UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

INVESTIGATION OF CHEMICALLY PRESTRESSED CONCRETE

A THESIS

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

Degree of

MASTER OF SCIENCE

By

DAKOTA WADE GENNINGS
Norman, Oklahoma
2018

INVESTIGATION OF CHEMICALLY PRESTRESSED CONCRETE

A THESIS APPROVED FOR THE
SCHOOL OF CIVIL ENGINEERING AND ENVIRONMENTAL SCIENCE

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There is no fear in love. But perfect love drives out fear, because fear has to do with punishment. The one who fears is not made perfect in love.

Acknowledgements

First, I would like to thank my Savior, Jesus Christ for every opportunity that He has offered me during my life. He is the author and perfecter of my faith. He blessed me with two wonderful parents, Barry and Tonya, who have always supported my education. They always pushed me to do my best in everything, and I would not have been able to accomplish all I have without them.

I must take the time to thank my loving wife, Valerie. She has suffered through all the long hours, lack of sleep, and stressful times with me. I am truly honored to have such a wonderful woman in my life. I love you so much Valerie, and I can never thank you enough for everything you have done during my time here at OU. I am excited to see where God leads us following this educational experience.

I also want to thank my close friends that I have made during my time at OU, Jacob and Stephen Roswurm, Connor Casey, and Alieu Jobe. They have helped me during my research along the way and have always supported me even when I did not believe in myself. I will always cherish the memories that I have with these friends.

I must also thank all my other family and friends that have supported me during my time at OU. They have prayed, called, and texted me consistently throughout my time, and I am forever thankful for all the support that it has provided. It would take far too many pages to say every name of each person that has helped me along the way, but I hope they all know how much their support has meant to me during my time at OU.

I would like to take special note to my grandparents. Thank you so much Bob and Christine Harwell, or Mimi and Papa, for always telling me to pursue a higher education. They always told me to be an engineer, and I am forever thankful for them to continually push me to follow my dream of becoming an engineer.

I also would like to thank Dr. Chris Ramseyer for all his support during this time at OU. He hired me as an undergraduate assistant and gave me an incredible opportunity to pursue a Master's degree with a research project. He has always given me incredible direction, and I would not have been able to accomplish anything without him.

I also want to thank Mike Schmitz for all his assistance and guidance in completing my research. You are such a wonderful mentor, and I cannot thank you enough for everything that you do for myself and every other student. This research could not have happened without the help of CTS Cement Manufacturing, and the guidance of Mr. Ed Rice. I also want to thank the other members of my committee, Dr. Royce Floyd and Dr. Jeff Volz, for assisting and guiding me in the completion of my thesis. Lastly, thank you to the entire staff of the CEES department. To Molly, Brenda, Susan, and Audrey, thank you for all your assistance during my time at OU.

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Abstract

This research investigated the possibility of prestressing a concrete element by inducing expansion of the concrete paste at an early age. This behavior is being called chemically prestressed concrete, for this project, was studied by varying the amount of expansion. A literature review was performed which outlines different experiments investigating the chemical prestressing of concrete. Two of the main focuses of the literature review are the chemical structure of calcium sulfo-aluminate cements and chemically induced axial force.

Phase one of this research was to investigate the varying levels of expansion by using 21%, 23%, 25%, 27%, and 29% replacement by weight of portland cement with an expansive mineral admixture. The mix designs developed in phase one of this research utilized the varying percentages of expansive mineral admixture. The concrete's expansion or shrinkage was measured over an extended period using restrained prisms and restrained cylinders. The specimens were wet cured for the first seven days, allowing expansion to develop. The prisms were measured using a length comparator. The restrained cylinders were measured using a vibrating wire strain gage (VWSG) system. The VWSG were connected to a Geokon data acquisition system to constantly read the expansion or shrinkage at an interval of 15 minutes.

Phase two of this research investigated the use of internal restraint to develop the prestress of the concrete. The internal restraint conditions included four types of steel fibers: CTS proprietary, Novocon 1050 he, Novocon XR, and Dramix. The mix design with 25% replacement of Portland cement with the expansive mineral admixture was used throughout phase two. The same type of restrained prisms and restrained

cylinders were monitored to determine the amount of restraint provided by each fiber type.

Phase three of this researched included casting a series of slabs to examine the behavior on a larger scale. Three slabs were cast using the 25% replacement of Portland cement with the expansive mineral admixture to monitor the amount of restraint provided by the differing reinforcements. Slab 1 had no reinforcement of steel fibers in the 25% replacement of Portland cement with the expansive mineral admixture, slab 2 had a No. 5 bar around the edges of the slab, and slab 3 had the Novocon XR steel fibers. All three slabs were instrumented with three VWSG's throughout. The VWSG's were placed longitudinally along the tip and midpoint and transversely in the midpoint of the slab.

The tests conducted show how significantly a change in the percentage of expansive mineral admixture can affect the expansion of the concrete. The results show a trend in which increasing expansive mineral admixture created increased expansion. The steel fibers created internal restraint of the expansion, but each fiber type created a different level of restraint. The fibers internal restraint can create a material induced prestress by restricting the expansion and carrying the associated stress from restraining the expansion. Chemically prestressed slabs have the potential for becoming used in industry, but the sizing effect must be accounted for when designing.

Chapter 1: Introduction

1.1 Problem Summary

Prestressed concrete is a form of concrete with a force induced into the reinforcing steel prior to casting to resist the tensile forces at service loads. Since concrete is weak in tension and strong in compression, prestressing the steel allows the concrete to only carry compression stress. After casting and release, the reinforcing steel carries high tensile forces while the concrete carries the compressive forces. Prestressing the reinforcement in the concrete increases the flexural properties of the section, such as bending, shear and torsional resistance, while also resisting crack propagation and deflection. Once prestressed concrete is placed in service, the already present forces inside of the member helps to resist the tensile forces that service loads will induce. Due to the increased strength of the member that prestressing creates, the size of a prestressed beam can be significantly smaller than a reinforced beam for the same length and loading conditions. Prestressed concrete can make more effective use of reinforcement and concrete than reinforced concrete, but the required quality of materials is increased as well to handle the force induced prior to casting.

There are multiple types of prestressed concrete such as pretensioned prestressed, post-tensioned, and chemically prestressed. Typical prestressed concrete is when the reinforcing steel is tensioned prior to casting. Post-tensioned concrete has conduits placed in the formwork for the steel to be placed into. The prestressing tendon is placed prior to casting and stressed after the concrete has already hardened. In post-tensioned concrete the force is transferred from the steel to the concrete by the anchorage. One of the main benefits of Post-Tensioned concrete is the reinforcing for tensile forces while providing compressive forces into the concrete simultaneously. Due to the reducing of tensile forces in the member, post-tensioned concrete members can have longer spans and smaller cross sections in comparison to reinforced concrete members. Chemically prestressed concrete is a type of concrete that develops a high expansive energy to induce stress into the reinforcing steel.

Chemically prestressed concrete develops high expansion to induce a stress into the reinforcement. Since the concrete itself is creating the high expansion, chemically prestressed concrete has also been known as self-stressing or self-prestressed concrete. The shrinkage compensated cement that is required produces ettringite crystals in the chemical structure of the concrete, which causes the high expansion. Shrinkage compensated cements have been used alongside of Portland cement to create the high expansion. This is done by using a percentage of replacement of an expansive mineral admixture alongside of the Portland cement.

Chemically prestressed concrete creates the stress introduced into the reinforcement by high expansion. This expansion removes the need for a hydraulic jack that is used for either typical prestressed or Post-Tensioned concrete. The use of steel fibers is another way to reinforce a chemically prestressed member. The use of fibers can reduce the amount of steel that is needed for a chemically prestressed member, and the manual labor associated with laying conventional reinforcing bars can be reduced or even eliminated. The steel fibers are placed directly into the mixture of concrete while the mixing is occurring. Chemically prestressed concrete creates high expansion which in term could reduce the amount of shrinkage the concrete exhibits. When concrete shrinks, cracks begin to form from drying shrinkage. However, due to the high expansion, the shrinking that chemically prestressed concrete would experience would have potentially been offset by the expansion that already occurred.

The focus of this research was to begin to characterize chemically prestressed concrete in terms of material properties, such as expansive behavior, shrinkage behavior and resulting strengths. Chemically prestressed slabs could become useful in residential construction, but before a full-scale slab can be cast, the material properties must be understood. To understand chemically prestressed concrete material properties, a range of expansive mineral admixture percentages must be examined to understand what percentage of expansive mineral admixture is needed to create chemical prestress. Each of the mixes with different percentages was tested to observe the differing levels of expansion. Then a dosage was chosen to introduce steel fibers to observe how much restraint the steel fibers will create. Specimens were cast to characterize the modulus of rupture strength to understand the how the base percentage of expansive mineral admixture performed. Then steel fibers were introduced to a percentage to see how the strength was affected. Finally, three slabs were cast to monitor the large-scale implementation of the expansive mineral admixture and different restraining conditions.

1.2 Objectives

There are three main objectives that this research explored. First, does an increase in the percentage of expansive mineral admixture for a mix result in higher expansion of specimens during the curing period. Second, chemical prestressing of concrete can reduce cracking to allow for a more aesthetically pleasing surface and increased durability. Third, the amount of restraint can affect the amount of expansion a specimen will exhibit (Roswurm 2013).

The objectives discussed previously will be achieved by completing testing procedures. First, a comparison of the effects of differing expansive mineral admixture percentages had on the expansion and strength of the mix. Second, determine how specimens will react to the differences in expansive mineral admixture percentages. By understanding these differences, the effects of chemically prestressed concrete can be better understood through the differing percentages of expansive mineral admixture for each mix. Finally, determine the optimal percentage of expansive mineral admixture to achieve chemical prestress inside of the specimens.

Chapter 2: Literature Review

2.1 Concept of Prestressed Concrete

Concrete is weak in tension but strong in compression. As such, concrete members typically fail due to tensile stresses that cause cracking. One method of reducing the tensile forces in a concrete member is to prestress the reinforcement. The prestressing of the reinforcing steel is done by applying a concentrated tensile force in the longitudinal direction. The concrete is then cast around the reinforcement and allowed to harden to a minimum strength. The formwork is then removed and the applied tensile force in the reinforcement is removed. Upon releasing this external force, the reinforcement tries to return to its original length, but due to the bonding with the concrete is unable to. The result is that the concrete goes into compression and the reinforcement into tension. The application of this force helps reduce the tensile forces that the concrete specimen will feel once service loads are applied. The prestressing principle that describes a typical prestressed concrete is known as linear prestressing (Nawy 1989).

Figure 1 illustrates a setup at a prestressing abutment for tensioning of the reinforcement. The reinforcement steel is tensioned to the desired stress to handle the specified service loads that the member is designed for. The steel exerts a force on the concrete, which is not true of typical reinforced concrete. This force allows for "a relatively high controlled recovery of cracking and deflection," (Nawy 1989). The introduction of prestress creates a more efficient member which can allow for decreases in member sizing for identical loading conditions in comparison to reinforced concrete.

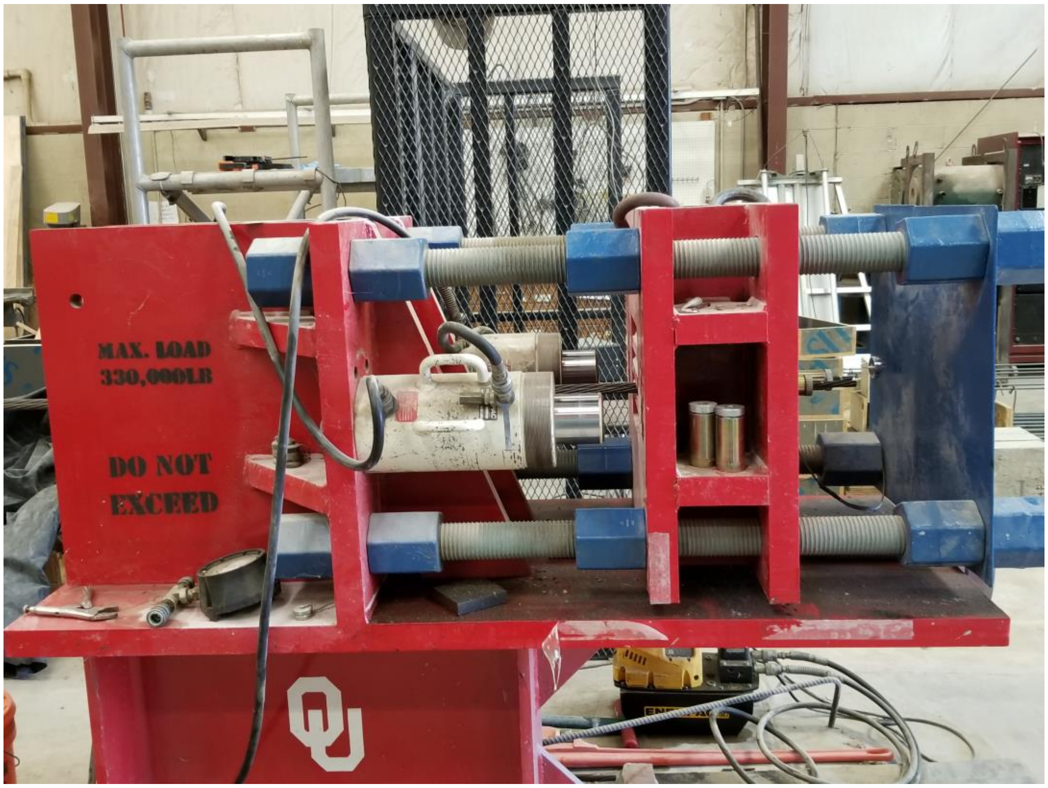

Figure 1, Prestressing Bed Setup

2.2 Concept of Chemically Prestressed Concrete

Compared to typical prestressed concrete, chemically prestressed concrete develops a high expansive energy in the cementitious material (Sahamitmongkol and Kishi, 2011b) and not due to an external force. Chemical prestressing is also known as self-stressing due to the expansive energy creating stress inside of the concrete from the expansion (Sahamitmongkol and Kishi, 2011b).   The process of self-stressing can eliminate any prior tensioning of the reinforcement since the high expansion creates the stress inside of the concrete. This free expansion in the concrete transfers force to the reinforcement via bonding and creates tension in the reinforcement and a compressive force in the concrete prior to the application any external loads.

Typically, the expansive cementitious material used to chemically prestress concrete can also be used to create shrinkage compensating concrete. However, the main difference between shrinkage compensating concrete and chemically prestressed concrete is the expansion rate, which is higher for chemically prestressed concrete than shrinkage compensating concrete (Hosoda and Kishi, 2003).

2.3 Flexural Properties

2.3.1 Tension Stiffening

Tension stiffening is a structural property that allows concrete to, "carry a part of tensile force even if cracks are induced into [reinforced concrete] element and tensile stress carried by reinforced concrete element becomes superior to that carried by only bare steel bars at the same deformation" (Sahamitmongkol and Kishi, 2011a). This property is important because it uses average stresses and strains to understand the member's behavior. To measure the tension stiffening, Hosoda and Kishi's study placed strain gages along a specimen's ribbed reinforcement during a loading scenario, which is shown in Figure 2. The samples were placed in moist curing conditions until twelve hours before the loading commenced. The strain gages recorded the strains experienced during the loading, which was performed until the reinforcing bar yielded.

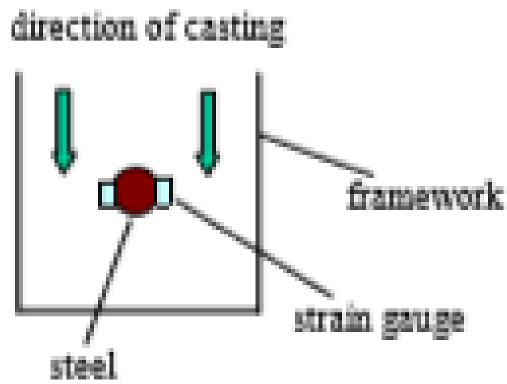

Figure 2, Orientation of Specimen with Concrete Casting Direction (Hosoda and Kishi 2003)

For chemically prestressed concrete, the cracks appeared in a small region, which resulted from higher tension stiffening of the chemically prestressed concrete. However according to Sahamitmongkol and Kishi (2011a), the described modeling of tension stiffening does not reflect all possible permutations for this material property, which calls for more elaborate testing.

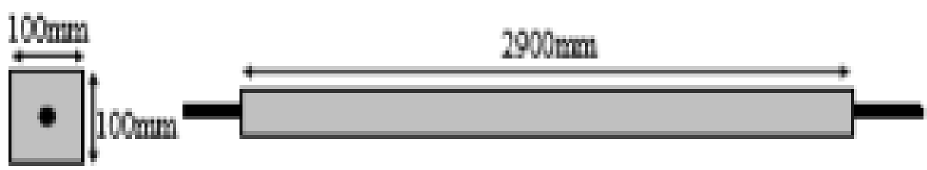

Figure 3, Setup of Tension Stiffening Experiment (Hosoda and Kishi 2003)

Both studies determined the difference in tension stiffening for each type of concrete and showed how chemically prestressed concrete performs better in tension stiffening (Sahamitmongkol and Kishi, 2011a, Sahamitmongkol and Kishi, 2011b).

2.3.2 Bond Characteristics

The bond characteristics of concrete come into play after cracking has occurred due to the separation of concrete and reinforcing bar. The way that the stress is handled by concrete is characterized by bond effects. Hosoda and Kishi's (2003) experiment showed that the cross-sectional area and thickness of the cover of the chemically prestressed concrete specimen has a significant effect on the bonding characteristics. This experiment only tested two cross sectional areas consisting of 100 x 100 mm^2 and 200 x 200 mm^2. Testing other sizes could present patterns that were missed by only testing two cross sectional areas. Figure 4 shows the test setup for the bonding characterization experiments.

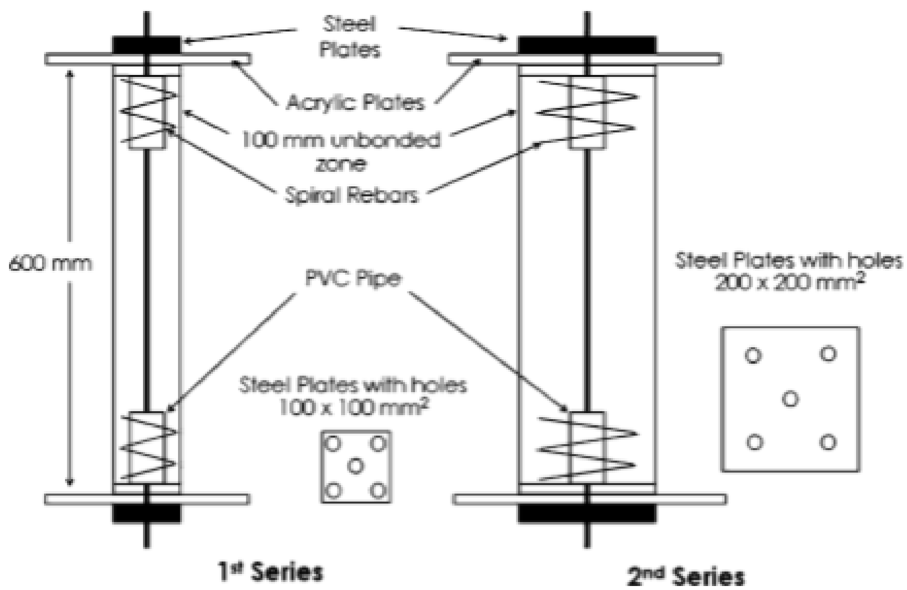

Figure 4, Bonding Characteristic Test Setup (Hosoda and Kishi 2003)

Hosoda and Kishi (2003) showed that the average bond for chemically prestressed concrete and reinforced concrete are essentially the same. However, chemically prestressed concrete is able to achieve higher bond stress at the end of the specimen due the transfer of stress being concentrated at the end of specimen. Due to this location of transfer of stress, chemically prestressed concrete can reduce the elongation of the reinforcement steel. Hosoda and Kishi also found that chemically prestressed concrete can handle higher bond stress at a cracked location due to chemically prestressed concrete being able to handle tension stiffening better than reinforced concrete.

2.3.3 Plastic Deformation

Plastic deformation of concrete is deformation that is occurs before cracking begins. One study evaluated how concentric reinforcement affected chemically prestressed concrete in terms of plastic deformation (Sahamitmongkol and Kishi, 2011b). Figure 5 shows the flexural testing setup for the monitoring of strain and cracking. Overall, the study found that the plastic deformation of chemically prestressed concrete was higher than the plastic deformation of reinforced concrete. The chemically prestressed concrete also displayed the ability to distribute the loads along a constant moment span. The chemically prestressed concrete had several cracks induced upon it, but the cracks developed lower on the specimen than for the reinforced concrete. Sahamitmongkol and Kishi (2011b) concluded that, in terms of plastic deformation, the properties of chemically prestressed concrete and chemically prestressed mortar are not discernably different if the heights of the samples are the same.

