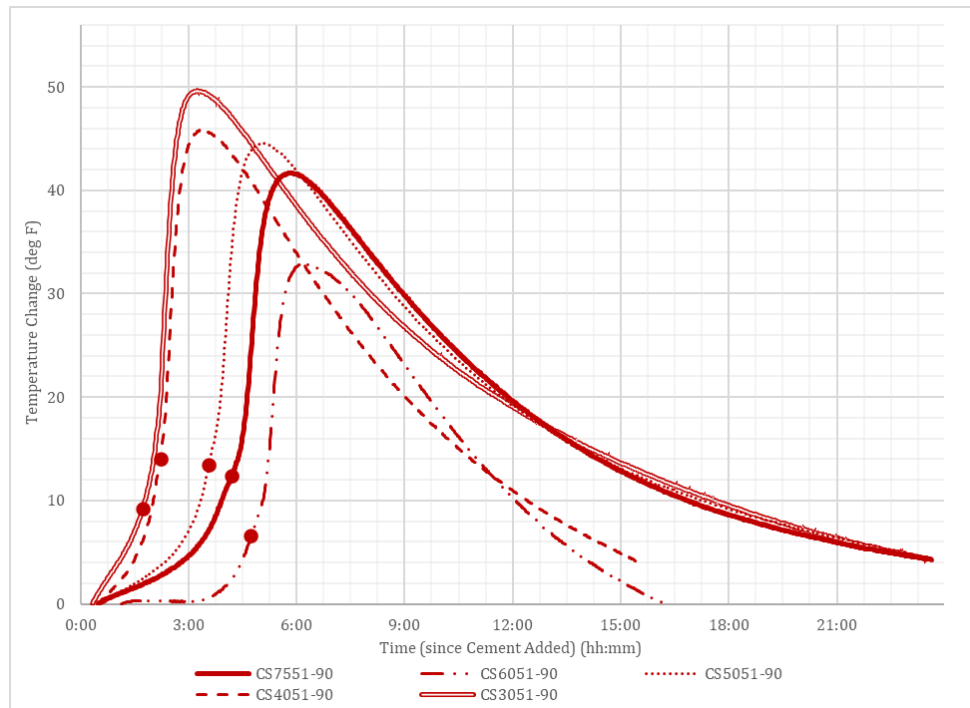


Figure 86: Temperature Setting Curves at 90°F

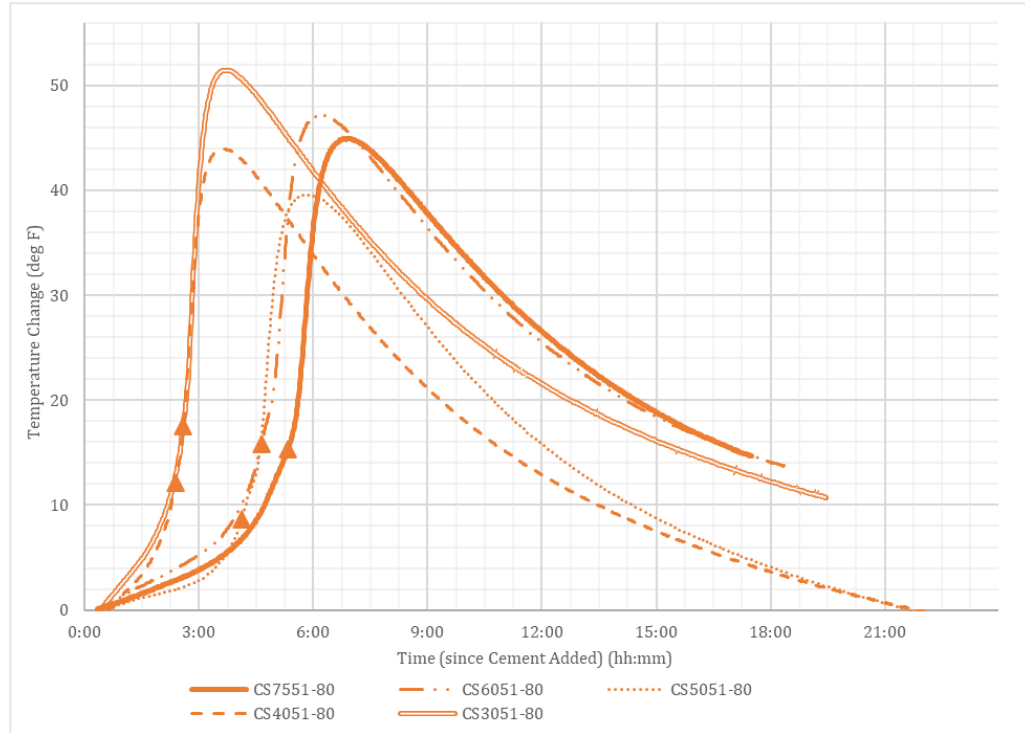


Figure 87: Temperature Setting Curves at 80°F

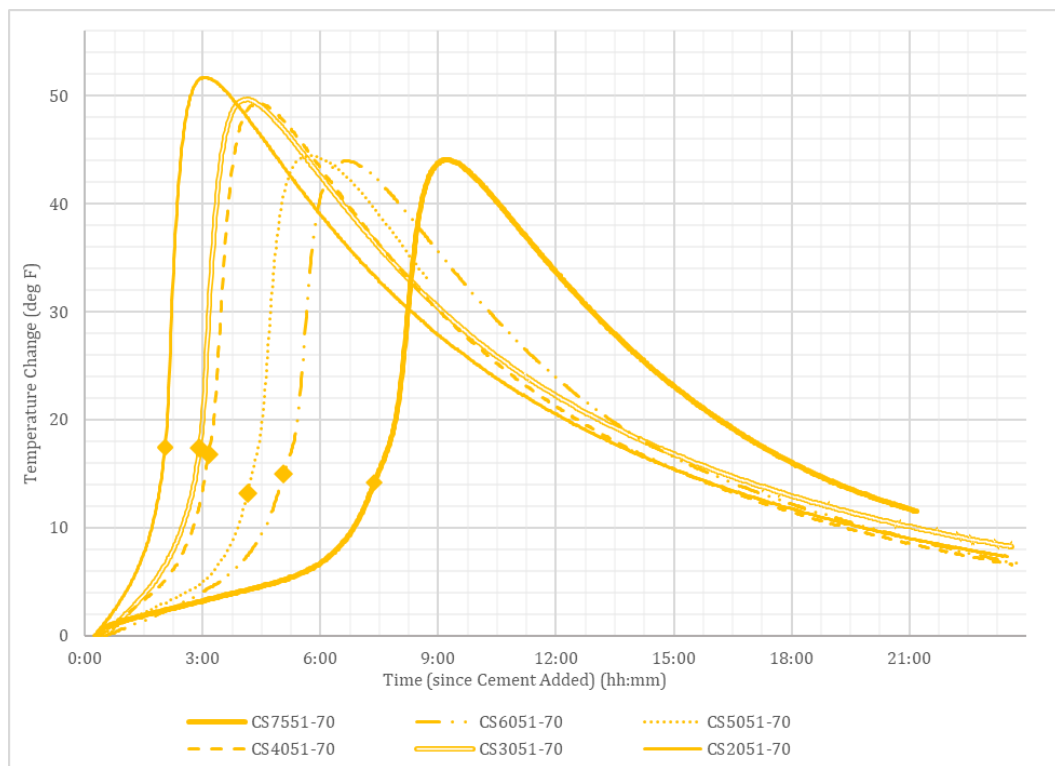


Figure 88: Temperature Setting Curves at 70°F

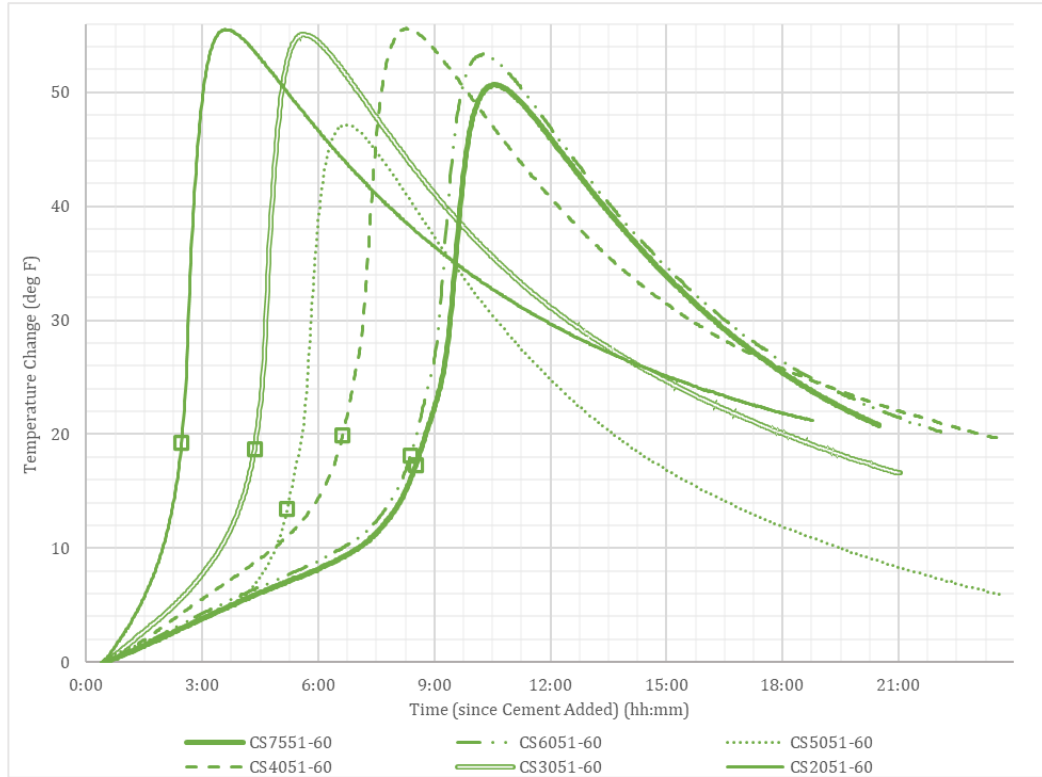


Figure 89: Temperature Setting Curves at 60°F

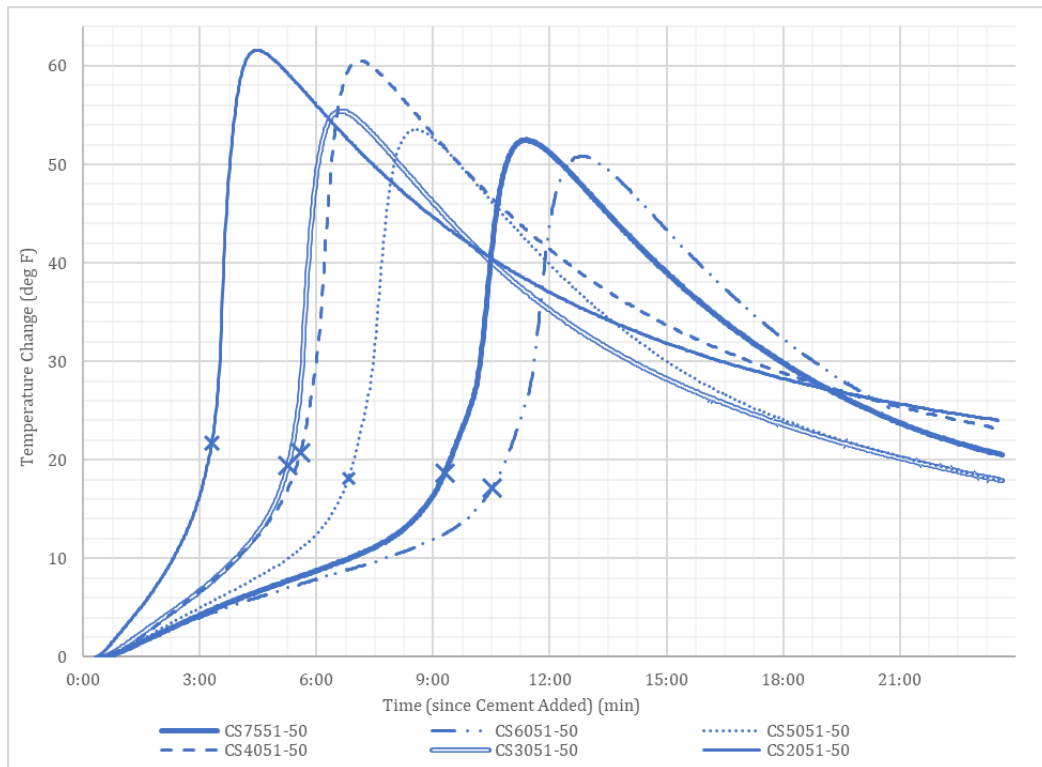


Figure 90: Temperature Setting Curves at 50°F

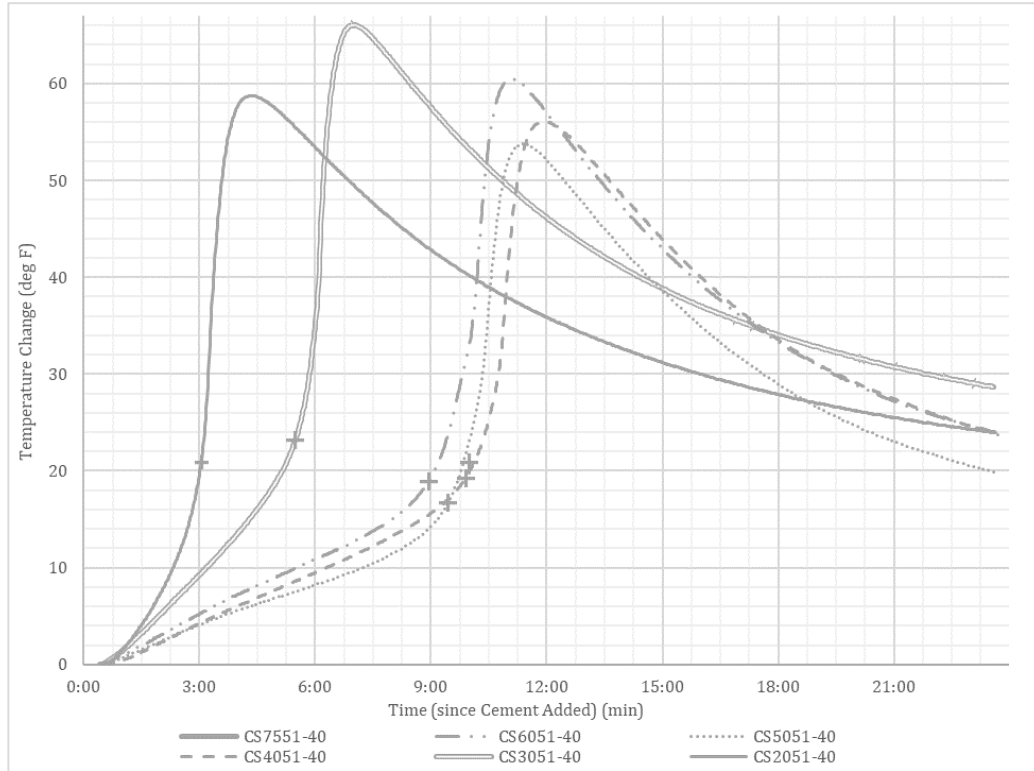


Figure 91: Temperature Setting Curves at 40°F

As noted with slump loss behavior, irrespective of ambient temperature, the internal temperature of the concrete fell between 50°F and 75°F, which highlights interesting trends in the setting behavior of these mixes. For ambient temperatures falling in this range, the effect of adjusting the citric dosage is fairly consistent between increments, with the timing of set and peak heat basically changing linearly with respect to dosage. Outside of this functional range, however, the mixes start to cluster together, which indicates the existence of a threshold dosage of citric acid retarder that is approximately 0.50% for temperatures above the functional range, and 0.30% for temperatures below it.

These curves of the set times at each temperature range are plotted as shown in Figure 92, the trends are even more clear. Above the 70°F temperature range, there is a significant increase in setting times above 0.50% citric acid retardation, but very little difference in effectiveness for dosages below, which can be seen even more clearly in Figure 93. Additionally, for all mixes below 0.75%, there is only a small difference in set time with changes in ambient temperature at 70°F and above, but ambient temperature leads to significant increases in setting time below 70°F.