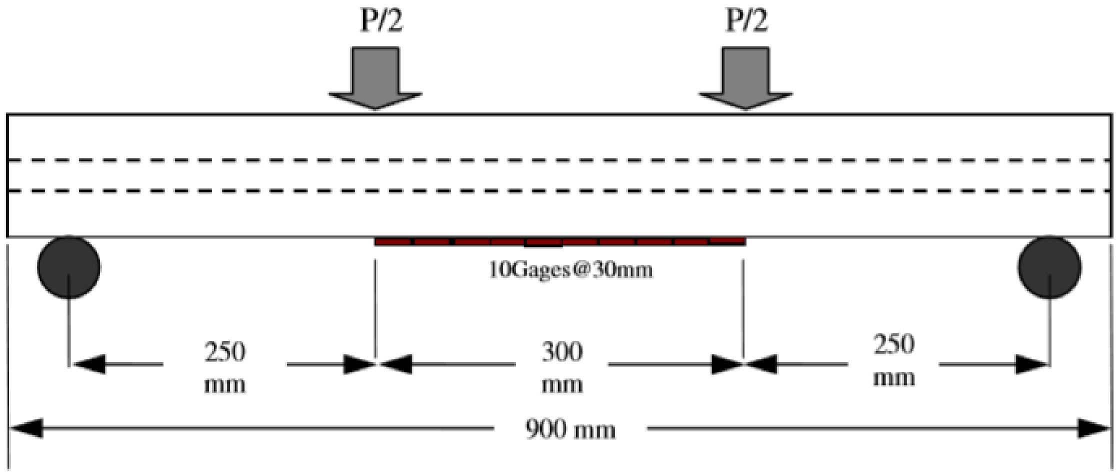

Fig. 4. Loading conditions.

Figure 5, Flexural Testing Setup (Sahamitmongkol and Kishi, 2011b)

2.4 Crack Formation

An issue with most types of concrete is the potential for cracking, including typical prestressed concrete. However, using expansive concrete can reduce the cracking. A major application of the expansive concrete is when shrinkage is a potential issue, for example when a concrete member is exposed for the public to see. People generally do not feel safe when cracks are visible in the concrete members because they do not know the material properties of concrete. The introduction of expansive additives and proper restraint has allowed chemical prestressing to occur in expansive concrete.

Analyzing how the crack formations affects the different results of the experiments that are conducted can show how chemically prestressed concrete handles crack development. Expansive agents in the concrete mixture cause concrete crack resistance to increase. One of the most prominent improvements of chemically prestressed concrete is the crack resistance that accompanies the chemically induced prestressing. For Hosoda and Kishi (2003), conducted tests to examine crack existence through a flexural test. The flexural specimen setup is shown in Figure 6. The flexural testing setup of specimens and strain gages is shown in Figure 7. These tests were conducted on a typical design for regular concrete mixing, but the second group of test specimens was a chemically prestressed concrete mix, focusing heavily on expansive concrete.

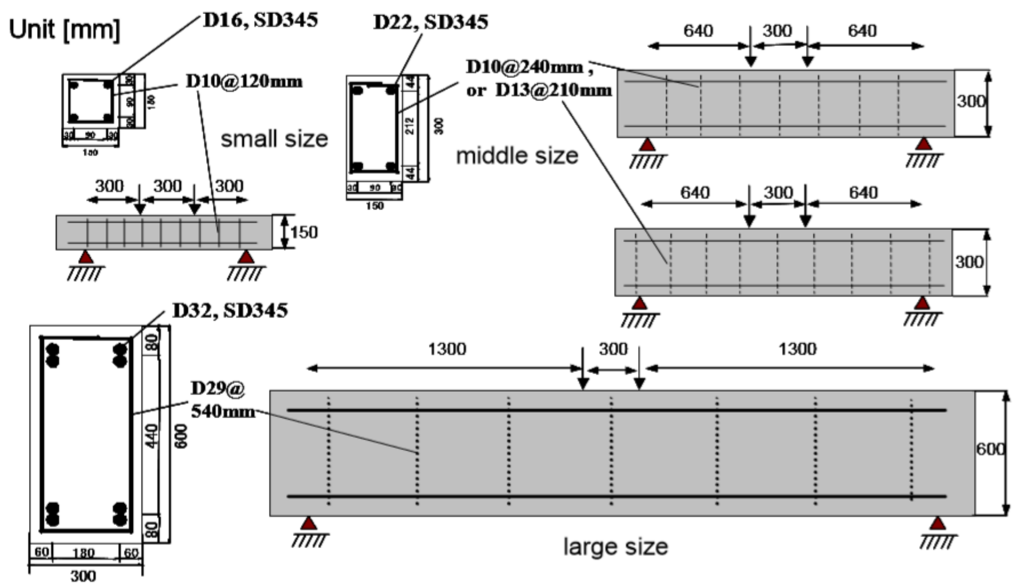

Figure 6. Orientation and Sizes of Specimens (Hosoda and Kishi 2003)

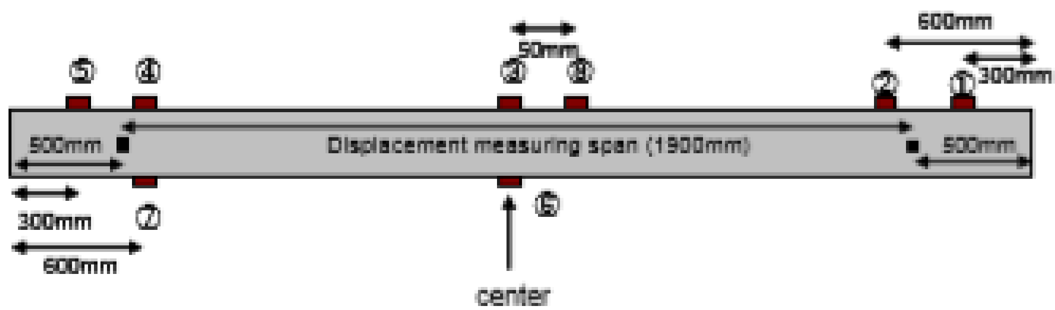

Figure 7. Placement of Strain Gages for Flexural Testing (Hosoda and Kishi 2003)

The experiments showed that the tension stiffening of chemically prestressed concrete was higher than typical concrete. The tests also showed that the crack width of the chemically prestressed concrete was small and due to several structural properties of the expansive concrete. A larger load was necessary to alter the crack width in chemically prestressed concrete; whereas in typical concrete, the load increase altered the crack width immediately. A contributing factor to the crack width was the fracture energy of concrete (Hosoda and Kishi, 2003). For chemically prestressed concrete, Hosoda and Kishi concluded that the fracture energy is higher when restrained in multiple directions.

2.5 Expansive Properties

An important contribution to the expansion is how the specimens are cast and what environment is experienced in their early life. Whenever specimens can wet cure for an extended amount of time, the concrete experiences a higher percentage of self-stressing. "A specimen cured for a prolonged period in water at 140 ^{o}F – after being cured in air for 8 hr. at 140 ^{o}F prior to demolding- gained 75 percent of the maximum possible pre-stress in 24 hr., 90 percent in 48 hr., and 99 percent after 70 hr." (Benuska et al., 1970).

Itani (2017) used a very similar testing protocol in terms of percentages of expansive mineral admixture to characterize the force that corresponded to the maximum expansion as this project. Itani tested 21%, 23%, 25%, 27%, and 30% expansive mineral admixture. Itani discusses the effect of the maximum induced force occurring during the wet curing time of the specimen life. The induced force is related to the expansion that the specimen exhibited by the following equation. This equation is a reorganized mechanics of materials equation for deformation (ΔL) due to a uniaxial force (F).

$$F = \frac{\Delta L * E * \mathrm{A}}{L}$$

Where
ΔL= Change in Length (Readings from C-878 Specimens)
$A = \frac{\pi d^2}{4}$
d=3/16 inch
L=10 inches
E=29,000 ksi

The specimens were cast in accordance with ASTM C-878. The specimens were measured with a length comparator every seven days until 28 days were reached. The specimens were lime water cured for the first seven days of the specimen's life. The general trend of increasing expansive mineral admixture percentage corresponding the increased axial force is easily shown in Figure 8. It should be noted that in this equation the force (F) is developed over a period of time due to the expansive behavior of the concrete.

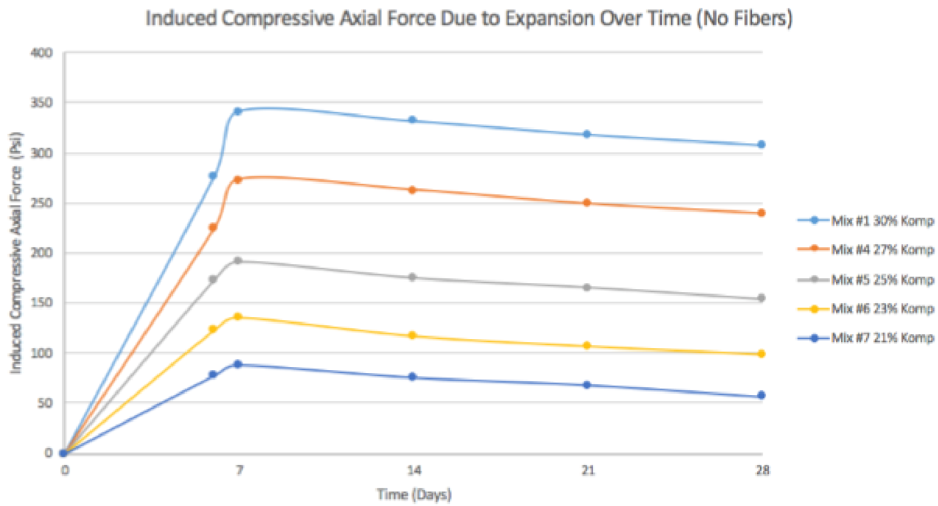

Figure 3.1.1 Induced Compressive Axial Force due to Expansion Over Time plot for Fiber Free Mixes

Figure 8, Axial Force Induced with Differing Expansive mineral admixture Percentages (Itani 2017)

Itani (2017) states that the higher percentages of expansive mineral admixture specimens developed cracking in the later stages. He states that this cracking should not be considered shrinkage cracking, but he states that the more probable cause of cracking was large expansions in the paste. To help balance this large expansion that causes cracking, fibers were added to the mixture to create a restraining effect.

Itani (2017) introduced glass and steel fibers into the mixtures, but the percentage of expansive mineral admixture remained the same throughout to characterize the effects of the fibers. The 30% expansive mineral admixture mixture was used to see if the restraint provided by the fibers would be able to prevent the cracking that the original mixture showed. Figure 9 illustrates that the fibers did decrease the amount of expansion the specimen exhibited by lowering the induced axial force.

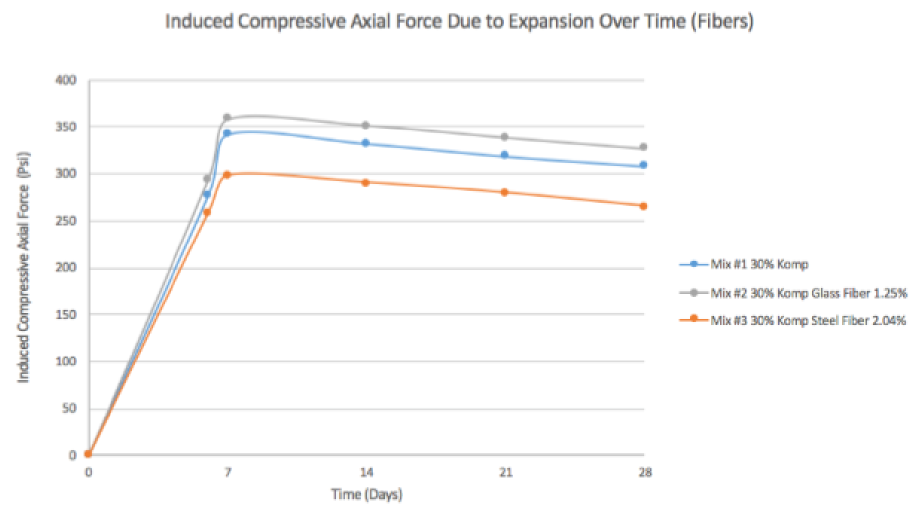

Figure 3.2.1 Effect of Steel and Glass Fibers on Mix #1 Plot

Figure 9, Axial Force Induced with Steel and Glass Fibers (Itani 2017)

The percentage of fibers appeared to have an effect on the overall restraint that the fibers provided. Itani shows that differing percentages of fibers can greatly affect the restraint induced on the mixture. Figures 10 and 11 show the differing percentages and types of fibers for a given percentage of expansive mineral admixture mixture. In Figure 10, it can be seen that the differing percentages of fiber do not affect the overall restraint provided by the fibers. The restraint is relatively consistent for all the steel fiber types.

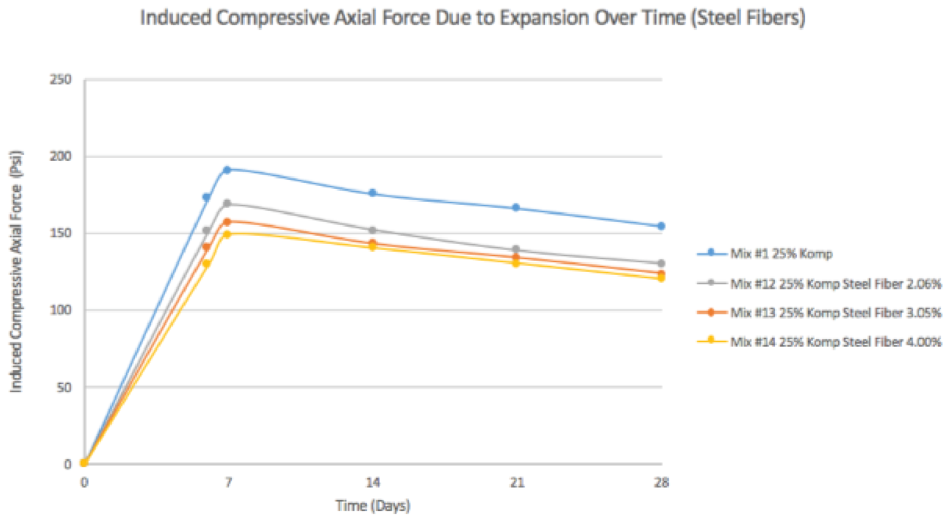

Figure 3.2.2 Effect of Steel Fibers on Mix #5 Plot

Figure 10, Induced Axial Force with Differing Steel Fiber Percentages (Itani 2017)

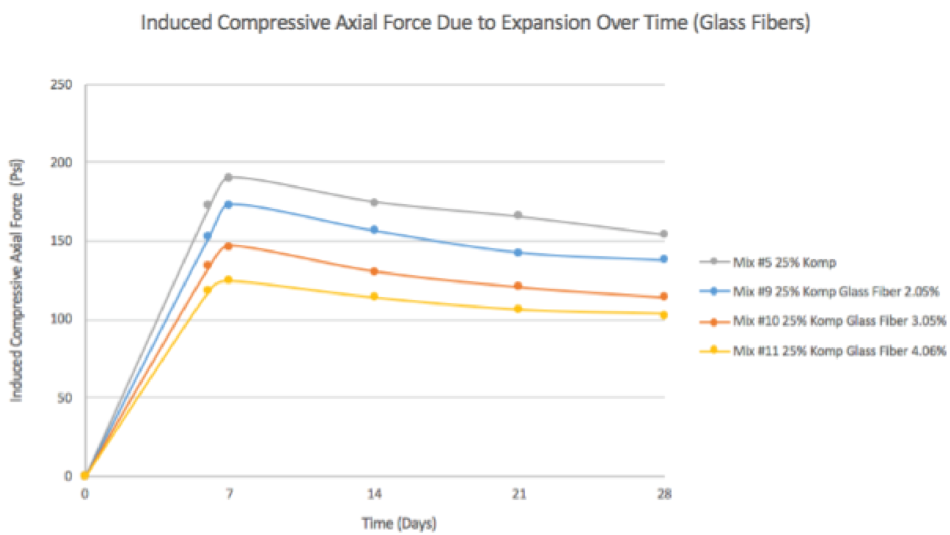

Figure 3.2.3 Effect of Glass Fibers on Mix #5 Plot

Figure 11, Induced Axial Force with Differing Glass Fiber Percentages (Itani 2017)

However, the previous statement about affecting the overall restraint cannot be applied to the glass fibers. The restraint provided by the differing percentages of the glass fibers greatly depends on the amount of fibers. Itani (2017) states that the glass fibers have a non-linear behavior in terms of restraint as compared to the steel fibers. He suggests that this is potentially due to the grid interlocking that was present in the glass fibers, while the steel fibers did not create that same type of restraint inside of the specimens.

Itani (2017) concluded that the increase in expansive mineral admixture percentage is proportional to the overall expansion. All fibers did provide restraint, but the differing fiber types provided different amounts of restraint. With the combination of 25% expansive mineral admixture and fibers, an overall expansion of 0.01522 inches was experienced.

2.6 Chemical Structure of Cementitious Material

The expansive concrete is generally created by using a special type of cement, Calcium Sulfo-Aluminate, or CSA. There are multiple types of CSA cements, but Type K cement is made to be used alongside of portland cement. The following chemical reaction can show the formation of the ettringite that is heavily correlated to high expansive properties (Chen et al., 2012). The $C\hat{S}$ terms in the chemical equation are different types of calcium sulfates requires to produce the ettringite.

$$C_4A_3\hat{S} + 2C\hat{S}H_2 + 34H \rightarrow C_6A\hat{S}_3H_{32} + 2AH_3$$

The $C_6A\hat{S}_3H_{32}$ product from the chemical reaction is the ettringite formation that contributes to the expansive properties of the cement. This process is dependent upon the quantity of ettringite that is formed to find how much expansion will be produced. According to Chen et al. (2012), “The cement pore structure affects the mobility of ions and the amount of space for reaction products to form. It has been suggested that the formation of ettringite confined to the vicinity of aluminum-bearing grains results in large expansions. Therefore, ettringite formation in pastes with denser pore structures could cause more expansion.” There are multiple aspects that can affect the amount of expansion of a CSA cement at the microscopic level. Chen et al. (2012) also states that the size of the clinker of $C_4A_3\hat{S}$ can affect the rate and magnitude of the overall expansion created and uses three different clinker sizes throughout the research.

Chapter 3: Research Protocol

3.1 Mix Design

3.1.1 Phase I Mix Design

The mix design for phase I held the water to cement ratio constant at 0.5 and the total cementitious materials constant at 580 lb/yd^3. The primary variable was the percentage of expansive mineral admixture in the mix. The concrete mix designs for phase I are presented in Table 1. The expansive mineral admixture used was Komponent®.

Table 1, Concrete Test Matrix for Phase I

Percentage of Expansive Mineral Admixture	**21%**	**23%**	**25%**	**27%**	**29%**
Portland Cement	458.2 lb	446.6 lb	435.0 lb	423.4 lb	411.8 lb
Komponent®	121.8 lb	133.4 lb	145.0 lb	156.6 lb	168.2 lb
Total Cementitious Material	580 lb	580 lb	580 lb	580 lb	580 lb
Coarse Aggregate	1772.6 lb	1772.6 lb	1772.6 lb	1772.6 lb	1772.6 lb
Fine Aggregate	1367.2 lb	1366.2 lb	1362.8 lb	1361.0 lb	1360.1 lb
Water	293.8 lb	293.8 lb	293.8 lb	293.8 lb	293.8 lb

Note: All weights shown for lb/yd^3

When phase I had been completed, a percentage was chosen to implement fibers to monitor the new levels of expansion. The 25% mix was chosen to implement the fibers in phase II of the research. The 25% was chosen due to the expansion being high enough to account for the restraint provided by the fibers. The 27 or 29% could have been chosen, but the 25% was the first percentage that achieved a high enough expansion.

3.1.2 Phase II Mix Design

The mix design for phase II used 25% expansive mineral admixture with four different types of fibers implemented to monitor the differing levels of expansion and restraint provided by the fibers. The four fiber types were Novocon XR, Novocon 1050 he, CTS proprietary, and Dramix. Each fiber had a different size and shape orientation and design to capture the different amount of restraint provided. The CTS Proprietary was a stainless-steel hooked end fiber and had an average length of 2 inches and diameter of 0.022 inches. Novocon XR was a stainless-steel filibrated fiber and had an average length of 2 inches and diameter of 0.096 inches. The Novocon 1050 he was a hooked end fiber and had an average length of 1.5 inches and diameter of 0.041 inches. The Dramix was a straight fiber had an average length of 0.5 inches and diameter of 0.008 inches. The concrete mix designs for phase II are presented in Table 2. The four investigated fibers types are presented in Figure 12. The individual fibers are presented in Figures 13—16.