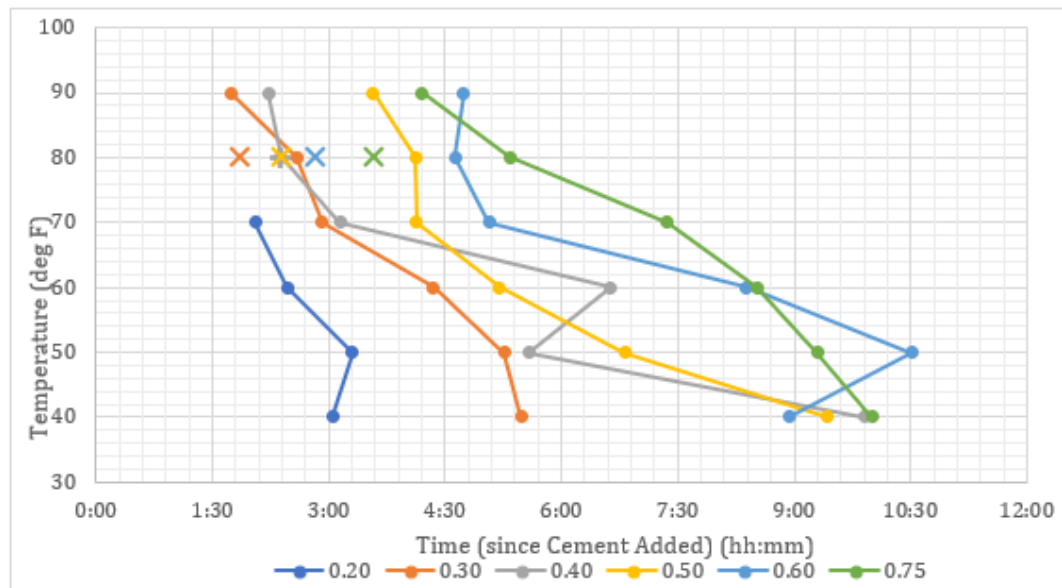


Figure 92: Set Time vs. Ambient Temperature at Different Citric Dosages, with "X"s Marking Penetrometer Results

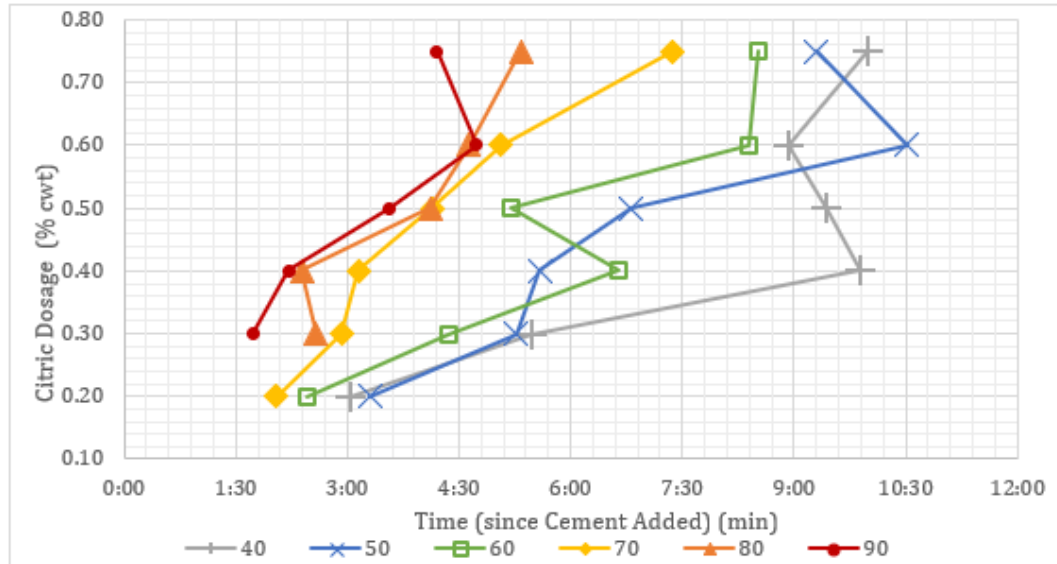


Figure 93: Citric Acid Dosages vs. Set Time for Various Ambient Temperature Ranges

A few key observations can be made. First, except for the 40°F mixes, the set time approximations from this method are all at least 40% larger than those determined penetrometer results and the percentage of increase grows with increasing citric dosage. This is reasonable, as the depth of the observed cracking in the sides of the demolded penetrometer specimens decreased with increasing citric dosage. In other words, less of the concrete mass sets as the citric dosage increases, so the penetrometer result would be a less accurate measurement of set time. Second, there are clear thresholds for both temperature and citric acid dosage. The set times for mixes above 70°F ambient temperature all begin to cluster irrespective of citric acid dosage, as shown in Figure 93. Increasing the dosage is not particularly effective in extending set time below approximately 0.50%, demonstrated by the near overlap of the 0.40% and 0.30% curves in Figure 92. The jump from 0.20% to higher dosages appears to be more a function of insufficient dosage leading to only slight retardation occurring, based observations from

the original mortar cube trials, with an without a nominal citric dosage. In fact, the 0.40% curve shows the greatest effect from changing ambient mix temperature, giving an approximation of what threshold for citric acid retardation dosage should be and leading to the recommendations put forth in Table 22.

Table 22: Recommendations for Citric Acid Retardation Dosages based on Ambient Mixing Temperature.

Temperature Range	Recommended Citric Acid Dosage	
	Minimum Dosage	~6h Set Time Dose
87°F -97°F *	Mixing Not Recommended	
77-86°F	0.75%	0.80%**
67-76°F	0.60%	0.65%
57-66°F	0.50%	0.50%
47-56°F	0.40%	0.40%
38-46°F *	0.30%	0.35%

*No baseline mixes were conducted below 38°F or above 97°F

**estimated

As a result, this further validates the threshold for the functional internal temperature range upper bound being between 60°F and 70°F, with a threshold citric acid retardation dosage falling between 0.40% and 0.50% required for affecting the hardening reactions. Notably, however, there is significant spread in the data as temperature was the only ambient condition controlled, without accounting for cloud cover, wind, or humidity. Therefore, these are general approximations for sunny conditions, whereas it has been observed that these times can be longer under cloudier or high humidity conditions, though the exact degree has not been assessed. Unlike the slump loss behavior, however, internal temperature does not appear to correlate strongly with variations in set time behavior. Figure 94 shows all of the curves superimposed while Figure **Error!**

Reference source not found. recolors those curves according to the same convention as Figure 75.

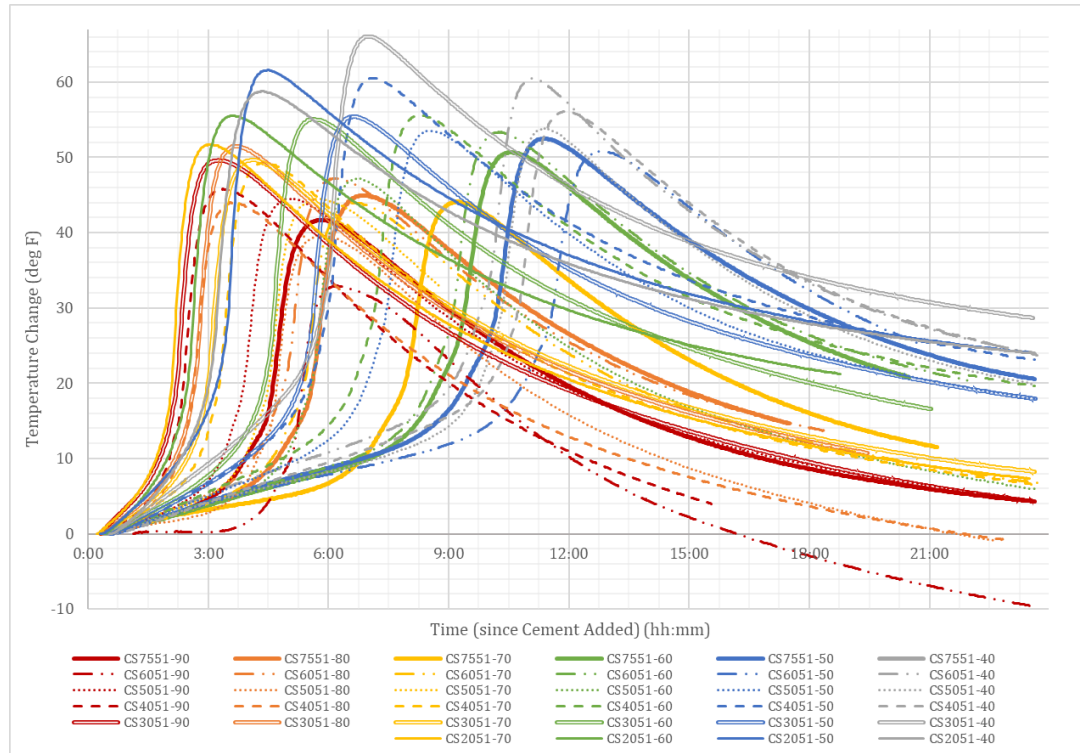


Figure 94: Superposition of Setting Curves and Citric Acid Retardation Mixes in Figures 86-91

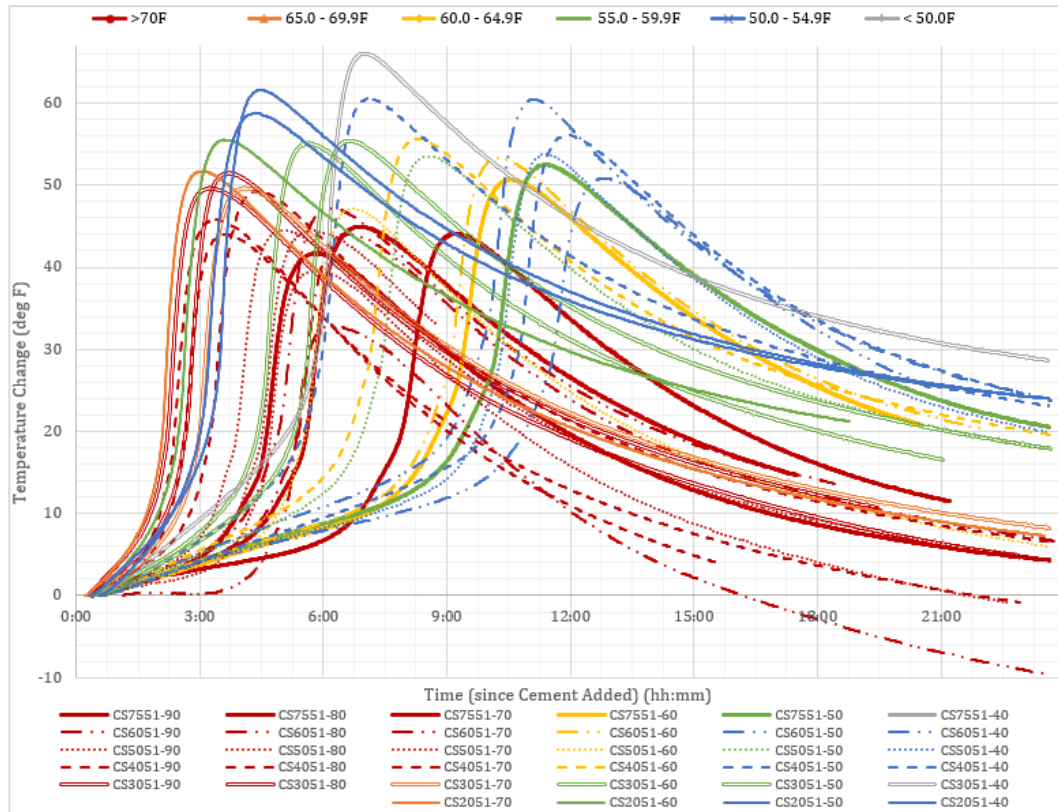


Figure 95: Superimposed Temperature Setting Curves Color-Coded Based on Internal Temperature

The only apparent trend shown by this recoloring is that cooler mixes tend to exhibit a greater heat gain with respect to their hotter counterparts. However, a significant factor is that due to the $\sim 20^{\circ}\text{F}$ range of internal temperatures, cooler mixes tended to start below the ambient temperature of the room where the calorimeter was stored, and gain heat from convection with the enclosed air, while the reverse held for the hotter mixes.

On the other hand, similar to the trends in slump loss behavior, lowering concrete internal temperature also retards behavior. In Figure 96, while the peak heat gain for the temperature suppressed mix does not appear different from unsuppressed mixes, the temperature suppressed mix has a significant increase in the time to final set. Not only

does the mix outperform all of other mixes at 90°F, but it performs almost identical to the performance of a mix one dosage higher at the 80°F temperature range, and comparable to the middle dosages of citric acid for mixes in the functional range.

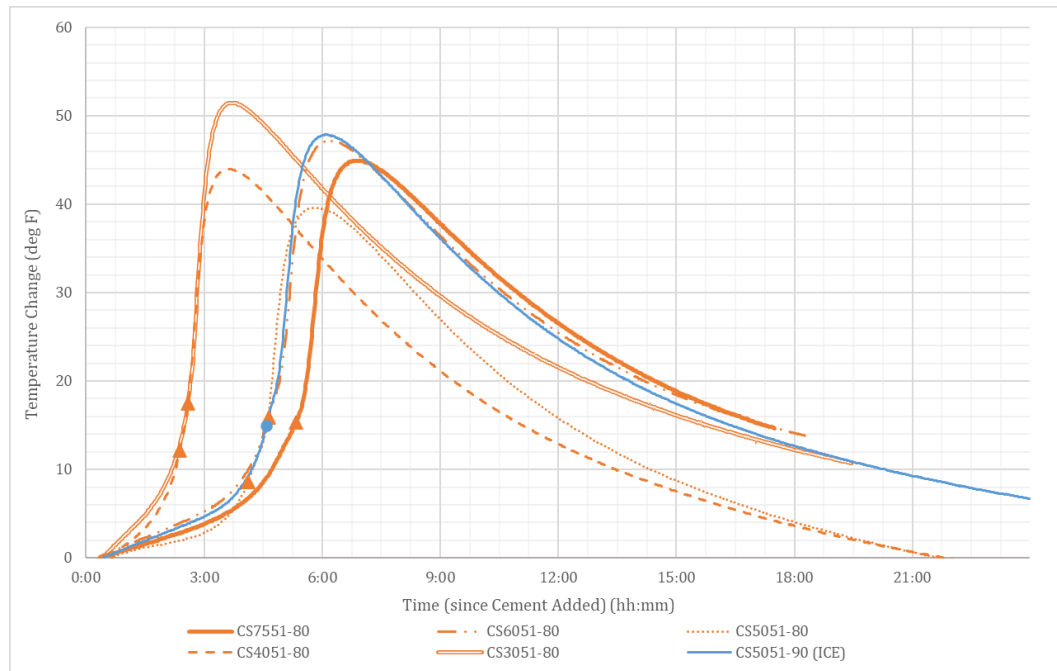


Figure 96: 0.50% Citric, 90°F Mix Suppressed with Ice as Compared to 80°F Heat Gain Curves

Figure 97 demonstrates that this process works in reverse as well, though it seems elevating internal temperature with hot water has less of an effect than internal temperature suppression with ice. The red line is a mix with 0.50% citric conducted at 48°F, the lower limit of the 50°F range, and with internal temperature elevated using 88°F hot water in the mix, the setting behavior exhibited by this mix falls somewhere between the 0.50% and 0.40% mixes conducted at the temperature range below, or the 0.30% citric dosage at the 50°F interval.

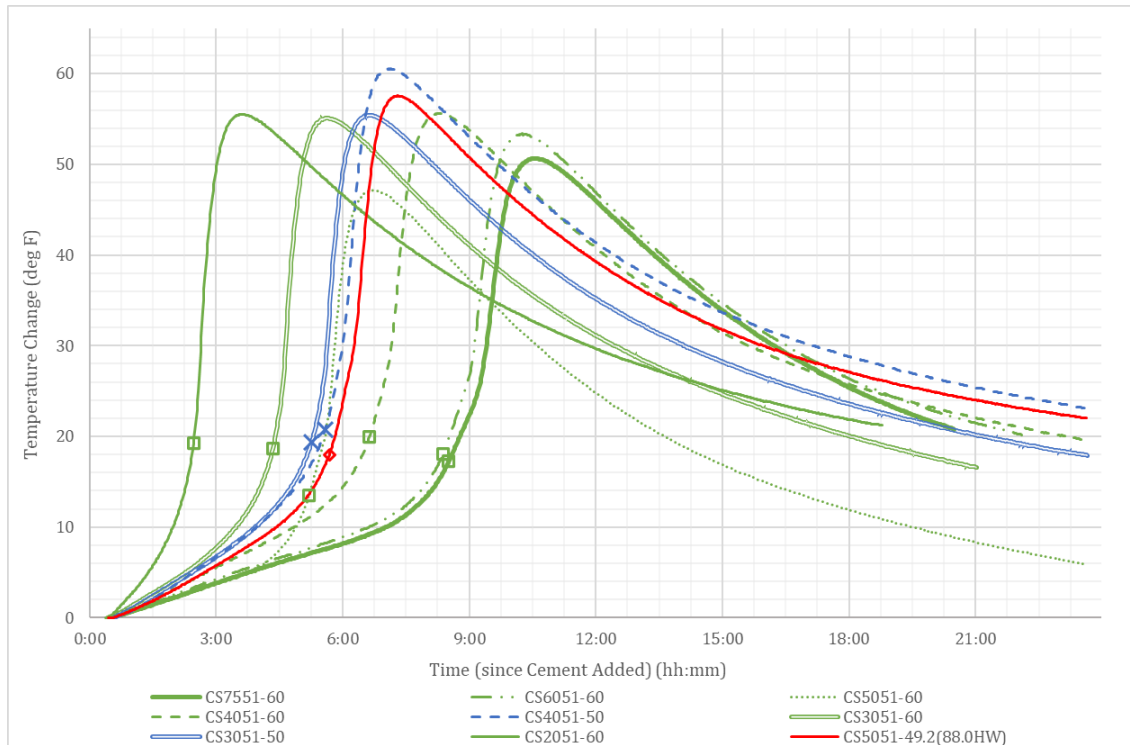


Figure 97: 0.50% Citric, 50°F Interval Mix with Internal Temperature Elevated Using 88°F Mix Water, Compared Against Similar 50°F and 60°F Curves.