Due to the introduction of fibers into the concrete, the fiber development length became a consideration. Development length can be defined as," the development length concept requires minimum lengths or extensions of reinforcement beyond all points of peak stress and points where reinforcement is bent or terminated. From a point of peak stress in reinforcement, some length of reinforcement is necessary to develop the stress," (ACI 318, 2014). The fibers act as small reinforcing bars in the concrete, but due to decreased diameter of the fiber, the required development length also decreased. The required development length of a No. 7 reinforcing bar is 41 inches using ACI 318-2014's simplified equation. However, the diameter of a No. 7 reinforcing bar is 0.875 inches. The largest diameter of the fibers is 0.091 inches, which is less than 1/8 the diameter. If the diameter is almost 9 times smaller, then the required development length also reduces. However, the simplified equation used previously cannot be applied to the fiber development length calculation due to the specified conditions. The development length of each fiber was different due to having a different length, diameter, and shape. However, since the mechanical element varied for the fibers, the resulting development length varied as well.

Table 2, Concrete Test Matrix for Phase II

Fiber Type with 25% Expansive Mineral Admixture	25% No Fibers	CTS Proprietary	Novocon 1050 he	Novocon XR	Dramix
Portland Cement	435.0 lb	435.0 lb	435.0 lb	435.0 lb	435.0 lb
Komponent®	145.0 lb	145.0 lb	145.0 lb	145.0 lb	145.0 lb
Total Cementitious Material	580 lb	580 lb	580 lb	580 lb	580 lb
Coarse Aggregate	1772.6 lb	1772.6 lb	1772.6 lb	1772.6 lb	1772.6 lb
Fine Aggregate	1362.8 lb	1362.8 lb	1362.8 lb	1362.8 lb	1362.8 lb
Water	293.8 lb	293.8 lb	293.8 lb	293.8 lb	293.8 lb
Fibers	0 lb	90 lb	90 lb	90 lb	90 lb
Glenium	0 mL	0 mL	0 mL	0 mL	45 mL

Note: All weights shown for lb/yd^3

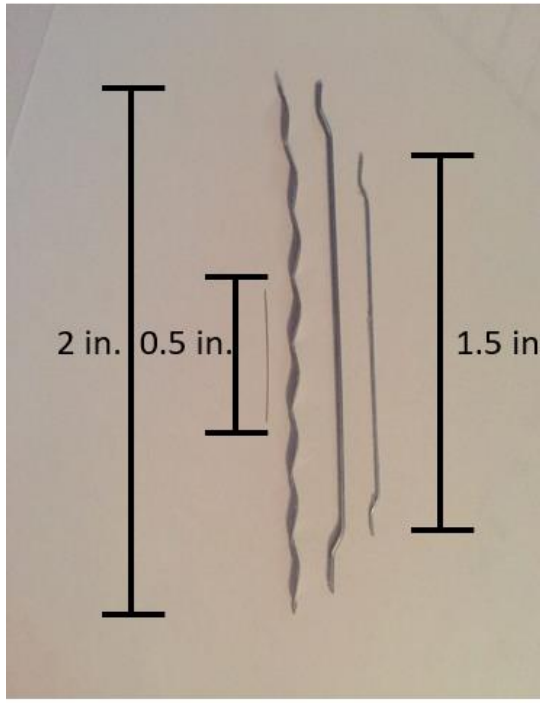

Figure 12, All Four Fiber Types Left to Right (Dramix, Novocon XR, CTS Proprietary, Novocon 1050 he)

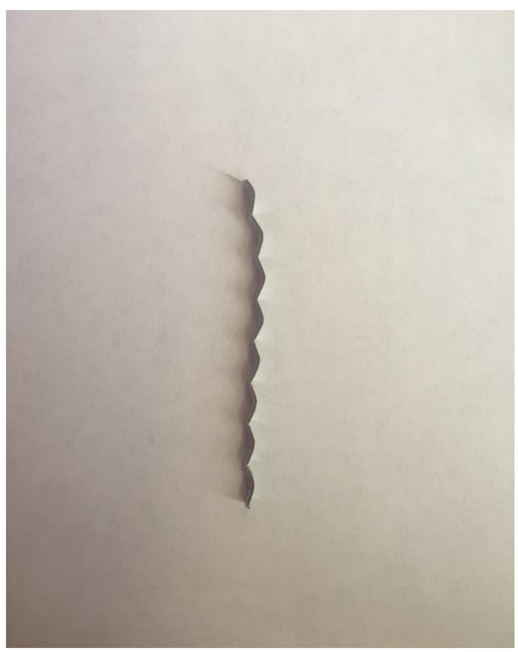

Figure 13, Novocon XR Fiber

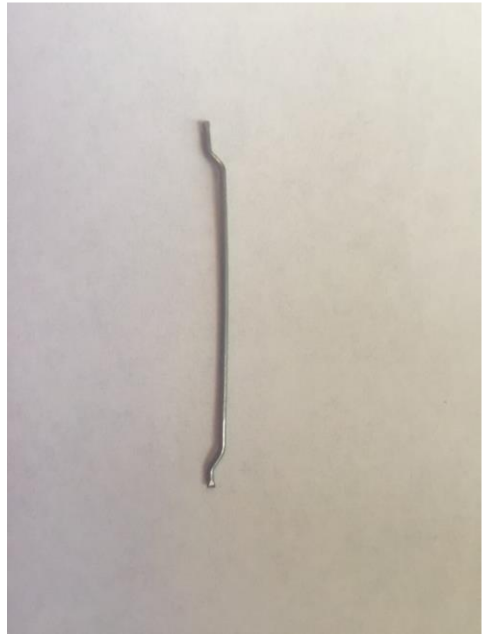

Figure 14, Novocon 1050 he Fiber

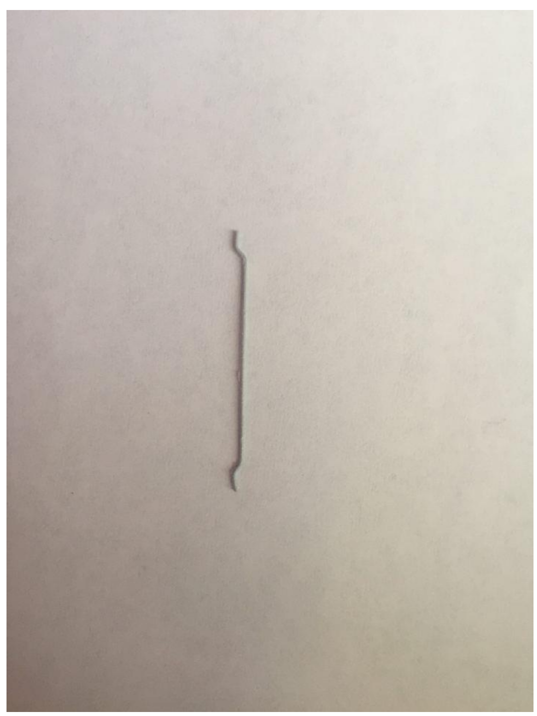

Figure 15, CTS Proprietary Fiber

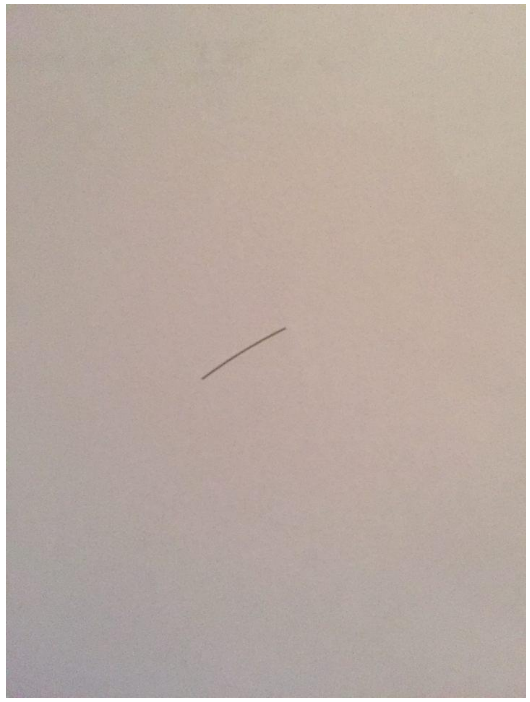

Figure 16, Dramix Fiber

3.1.3 Phase III Mix Design

The mix design for phase III is presented in Table 3. The three slabs in phase III had the same concrete mixture with a 25% expansive mineral admixture. The variable in these tests were the type of reinforcement for each slab. Slab 1 was plain concrete and had no reinforcement of any kind. Slab 2 had a No. 5 reinforcing bar along the edges throughout. Slab 3 had the Novocon XR fibers implemented into the mixture. Each slab was 36”x100”x5”. Figure 17 shows the setup for slab 2 with the No. 5 reinforcing bar along the edges. Figure 18 shows the setup for slabs 1 and 3.

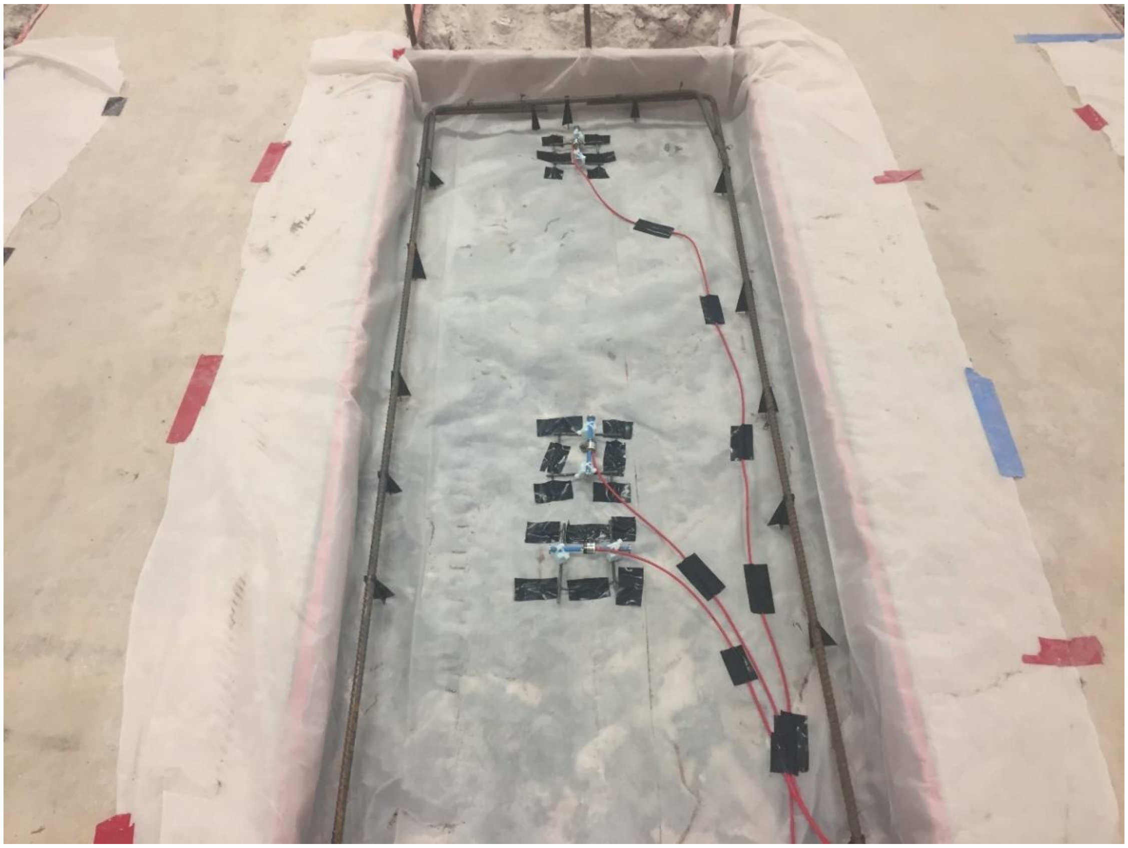

Figure 17, Instrumented Slab with No. 5 Reinforcing bar

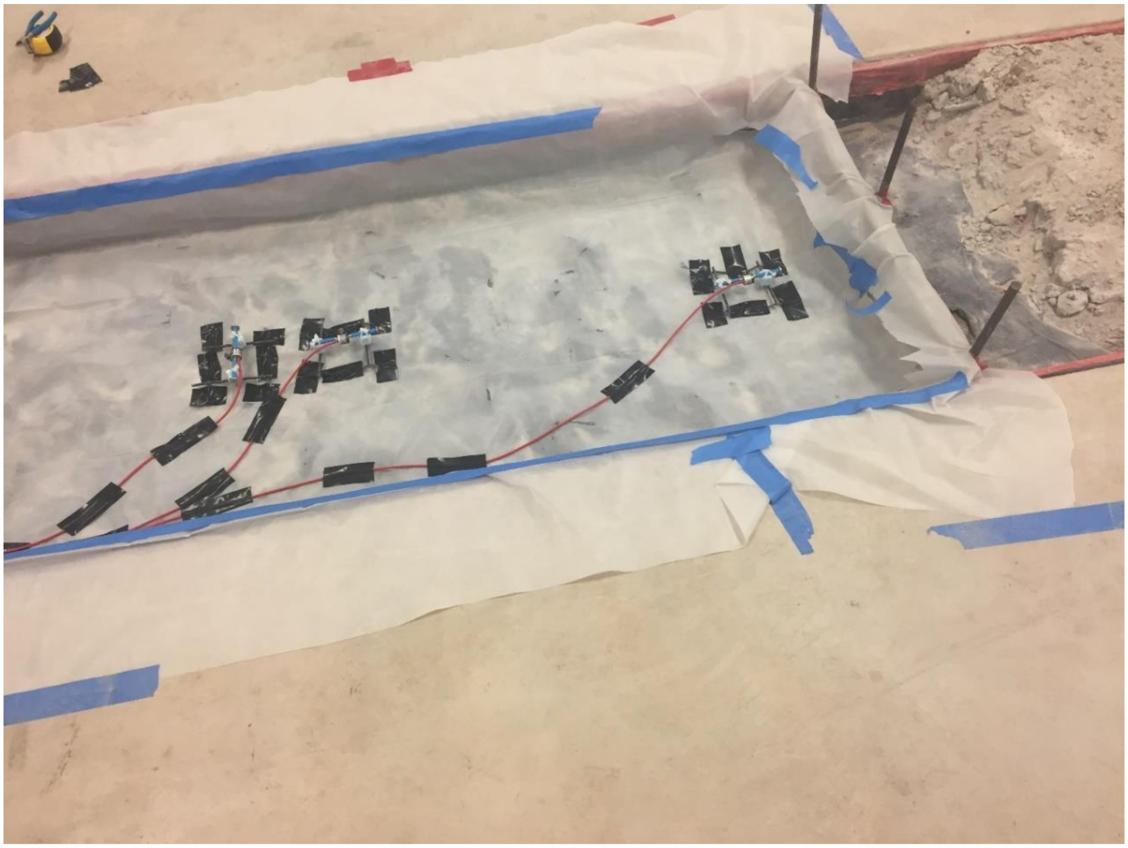

Figure 18, Setup for Slab with Fibers or Control Slab

Table 3, Concrete Test Matrix for Phase III

Slab Type	**25% No Reinforcement**	**25% No.5 Reinforcing bar**	**25% Novocon XR**
Portland Cement	435.0 lb	435.0 lb	435.0 lb
Komponent®	145.0 lb	145.0 lb	145.0 lb
Total Cementitious Material	580 lb	580 lb	580 lb
Coarse Aggregate	1772.6 lb	1772.6 lb	1772.6 lb
Fine Aggregate	1362.8 lb	1362.8 lb	1362.8 lb
Water	293.8 lb	293.8 lb	293.8 lb
Fibers (Novocon XR)	0 lb	0 lb	90 lb
Glenium 7920	230 mL	230 mL	250 mL

Note: All weights shown for lb/yd^3

3.2 Testing Protocol

3.2.1 Testing Protocol for Phases I and II

The slump test is a way to characterize the consistency of the concrete. The slump test results provide a way to represent the concrete's flowability at a young age. Any noticeable changes in slump can show a problem in the concrete mixture. The slump tests were conducted in accordance with ASTM C-143. This test was executed for every mix.

The unit weight test is a way to represent that quality of a mix. The unit weight of a given mix is compared to a theoretical unit weight. The comparison is recorded as a percent difference. The unit weight tests were conducted in accordance with ASTM C-138.This test was executed for every mix in phases I and II.

The temperature of a mix effects the curing of the concrete. If the mixture is too hot or cold, the mix will not perform as well. If a mixture was expected to be too hot or cold, the mix water was adjusted with either cold water or hot water, respectively. The temperature of concrete was measured for every mix.

The air content test measures the amount of air in the concrete. There is no practical way to achieve an air content of 0%, but the goal was to reach approximately 2% air for each mix. The 2% allows for air to be entrapped in the concrete, but the concrete does not have too many air pockets that could negatively affect the mixture. The air content test was conducted in accordance with ASTM C-231. This test was conducted for every mix in phases I and II.

The compressive strength of concrete is useful in determining the quality of the mix. For this study, 4”x8” cylinders were cast. For all the compressive cylinders, tests were conducted at 24 hours, 7 days, 14 days, 28 days, and 1 year if available. All the compressive cylinders without fibers were consolidated using an external vibrator, following the specifications of ASTM C-39. The compressive cylinders using fibers did not use external vibration. This was not implemented to allow for true randomness of the orientations of the fibers. The compressive strength tests were conducted in accordance with ASTM C-39. This test was conducted for every mix. Figure 19 shows the Forney Compression Testing Machine used for all compression testing.

Figure 19, Setup for C-39 Test

The Modulus of Rupture (MOR) of concrete is useful in determining the strength of a mix. For this project, the specimens were cast to be 6”x6”x22”. In the Figures 20 and 21, a MOR form can be seen. The MOR forms were constructed using Ellis Construction Board for quality and reusability. The first set of MOR’s were tested at 28 days following a 7-day period of wet curing. The second set of MOR’s were tested at 14 days and 28 days to capture early strengths. The MOR tests were conducted in accordance with C-78. There were three specimens cast for each mixture. This test was conducted for every mix in phase II.

Figure 20, MOR Form Side View

Figure 21, MOR Form Top View

There were two tests run to measure the expansion of the concrete in this study. The hand specimens were cast in accordance with ASTM C-878 specifications. The specimens were measured using a length comparator to monitor the expansion following the guidelines of the ASTM. Every ASTM C-878 specimen was measured using the length comparator shown by Figure 22. This test was conducted for every mix in phases I and II.

Figure 22, C-878 Length Comparator

To collect more precise expansion data, 6”x12” cylinders were instrumented with Vibrating Wire Strain Gages (VWSG) as presented in Figure 22. The gages were placed into lead wire holders, which slipped onto the middle of the dumbbell. The lead wire holder once instrumented with the gage had a hose clamp placed around and tightened fully as shown in Figure 23. The strain gages were held inside of the 6”x12” by zip ties to allow for the gage to be in the middle of the specimen as shown in Figure 23. The concrete was then placed around the VWSG inside of the 6”x12” as shown in Figure 24. The wire leads fed back into the data collection system, a Geokon data logger. The logger then collected incremental readings at 15 minutes continuously.

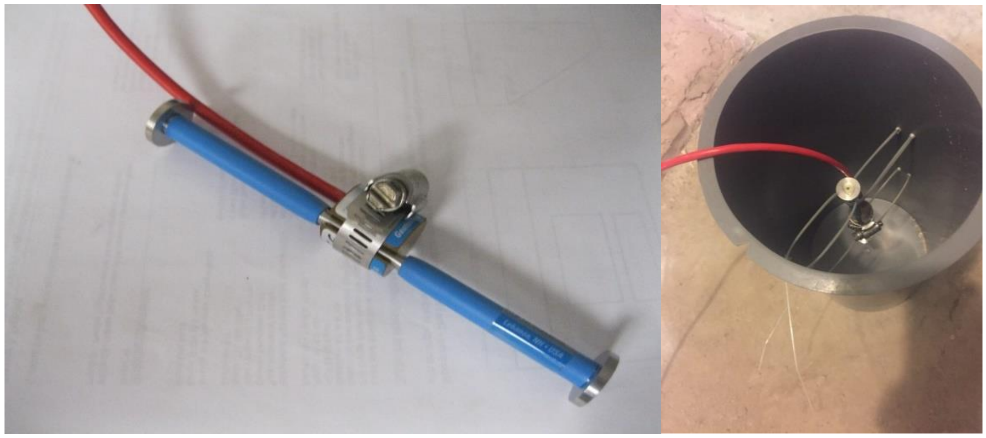

Figure 23, VWSG with Hose Clamp and 6”x12” Fully Assembled

Figure 24, 6"x12" Restrained Cylinder

The ASTM C-878 expansion specimens were tested at 6 hours. Subsequently, the specimens were placed into a tub of lime water for the first 7 days of curing. The following readings were taken daily for the first 14 days, then 21 days, 28 days, and monthly until a final reading at 1 year if available. With each set of expansion specimens, two 6”x12” cylinders were cast alongside the C-878 specimens. These cylinders were wet cured for the first 7 days to mirror the same process as the C-878 specimens. The Geokon data acquisition system was set for an interval of 15 minutes for approximately 1 year. All these results were graphed for each mixture in this project. Figure 25 shows a 6”x12” in a water curing condition.