Figure 98 shows the 50°F curves with 2 heated mixes; firstly, the same 50°F ambient conditions heated to above this range with hot water at 88°F, and second, a mix in ambient conditions below this range, at 37°F, elevated to 62°F by addition of mix water at 115°F. While this shows a similar trend for temperature elevation of ~10°F, the results are more limited for elevating temperatures to a higher degree, presumably due to convection with ambient conditions rapidly restoring internal temperature to ambient conditions. Consequently, the 88°F hot water mix only performs comparably to a mix with one or two citric dose higher without temperature elevation. The ability to cool mixes using ice is far more effective as ambient conditions must not only warm the

water up but input the necessary latent heat for melting the ice, making cooling mixes more effective than heating them.

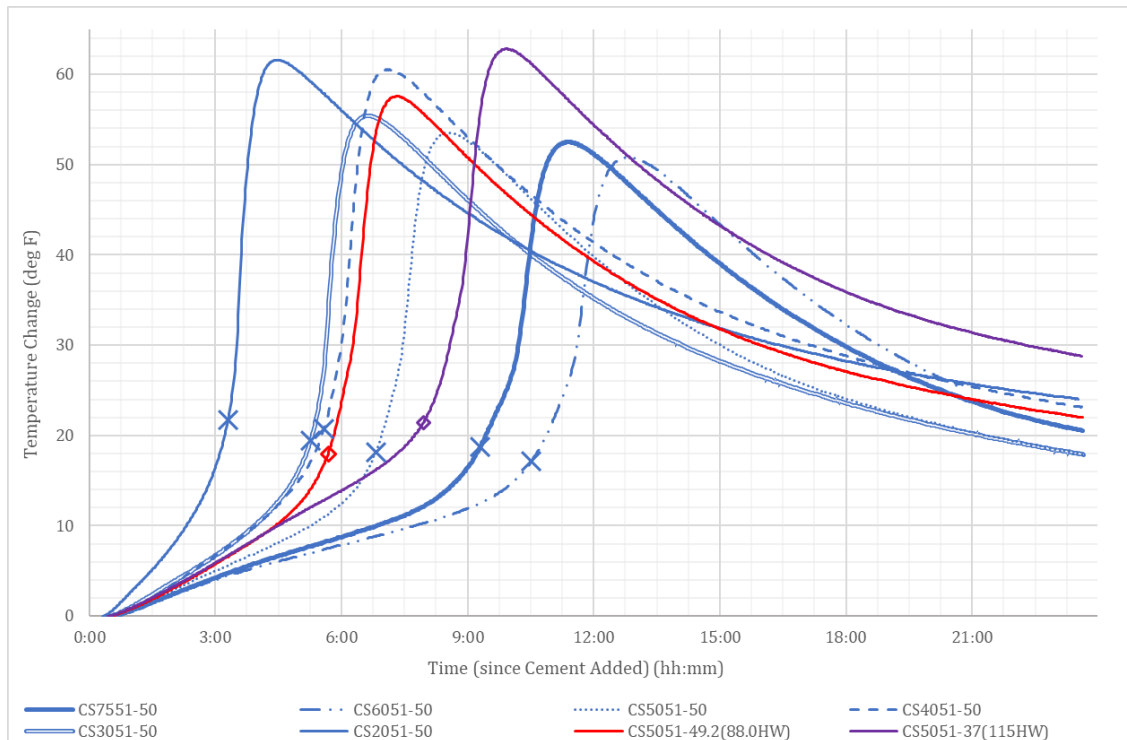


Figure 98: 50F Calorimeter Heat Gain Curves with 2 Mixes Heated above 50 with Warm Water at Various Temperatures.

The target of both mixes was originally for the mix to exceed the presumed threshold temperature of 65°F. The 50°F mix stopped just short of this threshold at 62°F, close enough for some results to be analyzed. However, the significant temperature differential of the 37°F mix cooled the water and mix so quickly, even with preheating the mixer to this target of 65°F just prior to mixing, and it was deemed infeasible. While the 25°F differential between ambient and internal temperature was created initially for this mix, the internal mix temperature dropped to 53°F in just 10 minutes, from after the addition of the cement, to when the first slump test was taken. It returned to ambient

condition 30 minutes after the start of mixing. This again shows that there are limitations to the effectiveness of internal temperature control, especially as the magnitude of induced temperature change increases, though unlike with workability, there was a reduced setting time measured.

This result for both set time and slump loss shows that while the functional range for BCSA concretes poses significant limitations on field usage, particularly in hot environments and the summer months, solely by suppressing internal temperatures it is possible to mitigate this challenge. However, there is still a tighter tolerance on maximum usable temperature than on conventional concrete. Additionally, this shows that the reverse can be used to leverage mixing during particularly colder periods, with some key limitations. First, it is easier to suppress temperature because melting ice can be used, as evidenced by the fact that only 1/3 of the temperature suppressed mix water replaced with ice to yield similar or better results to the elevated temperature mix with all of the water at 90°F. Second, these results likely predict unconservative, shorter set times for cooled mixes, and overconservative, longer times for heated mixes, because the calorimeter is nearly isothermal, whereas field tracking of internal temperature during the companion slump loss testing showed that the temperature returned to the unregulated range within 45 minutes to an hour after mixing at ambient conditions. This may particularly affect the 37°F mix under constant conditions, which may have inhibited set, but at least demonstrates that elevating mix temperature under such a borderline condition when temperatures are expected to rise can be beneficial, to accelerating set without affecting working time.

Alternatively, the other test method for extending and regulating field workability was increasing the dosage of HRWR, which was promising for not only increasing initial workability, but also reducing the slump loss rate. However, the result with respect to set time, shows a different trend, as seen in Figure 99.

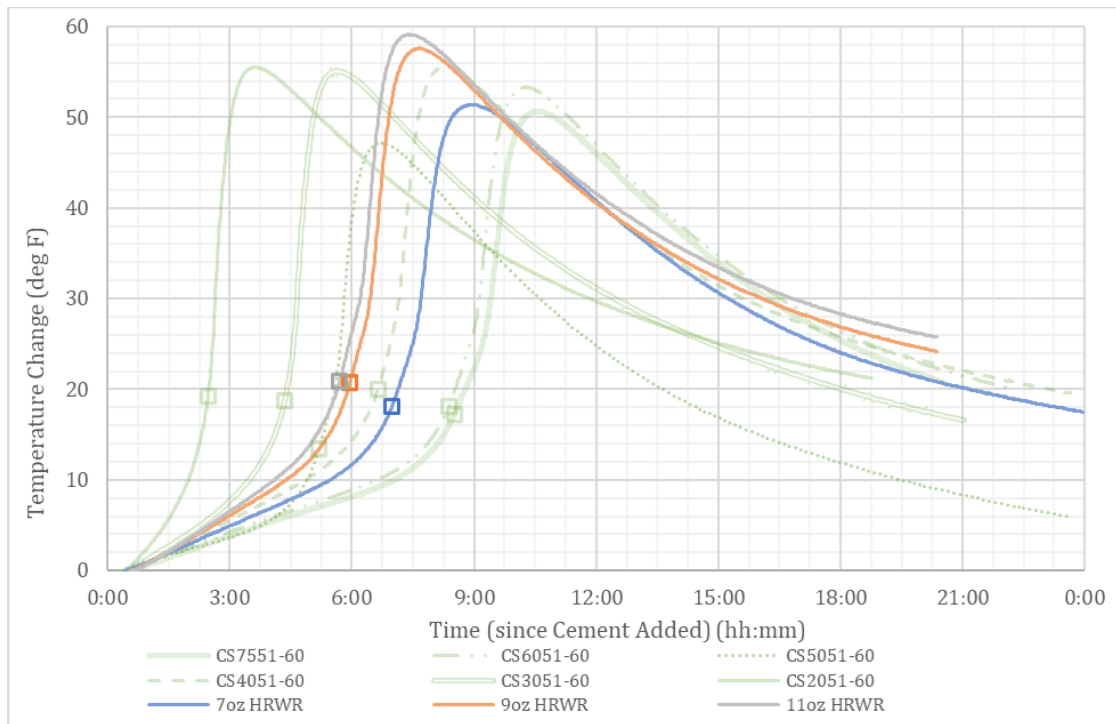


Figure 99: 0.50% Citric Acid, 60°F Mixes, with Variable HRWR Dosages, as Compared to Baseline 60°F Mixes.

The 9oz HRWR dosage, shown in orange is the default, and would align closely with the 0.50% dotted green line except for the fact that limited insulation and seasonal differences resulted in a variation in ambient room temperature where testing was conducted. Furthermore, varying the HRWR dosages shows an increase in set time with a decrease rather than an increase in HRWR dosage, despite extending working time. In

other words, increasing admixture dosage to improve workability, will extend working time but lead to more aggressive setting.

4.3 Phase 3 – Large Scale Testing

The large-scale slab pours validated the application of expansive BCSA at scale in the field, as the varying properties of the cement relative to conventionally concrete poses some unique challenges to implementation relative to current practice.

As the lab lacked a mixer with sufficient capacity to pour the 2.5 yds required for each slab, these slabs were cast in partnership with Schwarz Ready Mix, using a 10 yd mixer truck that they were willing to lend for casting. For efficiency and ease of casting the slabs, aggregates and portland cement standard for Schwarz batching operations were used in these mixes, with only the CSA cements, admixtures and half of the batch water added on site. For the reference slab, a standard class AA mix targeted to reach the same 2.5-3ksi at 3d was directly delivered in a Schwarz mixer truck. For the other two mixes, CSA cement, water and admixtures were added on site. Figures 100 and 101 show the process of using a construction forklift and hopper to introduce the CSA cements to the drum, followed by a pallet of water buckets to provide the additional mix water, which was adjusted for daily aggregate moisture contents to the drum to hydrate the cement, and then taking fresh properties.



Figure 100: Addition of the Expansive BCSA Cement (left) Followed by Buckets of the Remaining Water, Dosed with Second Half of the Citric Acid and HRWR (right)



Figure 101: Filling a Buggy with Final Expansive BCSA Mix and Taking a Slump Measurement

To prevent any potential flash set due to premature hydration of cement without retardation, the citric acid dosage was split in half with 2- 30 lb. buckets of water dosed with the first half of citric and added before the cement, with the remaining citric acid and HRWR added to the rest of the water that was added to the mixer after the cement. A more detailed schedule of mix order and timing is listed in Table 23.

Table 23: Order of Mixing Procedures and Timings for Full Scale Slabs

Event	Design Slab		
	Expansive CSA Slab	Type K CSA Slab	Reference Slab
Truck Arrives on Site	All of the aggregate and half of the mix water are preloaded in the drum	All of the aggregate, half of the mix water, and the portland cement fraction are preloaded in the drum	Pre-mixed class AA concrete is already in the drum
Drum is charged with citric acid	Half of the citric acid is added to 2- 30lb buckets and allowed to mix for 2min.	Half of the citric acid is added to 2- 30lb buckets and allowed to mix for 2min.	-
CSA cement is added	BCSA cement is added to the drum	Type K CSA cement fraction is added to the drum	-
Remaining water added	Remainder of the mix water with second half of the citric acid is added, followed by HRWR	Remainder of the mix water with second half of the citric acid and HRWR is added	-
Mixing Time	6 minutes	12 minutes	-

After mixing, a conventional slump measurement was taken on each slab, and then the concrete was slowly placed in the forms and raked until the forms were completely filled and at the approximate final level, as shown in Figures 102 and 103. The slabs were then roughly screeded level using a power screed, shown in Figure 104, and bull floated to finish. Afterwards the slab was post-tensioned, shown in Figures 107 and 108, then wet cured, as shown in Figure 109.



Figure 102: Slowly Using the Mixer Truck Chute to Fill the Slab Forms



Figure 103: Raking the Concrete as it Comes Out of the Chute to the Approximate Slab Elevation



Figure 104: Using a Power Screed to Roughly Finish the Slab to the Proper Slab Elevation



Figure 105: Rough Finish of Slab after Screeding



Figure 106: Final Finish of Slab after Bull Floating



Figure 107: Post-Tensioning the Slab



Figure 108: Loaded Post-Tensioning Double Anchorage used for Placement of the Load Cell



Figure 109: Wet Curing of Slab after Post Tensioning Using Wet Burlap Covered with Plastic

The slab instrumentation was placed at just outside the maximum expected edge moisture variation distance of 5 ft. per the PTI design guide, at 55 in. measured from the slab edges in both directions, and at the idealized beta distance where the maximum flexural stresses are anticipated to occur, 40 in. This allows for approximating the stress profile in both directions of the slab at the peaking points and average across the slab interior. The slabs were post tensioned based on strength gain to ~3ksi, which corresponded to 7 days for the reference slab due to a cold snap occurring the day after casting, the targeted 3 days for the type K slab and 20 hours for the expansive BCSA slab. The BCSA slab was delayed prevented same day post tensioning, despite cylinders registering sufficient strength at approximately 7 hours, within the targeted 6-8h range, due concerns from demolding. The mix had an extra dose of citric relative to the recommendations from the temperature study to guarantee no flash setting in the truck from potential scale effects on the mix being in a truck. Consequently, though the surface had hardened, and cylinders made strength, when the forms were removed the sides of the slab were still soft enough that a fingernail could dig in while scratching it. Some of the remnant concrete around the slab was also soft enough to crumble in hand when any force was applied. Therefore, there was no confidence in the interior of the slab reaching strength in the same day, and the slab was post-tensioned the following morning. This behavior mirrors what was observed with the larger mass penetrometer specimens, indicating that setting is likely affected by exposure conditions such as surficial evaporation, and that citric dosing can be reduced as mix volume increases. There is reasonable confidence that same day post-tensioning would have been achieved at the lower recommended dosage.

4.3.1 Slab Stress and Strain Profiles

Three critical points were established for characterizing slab behavior, end of casting, to characterize dimensional stability prior to set and under relatively unrestrained conditions, after post-tensioning and during wet cure, to characterize magnitude of expansion while cement is activated by the wet cure, and after wet curing to establish the magnitude of losses and shrinkage after expansion ends. Figures 110–112 show the strain variation with respect to time at the beta distance and midspan in each direction for the expansive BCSA, 25% Type K, and reference portland cement slabs, with time 0 being the start of casting.

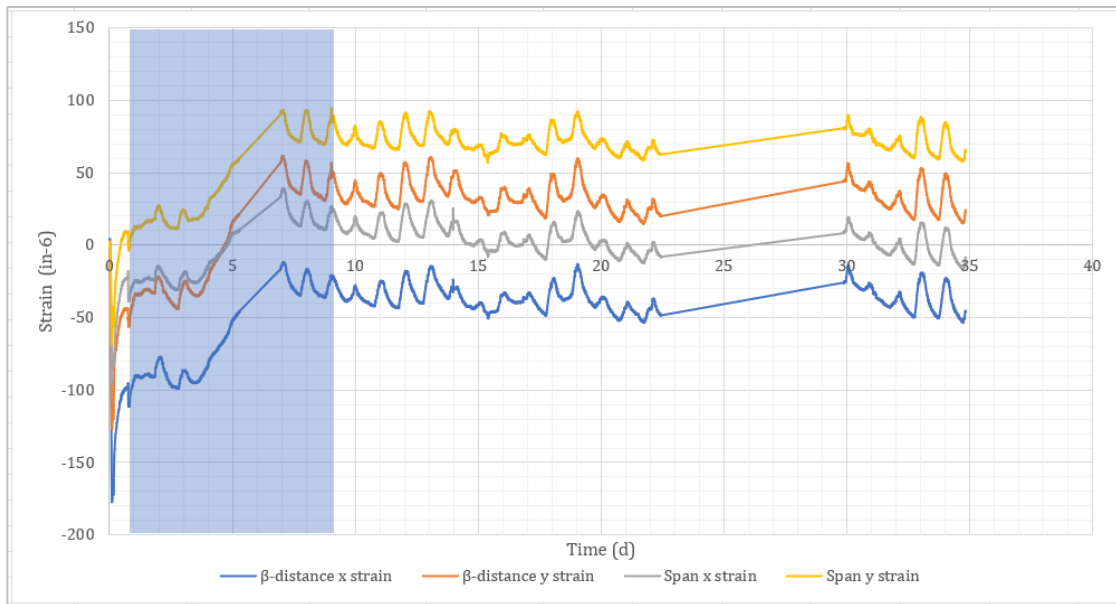


Figure 110: Raw Change in Strain at Midspan and Beta Distance in Each Direction for the Expansive BCSA Slab.

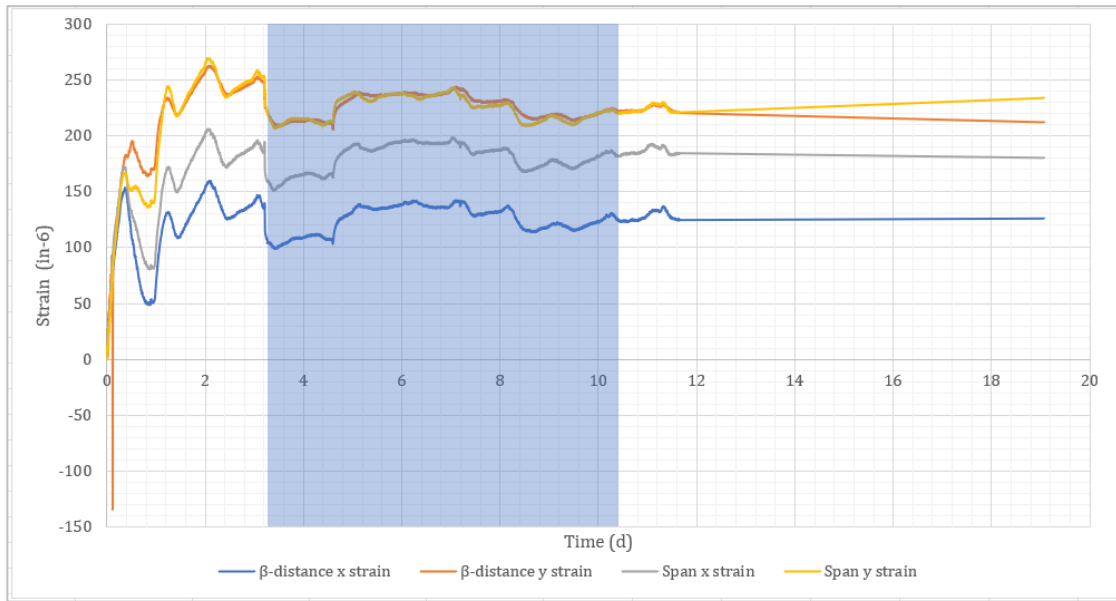


Figure 111: Raw Change in Strain at Midspan and Beta Distance in Each Direction for 25% Type K CSA Slab.

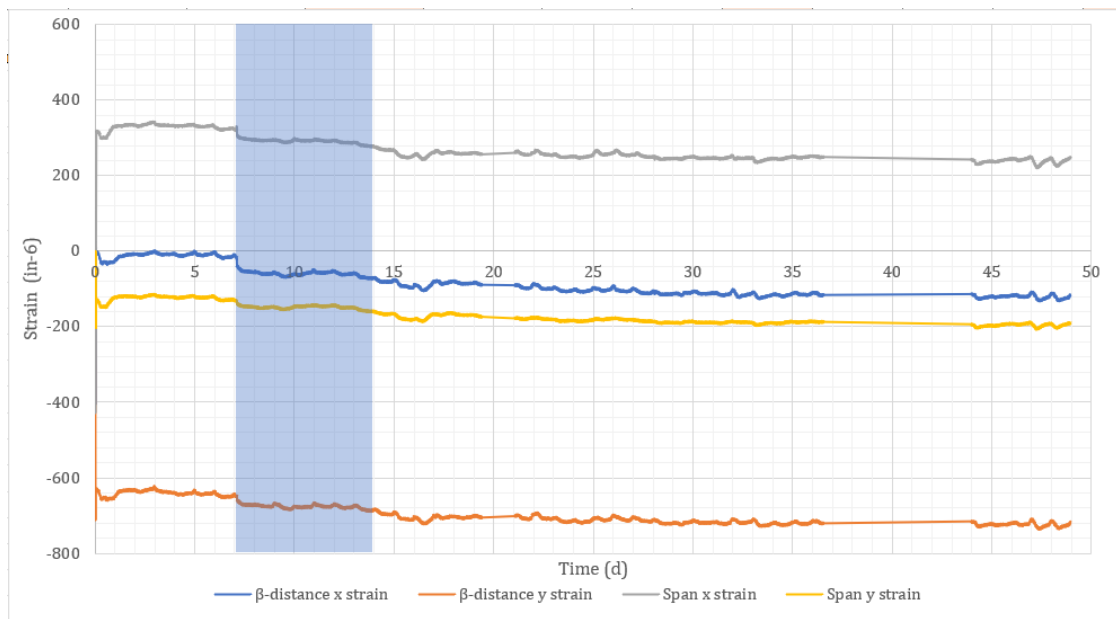


Figure 112: Raw Change in Strain at Midspan and Beta Distance in Each Direction for Reference Portland Cement Slab

While the Type K slab data is relatively easy to analyze in its raw form, the conventional portland cement concrete slab was disturbed significantly during casting, affecting initial readings, while the extreme autogenous shrinkage at set make it difficult to compare the expansive BCSA results. Therefore, Figures 113 and 114 adjust the raw strain data for each slab so that the initial reading at set for the expansive cement slabs is taken as zero, and corrects the reference slab so that the significant spikes or drops in strain due to disturbance during the pour are removed and the initial strains are similarly considered zero.

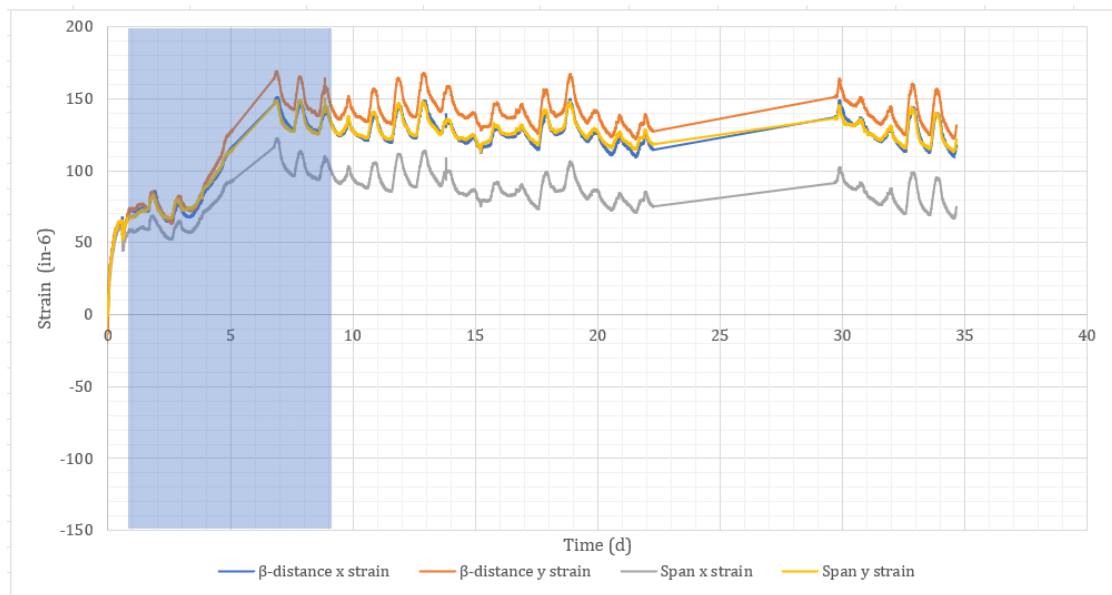


Figure 113: Corrected Expansive BCSA Slab Data to Remove Shrinkage Prior to Set.

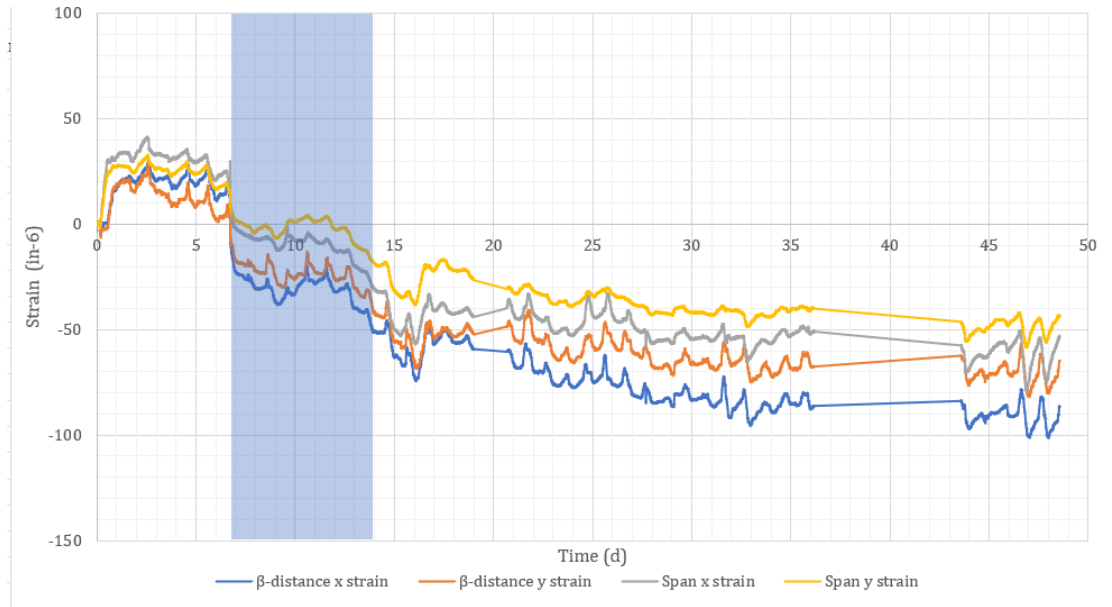


Figure 114: Corrected Conventional Portland Slab Data to Remove Distortions due to Casting Disturbance

These corrections lead to some interesting observations. First, despite PTI expectations of highest stresses and strains at the β -distance, data in Figures 111, 113, and 114 for all three slabs shows very little difference in strain magnitudes between the two points measured, while this may be due to the short span or relatively low equivalent prestress force, only 100 psi on the cross section outside of the anchorage zones, this is surprising. This suggests that the critical section for expansive cement concretes may be larger or more variable than the PTI model currently predicts.

Secondly, strains within the slab can fluctuate with weather conditions. Day to day there are fluctuations of 20-30 μ strain across the cross section, which has broader implications for post-tensioning in general as this represents potential strain reduction that could significantly reduce precompression. To put this in perspective, the elastic shortening of the slab as measured by the VSWG's, can be estimated as around ~25-30

μ strain for the expansive BCSA concrete, and slightly less for the others as they were tensioned at later ages and higher stiffnesses. Moreover, this this approximately tracks with the elastic shortening strains from the creep columns; the 800 μ strain of shortening resulting from 1800 psi of load would predict around 35 μ strain for the $\sim$ 80 psi actual effective cross section stress. Therefore, day to night fluctuations in stresses represent changes as significant as the elastic shortening losses that can further lead to poor prediction of prestress losses. A further point is that these cycles approximately track with the weather at the time, lower peaks representing cooler or cloudier days. The only time this cycling was not observed was during wet curing after replacing the wet burlap with wet sand and covering the slab, as this presumably presented enough thermal mass to resist excessive heating and cooling, which might mitigate these fluctuations post-construction, but need to be accounted for, with load applications during construction.

To further validate these results all slabs had two strands equipped with double anchorages and to monitor the strand stress in one strand in each direction for at least the duration of the wet cure. For these direct prestress readings, the strands were stressed until the prestressing jack readout was 4000 psi. This jack stress was correlated to the actual applied load by calibration with both a Baldwin Zwick machine, used to calibrate most load cells and equipment in the lab and the load cell used for the prestressing bed in the lab to yield the loading curve correlations shown in Figure 115.

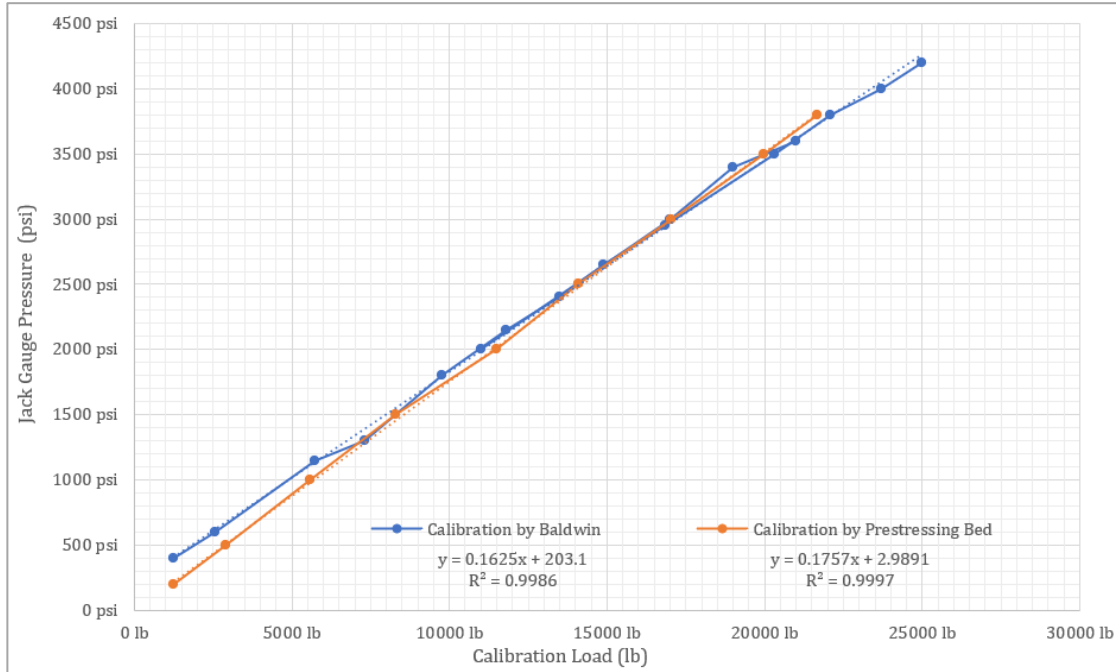


Figure 115: Calibration of Prestressing Jack by Baldwin Zwick Testing Machine and 50k Load Cell Used for the Prestressing Bed

Based on an assumed anchor seating of ¼ in., the extremely short length of the slab yields an estimated seating loss of 56.5ksi, or 8.65k based on Equation 7.

$$\Delta f_{AS} = \frac{\Delta_{seat}}{L} E_{ps} \quad (7)$$

Even considering these losses, the point to overstress all strands was chosen as ~23k, 4000 psi on the jack, for safety considerations despite a targeted design force 21k.

While this only represents overstressing by ~1/3 of the expected immediate prestress loss, overstressing further was deemed unsafe for the compressive strengths achieved at an early age without exceeding the $1.2f'_{ci}$ limit for concrete bearing strength in the anchor zone at the time of loading or waiting for a longer for strength, which would defeat the principle of achieving same day or at least rapid post-tensioning. Similarly, it was deemed excessive to increase the size of the slabs to reduce such losses as it would

at minimum, need to more than triple the plan dimensions, corresponding to at least 10x the pour volume for anchor seat losses to approach reasonable values. The final direct load readings and anchor losses are shown in Figure 116.