Figure 25, Wet Curing of 6”x12”

For a better understanding of the phase III mix, a load deflection test was created to capture the amount of ductility the fibers created. There is not a governing ASTM for this type of a test. However, a linear variable differential transformer (LVDT) can be used monitor the load and deflection of the specimen. This was done on a MOR specimen that was tested in accordance with ASTM C-78 in regard to the speed of the load application, but the test overall was a modified MOR developed to measure deflection. To monitor the deflection, a metal angle was epoxied to the side of the specimen. The metal angle was epoxied so that the tip of the leg of the angle epoxied to the specimen aligned with the bottom of the specimen. The LVDT stroke reached to the bottom of the leg of the angle that was protruding from the specimen. As the load increased from the test head, the specimen began to deflect. As the specimen began to deflect, the LVDT stroke shortened, which corresponded to a measured deflection. The specimen was tested to failure, and the measured load and deflection were recorded. In Figure 26, the testing setup for the modified MOR test can be seen.

Figure 26, Load Deflection Test Setup for the Modified MOR Test

3.2.2 Testing Protocol for Phase III

After all the different mixtures had been conducted, a mixture was selected for a large-scale implementation. A slab of 3' by 8' was cast with fibers to capture how a large-scale specimen will react with regards to the expansion. There was also a control slab cast with no fibers, and a slab with No. 5 reinforcing bar around the perimeter will also be cast. The two slabs with some type of reinforcement will help determine how differing types of reinforcing affects the restraint provided. All the slabs had three different VWSG's cast integrally within them. Each was located at a different location to capture a comprehensive representation of the expansion that each slab experiences. The first is located 6 inches from the top end of the slab. The second is located directly in the middle of the length of the slab. The final gage is located 6 inches from the middle slab, but it is placed transversely to determine if the expansion is differing between the directions of the slab. Figure 27 shows a schematic for the placement of VWSG for the slabs.

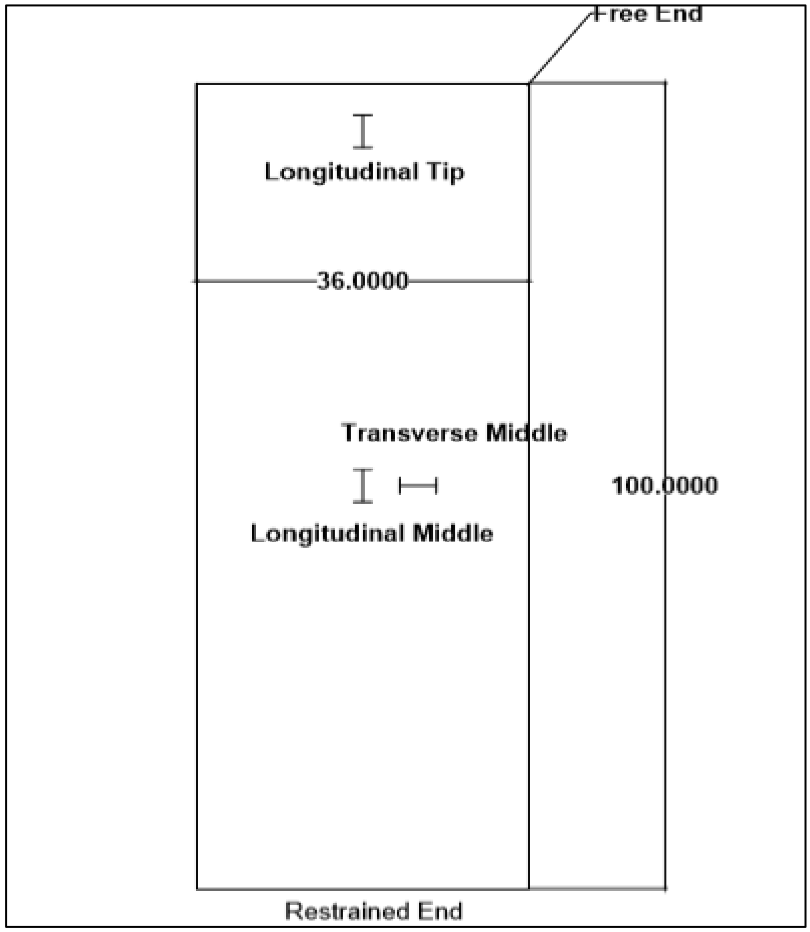

Figure 27, Layout of Slab VWSG

3.3 Mixing Protocol

Every mixture was batched following the guidelines set by ASTM C-192. The protocol of mixing time with 3 minutes mixing, 3 minutes resting, and 2 minutes mixing was followed for every mix. The aggregates used for every pour were #67 coarse aggregate and fine aggregate sand that fulfills the requirements of ASTM C-33. A high range water reducer, Glenium 7920, was used when required to allow more workability of the concrete. The batch using the Dramix fibers, and the slab mixes were poured using water reducer. The water reducer was placed into the mixture after all aggregates, cement, and water had been placed into the concrete mixer. When determining the water content for each mix, ASTM C-566 was followed. Whenever the concrete was cast, the fresh property tests were conducted.

The aggregates for a mix were gathered 24 hours before pouring was to be conducted. The aggregates were weighed into 50 lb buckets. A small sample of the aggregates were weighed out into a small pan and placed into a heating oven following the guidelines of ASTM C-566. These samples were used for determining the moisture content of the aggregates. Following the weighing out, lids were sealed to the top of the buckets to maintain the moisture content. The cementitious materials were weighed out at the same time. Once all the aggregates and cementitious materials were weighed out, the buckets were placed into an environmental chamber to maintain the temperature, moisture content and integrity of cementitious materials. On the day of pouring, the aggregate weights were adjusted for the measured moisture content.

When the aggregates were added to the concrete mixer the aggregates were alternated to produce the most uniform distribution of aggregate possible. Then half of the mix water was placed into the mixing instrument. Half of the cementitious materials were then added, which was half of the Portland Cement and half of the expansive mineral admixture. Approximately one quarter of the mix water was then placed into the mixture. The remaining cementitious materials were placed into the mixture. Finally, the remaining mix water was poured into the mixture slowly to capture all the cementitious material around the edge of the mixing instrument to lower the amount of loss. The time at which the last water was added to the mixing drum was recorded.

The slabs required a larger volume, so a 24 ft^3 concrete mixer was used to accommodate the larger batch volume. When casting the slabs, a concrete buggy was rented to transport the concrete to the location of pouring. Once in place, the concrete was poured and placed using shovels and trowels. In order to better consolidate the slabs, an electric concrete vibrator was used. Once the desired height of slab was reached, trowels were used to put a smooth finish on the surface. These practices were done to mimic what would be done in industry whenever a slab is cast. Figures 28 and 29 show the concrete buggy and the concrete mixer used for the slab mixtures. Figures 30 and 31 shows how the concrete was placed and consolidated.

Figure 28, Concrete Buggy

Figure 29, Concrete Mixer for Slabs

Figure 30, Placing Concrete in Forms from Concrete Buggy

Figure 31, Vibrating Rod Consolidating Slabs

Chapter 4: Test Results

4.1 Phase I Results

The phase I investigation varied the percentage of expansive mineral admixture. The compressive strength and expansion data were collected until 1 year. No high range water reducer was used for this phase as the mixtures all had sufficient workability. All mixtures of varying expansive mineral admixtures were completed within two weeks. The individual mix sheets can be found in the appendix. Table 4 shows the fresh and hardened properties of the phase I mixtures. Table 5 shows the modulus of rupture results for 25% expansive mineral admixture. Table 6 shows the modulus of rupture results for the second set of 25% expansive mineral admixture. The first set of MOR’s were cast to establish a baseline for the phase II MOR’s. A second set of MOR’s were cast from a different batch to capture the early age behavior of the concrete for 14 days as well as 28 days.

Table 4, Fresh and Hardened Properties of Phase I Mixtures

Mix Specification		Units	21%	23%	25%	27%	29%
Slump		*(in)*	4	4.5	4	4	4.125
Unit Weight		*(lb/ft^3)*	147.2	147.12	146.8	146.96	147.96
Batch Temperature		*(ºF)*	74	74	75	80	80
Air Content		*(%)*	1.2	1.2	1.3	1.1	1.3
Compressive Strength	**7 Day**	*(psi)*	4460	4230	3970	3490	3340
	28 Day	*(psi)*	5710	5570	5060	5210	4530
Expansion (C-878)	**7 Day**	*(in^{-6}/in)*	790	1360	2020	2550	3340
	28 Day	*(in^{-6}/in)*	490	1060	1760	2230	3130
	1 Year	*(in^{-6}/in)*	250	790	1410	1870	2700
Expansion (VWSG)	**7 Day**	*(in^{-6}/in)*	779	1346	1990	2169	3085
	28 Day	*(in^{-6}/in)*	533	1098	1883	2104	3237*
	1 Year	*(in^{-6}/in)*	235	743	NA	NA	NA

Note: * indicates only a single reading from a single VWSG due to the other VWSG not producing values

Table 5, MOR Results for 25% Expansive Mineral Admixture First Set

MOR Strengths at 28 Days				
	Load (lb)	***Average Width (in)***	***Average Depth (in)***	***Modulus of Rupture (psi)***
Specimen 1	7360	6.215	6.001	591.92
Specimen 2	5745	6.231	6.009	459.62
Specimen 3	6175	6.238	6.005	494.13
Average Strength	515 *psi*			

Table 6, 14 Day and 28 Day MOR for 25% Expansive Mineral Admixture Second Set

MOR Strengths at 14 Days				
	Load (lb)	***Average Width (in)***	***Average Depth (in)***	***Modulus of Rupture (psi)***
Specimen 1	6170	6.138	6.128	481.83
Specimen 2	4860	6.142	6.071	386.44
Specimen 3	4760	6.139	6.029	383.96
Average Strength	417 *psi*			
MOR Strengths at 28 Days				
Specimen 1	4320	6.123	5.993	353.59
Specimen 2	4690	6.159	6.084	370.30
Specimen 3	5415	6.174	6.150	380.43
Average Strength	380 *psi*			

4.2 Phase II Results

Phase II investigated four types of steel fibers when used in the 25% expansive mineral admixture mix design. The compression data was collected through 28 days because 1 year was outside of the time frame of this project. The C-878 and VWSG expansion data was collected through 7 months because 1 year was outside the time frame of this project. High range water reducer was used for the Dramix fiber mixture, at a dosage of approximately 10 oz/cwt, due to high number of fibers to maintain the same volumetric ratio. The individual mix sheets can be found in the appendix. Table 7 presents the fresh and hardened properties of all phase II mixes. Tables 8-12 show the results of the modulus of rupture tests for each respective fiber. Table 11 specifically shows the results of the modulus of rupture test for the second set of Novocon XR fiber mixture. Figure 32 shows the load deflection curve of the Novocon XR fiber modified modulus of rupture specimen. A second set of MOR’s was cast to capture the early age behavior of the mixture at 14 days as well as 28 days.

Table 7, Fresh and Hardened Properties of Phase II Mixtures

Mix Specification		Units	CTS Fiber	Novocon 1050 he	Novocon XR	Dramix
Slump		*(in)*	0.5	0.75	1	4
Unit Weight		*(lb/ft^3)*	149	150.2	147.92	146.8
Batch Temperature		*(^oF)*	78	79	80	75
Air Content		*(%)*	1.7	1.8	1.9	1.3
Compressive Strength	**7 Day**	*(psi)*	3965	4626.667	3385	3813
	28 Day	*(psi)*	6697.667	5958	6422.333	5725.333
Expansion (C-878)	**7 Day**	*(in^{-6}/in)*	1400	1110	1160	1220
	28 Day	*(in^{-6}/in)*	1200	860	860	880
	1 Year	*(in^{-6}/in)*	NA	NA	NA	NA
Expansion (VWSG)	**7 Day**	*(in^{-6}/in)*	712	1308*	677	688
	28 Day	*(in^{-6}/in)*	747	1146*	578	621
	1 Year	*(in^{-6}/in)*	NA	NA	NA	NA

Note: * indicates only a single reading from a single VWSG due to the other VWSG not producing values

Table 8, 25% Expansive Mineral Admixture with CTS Fibers MOR

MOR Strengths at 28 Days				
	Load (lb)	***Average Width (in)***	***Average Depth (in)***	***Modulus of Rupture (psi)***
Specimen 1	9750	6.415	6.024	753.89
Specimen 2	8350	6.328	5.976	665.08
Specimen 3	8120	6.411	6.043	624.31
Average Strength	681 *psi*			

Table 9, 25% Expansive Mineral Admixture with Novocon 1050 he Fibers MOR

MOR Strengths at 28 Days				
	Load (lb)	***Average Width (in)***	***Average Depth (in)***	***Modulus of Rupture (psi)***
Specimen 1	6800	6.069	6.024	555.77
Specimen 2	8240	6.100	6.137	645.59
Specimen 3	6430	6.116	6.079	512.10
Average Strength	571 *psi*			

Table 10, 25% Expansive Mineral Admixture with Novocon XR Fibers MOR

MOR Strengths at 28 Days				
	Load (lb)	***Average Width (in)***	***Average Depth (in)***	***Modulus of Rupture (psi)***
Specimen 1	7860	6.383	6.031	609.38
Specimen 2	8255	6.260	6.010	657.15
Specimen 3	10115	6.397	6.074	771.46
Average Strength	679 *psi*			

Table 11, 14 Day and 28 Day MOR for 25% Expansive Mineral Admixture with Novocon XR Fibers Second Set

MOR Strengths at 14 Days				
	Load (lb)	***Average Width (in)***	***Average Depth (in)***	***Modulus of Rupture (psi)***
Specimen 1	6350	6.196	6.064	501.67
Specimen 2	6605	6.167	6.043	527.92
Specimen 3	6605	6.196	6.059	522.68
Average Strength	517 *psi*			
MOR Strengths at 28 Days				
Specimen 1	6700	6.195	6.060	530.10
Specimen 2	7215	6.136	6.136	580.35
Specimen 3	6150	6.162	6.065	488.39
Average Strength	533 *psi*			

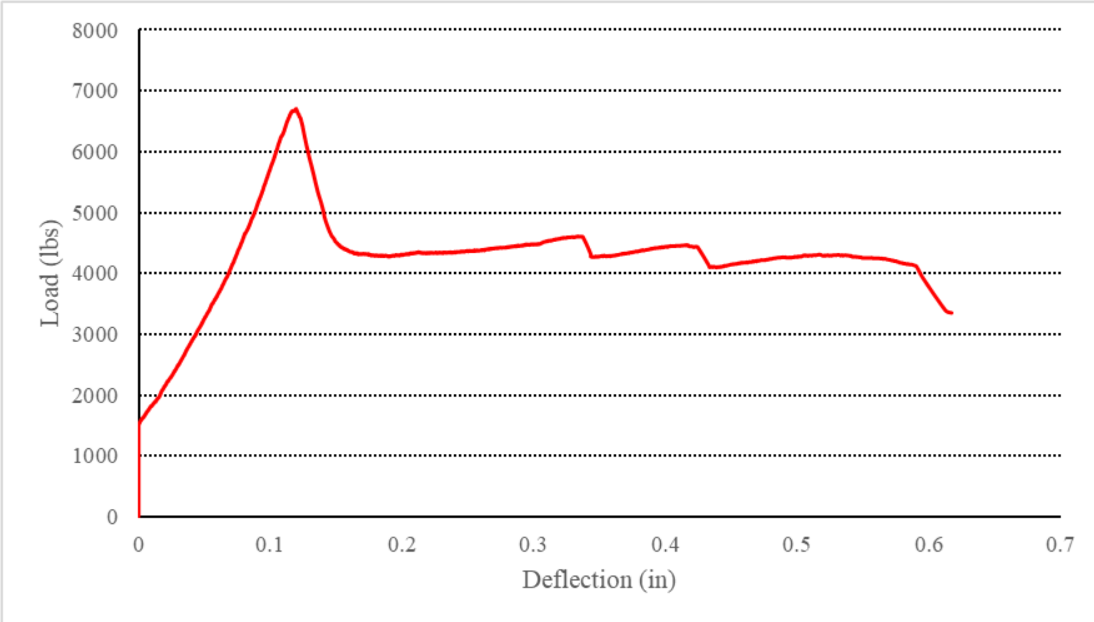

Figure 32, Load Deflection Curve for Modified MOR Test

Table 12, 25% Expansive Mineral Admixture with Dramix Fibers MOR

MOR Strengths at 28 Days				
	Load (lb)	***Average Width (in)***	***Average Depth (in)***	***Modulus of Rupture (psi)***
Specimen 1	8835	6.456	6.062	670.32
Specimen 2	9710	6.361	5.968	771.45
Specimen 3	9690	6.237	6.011	773.98
Average Strength	739 *psi*			

4.3 Phase III Results

Phase III was large scale implementation of the Novocon XR fibers with the 25% expansive mineral admixture. The compression and expansion data were collected to through 28-days. The expansion data was collected to the 28-day point at a rate of every 15 minutes. High range water reducer was utilized for all three mixes to ensure workability for placing the slabs. All three slabs were cast on the same day. The individual mix sheets can be found in the appendix. Table 13 presents the fresh and hardened properties of the phase III mixtures.

Table 13, Fresh and Hardened Properties of Phase III Mixtures

Mix Specification		Units	25% Expansive Mineral Admixture	No.5 Reinforcing bar Along Edges	Novocon XR Fibers
Slump		*(in)*	3.5	4	2
Batch Temperature		*(^{o}F)*	79	79	76
Compressive Strength	**7 Day**	*(psi)*	3930	4080	3840
	28 Day	*(psi)*	5390	5430	4610
Expansion (VWSG-Tip)	**7 Day**	*(in^{-6}/in)*	742	1328	1519
	28 Day	*(in^{-6}/in)*	863	1904	2378
Expansion (VWSG-Mid Longitudinal)	**7 Day**	*(in^{-6}/in)*	709	798	1352
	28 Day	*(in^{-6}/in)*	809	1061	1931
Expansion (VWSG-Mid Transverse)	**7 Day**	*(in^{-6}/in)*	617	1039	1407
	28 Day	*(in^{-6}/in)*	779	1549	2108

Chapter 5: Discussion of Results

5.1 Phase I Discussion

5.1.1 Compressive Strength

The differing levels of expansive mineral admixture did influence the compressive strength. The results shown in this section are from the compressive strength test ASTM C-39. The ASTM only requires a minimum of 2 cylinders to be cast. This project utilized 3 cylinders for each point. Each point shown in the figures is an average of 3 individual compressive cylinders.

As can be seen in Figure 33, the early age compressive strengths of the differing percentages of expansive mineral admixture are essentially the same at one day. This indicates that at one day there is very little influence on the compressive strength due to variations in the percent of expansive mineral admixture. However, at 7 days the compressive strengths vary a fair amount and are well ordered with the 21% mix having the highest value and the 29% mix having the lowest value. The range between the compressive strengths is approximately 1200 psi. At fourteen days of age the data remains well ordered with the 21% mix having the highest value and the 29% mix having the lowest value.