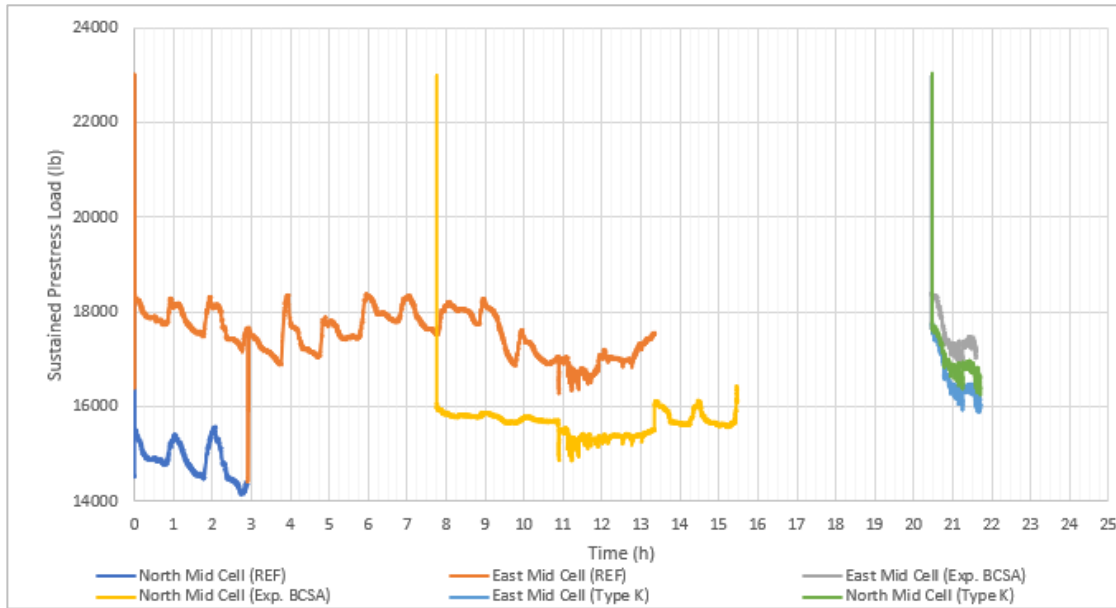


Figure 116: Slab Midline Load Cell Stress Reading

These measurements show reasonable, if not lower, anchor seating prestress losses, relative to what would be predicted using Equation 7. However, more interesting trends appear after prestress transfer, with day to day the load cells appear to show a cycling of gain and loss, similar to what was observed in the VWSGs, and on the order of approximately 0.80-1.0k. Based on strain compatibility, a 30 μ strain increase in strand elongation is equivalent to 855lb of additional force. The observed variations in the readings of the VWSGs embedded in the slab are within that targeted range, further validating the analysis of observed behavior from the strain gauge measurements.

Only one of the three strands in each direction was instrumented, so the exact magnitude of prestress losses, is unknown, however, assuming that the load cell readings are reasonably representative, dividing the load readings by the corresponding strain readings from the VSWG's can provide an estimated stress-strain ratio to approximate the development of the full scale slab elastic modulus, allowing for a similar scaling comparison as with creep and shrinkage. Figure 117 presents each of the load cell curves divided by one third of the slab area to yield an effective stress, and by the corresponding VSWG strain readings over their duration for this analysis.

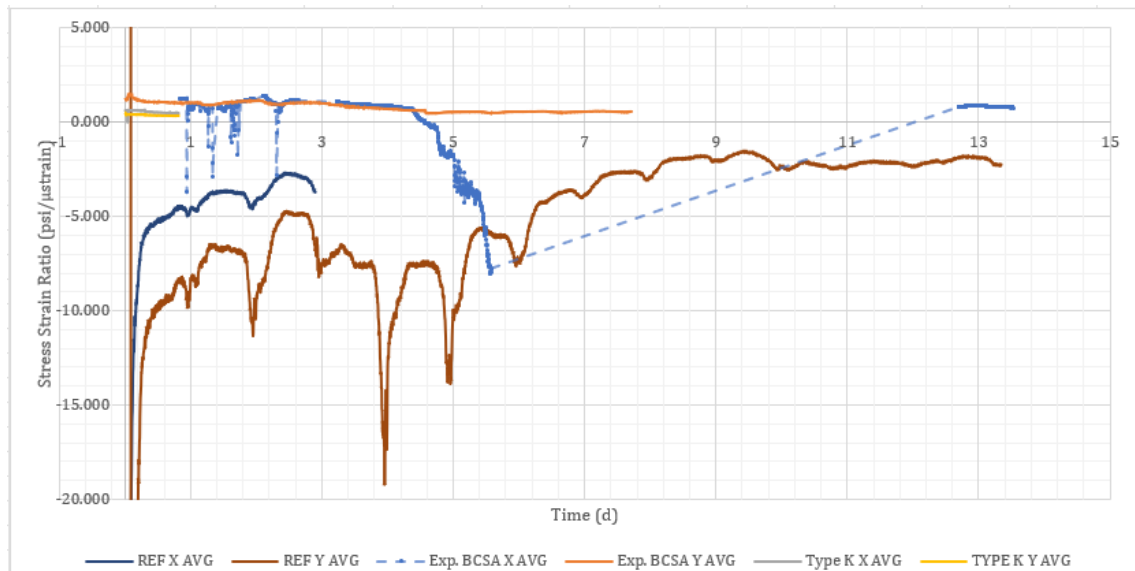


Figure 117: Approximate Stress Strain Ratio and Stiffness Development of Slabs over Time.

Unfortunately, during the data collection from the load cells rain repeatedly disturbed these recordings. This is most notable in the measurement of the average stress to strain in the Y direction of the expansive BCSA slab, where the wire connection appears to have become faulty and register significant errors in the data, however it is most significant that the data appears to return to a baseline comparable to its companion

Average X stress-strain reading. Additionally, while the faulty connection does completely cut off at ~6 days, a different load cell was connected at 12 days, when the Type K specimens were loaded, and the readings appear to follow the projection of the earlier data curve for the average X data. A similar rain event occurred at ~1 day after loading the type K strands, leading to limited data for this slab. Consequently, due to these collective errors from accuracy of load cell calibration, only having one strand instrumented in each direction, and only weather induced disruptions in the readings, the magnitude of the data is highly inaccurate, however the curvature of the graphed stress-strain ratio can be used to support some analysis of the elastic modulus development for the large-scale slabs, as there is general agreement with the rate of modulus development seen in material property testing.

While there is a very small amount of data collected for the type K slabs, the curves are highly linear. Similarly, even though there is significant noise in the connection of the X data for the expansive BCSA slab small portion, it returns to a linear baseline that follows the linear behavior of the Y load cell. The reference slab on the other hand follows significantly curving baseline, with spikes over the first week after loading due to the day-to-day and day-to-night temperature fluctuations inducing additional thermal strains. The near linearity of the expansive concrete data is extremely striking when placed in context of this reference slab, especially considering that the 0 time on Figure 117 is the time of post-tensioning for each slab, ~20 hours for the expansive BCSA slab, 3 days for the Type K slab and 7 days for the reference slab. Despite being post-tensioned four days earlier and only replacing a quarter of the portland cement with the expansive Type K CSA cement, the stiffness of the type K slab is basically fully

achieved at post-tensioning. The stress strain ratio of the reference slab doesn't begin to level off until around 8 days after post tensioning, more than 2 weeks after casting. Therefore, it appears that the addition of CSA cement, regardless of the type and whether or not it is rapid setting leads to a much faster elastic modulus and stiffness development as compared to conventional portland cement, which is a trend also observed in small-scale property testing. This enables approximate determination of strains using a constant elastic modulus as determined from small scale testing, since modulus development appears to have fully occurred prior to loading. This approximation yields Figure 118.

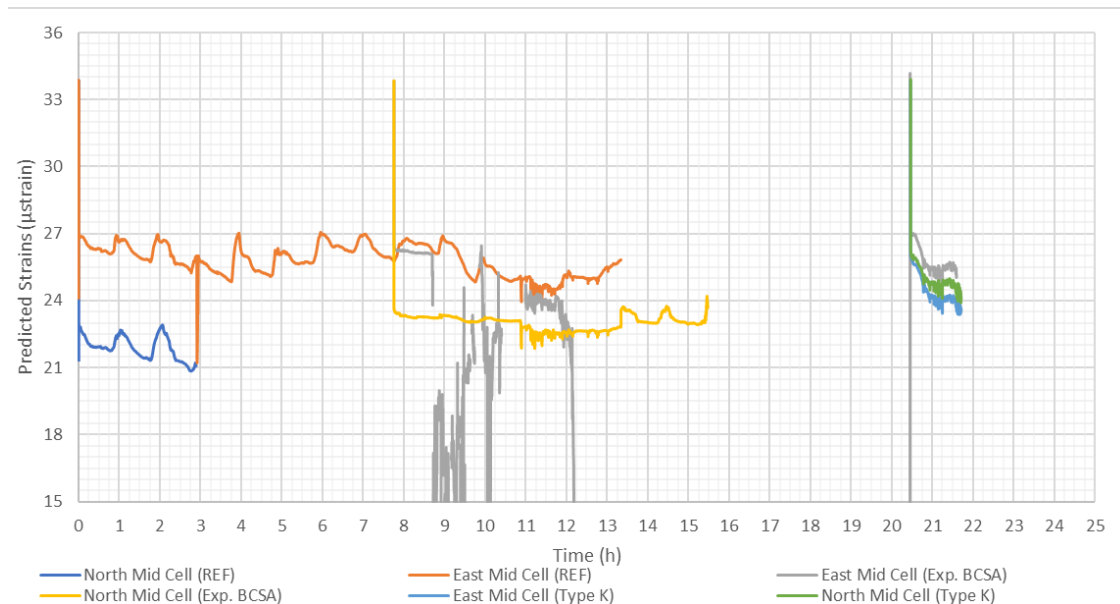


Figure 118: Predicted Strains based on Constant Elastic Modulus

4.3.2 Comparison to Small-Scale Material Property Testing

Due to time limitations and delays, there is limited data on the prestress losses occurring after the end of the wet cure, with the last slab shown having only around 28 days of

data collection. However, as shown throughout the smaller scale material property testing, mechanical properties, as well as shrinkage and creep, develop very quickly after achieving compressive strength, as shown in Table 24, making even this limited data set useful.

Table 24: Early Age Fraction of Final Long-Term Properties

Long-Term Property Test	7 days		28 days		3 mo.		Final Strains		Age of Final Measurement
Expansive BCSA									
Restrained Expansion (C878)	281	42%	512	77%	609	91%	666	100%	(6mo, 2w)
Unrestrained Expansion (C157)	281	34%	594	72%	709	87%	818	100%	(6mo, 2w)
Unrestrained Shrinkage* (C157-7d)	298	0%	264	11%	174	42%	174	42%	(6mo, 2w)
	-		-						
Total Creep + Shrinkage	324	55%	480	82%	-538	92%	-585	100%	(7mo.)
Shrinkage from time zero*	316	0%	255	19%	219	31%	176	44%	(7mo.)
	-		-						
True Creep	640	84%	736	97%	-757	99%	-761	100%	(7mo.)
25% Type K CSA									
Restrained Expansion (C878)	97	79%	107	87%	107	87%	123	100%	(8mo.)
Unrestrained Expansion (C157)	93	34%	133	49%	220	81%	270	100%	(8mo.)
Unrestrained Shrinkage* (C157-7d)	127	0%	-46	136%	-200	257%	-258	303%	(8mo.)
Total Creep + Shrinkage	100	-12%	317	39%	-630	78%	-805	100%	(7mo. 2w)
Shrinkage from Time Zero – VWSG Creep Column Companion Specimens	327	0%	78	76%	-104	132%	-187	157%	(7mo. 2w)
	-		-						
True Creep	227	37%	395	64%	-526	85%	-618	100%	(7mo. 2w)

*Values for percent of shrinkage and shrinkage from time zero, are measured a percentage of original expansion as measured from end of 7d wet cure

As listed in Table 24, and more clearly shown in Figure 119, expansive BCSA concrete long-term properties also occur on an accelerated schedule; consistently achieving approximately 40% of its expansion potential in 7 days, 80% in 28 days, and basically

all of its expansion potential within 3 months. On the other hand, the Type K cement concrete has more variability, achieving anywhere from 40-60% of its expansion potential at 7d, and only 70% at 28d. Moreover, this expansion is far less in magnitude compared to expansive BCSA cement, while the shrinkage recovery rate after removal from wet curing is comparable between the cements. Even more significant is the rate to full creep for the expansive BCSA cement concrete, where as much as 90% occurred in just the 7d wet curing period and 98% occurred by the time the concrete reached 28d strength, versus only 60% and 80%, respectively for Type K CSA cement concrete, which is already fast relative to portland cement.

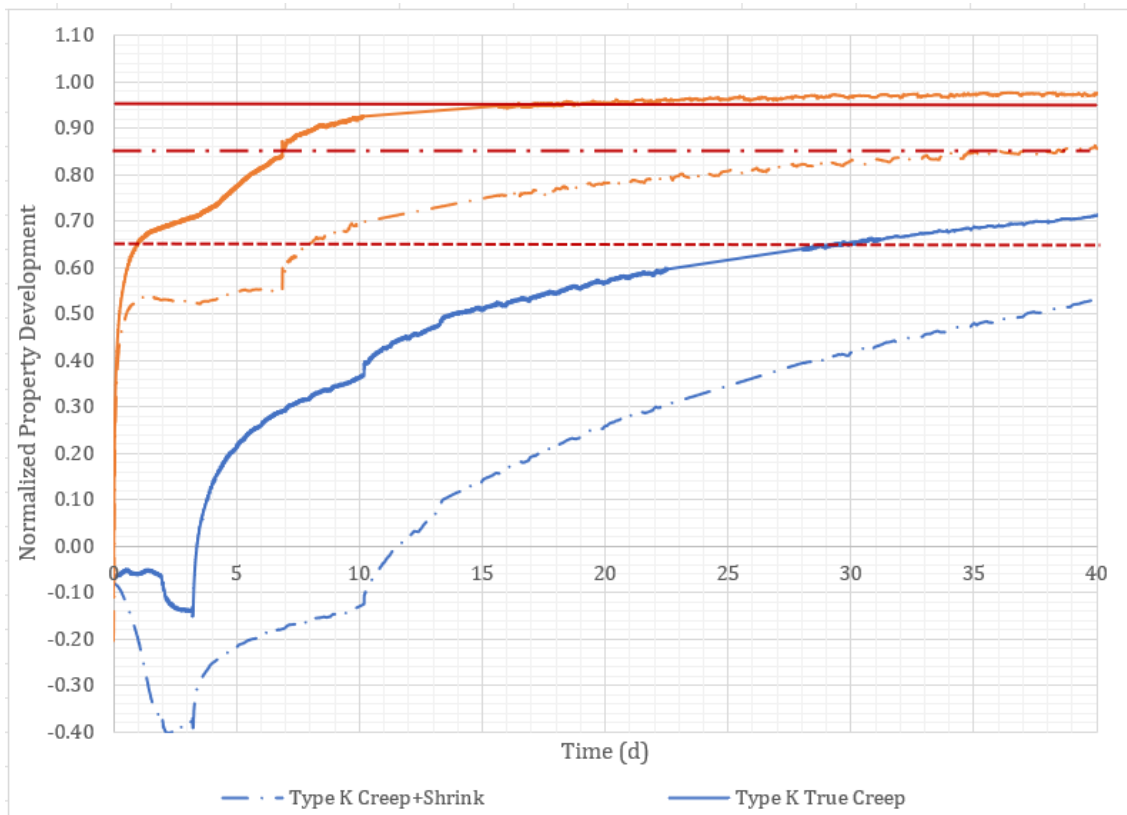


Figure 119: Normalized True Creep and Combined Creep and Shrinkage for 25% Type K and Expansive BCSA Concrete.

There is a significant difference in the stress state of the slabs compared to the creep columns as the design compression of 100 psi across the cross-section was considered too low to get meaningful creep results. Therefore, the creep specimens were instead stressed up to allowable limits to create an upper bound for the most extreme case of creep and shrinkage to then relate to the slabs. The congruence of the C157 and C878 results with the VWSG data and companion shrinkage specimens shows that even high restraint forces up to the $0.6f'_{ci}$ used in the creep columns do not appreciably affect shrinkage. The difference, however, will affect creep across the cross section and measured elastic strains, as well as the magnitude of expansion. While the columns were loaded up to $0.6f'_{ci}$, or ~1800 psi across the cross section, outside the anchorage zones of the slab the effective design concrete stress was only 100 psi, with the excessive anchor seating losses further reducing this to 80 psi, so creep will be relatively small, on top of the reduced creep behavior noted in the creep column study in the long-term.

Third, post-tensioning provides significant restraint, even at the low effective net stress of 100 psi, and the boundary conditions of being on grade induce additional restraint due to friction. The total observed expansion of approximately 150 μ strain for the expansive BCSA, and 200 μ strain for the type K cement during the 7-day wet curing period was only half of the results from either VWSG, C157, or C878 results, as shown in Figure 120.

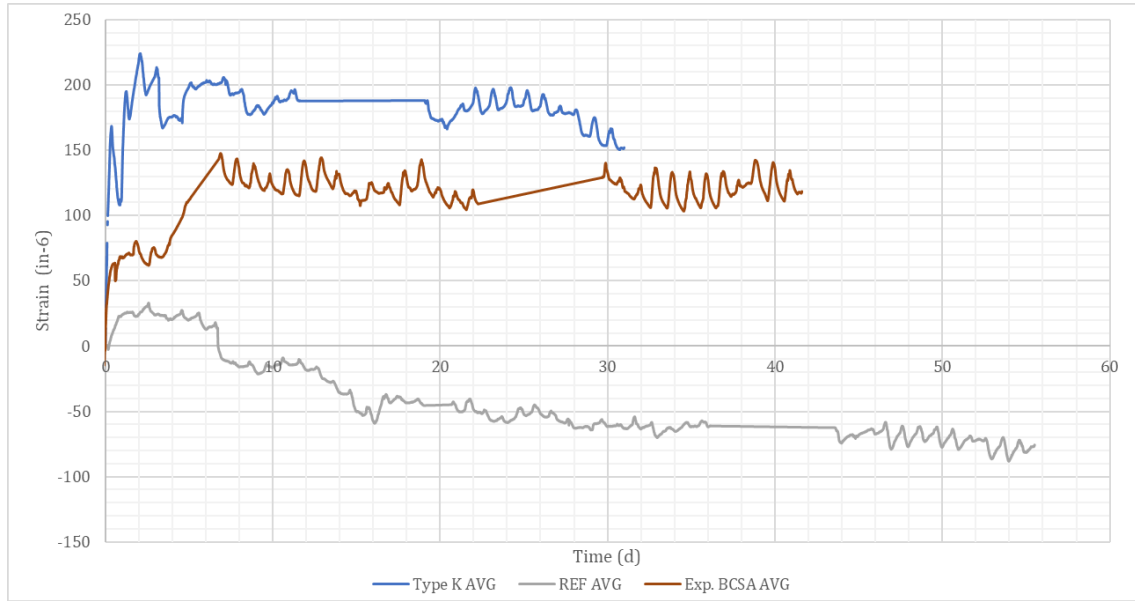


Figure 120: Average VWSG Measured Slab Strains with Time Zero as End of Casting

Notably, however, both expansive cements exhibit significant expansion prior to application of prestress that would not lead to chemical prestress, and even the reference slab shows as much as a 25 μ strain increase. Therefore, Figure 121 adjusts the slab expansions so the zero-time match to the time of post-tensioning to better visualize the expansion under loading, and only consider the strains that will affect the slab stress state. Table 25 lists the measured load cell stresses and strains, as well as the VWSG strains to approximate chemical prestressing potential.

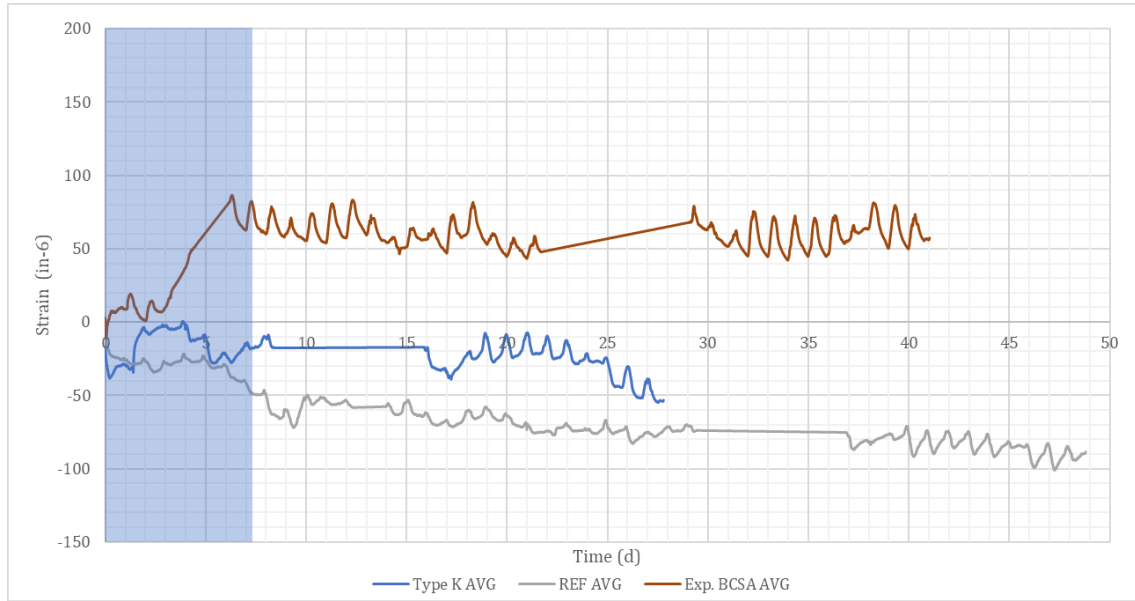


Figure 121: Average VWSG Measured Slab Strains with Zero Time as Start of Post-Tensioning

Table 25: Measured Stress Strain Behavior of Slabs and Chemical Prestress Potential

Event	Design Slab		
	Expansive CSA Slab	Type K CSA Slab	Reference Slab
Average Initial Prestress on Measured Strands (Initial prestress force after overstress to 23000lb)	17.08k	17.81k	17.00k
Equivalent Effective Initial Concrete Stress	81.3 psi	84.1 psi	81 psi
Equivalent Effective Concrete Strain from Stress	-26.0 μ strain	-28.7 μ strain	-25 μ strain
Equivalent Effective Concrete Strain from Gauge	-13.4 μ strain	-21.2 μ strain	-13.1 μ strain
Magnitude of Restrained Expansion (+)/Shrinkage (-) (Unrestrained)	72 μ strain (330 μ strain)	13.2 μ strain (120 μ strain)	-64.2 μ strain (n/a)
Approximate Induced Chemical Prestress	225.1 psi	38.7 psi	n/a
% Increase of Equivalent Concrete Prestress	276.9%	46.0%	n/a
MOE (ksi)	3123 at 1 day	2932 at 3 days	3236 at 7 days

The component of this that occurred under post tensioning was measured as 72 and 16 μ strain for the expansive BCSA and Type K respectively, which is a significant difference from the small-scale property testing. The difference in curing procedures could account for some of this, as large-scale slabs could not be fully submerged in water the way any of the other specimens were. Therefore, even with the burlap and wet sand maintaining the surface at a saturated and moist condition, the capillary action to get water penetration deeper into the slab may not have been as strong. Additionally, there is an assumption of uniform stress distribution that may not be accurate for the large-scale slab, and there is crucially the fact that unbonded strands do not perfectly follow strain compatibility which leads to discrepancies in load measurement, taken off of the strands, and strain measurements, taken from embedded VSWG that are bonded to the concrete. For the expansive BCSA specimen, post-tensioning also occurred at sunrise, which creates questions about the uniformity of any thermally induced strains in the slab, and whether the thermocouples on the VSWG effectively captured this behavior Geokon (2019) recommends a default thermal expansion coefficient for concrete of 10 μ strain/ $^{\circ}$ C, so even a 3 $^{\circ}$ F variation from nonuniform heating in the slab not captured by the VSWG can explain the discrepancy in anticipated strains based on load cell readouts and VSWG measured strains due to prestress application. Additionally, the rapid occurrence of creeping strains after loading leads to a significant reduction within a few hours that is difficult to differentiate between. Finally, there is the highly nonlinearity of expansion induced strains and stresses with chemical prestressing. For differential strains due to thermal expansion, strain compatibility can

be used as shown in Figure 122 to determine the mechanical variation due to a net expansion differential, ε_T , that does not change with reinforcing ratio.

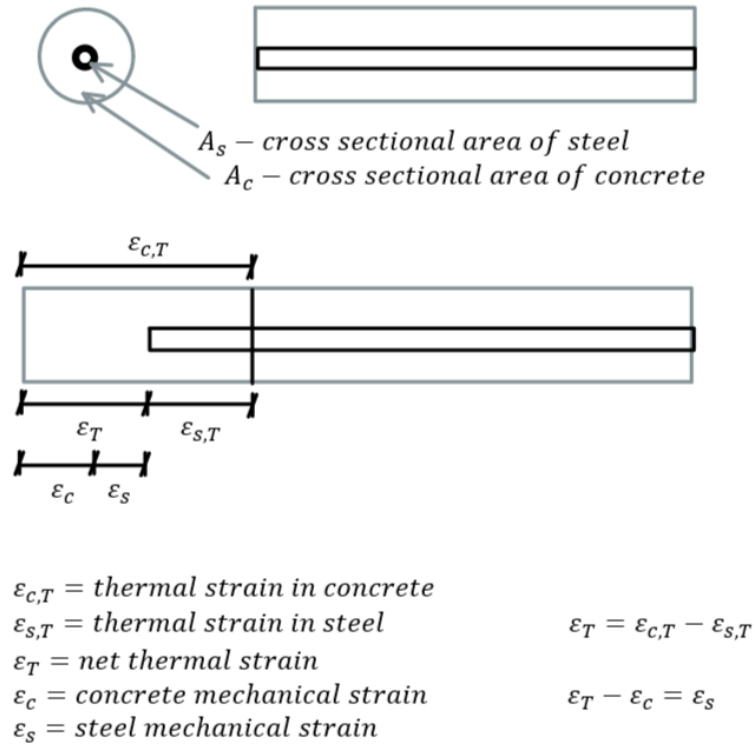


Figure 122: Conventional Strain Compatibility Method for Stress-Strain State Determination due to Thermal Self Stress

However, for chemically induced expansion, increasing restraint causes variation in this net strain differential, and this nonlinearity prevents comparison. Both Roswurm (2018b) and Wyrzykowski (2018) observed highly nonlinear effects as reinforcing ratio increased, making it difficult to determine the exact expected reduction of expansion as reinforcing ratio increases, let alone the effects of the added restraint due to other non-uniform sources such as subgrade friction, even though friction was minimized by including a vapor barrier.

Despite difficulty in predicting the reduction in expansion under restraint, the 72 μ strain of expansion for expansive BCSA and 13.2 μ strain for Type K CSA concrete represents some degree of chemical prestressing from the restrained expansion. Considering that based on MOE testing, the stiffness of both concretes at post-tensioning was approximately 3000 ksi, even this limited amount of chemical prestressing is equivalent to a 46% and 276% increase in prestress for the type K concrete and expansive BCSA, respectively. This represents doubling to tripling the gross design prestress for the expansive BCSA and even for the type K concrete, almost doubles the average effects of anchor seating losses, which shows significant potential to not only mitigate prestress losses, but for the expansive BCSA, allows for a significant decrease in required prestress force. Additionally, the significantly more aggressive expansion under restraint and lowered shrinkage after the end of wet curing are consistent with trends observed with earlier property testing.

Thus, is general agreement between both short-term hardened properties such as elastic modulus and compressive strength, and long-term properties such as expansion and shrinkage, the only property that was not effectively correlated was the modulus of rupture. The only major challenge to correlating results is establishing consistent fresh properties for the mix, due admixture dosages, as significant size effects were observed in scaling up the expansive BCSA mix from material property testing to a 2.5 cubic yard pour in a mixer truck. Another challenge is that similar differential setting behavior was observed with the large volume expansive BCSA pour as with the penetrometer specimens during the material property establishment, so there needs to be greater understanding of setting effects on large mass expansive BCSA concrete.

5.0 Summary, Conclusions and Recommendations

This research project focused on assessing the utility of expansive BCSA and Type K CSA cements towards resisting subsurface movements in slabs-on grade. Post tensioning of slabs on grade is generally conducted to improve the flexural capacity of slabs to resist against shrinkage and swelling of expansive soils, thereby an increase in prestress due to induced expansion, generally termed chemical prestressing should increase the flexural capacity and improve performance of such slabs. Additionally the rapid hardening and strength gain of the expansive BCSA as compared to Type K cement concrete or conventional portland cement concrete can accelerate the construction process, leading to faster and more efficient completion of residential buildings.

The first phase of this project confirmed the reactivity of the cement and developed a viable mix with sufficient workability and strength for use in post-tensioned slabs on grade. The second phase established material properties, including compressive and flexural strength, stiffness and dimensional change to evaluate the mechanical performance of the mixes. Then the third phase scaled up those results to a full-scale slab to assess viability in field application and compare the performance of the alternative mixes.

5.1 Material Property Conclusions

In terms of material properties, the expansive BCSA cement examined in this research is fundamentally different from shrinkage compensating cements such as Type K CSA

examined in this work, that are currently employed as an additive replacement in conventional portland cement concrete.

5.1.1 Strength and Stiffness Properties

- The expansive BCSA cement is sensitive to water reducing admixtures, which can potentially act as air entraining admixtures as well, even at low doses.
- The expansive BCSA cement exhibited rapid hardening and quickly achieve far higher strengths relative to conventional portland cement concrete, with or without expansive CSA cement replacement, for the same proportion of cement in the mix design.
- Wet curing delayed strength gain, but allowed for longer, steadier strength gain, therefore expansive BCSA concrete, when removed from wet curing conditions, had lower strength relative to specimens allowed to dry cure for the preceding 4-7 days, but rapidly caught up and exceeded their strength.
- Specimens wet cured for periods of 7 days or longer exhibited shrinkage cracking from autogenous shrinkage after being removed from wet cure, and the longer the duration of the wet cure the more aggressive such shrinkage cracking was observed to be.
- This shrinkage cracking appeared to be surficial in nature and had no observed effect on compressive strength but appeared to likely affect modulus of rupture.
- While wet curing significantly increased the modulus of rupture of expansive BCSA, this gain was offset during later drying, which observed as much as a 40% reduction from peak wet cured moduli, and a 15% reduction relative to solely dry cured specimens.

- ACI correlations for modulus of rupture are reasonably accurate for a Type K CSA additive cement concrete mix—though they may need some adjustment or correction factors. These correlations were inaccurate for expansive BCSA concretes, which have a linear rather than square root correlation between compressive strength and modulus of rupture.
- A similar pattern was observed for elastic modulus. ACI correlations for modulus of elasticity were only slightly overestimated for a Type K CSA additive cement concrete mix. However, the correlation was inaccurate for expansive BCSA concretes, which have an even stronger linear correlation of compressive strength and elastic modulus as compared to modulus of rupture.

5.1.2 Creep and Shrinkage

- The expansive BCSA concrete is a true expansive concrete rather than just shrinkage compensating, it exhibited $\sim 1/3$ of the shrinkage of the Type K mix, and 3x the expansion, holding a net expansion even under restrained conditions, which creates the potential for chemical prestressing.
- Results from the companion shrinkage specimens paired with the creep column testing showed shrinkage in volume for both the expansive BCSA cement and the Type K CSA cement at early ages, i.e. before setting. This shrinkage occurs particularly rapidly for the expansive BCSA cement as a consequence of its rapid hardening properties.
- As this shrinkage occurs just prior to the initial set it should not induce any internal stresses on the concrete but represents a significant consideration for

predicting volume change stresses on surrounding structures when casting expansive concrete adjacent to existing concrete.

- The expansion from the type K cement countered approximately half of the creep potential during the curing period, while the expansion of the expansive BCSA cement almost completely counteracted creep behavior.
- The creep and shrinkage results validate previous findings of significantly reduced creep potential from fully replacement of portland cement with CSA cements.

5.1.3 Temperature Effects

- The expansive BCSA concrete is more temperature sensitive than either previously examined non-expansive BCSA cements or the expansive Type K additive cement examined in this research and therefore requires higher dosages of citric acid for adequate retardation.
- While ambient temperature and citric acid dosage have some impact on slump loss for the expansive BCSA cement, internal temperature was by far the greatest factor. There is a threshold internal temperature of 65°F, above which slump loss increases significantly.
- Cooling an expansive BCSA mix to adjust internal temperature can increase slump, without increasing citric acid or HRWR dosages. A mix with temperature suppressed in this manner behaved roughly equivalent to a mix with an ambient temperature one interval lower than it was mixed at with a citric acid dosage equivalent to or one increment lower than the mix was dosed at.

- There are some limits to temperature suppression or elevation for the expansive BCSA cement as exposure to ambient conditions can quickly bring internal temperatures up in as short a period as 30 minutes. Therefore, the determined limit of effectiveness for inducing a change in this manner is 10-15°F.
- Expansive BCSA concrete was observed to be highly thixotropic, as motion prolongs adequate slump loss and workability.
- Slump loss is in general a poor assessment of the expansive BCSA concrete behavior. While the concrete may lose slump quickly, for slumps above ~2 in. slump, the mix was observed to exhibit highly thixotropic properties, whereby vibration or agitation can easily return it to a gelatinous state that is more workable than the slump would imply. Below 2 inches, the concrete begins to dry out and lose this property. For temperatures below ~80°F this loss of workability is gradual, while for higher temperatures it basically corresponds to the initial set.
- Varying the dosage of HRWR was shown to have a positive correlation with reducing slump loss and extending working time for the expansive BCSA cement. The additional 2oz/cwt from the 9oz/cwt to the 11oz/cwt dosed mix showing and increase in working time as measured by slump loss of nearly 45 minutes.
- Penetrometers inaccurately assess the set time for large masses of the expansive BCSA concrete, which may set first in the surface layer, but not at depth.
- The set of the expansive BCSA concrete occurs at a point after the end of the dormancy period during the initial stages of the heat gain period.