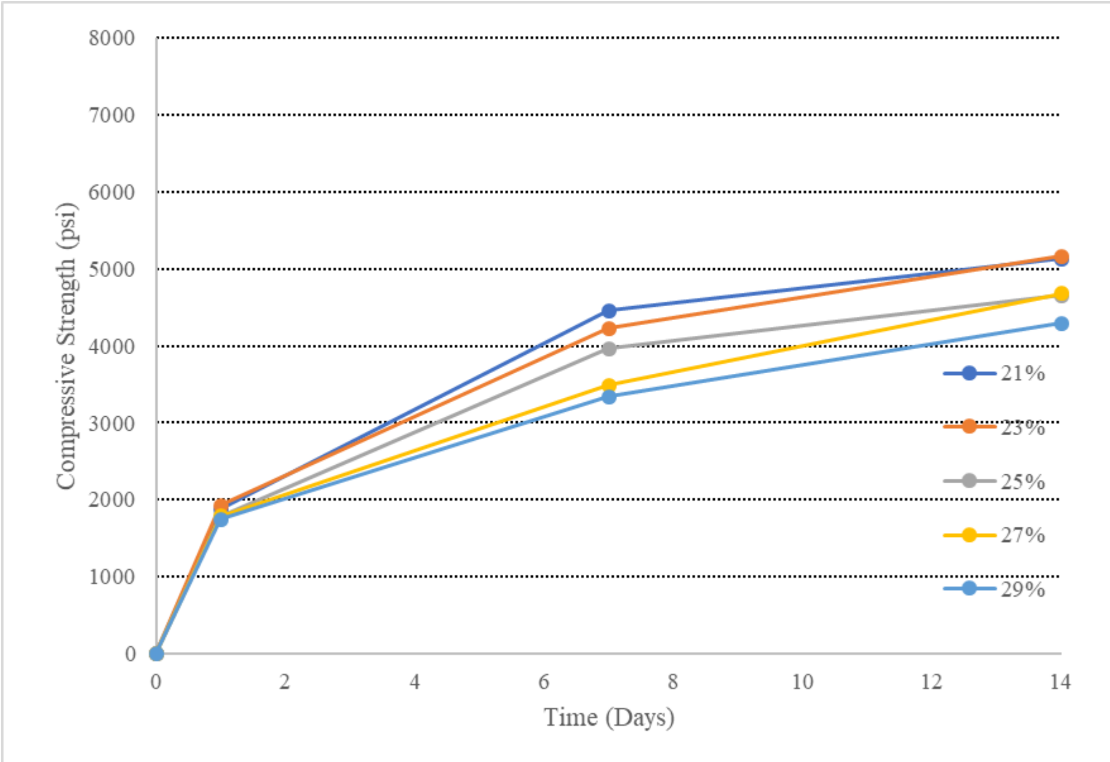

Figure 33, Compressive Strength of All Percentages of Expansive Mineral Admixture for 14 Days

The well-ordered trend of increasing compressive strength as the percentage of expansive mineral admixture decreases remains generally true at 28-days, as seen in Figure 34. The range at 28 days is 1200 psi. There is a slight deviation in the general trend with the 25% and 27% mixes changing positions by a small amount. The 27% expansive mineral admixture achieves a slightly higher compressive strength, but the difference is very small in magnitude.

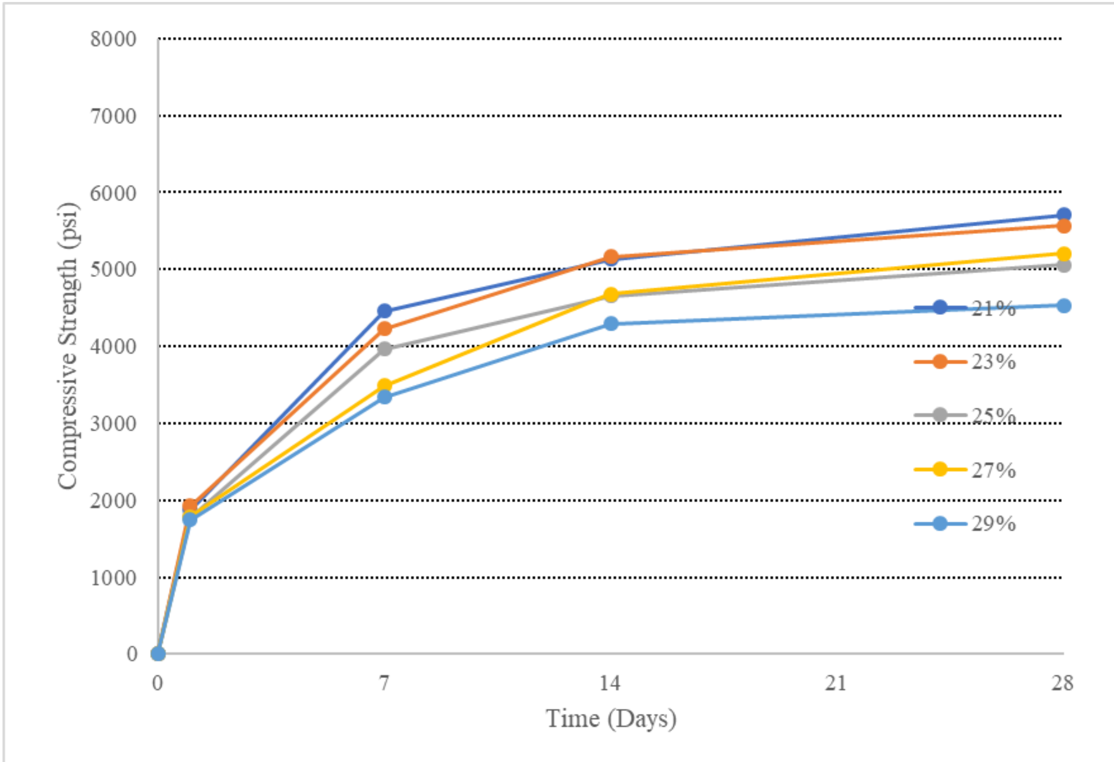

Figure 34, Compressive Strength of All Percentages of Expansive Mineral admixture for 28-Days

The trend of less expansive mineral admixture producing a higher compressive strength is not necessarily true at 1 year. As seen is Figure 35, the 21% expansive mineral admixture does achieve the highest compressive strength. It can be observed that the magnitudes of the compressive strength are relatively equal. The compressive strength range at one year is approximately 700 psi, which is fairly insignificant. This is the smallest range for this data in the periods tested. Due to the small range of difference, the compressive values can be taken to be approximately the same. The differences of compressive strength were probably due to small differences in the concrete mix.

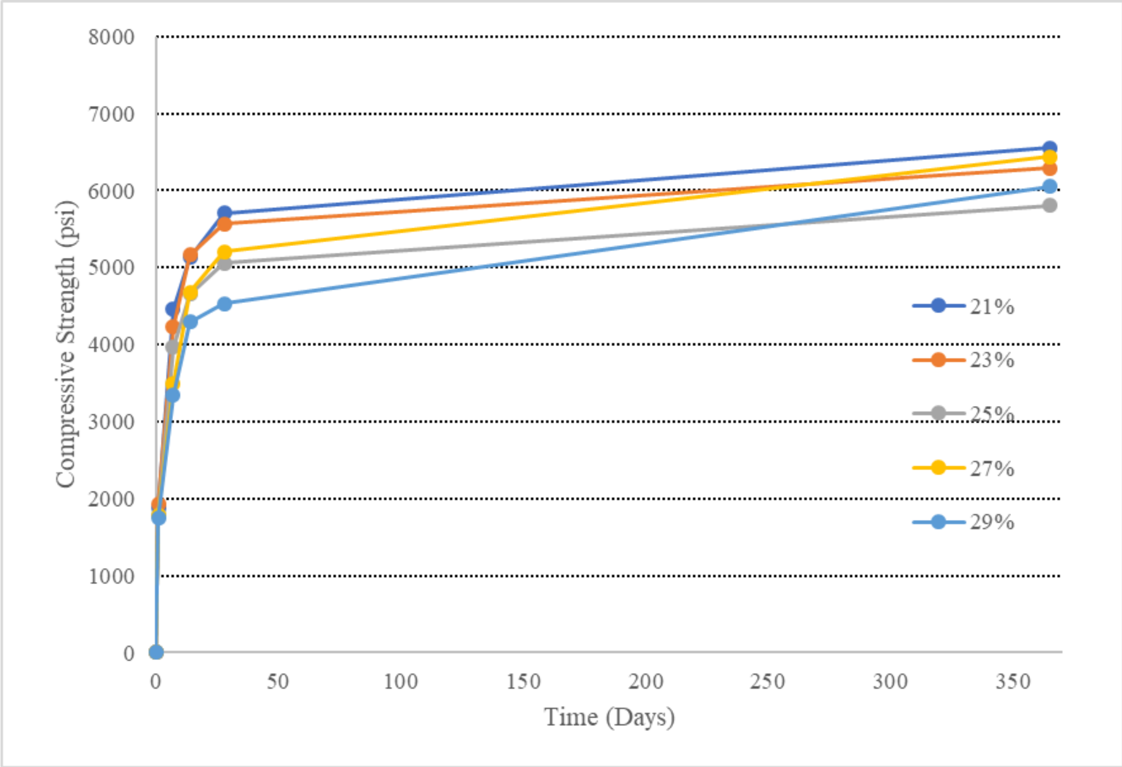

Figure 35, Compressive Strength of All Percentages of Expansive Mineral admixture for 1 Year

5.1.2 C-878 Expansion

The expected behavior due to increasing the percentage of expansive mineral admixture was that there would be an increase in the overall expansion. But the magnitude of expansion and difference between percentages was unknown. The expansion was measured according to ASTM C-878 for the restrained prisms. There were three restrained prisms cast for each percentage, and all three prisms were measured each time. The points in the figures in this section represent the average measurement of the three prisms for a given time.

In Figure 36, the levels of expansion are shown for the phase I, 21-29% expansive mineral admixture mixtures through 14 days. For the 21% through 27% mix designs, the expansion ends after the 7 days of water curing. However, the 29% expansive mineral admixture continues to expand for 2 additional days, but the continued expansion is not much. The overall expansion does increase as the percentage of expansive mineral admixture increases. The amount of shrinkage exhibited decreases as the amount of expansive mineral admixture increases for the first 14 days.

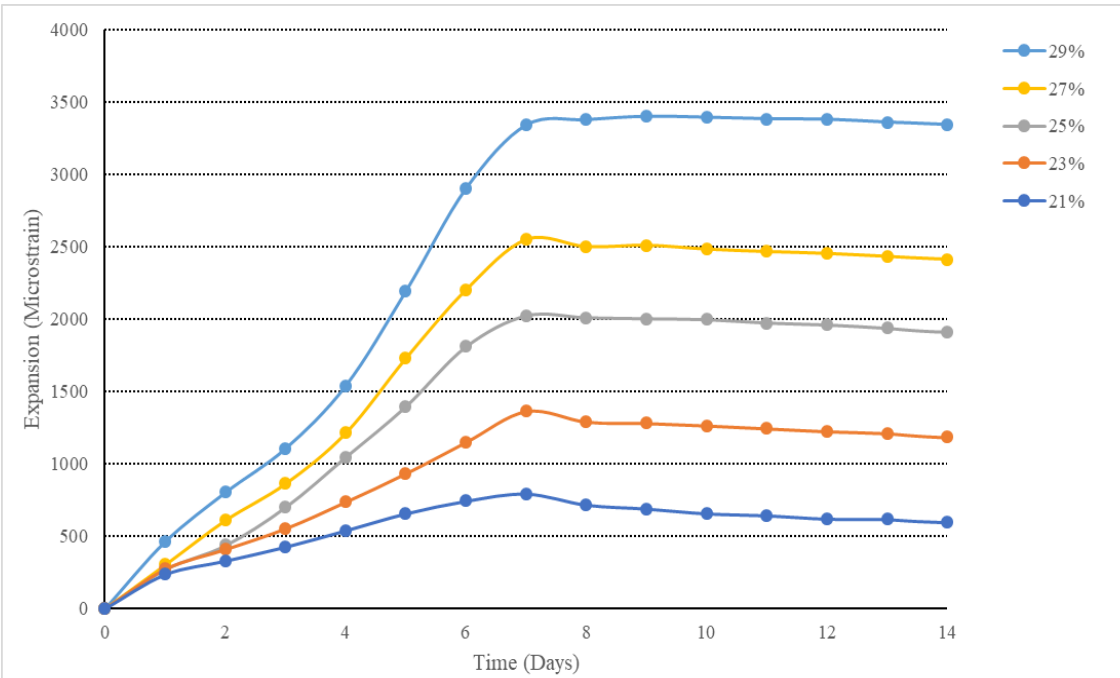

Figure 36, Expansion (C-878) of All Percentages of Expansive Mineral Admixture for 14 Days

As the percentage of expansive mineral admixture increased, the overall expansion increased. However, the magnitude in the difference of the expansion showed two locations that had a larger growth than compared to the previous. There are two larger gaps between the 23-25% and the 27-29% locations. In Table 14, the maximum expansion of each percentage is shown. In Table 15, the percentage increase of maximum expansions in comparison to the 21% expansive mineral admixture maximum expansion is shown.

Table 14, All Percentages of Expansive Mineral Admixture Maximum C-878 Expansion

Percentage of Expansive Mineral Admixture	Maximum Expansion (Microstrain)	Expansion at 1 Year (Microstrain)	Difference
21%	793	253	540
23%	1363	787	577
25%	2023	1413	610
27%	2550	1867	683
29%	3400	2700	700

Table 15, All Percentages of Expansive Mineral Admixture Percent Increase Compared to 21%

Percentage of Expansive Mineral Admixture	Percent Increase Compared to 21% (%)
23%	72
25%	155
27%	221
29%	329

In Table 15, the percent increases all remain relatively consistent until the 25% and 29%. There appear to larger percentages of increase, but the equation of the maximum expansion versus percentage of expansive mineral admixture suggests that there is linearity. This suggests that there was just natural variability of the concrete mixes that caused an apparent increase, but the trendline suggests that the maximum expansion increase is linear. The equation produced has an associated R^2 of very near one, which suggests that the linear trendline is successful in describing the increase of maximum expansion versus the percentage of expansive mineral admixture. This equation is shown in Figure 39.

Figure 37 presents a 28-day graph of the expansions. The amount of shrinkage continues to decrease as the percentage of expansive mineral admixture increases.

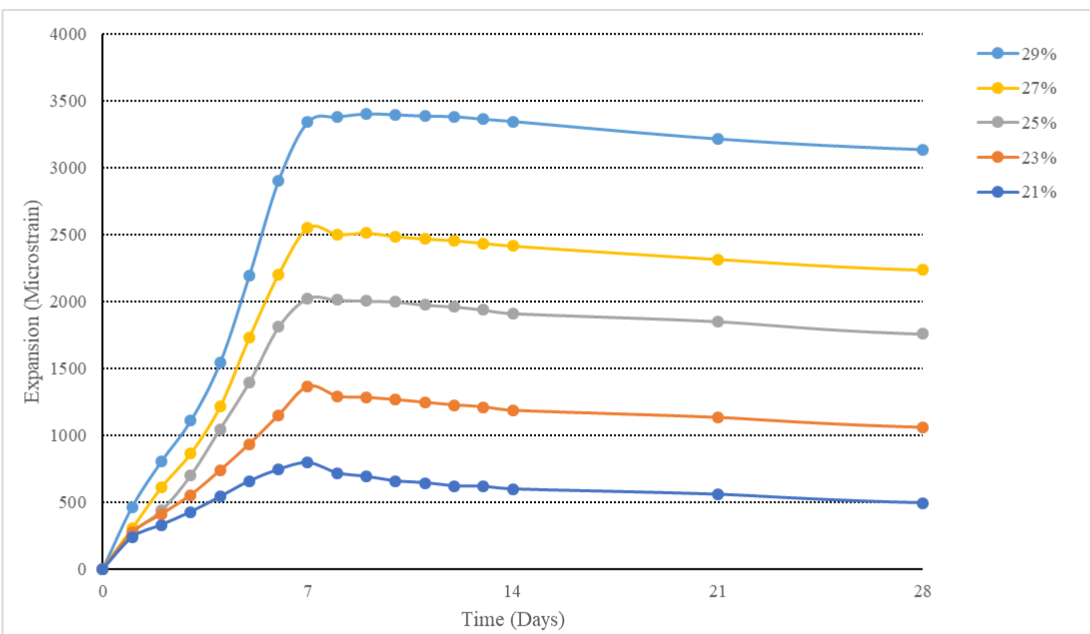

Figure 37, Expansion (C-878) of All Percentages of Expansive Mineral Admixture for 28-Day

Figure 38 shows the 1-year expansion for all percentages of expansive mineral admixture. The amount of shrinkage never exceeds the expansion at 7 days when wet curing ended. There are increases in expansion at the eleven month point for the 25-29%, but the 21-23% have an increase at the 1-year point. The explanation to the expansion is the environmental chamber the specimens were held in had a water curing condition for a different project. The increased humidity created a water curing effect on the specimens, hence the expansion. However, the specimens should not expand after the initial water curing since the expansion should have concluded. This suggests that the high level of expansive mineral admixture for the percentages in this project could continue expanding if the water curing condition was extended, but the continued expansion could have been normal swelling of the concrete. However, there were no tests conducted to determine how an extended water cure might extend the expansion period of the specimens.

The C-878 specimens began to shrink after the 7 days of water cure ended. The amount of overall shrinkage that the specimen felt through one year is the drying shrinkage. The drying shrinkage is represented in Table 14 by the column titled Difference. The difference between the maximum expansion and the final expansion reading at one year presents how much the specimen shrank. As the percentage of expansive mineral admixture is increased the accompanying drying shrinkage also increases slightly. However, the amount of shrinkage overall is relatively equal across all the percentages of expansive mineral admixture. The general trend of increasing percentage of expansive mineral admixture increases the amount of drying shrinkage can be presented.

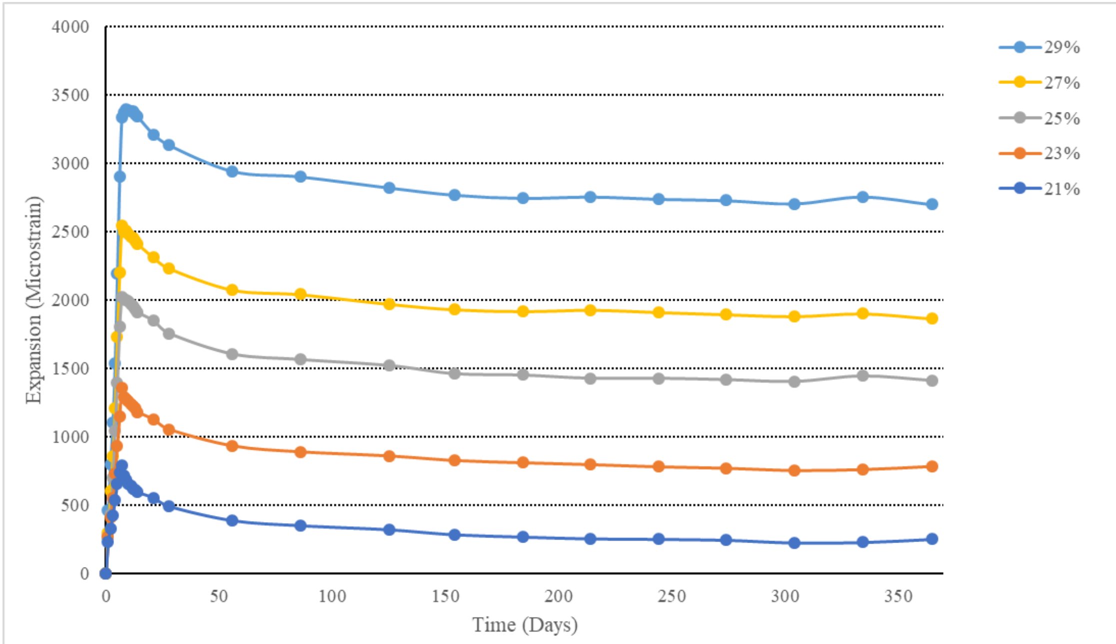

Figure 38, Expansion (C-878) of All Percentages of Expansive Mineral Admixture for 1 Year

This project characterized the expansion for 21%-29% expansive mineral admixture. The increase of expansion in proportion to the increase in percentage of expansive mineral admixture can be described as linear function, which is shown in Figure 39. The trendline fits almost perfectly with the maximum expansions of each percentage of expansive mineral admixture. The R^2 value associated with the trendline is very near 1.0, which shows that the line is a very good representation of the data. However, Stephen Roswurm (2018) performed the same tests, C-878, on 15-21% expansive mineral admixture. The associated trend line does not have the same slope as the trendline for the 21%-29%. This suggests that there is something occurring in the pore structure of the concrete around the 20% mark. The associated R^2 for the 15%-21% is approximately 0.908, which is still a good representation, but not as good as the trendline for 21%-29%. According to the equation associated with the 15%-21%, the expansion by the 29% should be approximately 1200 microstrain. This is not even close to the actual expansion recorded which was 3400 microstrain. At around 20% expansive mineral admixture, a potential explanation of why the more aggressive expansion occurs is that something changes in the concrete crystal structure. However, the exact cause is unknown.