- Calorimetry results reinforce the idea of a threshold temperature for behavior of the expansive BCSA cement as well as a functional range as defined by internal temperature. For the 50°F and 60°F ranges, each citric dose extended set by a similar interval. The 70°F followed this trend less closely, and for the extremes outside this functional range (90°F, 80°F, 40°F), the variation in citric dosage showed clustering in set time and heat gain curves.
- Unlike slump loss however, no major correlation between setting behavior and internal temperature was apparent.
- Similar to trends noted with slump loss behavior, suppressing the mix temperature with ice leads to setting time comparable to a mix with one dosing increment higher of citric acid, and one temperature interval lower.
- Calorimetry results showed that increasing the dosage of high range water reducer actually led to a faster setting time, despite extending working time. This is potentially because it leads to better dispersion of water and faster time to fully hydrate all of the cement.

5.2 Large Scale Slab Conclusions

- Even at low levels of prestress, post tensioning can provide sufficient restraint to induce chemical prestress on the same order of magnitude as the mechanical prestress, for both the Type K and expansive BCSA cements used in this research.

- Expansive BCSA exhibits significant size effects with HRWR admixtures, achieving far greater slump for the same dosage in larger scale pours.
- Surficial hardening observed in slabs mirrors observations with penetrometers suggesting an evaporative mechanism for setting and early hardening of concrete.
- Exposed post-tensioned slabs can be subject to thermal cycling of the prestress, resulting in changes in prestress force on the order of over a kip, or 5% of the standard 26 kips generally applied to strands for post tensioned slabs on grade. While this may not matter for engineers designing for service, this can be important for any outside analysis of construction loading which may occur while the slab is still exposed and can potentially be more severe than service loading.
- Very little variation was observed in strain measurements at the PTI predicted critical section at the β -distance and within the presumed edge moisture variation distance. This suggests that the critical zone of failure may be larger than PTI models currently predict.
- Elastic Modulus development of slabs followed the same trend of rapid gain as small-scale specimens.
- Shrinkage of expansive concrete was consistent irrespective of reinforcing ration and restraint conditions.
- Expansion was affected by the degree of restraint, exhibiting a highly nonlinear relationship.

- The expansion of Type K cement yielded a 46% increase in effective concrete stress, sufficient for compensating for the majority of prestress losses.
- The far more aggressive expansion of BCSA concrete not only counteracted prestresses losses but represents doubling to tripling of the effective concrete stress allowing for reductions in strand stressing though structural testing is required to establish the exact effect on ultimate capacity as this may not accurately represent a uniform increase in prestress.

5.3 Recommendations

5.3.1 Application of Expansive Cements

While the final results of this research show significant advantages, such as higher strengths, significant chemical prestress potential and possibility for early age or same day post-tensioning, the process shows that there is still a need for significant improvements and a wider breadth of data for comprehensive field use. This expansive BCSA can be viable for post-tensioning applications in the future, but not now. There is still insufficient characterization of its properties, which poses challenges due to how much it deviates from conventional portland cement behavior.

- Compressive and flexural strength are both gained rapidly, allowing for opening to service much faster than with conventional portland cement. Next day service loading is not unreasonable if curing temperatures are at or above the functional temperature range.

- There is a tighter tolerance on mixing conditions; without altering internal temperature, expansive BCSA concrete should only be mixed between steady temperatures of 50-75°F.
- With temperature suppression, mixing is recommended up to at most 85°F with any confidence in having sufficient working time for any mix larger than 5cf.
- With temperature elevation, mixing is recommended down to 40°F and rising at the coolest, which is standard for conventional portland cement concrete.
- For mixes between 40°F and 60°F a minimum citric dosage of 0.30% by cement weight is recommended, up to 0.50% for hardening and strength gain sufficient for light loading in the same day or overnight if temperatures remain warm enough.
- From 55-65°F, citric dosing is variable and affected by other conditions such as cloud cover and humidity, above 65°F a minimum dosage of 0.50% is recommended.
- 7 days is recommended as the ideal wet curing period. It leads to sufficient expansion, approximately 1/3 of the ultimate expansion potential and a reasonable additional gain in ultimate compressive strength of ~3ksi. Periods longer have limited additional increase in compressive strength and show more aggressive cracking presumably from drying shrinkage.

Large scale pours face limitations observed in this research that require further study for full viability of expansive BCSA, including the risk of differential setting, need for quantification of the magnitude of chemical prestressing increase in flexural capacity,

and assessment of surface cracking effects on durability, particularly with regards to freeze-thaw in the US, as states like Oklahoma and Texas where expansive soils are widely present also have high free-thaw potential.

5.3.2 Future Research

- Both the slabs and the large block penetrometer specimens showed differential setting, with the surface of specimens exposed to air fully hardening, but the interior, covered by forms remaining soft. Therefore, a more comprehensive analysis of setting behavior, and potential evaporative effects on set time is needed.
- Similarly, a more comprehensive evaluation of retardation and temperature is needed. In this research, solely ambient temperature was addressed, while it was observed that humidity, wind and cloud cover/sun exposure all affected the working time of the mixes.
- Additionally, the reduction in flexural strength and observed cracking presents a need for research into longer term durability performance of specimens, particularly freeze-thaw and corrosion potential to compromise concrete structural integrity.
- A major challenge within this project was collecting sufficient data points for assessment of behavior, which was further compounded by trouble with gauges and sensors malfunctioning in the middle of testing. That said, this project showed that two-way behavior for slab-on-ground had low interaction between directions which makes one-way pour strips a potentially effective method for

more comprehensive instrumentation of a post tensioned slab on ground profile of expansive behavior. This can also allow for more easily performing mechanical testing of slabs to failure, to assess the true magnitude of prestress and capacity increase.

- Creep behavior showed interesting trends, such as the approximately constant strain after one day that lasted for the remaining duration of the wet cure as expansion and creep effectively countered one another. Additionally, the nonlinearity of expansion under restraint requires further investigation of creeping behavior.
- One of the major limitations of expansive CSA cements is the need for wet curing and maintaining moisture for expansion to occur, therefore replicating at least small scale, and potentially similar large-scale slabs using internal curing is recommended. This method presents a potential low maintenance method for using expansive CSA slabs as expansive behavior may be less effected by limited curing and the need to effectively maintain wet curing environmental conditions.
- Similarly, CSA cements are a point of significant potential with ultrahigh performance concrete (UHPC). Rapid setting BCSA cements currently see some of their greatest use in transportation projects because they can gain strength overnight leading to reduced road closures. Development of UHPC mixes with these cements can increase versatility in such applications, particularly for high strength retrofit and repair.

- Modelling the nonlinearities of restraint impacts on expansion can allow for better characterization and prediction of chemical prestressing magnitude.
- Finally further research into bonding behavior of BCSA in general, and expansive BCSA, in particular, can allow for wider usage for repair and retrofit applications. Bond behavior to steel can lead to better approximations for transfer and development length in prestressed applications, while establishing bond behavior between expansive BCSA concrete with itself and conventional portland cement can aid in design for repair and retrofit projects.

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7.0 Appendix

Appendix 1: Raw Calorimetry Curves

As there were significant fluctuations in the starting room temperature from summer to winter, in addition to the temperature of the mix relative to room temperature fluctuating over a 20°F range, the curves in the thesis were all normalized to the starting temperature, after the isothermal box stabilized as the zero point. The raw data without this adjustment, but with baseline temperature subtracted out, are included below.

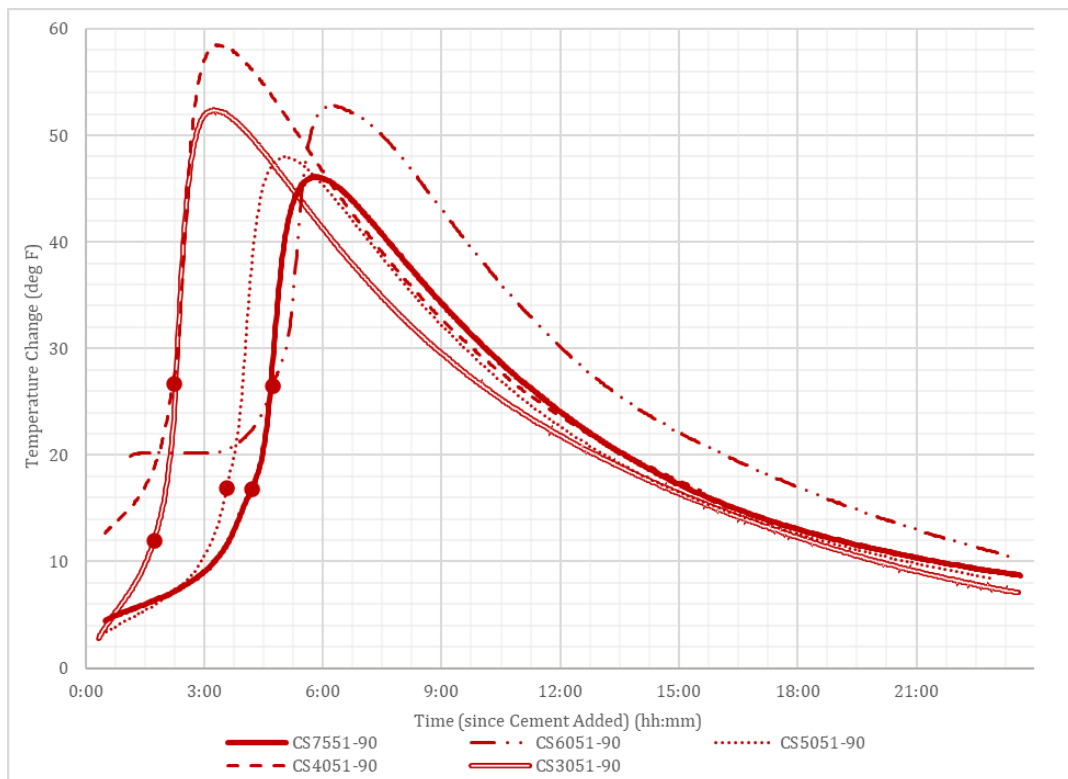


Figure A- 1: Raw Temperature Setting Curves at 90°F

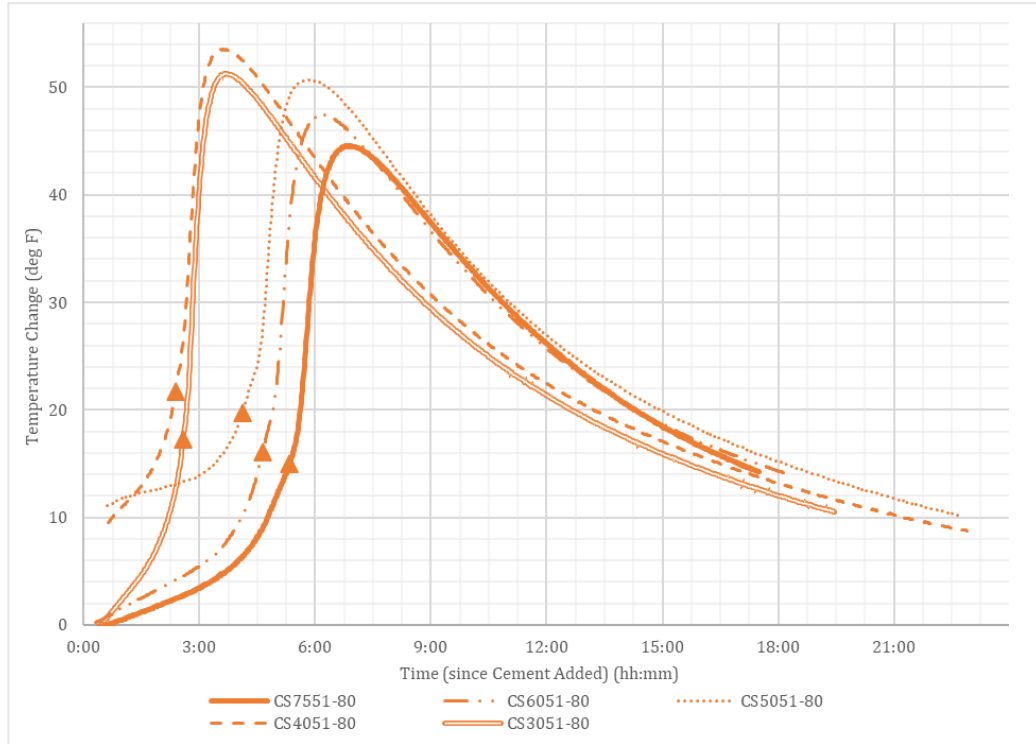


Figure A- 2:Raw Temperature Setting Curves at 80°F

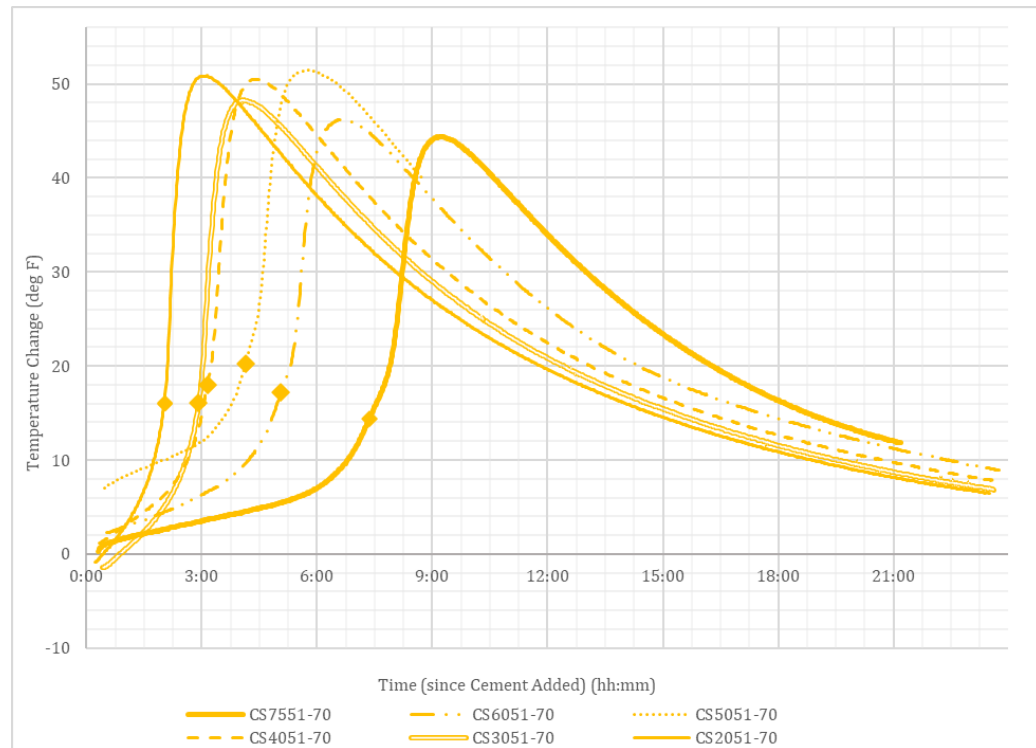


Figure A- 3: Raw Temperature Setting Curves at 70°F

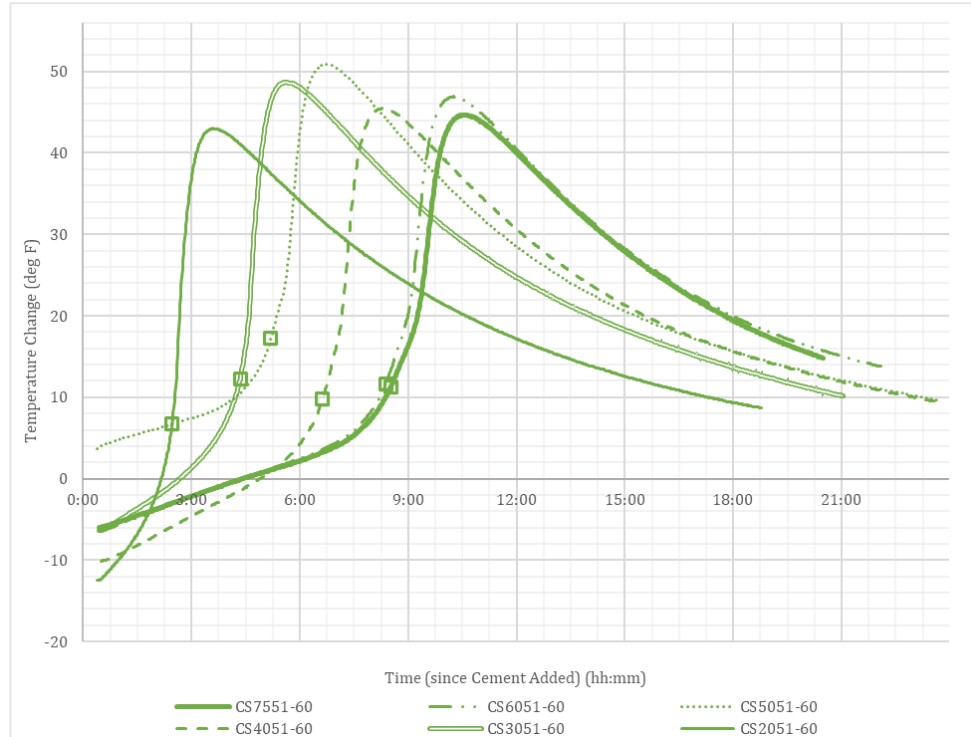


Figure A- 4: Raw Temperature Setting Curves at 60°F

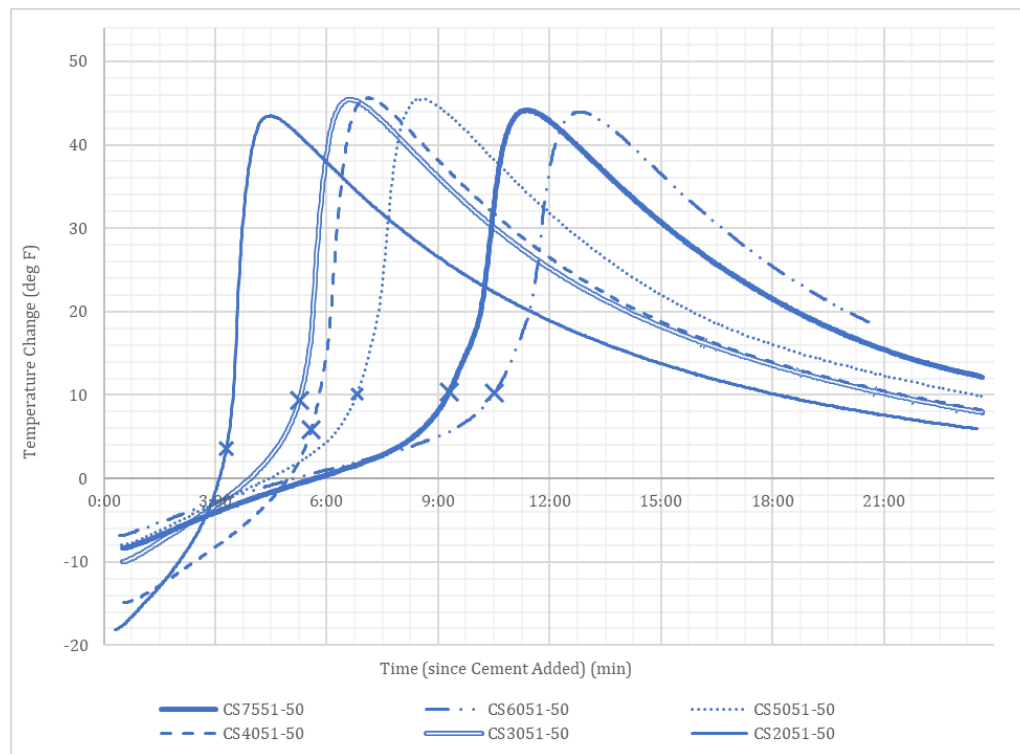


Figure A- 5: Raw Temperature Setting Curves at 50°F

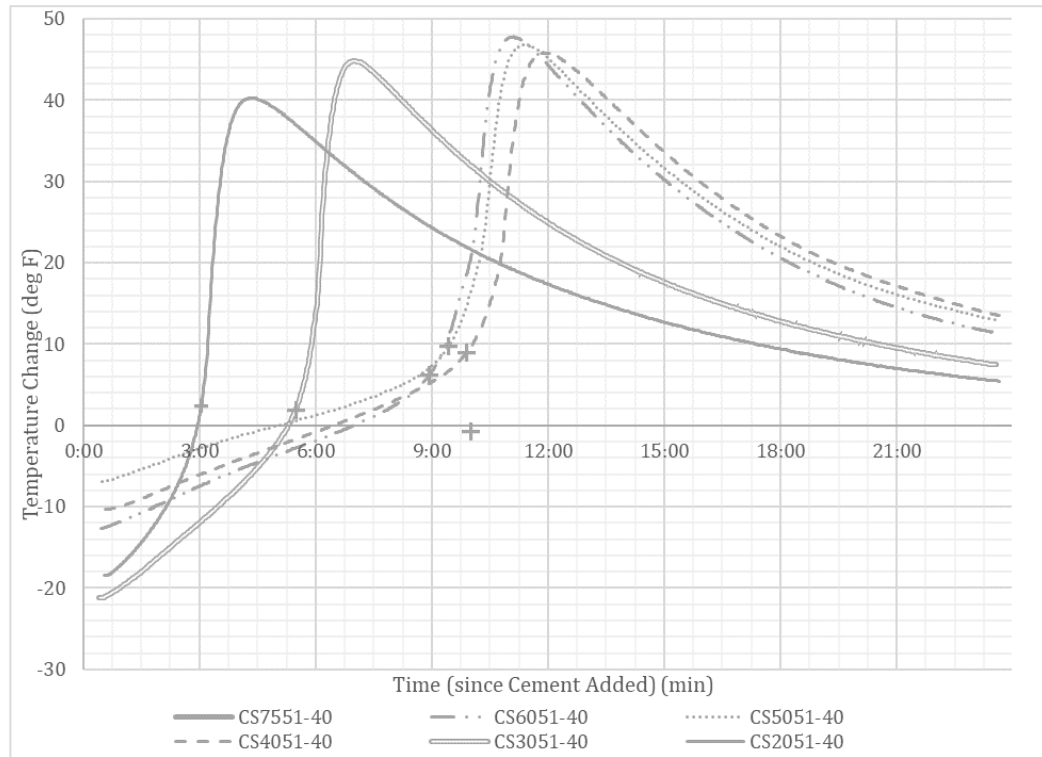


Figure A- 6: Raw Temperature Setting Curves at 40°F

Expansive BCSA

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CS7551 - MOE				8/4/2022		Moisture Content		MC using 4-6lb		
w/cm =	0.5			Sand % water =	0.802%	Sand:	Wt. (lb.)			
PC =	0	type III		Rock % water =	0.199%	Pan -	0.39	MC =	0.802%	
CS =	564					Pan + wet sand -	10.44			
Komp =	0					Pan + dry sand -	10.36			
FA =	0					Aggregates:				
% Citric	0.40%			start:	7:51	Pan -	0.79	MC =	0.199%	
arse Fine Ratio:	45 / 55			batch:		Pan + wet agg -	5.82			
				stop:		Pan + dry agg -	5.81			
Theoretical Weight: Volume:				SG	SSD					
Portland Cement	0.0	0.00		3.15	-	Mix Timing -	Small Mix : mix citric and high range i			
ChemStress Cement	564.0	3.14		2.88	-		Large Mix : mix citric and high range i			
Komponent	0.0	0.00		2.88	-					
Fly Ash	0.0	0.00		2.58	-					
Rock	1415.0	8.46		2.68	0.70%	b/bo =	0.65	Fineness Modulus =	2.5	
Sand	1697.1	10.34		2.63	0.86%	DRUW =	101.0			
Water	282.0	4.52		1.00	-					
Air entrapped 2.0%	0.0	0.54								
Total:	3958.1	27.0								
		1yd	67.5	cf						
Portland Cement	0.0	0.00	lb							
ChemStress Cement	564.0	1410.00	lb							
Komponent	0.0	0.00	lb							
Fly Ash	0.0	0.00	lb							
Coarse Aggregate, #67	1417.8	3544.46	lb							
Fine Aggregate, Dover Sand	1710.8	4276.88	lb							
Water	290.1	725.21	lb							
Air Ent. Admixture, oz	0	0.00	ml							
Citric Acid Retarder, lb	2.26	5.640	lb			Note: add 0.5% citric acid for longer set time; 25ml glenium for workability				
ADVA, (MRWR), oz	51	3770.18	ml		9.04255	29.57ml/oz				
DCI (accel with water), oz	0	0.00	ml							
Concrete temperature:	-			Expected Unit Weight:	146.60	Slump Loss:				
Air Temperature:	93			Measured:	35.84	143.36	7:58	Initial Slumj	7	7.5
Humidity:	-			Difference:	%	2.21%	8:11	10 min:	20	6.5
Air Content:	2.7%							20 min:		
Slump:	-							30 min:		
Unit Weight Pot Empty:	7.76			Unit Weight:	159.96	pcf		40 min:		
Unit Weight Pot Full:	43.6							50 min:		0

CS7551 -EXP																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																				
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CS6051 - Creep				9/9/2022		Moisture Content		MC using 4-6lb	
w/cm =	0.5			Sand % water =	2.528%	Sand:	Wt. (lb.)		
PC =	0	type III		Rock % water =	0.709%	Pan -	0.48	MC =	2.528%
CS =	564					Pan + wet sand -	4.13		
Komp =	0					Pan + dry sand -	4.04		
FA =	0					Aggregates:			
% Citric	0.60%			start:	7:18	Pan -	0.81	MC =	0.709%
Coarse Fine Ratio:	45 /55			batch:		Pan + wet agg -	7.91		
				stop:		Pan + dry agg -	7.86		
Theoretical Weight:		Volume:		SG	SSD				
Portland Cement	0.0	0.00		3.15	-	Mix Timing -	Small Mix	: mix citric and high range ir	
ChemStress Cement	564.0	3.14		2.88	-		Large Mix	: mix citric and high range ir	
Komponent	0.0	0.00		2.88	-				
Fly Ash	0.0	0.00		2.58	-				
Rock	1415.0	8.46		2.68	0.70%	b/bo =	0.65	Fineness Modulus =	2.5
Sand	1697.1	10.34		2.63	0.86%	DRUW =	101.0		
Water	282.0	4.52		1.00	-				
Air entrapped 2.0%	0.0	0.54							
Total:	3958.1	27.0							
		1yd	3	cf					
Portland Cement	0.0	0.00	lb		100	0.9	1		
ChemStress Cement	564.0	62.67	lb			2.3	2.55556		
Komponent	0.0	0.00	lb						
Fly Ash	0.0	0.00	lb						
Coarse Aggregate, #67	1425.0	158.33	lb						
Fine Aggregate, Dover Sand	1740.0	193.34	lb						
Water	252.8	28.09	lb						
Air Ent. Admixture, oz	0	0.00	ml		0				
Citric Acid Retarder, lb	3.38	0.376	lb		Note: add 0.5% citric acid for longer set time; 25ml glenium for workability				
ADVA, (MRWR), oz	51	167.56	ml		9.04255	29.57ml/oz			
DCI (accel with water), oz	0	0.00	ml						
		45-55	50-50						
Concrete temperature:	#N/A			Expected Unit Weight:	146.60	Slump Loss:			
Air Temperature:	78.4			Measured:	#N/A	#N/A	Initial Slump		
Humidity:	82%			Difference:	%	#N/A	10 min:		
Air Content:	#N/A						20 min:		
Slump:	-						30 min:		
Unit Weight Pot Empty:	7.76			Unit Weight:	159.96	pcf	40 min:		
Unit Weight Pot Full:	#N/A								

Type K

K3051 - MOR				8/5/2022				Moisture Content				MC using 4-6lb			
w/cm =	0.5			Sand % water =	3.000%			Sand:		Wt. (lb.)					
PC =	423	type III		Rock % water =	3.500%			Pan -		0.39	MC =	0.802%			
CS =	0							Pan + wet sand -		10.44					
Komp =	141							Pan + dry sand -		10.36					
FA =	0							Aggregates:							
% Citric	0.15%			start:	7:54			Pan -		0.79	MC =	0.199%			
arse Fine Ratio:	45 /55			batch:				Pan + wet agg -		5.82					
				stop:				Pan + dry agg -		5.81					
Theoretical Weight:				Volume:		SG	SSD								
Portland Cement	423.0		2.15			3.15	-	Mix Timing -	Small Mix :	mix citric and high range i					
ChemStress Cement	0.0		0.00			2.98	-		Large Mix :	mix citric and high range i					
Komponent	141.0		0.78			2.88	-								
Fly Ash	0.0		0.00			2.58	-								
Rock	1430.1		8.55			2.68	0.70%	b/bo =	0.65	Fineness Modulus =	2.5				
Sand	1715.3		10.45			2.63	0.86%	DRUW =	101.0						
Water	282.0		4.52			1.00	-								
Air entrapped 2.0%	0.0		0.54												
Total:	3991.5		27.0												
				1yd	67.5	cf	(-5lb water)								
Portland Cement	423.0		1057.50	lb		131.6									
ChemStress Cement	0.0		0.00	lb											
Komponent	141.0		352.50	lb											
Fly Ash	0.0		0.00	lb											
Coarse Aggregate, #67	1480.2		3700.51	lb		1850.25									
Fine Aggregate, Dover Sand	1766.8		4417.02	lb		2208.51									
Water	202.7		506.86	lb											
Air Ent. Admixture, oz	0		0.00	ml		2932.22									
Citric Acid Retarder, lb	0.85		2.115	lb		Note: add 0.5% citric acid for longer set time; 25ml glenium for workability									
ADVA, (MRWR), oz	51		3770.18	ml		9.04255	29.57ml/oz	837.817							
DCI (accel with water), oz	0		0.00	ml											
Concrete temperature:	85			Expected Unit Weight:	147.83			Slump Loss:							
Air Temperature:	98.4			Measured:	35.84	143.36	8:05	Initial Slumj	11	8.5					
Humidity:	50%			Difference:	%	3.03%	8:22	10 min:	28	7.5					
Air Content:	2.6%							20 min:		0					
Slump:	-							30 min:		0					
Unit Weight Pot Empty:	7.76			Unit Weight:	159.96	pcf		40 min:		0					
Unit Weight Pot Full:	43.6									0					

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K3051 - Creep				9/2/2022		Moisture Content		MC using 4-6lb	
w/cm =	0.5			Sand % water =	0.802%	Sand:	Wt. (lb.)		
PC =	423	type III		Rock % water =	0.199%	Pan -	0.39	MC =	0.802%
CS =	0					Pan + wet sand -	10.44		
Komp =	141					Pan + dry sand -	10.36		
FA =	0					Aggregates:			
% Citric	0.30%			start:	10:26	Pan -	0.79	MC =	0.199%
Coarse Fine Ratio:	45 /55			batch:		Pan + wet agg -	5.82		
				stop:		Pan + dry agg -	5.81		
Theoretical Weight:		Volume:		SG	SSD				
Portland Cement	423.0	2.15		3.15	-	Mix Timing -	Small Mix	: mix citric and high range ir	
ChemStress Cement	0.0	0.00		2.88	-		Large Mix	: mix citric and high range ir	
Komponent	141.0	0.78		2.88	-				
Fly Ash	0.0	0.00		2.58	-				
Rock	1430.1	8.55		2.68	0.70%	b/bo =	0.65	Fineness Modulus =	2.5
Sand	1715.3	10.45		2.63	0.86%	DRUW =	101.0		
Water	282.0	4.52		1.00	-				
Air entrapped 2.0%	0.0	0.54							
Total:	3991.5	27.0							
		1yd	3	cf					
Portland Cement	423.0	47.00	lb						
ChemStress Cement	0.0	0.00	lb						
Komponent	141.0	15.67	lb						
Fly Ash	0.0	0.00	lb						
Coarse Aggregate, #67	1433.0	159.22	lb						
Fine Aggregate, Dover Sand	1729.1	192.12	lb						
Water	290.2	32.24	lb						
Air Ent. Admixture, oz	0	0.00	ml		0.047				
Citric Acid Retarder, lb	1.69	0.188	lb			Note: add 0.5% citric acid for longer set time; 25ml glenium for workability			
ADVA, (MRWR), oz	51	167.56	ml		9.04255	29.57ml/oz			
DCI (accel with water), oz	0	0.00	ml						
		45-55	50-50						
Concrete temperature:	82.7			Expected Unit Weight:	147.83		Slump Loss:		
Air Temperature:	83.8			Measured:	36.84	147.36	Initial Slump	7	
Humidity:	62%			Difference:	%	0.32%	10 min:		
Air Content:	3.0%						20 min:		
Slump:	-						30 min:		
Unit Weight Pot Empty:	7.76			Unit Weight:	159.96	pcf	40 min:		
Unit Weight Pot Full:	44.6								