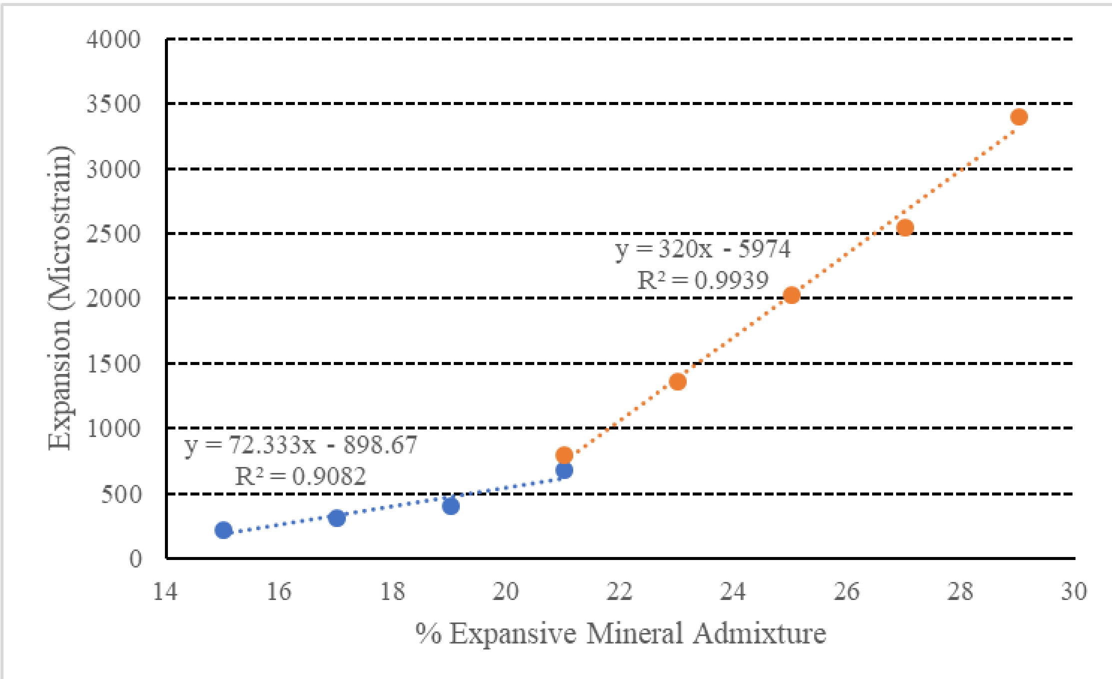

Figure 39, Trendline of C-878 Data for 15-29% Expansive Mineral Admixture (Roswurm 2018)

5.1.3 VWSG Expansion

The VWSG were cast in two 6”x12”’s for each mix design. Figure 40 presents the VWSG recorded expansion for 14 days. For the two lower percentages of expansive mineral admixture, the VWSG performed well in measuring the expansion and shrinkage of the specimen. However, 25% and higher were not able to be measured nearly as clearly due to the high expansion that the specimen exhibited. The VWSG used during this test have a published range of 2000 microstrains. The 25% through 29% mix designs exceeded this limit. The 21-23% had no erroneous data that would create a gap, but the higher percentages all start having significant amounts of scattered readings. The overall trend of the C-878 data showing that increasing the percentage of expansive mineral admixture is also shown by the VWSG data. The maximum expansions of each percentage of expansive mineral admixture is close in value between the C-878 and the VWSG.

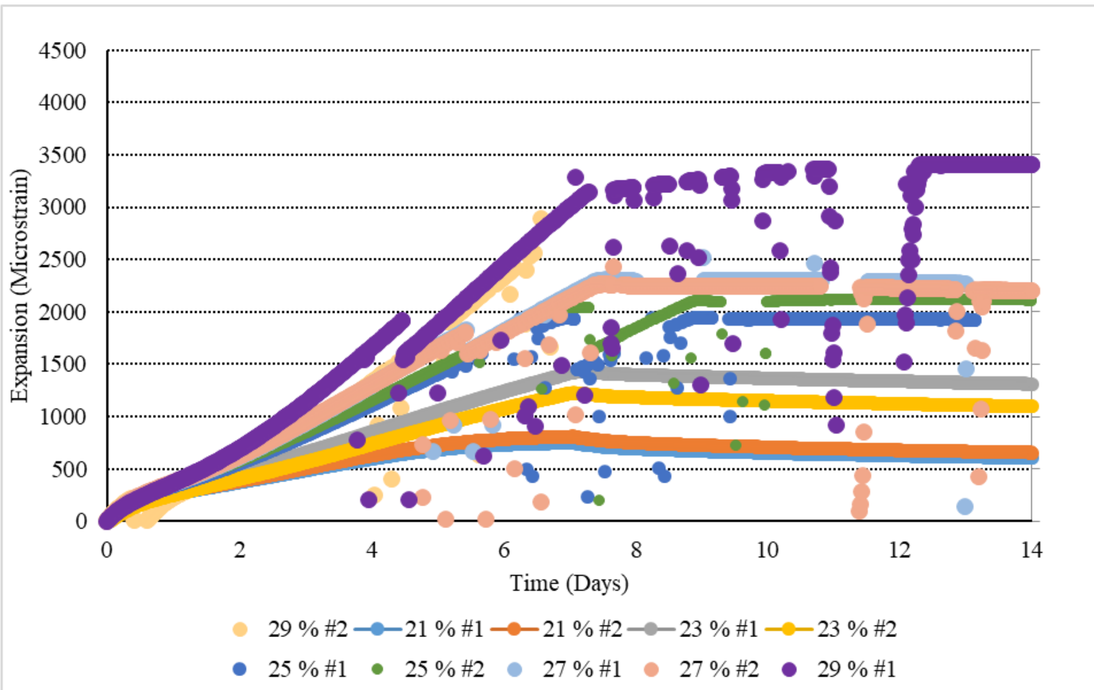

Figure 40, Expansion (VWSG) of All Percentages of Expansive Mineral Admixture for 14 Days

The erroneous data continued as the VWSG continued to collect data. Figure 41 shows the VWSG recorded expansion for 28 days. The 27% expansive mineral admixture exhibited lower expansion with the VWSG as compared to the C-878. However, the other percentages all continued to mimic their respective C-878 expansion. The 21-23% continue to show very smooth results.

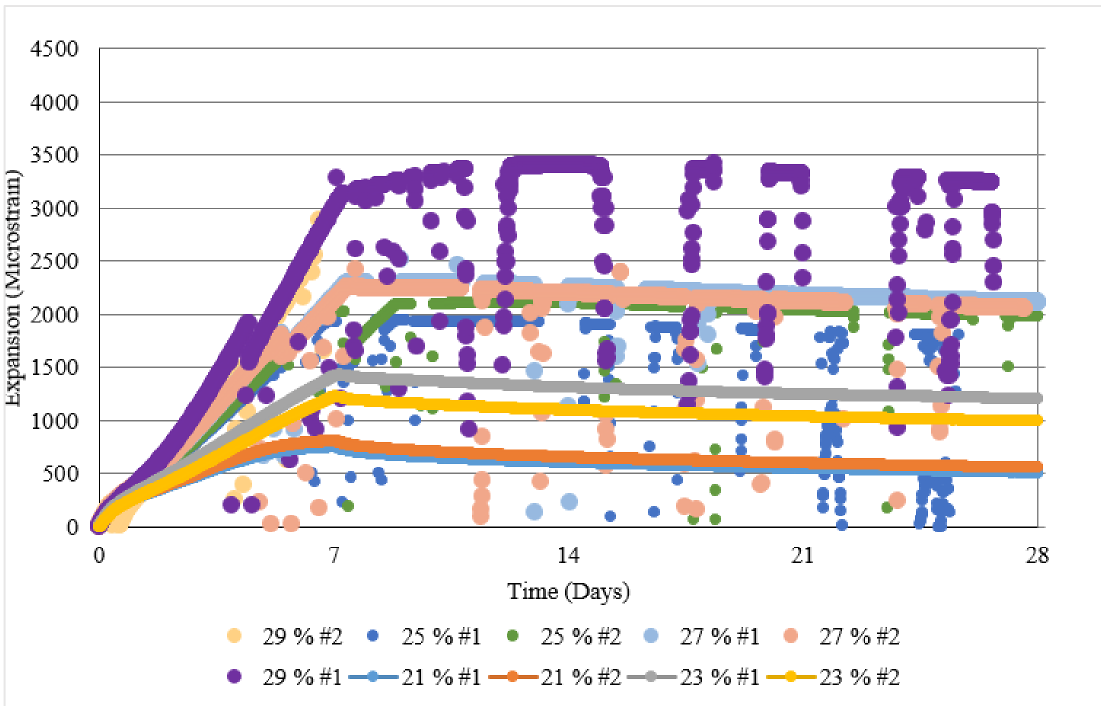

Figure 41, Expansion (VWSG) of All Percentages of Expansive Mineral Admixture for 28 Days

Figure 42 shows the 1-year results for the VWSG expansion of all percentages of expansive mineral admixture. The VWSG failed for the 25-29% expansive mineral admixture after about 210 days. This could occur because of a couple different reasons. The reason with the most logical backing would be that the VWSG cannot handle that high of magnitude of expansion. Therefore, the final range of expansion is too high for the VWSG to register without failing. Another possible reason for the failure in data collecting is that the Geokon data system had some kind of short in the circuitry. This type of behavior for VWSG's has been noted in the past whenever high expansion or shrinkage by a specimen is exhibited. However, this reason is simply an overarching potential issue for any type of data acquisition system.

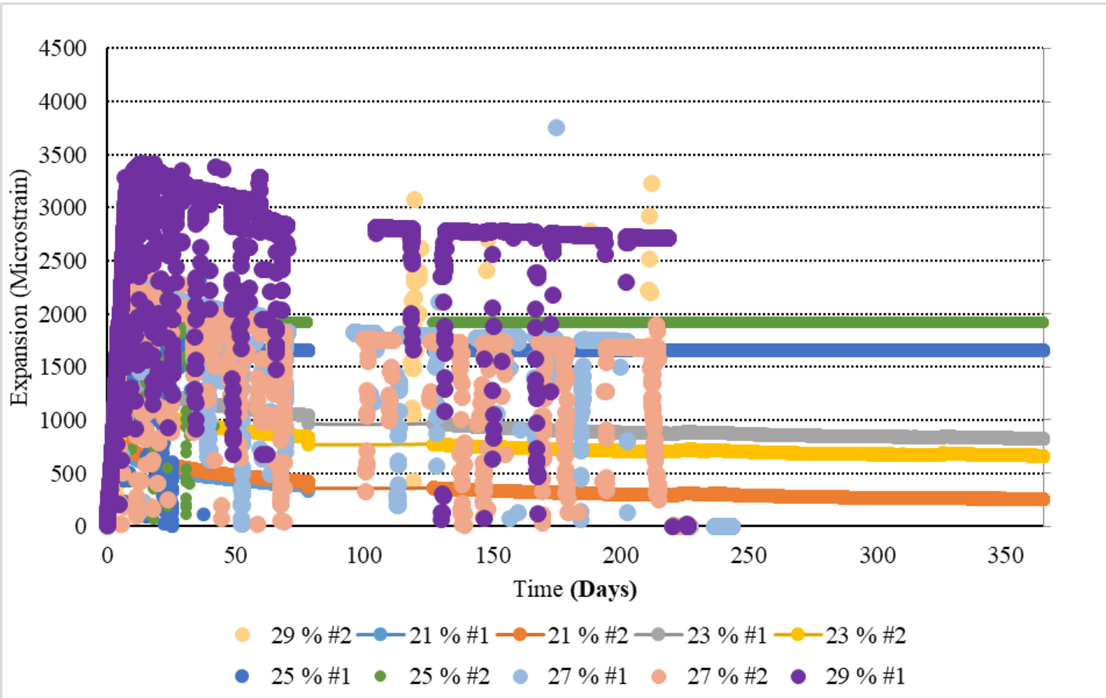

Figure 42, Expansion (VWSG) of All Percentages of Expansive Mineral Admixture for 1 Year

For the lower percentages of expansive mineral admixture, the VWSG performed better. As seen in Figure 43, the 21-23% expansive mineral admixture produced very smooth curves. The gap in the middle occurred due to a malfunction in the Geokon data system. The line bridging the gap simply connects the two with a straight line to continue to smooth overall plot of the expansion. The curves overlap each other for the 21% almost perfectly, but the 23% have a slight gap in between the curves. This difference is small, so the results show that the expansion is consistent between the two specimens.

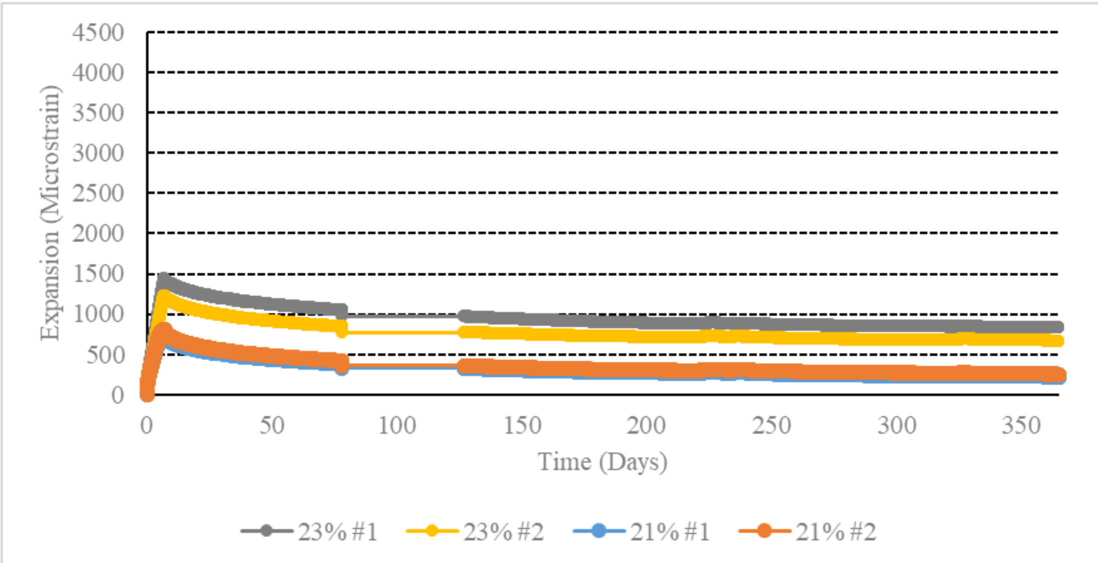

Figure 43, Expansion (VWSG) of 21% and 23% Expansive Mineral Admixture for 1 Year

5.2 Phase II Discussion- Influence of Fibers

5.2.1 Compressive Strength

The various fiber types did influence the compressive strength of the 25% expansive mineral admixture mix. The results shown in this section are from the compressive strength test ASTM C-39. The ASTM only requires 2 cylinders to be cast, but this project utilized 3 cylinders for each point. Each point shown in the figures is an average of 3 individual compressive cylinders.

The 25% expansive mineral admixture was chosen to investigate the influence of steel fibers on the compression, modulus of rupture, and expansion. The expected behavior was an increase compressive strength. One-year tests were not able to be conducted for the 25% expansive mineral admixture with fibers due to time constraints. In Figure 44, the compressive strength results are shown for each fiber type and the original 25% expansive mineral admixture mixture at 14 days. The compressive strength did increase whenever any of the fibers were introduced. The Novocon 1050 he fiber performed the best by increasing the compressive strength by almost 1200 psi. The remaining three fibers had increased the compressive strength by essentially the same amount of 500 psi at 14 days. Due to the small range of difference, the compressive values can be taken to be approximately the same. The differences of compressive strength were probably due to small differences in the concrete mix.

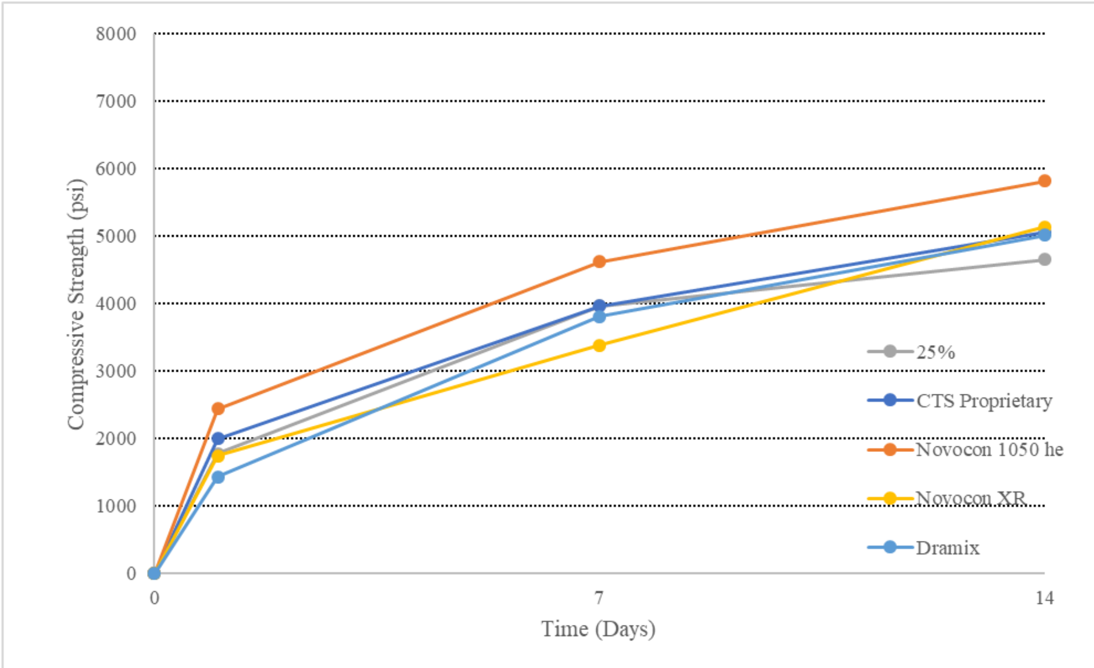

Figure 44, Compressive Strength of All Fiber Types and 25% Expansive Mineral Admixture for 14-Days

Figure 45 shows the 28-day compressive strength for all the fiber types and 25% expansive mineral admixture. The Novocon 1050 he gained very little strength at 28 days, while the CTS Proprietary fiber gained the most compressive strength. The Novocon XR fibers are only 200 psi lower, while the other fibers are 500 psi below the Novocon XR. The trend of fibers increasing the compressive strength is observed, but the CTS Proprietary and Novocon XR fiber performed the best at increasing the compressive strength.

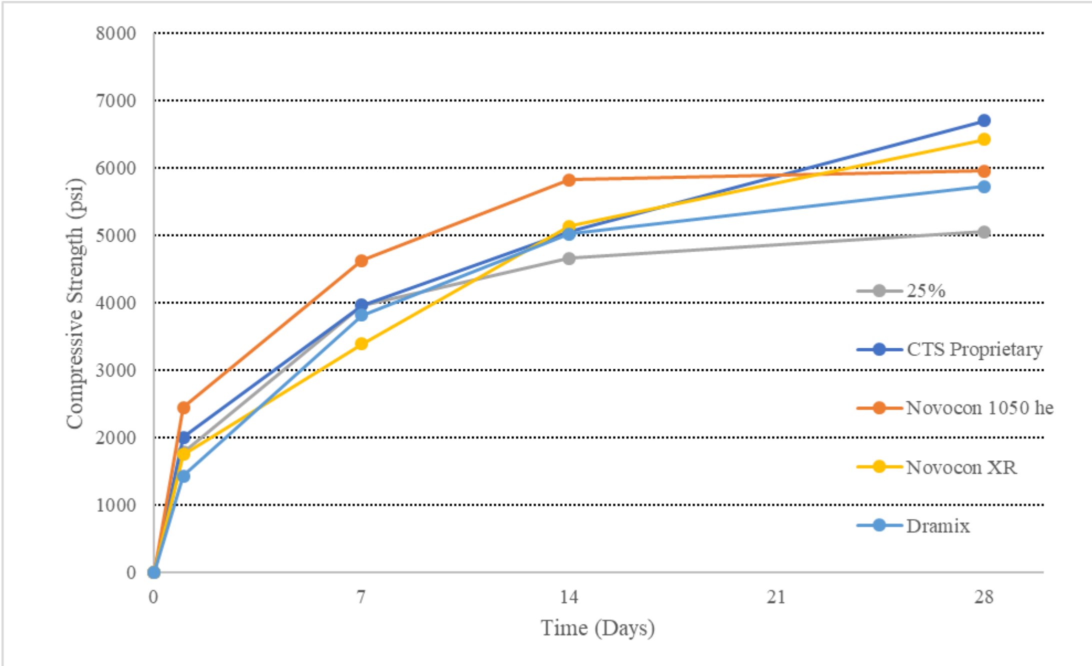

Figure 45, Compressive Strength of All Fiber Types and 25% Expansive Mineral Admixture for 28-Days

5.2.2 C-878 Expansion

The main purpose of this investigation was to characterize the behavior of the restraint that the various fibers provided for the 25% expansive mineral admixture. The C-878 specimens were cast to be able to directly compare the expansions of the specimens with fibers to the original mix of 25%. The expected behavior of the 25% expansive mineral admixture mixed with the fibers is that the overall expansion would be reduced. The expansion was measured according to ASTM C-878 for the restrained prisms. There were three restrained prisms cast for each percentage, and all three prisms were measured each time, with an initial reading taken at 6 hours. The points in the figures represent the average measurement of the three prisms for a given time.

In Figure 46, the levels of expansion are shown for the four fiber types and the original 25% expansive mineral admixture for 14 days. For all the mixtures with fibers, after the 7 days of water curing, the expansion ends. After the first 7 days, the specimens begin to exhibit shrinkage, which the two Novocon fibers and the Dramix fibers provide approximately the same restraint. The CTS Proprietary fibers provide far less restraint, but they also allow less shrinkage to occur for the first 14 days. The Dramix fibers show expansion for the day 10 reading, but the environmental chamber had another water curing condition for another project which increased the overall humidity. However, after the initial inducement of increased humidity, the Dramix fiber specimens begin to shrink again for the remainder of the 14 days.

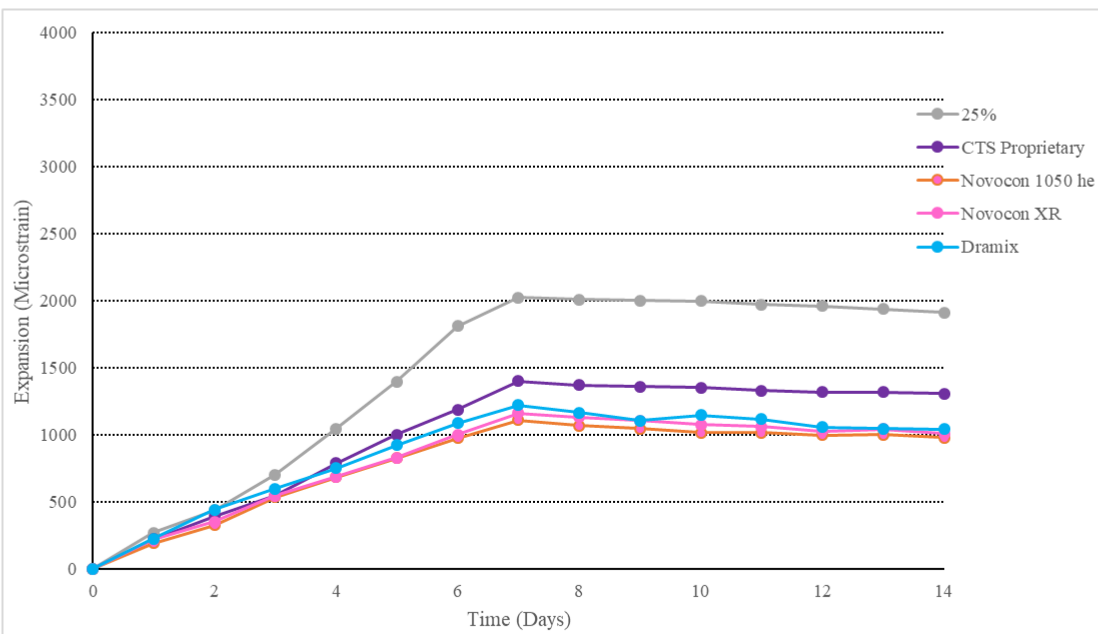

Figure 46, Expansion (C-878) of All Fiber Types and 25% Expansive Mineral Admixture for 14-Day

Figure 47 shows a 28-day graph of the expansion of the four fiber types and the original 25% expansive mineral admixture. The same trends that were present in the 14-day results are still present in the 28-day results. The CTS Proprietary fiber continues to allow the least amount of shrinkage, while the remaining three fibers are equal in terms of overall expansion of the specimen at 28 days. Both Novocon fibers and the Dramix fibers shrinkage trends have approximately the same slope as the original 25% expansive mineral admixture. However, the CTS Proprietary fibers have a flatter slope in comparison to the 25% expansive mineral admixture.

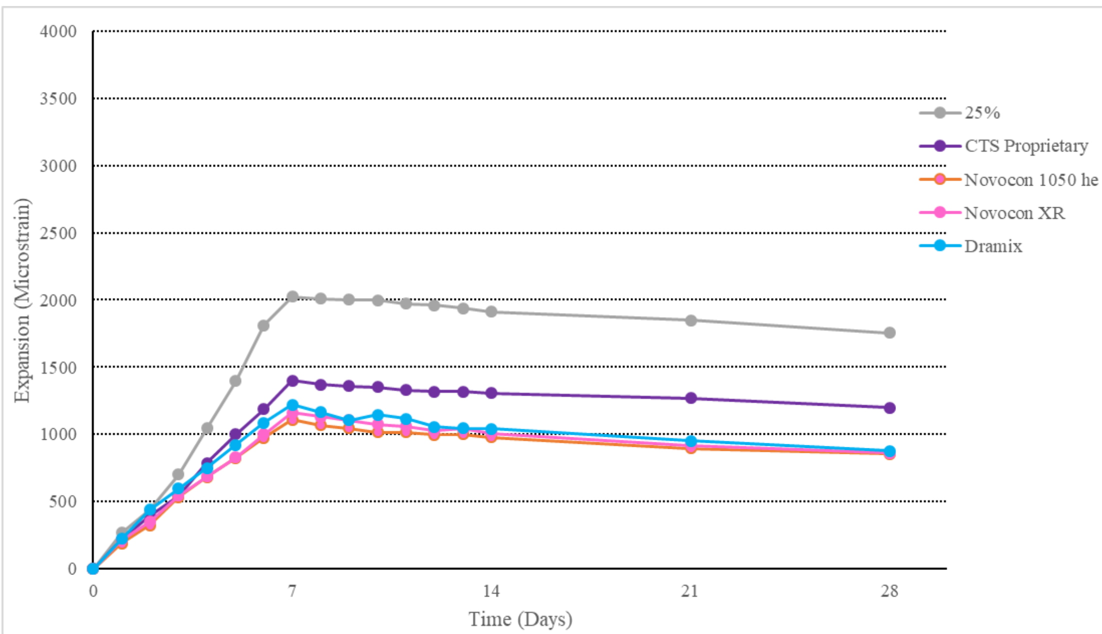

Figure 47, Expansion (C-878) of All Fiber Types and 25% Expansive Mineral Admixture for 28-Day

Figure 48 shows the 7-month expansion for the four fiber types and the 25% expansive mineral admixture. 1-year data was not collected for these tests as the allotted time did not allow for those tests to occur. The trends present in the 14 and 28-day expansion is still present. The CTS Proprietary fiber provided the least amount of restraint, while the remaining three fiber types produced very similar results. The final presented expansion values are within 50 με for the Novocon XR, Novocon 1050 he, and Dramix fibers. The CTS Proprietary fibers still allow more expansion to occur, which would ultimately allow for less stress to be induced into the steel fibers. However, the remaining three fiber types allow the stress to be transferred into the steel fibers by restraining the overall expansion.

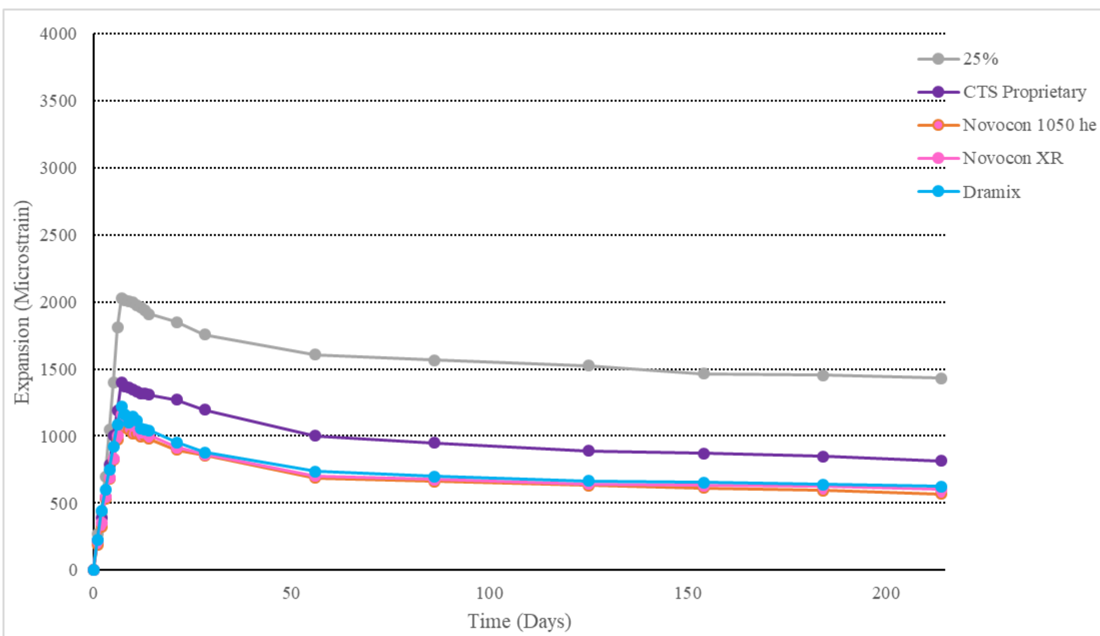

Figure 48, Expansion (C-878) of All Fiber Types and 25% Expansive Mineral Admixture for 7-Month

The C-878 specimens began to shrink after the 7 days of water cure ended. The amount of overall shrinkage that the specimen felt through one year is the drying shrinkage, but the C-878 specimens with fibers only have data through 7 months. The drying shrinkage is represented in Table 16 by the column titled Difference.

Table 16, All Fiber Types Maximum C-878 Expansion

Fiber Type	Maximum Expansion (Microstrain)	Expansion at 7 Months (Microstrain)	Difference
25%	2023	1430	593
CTS Proprietary	1400	817	583
Novocon 1050 he	1110	570	540
Novocon XR	1160	603	557
Dramix	1220	623	597

The C-878 specimens began to shrink after the 7 days of water cure ended. The amount of overall shrinkage that the specimen felt through one year is the drying shrinkage, but the C-878 specimens with fibers only have data through 7 months. The drying shrinkage is represented in Table 16 by the column titled Difference. The difference between the maximum expansion and the final expansion reading at seven months represents how much the specimen shrank. The baseline for comparison is the 25% expansive mineral admixture. The fibers all exhibited lower shrinkage at 7 months than the original 25% did except for the Dramix fiber C-878's. However, the difference between the 25% and the Dramix is 4 $\mu\varepsilon$, which is a negligible difference. Through seven months, the drying shrinkage of the C-878's with Dramix fibers appears unaffected by the addition of fibers. The CTS Proprietary Fibers allowed 10 $\mu\varepsilon$ less drying shrinkage than the 25%. The Novocon XR allowed 36 $\mu\varepsilon$ less drying shrinkage than the 25%. The Novocon 1050 he allowed 53 $\mu\varepsilon$ less drying shrinkage. The general trend of a larger fibers allowing less drying shrinkage to occur can be presented, but the smaller fiber allowed more drying shrinkage to occur than the original 25%.

5.2.3 C-78 Modulus of Rupture Strength and Ductility

The modulus of rupture test was conducted on all four fiber types and the original 25% expansive mineral admixture to establish a control. The first set of the MOR specimens were conducted to determine the 28-day strength. The second set of MOR specimens were conducted to gather a more comprehensive understanding regarding the early MOR strength. The second set were tested at 14 days and 28 days. The ASTM C-78 requires two specimens to be tested, but for all conducted tests in this project, three MOR specimens were cast. The specimens were water cured for 7 days. Then the specimens were placed in an controlled curing conditions location. The first sets were placed in an environmental chamber. The second sets were placed in the curling lab, which has less controlled temperature. The second set were cast alongside the slabs of phase III, which were also cast in the curling lab. The averages presented are for three separate specimens that were tested within 1 hour of each other. In Table 17, the first set of average strengths of four fiber types and 25% expansive mineral admixture are displayed.

Table 17, 25% Expansive Mineral Admixture and All Fiber Types Average MOR First Set

Average MOR Strengths at 28 Days		
	Average Strength (MOR)	***% Increase From 25%***
25% Expansive Mineral Admixture	515 *psi*	-
CTS Proprietary	681 *psi*	32.2
Novocon 1050 he	571 *psi*	10.87
Novocon XR	679 *psi*	31.84
Dramix	739 *psi*	43.50

Table 17 shows that the introduction of steel fibers into the mixture causes a significant increase in MOR strength. This result was expected due to a MOR test causing a brittle failure in concrete with no reinforcement. Once initial cracking began, the failure happened quickly. However, once steel fibers are introduced, the failure mode becomes more ductile, allowing for more load to be applied before ultimate failure. The initial crack did occur at the ultimate load the specimen held, but the test was able to continue due to the ductility the fibers created. The Novocon XR fiber and the CTS Proprietary fiber produced approximately the same percent increase in comparison to the original 25% which was approximately 32%. The Novocon 1050 he fiber produced the smallest percent increase at approximately 11%, but the 1050 he was the shortest fiber besides the Dramix. However, the Dramix fiber was able to overcome the length difference in number of fibers and had the largest percent increase of 43.5%.

The Dramix fiber did result in the most strength gain in the MOR strength, but the workability of the Dramix mixture was poor. The Dramix fibers are much smaller than the other fiber types, and the result is a much larger amount of fibers in this mixture, which results in a much stiffer mixture that had very low workability. The Dramix fibers were also dangerous to work with due to the small size and volume of fibers. The fibers are essentially needles and became embedded under fingernails and cut hands and arms while trying to finish the samples. Due to these concerns, the Dramix fibers were not chosen for the large-scale tests in phase III.

In Table 18, the second set of average strengths of the Novocon XR fiber and 25% expansive mineral admixture are displayed. All the strengths are lower than what the first set of MOR specimens produced. The specimens had good consolidation, but specimens simply failed at a lower load than expected. The testing was done the same as the first set, but specimens were just weaker. The exact reason as to why the specimens failed at such a drastically lower load is unknown, but the most probable reason is some form of user error was introduced during testing. The load rate was maintained as in all other tests, but the Forney load rate difficult to maintain the exact rate range that the ASTM requires, which is 25 to 35 lb/s. Another possible reason for the lower strength of the second set of MOR's is due to casting and curing conditions. This set was cast with the phase III slabs in the curling lab. This building is not as well insulated, and it is more difficult to control the temperature. The specimens were placed on a metal rods to allow drying. However, the slab that the metal rods were on was especially cold due to the weather conditions. The lower temperature might have not allowed the concrete to reach a high enough curing temperature.

Table 18, 25% Expansive Mineral Admixture and Novocon XR Fiber Average MOR Second Set

MOR Strengths at 14 Days	
	Average Strength
25% Expansive Mineral Admixture	417 *psi*
Novocon XR	517 *psi*
MOR Strengths at 28 Days	
25% Expansive Mineral Admixture	380 *psi*
Novocon XR	533 *psi*

As previously stated, the introduction of steel fibers increased the ductility of the MOR specimens. A test was developed to monitor the deflection of a MOR specimen as load was applied to understand the amount of ductility that was developed. The linear variable differential transformer monitored the deflection as load was applied. A failure load of 6700 lb was achieved for this specimen. Following the peak load, there was a significant decrease in load, but the separation of concrete activated the bond of fibers to the concrete. The fibers allowed for more load to be applied as the load slightly increased again until another decrease in load occurred. The test was concluded whenever the Forney stopped registering the deflection as the load had decreased to less than half of the peak load. This test was not repeated due to the cleanliness of the results from the first attempt. The resulting load deflection curve for the MOR specimen is shown in Figure 49.

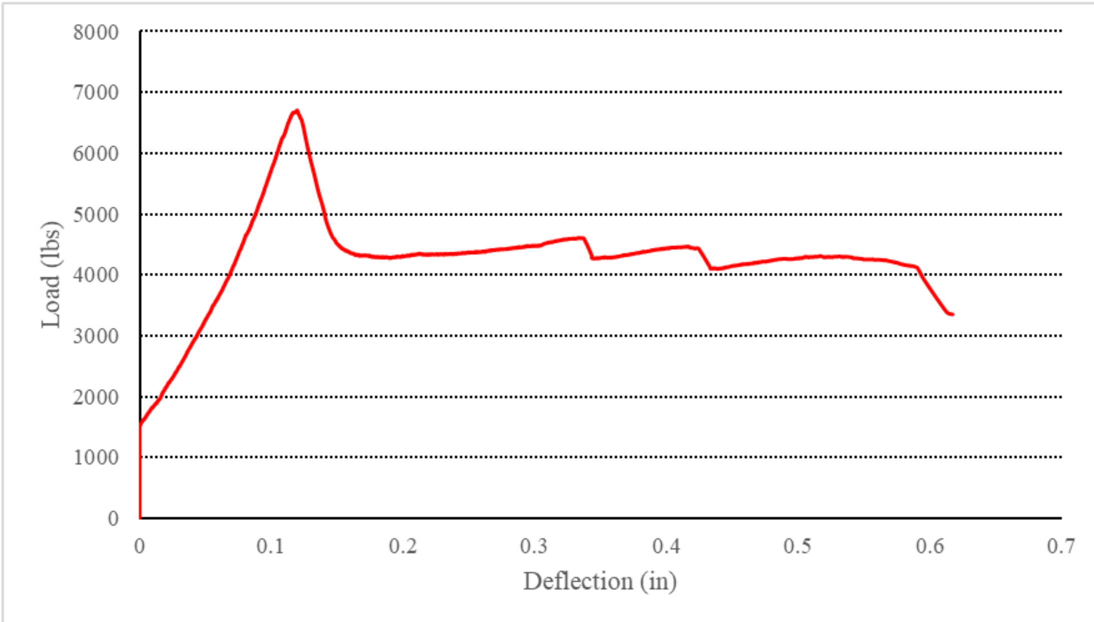

Figure 49, Load Deflection Curve Novocon XR Fiber MOR 1 Second Set

5.2.4 VWSG Expansion

New extended range VWSG were used to study one of the 6x12's for each fiber type with 25% expansive mineral admixture. The hope was that the extended range would perform better than the standard VWSG. For each set of 6x12's, 6x12 #1 was the standard VWSG, and 6x12 #2 was the extended range VWSG. Figure 50 shows the VWSG recorded expansion for 14 days. The 6x12 #2 of the Novocon 1050 he failed almost immediately, but the Novocon 1050 he #2 was included for completeness sake. The most probable reasoning is that the VWSG failed to register any readings, but the channel of the Geokon logger may have also been compromised.

The 6x12 #1 of each set produced a higher expansion than 6x12 #2. These results are bad due to the extended range VWSG required a specific wire and had individual calibration factors for each VWSG. All VWSG's were instrumented alike with the same type of wire, standard plucker, and thermistor with incorrect calibration. Due to all these mistakes in instrumentation, the VWSG results of 6x12 #2 for every fiber type are inaccurate.

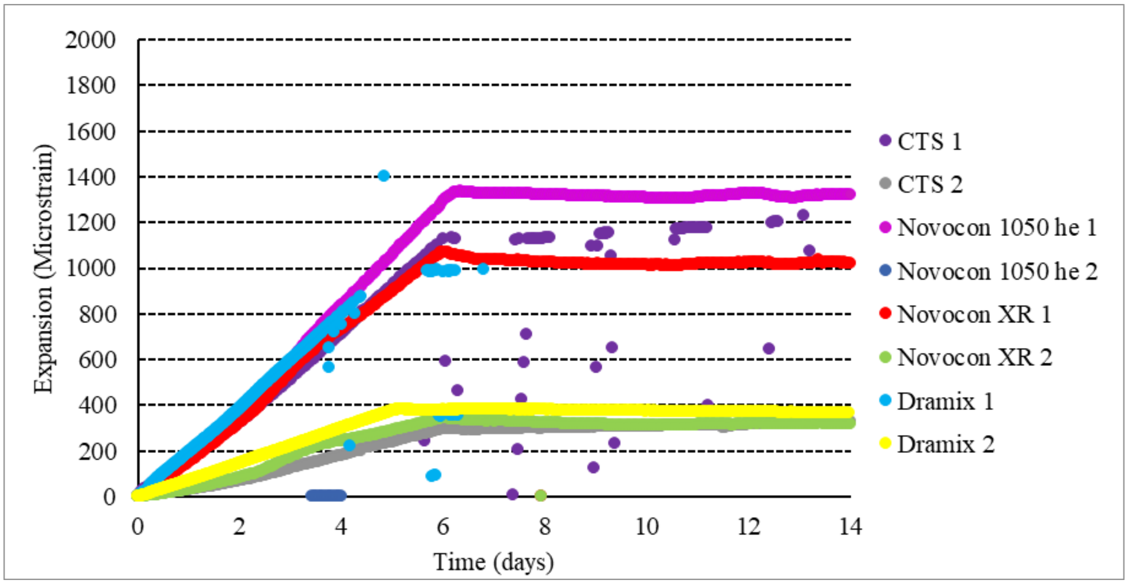

Figure 50, Expansion (VWSG) of All Fiber Types with 25% Expansive Mineral Admixture for 14 Days

The Dramix and CTS Proprietary fibers caused multiple issues whenever cast. The workability of the mixes was less than both Novocon fibers, but the standard VWSG data was skewed. There are multiple possibilities that could have caused this. The previously stated reasons still apply, such as some kind of short in circuitry or simply bad readings from the VWSG.

Figure 51 shows the VWSG recorded expansion for 28 days. The overall trend is like the C-878 data with the exception of the Novocon 1050 he fiber providing the least amount of restraint and the remaining three fibers providing very similar amounts of restraint. However, the amount of skewed data increases which is shown by the waterfall of data for the CTS Proprietary fiber #1 and the Dramix fiber #1. The true shrinkage doesn’t begin until around day 17. The most likely reason for this delayed shrinkage is the environmental chamber had water curing going for another project, which created a higher humidity.

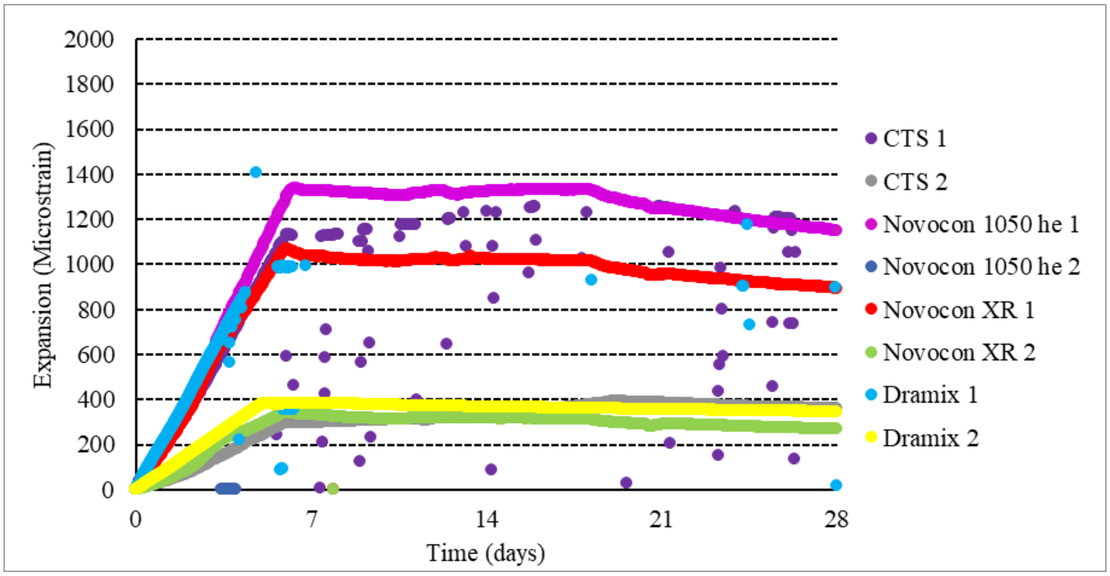

Figure 51, Expansion (VWSG) of All Fiber Types with 25% Expansive Mineral Admixture for 28 Days

Figure 52 shows the VWSG recorded expansion for 7 months. There is a spike in expansion around day 90, which was another environmental chamber water curing for another project. The same spike behavior occurs around day 160 for the same water curing of another project. The waterfall of data stopped for the curves after 60 days, except for a couple spots around 95 days. The overall trend follows what the C-878 data shows in term of expansion, except for the Novocon 1050 he fibers providing the least restraint instead of the CTS Proprietary fiber. However, by the 6 and 7-month point, the CTS Proprietary fiber and Novocon 1050 he fiber provided the same amount of restraint. The Novocon XR and the Dramix fibers both allow more shrinkage to occur than the other two fibers.

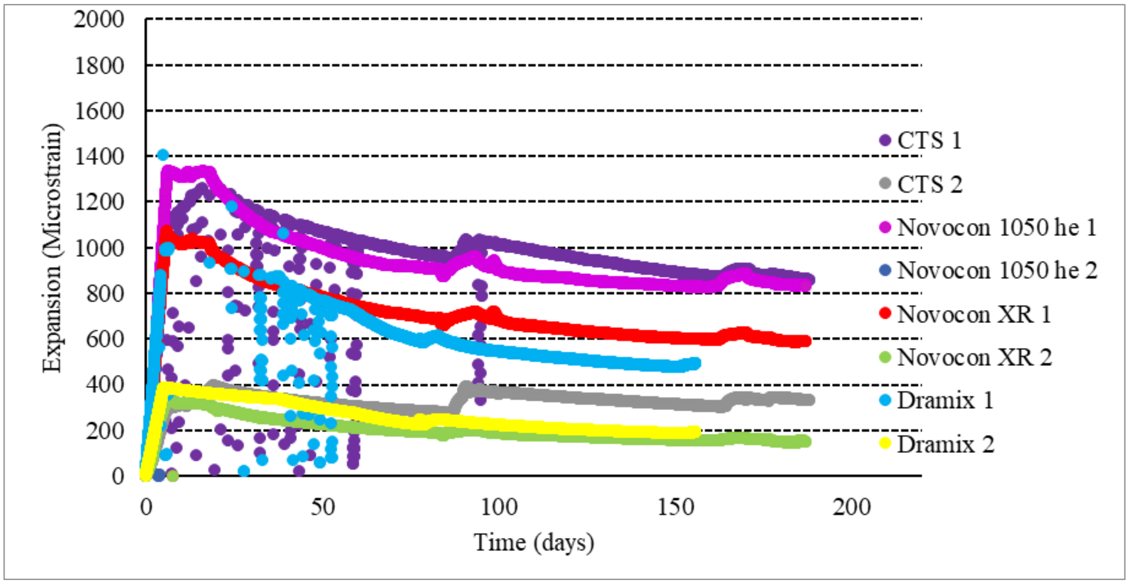

Figure 52, Expansion (VWSG) of All Fiber Types with 25% Expansive Mineral Admixture for 7 Months

Extended range VWSG were implemented into MOR’s to capture a slightly larger specimen’s influence on expansion. However, for the MOR VWSG’s, the proper wiring and calibration factors were accounted for. Each extended range VWSG had the individual calibration factor applied. Figure 53 shows the VWSG recorded expansion for the MOR specimens. While the magnitude of expansion for both mixtures is lower than expected, the specimen never shows shrinkage. There are several things that could contribute to the specimens not shrinking at any point. The MOR specimens were placed on a metal rods to allow drying without restraining expansion or shrinkage. However, the slab that the metal rods were on was especially cold due to the weather conditions. This might have prohibited some of the expansion that the specimens would have exhibited if a high enough temperature was achieved for curing.

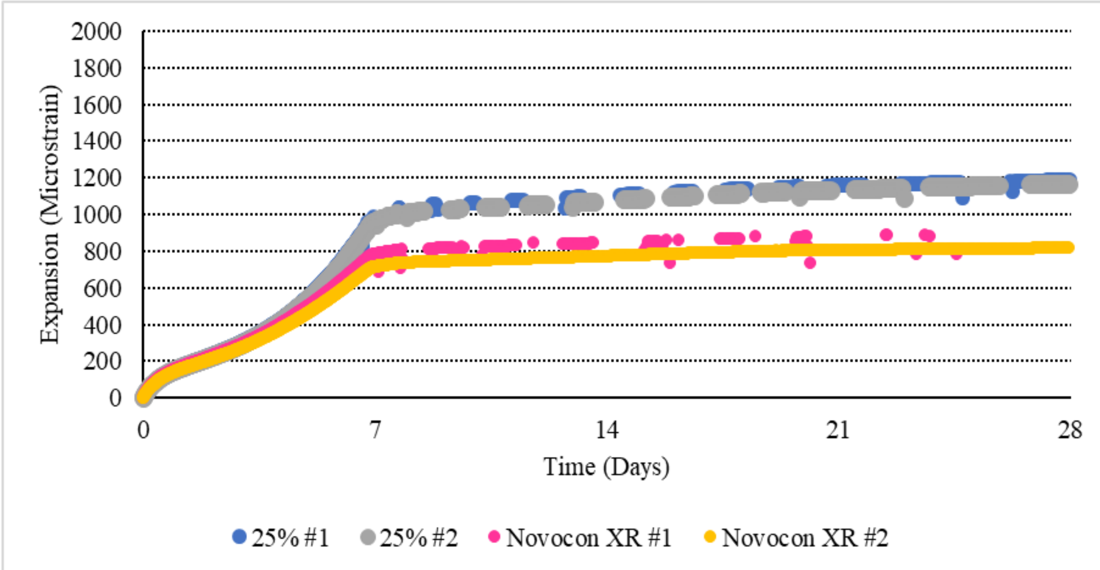

Figure 53, MOR Expansion (VWSG) of Novocon XR Fiber and 25% Expansive Mineral Admixture for 28 Days

There were multiple gaps in the data were erroneous data points occurred. The overall trend is identifiable despite the gaps in the middle of the curves. The 25% expansive mineral admixture expands more than the Novocon XR mixture, which shows the restraint provided by the fibers. The water curing ended at day 7, which is where the point of the expansion slowed significantly. The specimen continued to expand, but the slope of the curve is far less steep. The specimen might begin to shrink at a later age, but the time allowance for this project only allowed for 28 days' worth of data.

5.3 Phase III Discussion

5.3.1 Large Scale Effect of 25% Expansive Mineral Admixture

With the implementation of the Novocon XR fibers, three slabs were cast for testing. Since all the slabs had the exact same layout of VWSG throughout, comparing the individual type and location of VWSG can show trends. Figure 54 shows the schematic of the VWSG layout for the slabs to indicate which VWSG is being discussed. All VWSG's used in this phase were standard VWSG's not extended range. Figure 55 shows the longitudinal tip VWSG expansion data for each slab. The water curing for all three slabs was terminated at 7 days to mimic previous testing protocols from phase I and II. The slab with fibers expanded the most while the slab with no reinforcement expanded the least. The slab with No. 5 reinforcing bar along the edges expands more than the slab with no reinforcement but less than the slab with fibers.

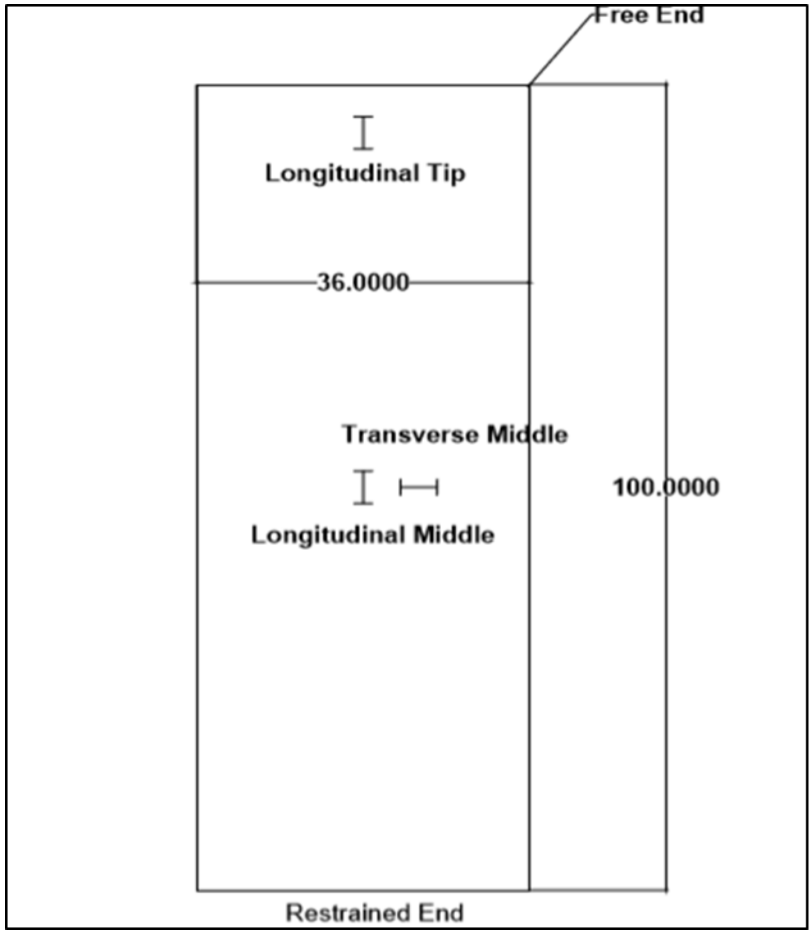

Figure 54, Layout of Slab VWSG

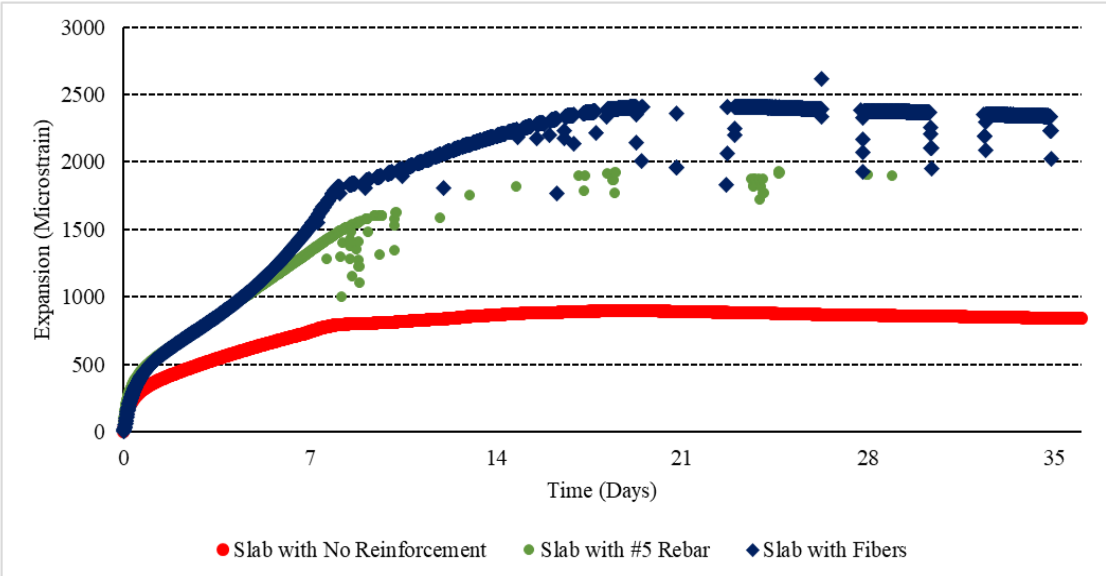

Figure 55, Longitudinal Tip Expansion (VWSG)

Figure 56 shows the expansion of the longitudinal middle VWSG of each slab. The slabs with Novocon XR fibers and No.5 reinforcing bar had several gaps in the curve, but the general trend is visible. The restraint from the No.5 reinforcing bar has more of an impact for the middle longitudinal VWSG expansion than the longitudinal tip VWSG. The middle longitudinal VWSG also was affected more by the pre-existing slabs on the sides of each slab. However, the slab with no reinforcement middle longitudinal VWSG still shows the same amount of expansion as the longitudinal tip VWSG.

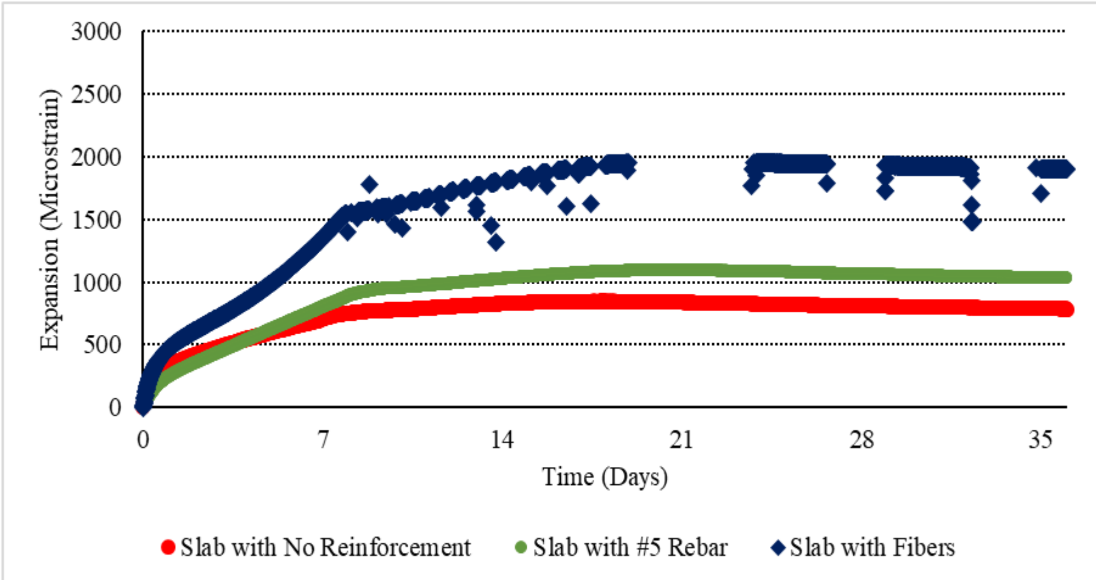

Figure 56, Longitudinal Middle Expansion (VWSG)

Figure 57 shows the expansion of the transverse middle VWSG of each slab. The general trend of the slab with no reinforcement expanding the least is still consistent with the findings of the longitudinal tip or longitudinal middle data. The transverse middle VWSG's were affected less by the restraint provided by the pre-existing slabs on the sides of each slab than the longitudinal middle VWSG's. The slab with No. 5 reinforcing bar had several gaps in the curve, but the general trend is visible for the middle transverse VWSG. The slab with no reinforcement middle transverse VWSG still shows the same amount of expansion as the longitudinal tip VWSG.

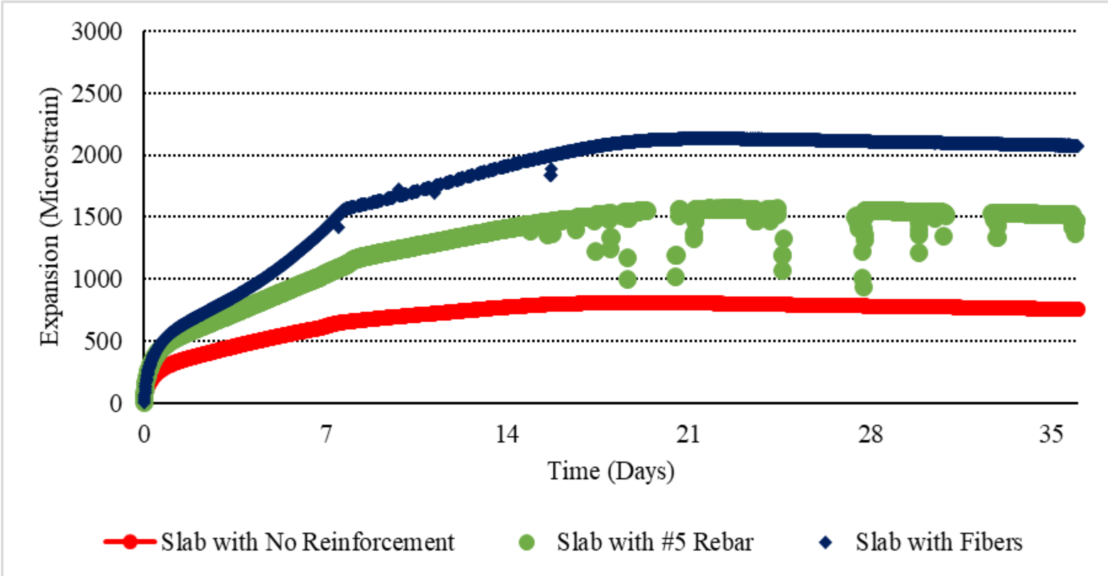

Figure 57, Transverse Middle Expansion (VWSG)

The general trend of the slab with no reinforcement expanding the least is consistent the findings of the longitudinal tip, longitudinal middle, and transverse middle data. The maximum expansion for all three slabs is recorded in the longitudinal tip. The transverse middle produces the next largest expansion for all three slabs. The longitudinal middle VWSG exhibits the lowest expansion of the three locations. Due to the tip of the slab being free to expand without a restricting slab or restraint, the maximum expansion occurring in the longitudinal tip VWSG makes sense.

An interesting trend developed for all three VWSG's for the slabs. The 25% expansive mineral admixture slab with no reinforcement expanded the least amount of the three slabs. According to the previous findings in this project, the slab with no reinforcement should have expanded the most. The most logical explanation of these results is that there was a significant loss of paste during the mixing process. For the slab mixtures, a larger mixer was used to accommodate the increased mixture size. However, this mixer tends to absorb a lot of paste during the mixing process. The three mixtures were done back to back, which is why the two later slabs appear less affected by the paste loss. The slab with no reinforcement would have ideally been recast, but time did not permit for this to occur.

Another possible reason that the slab with no reinforcement did not expand as much is that all of the slabs were cast into the ground with pre-existing slabs on both sides. The slab with no reinforcement may not have achieved a high enough temperature for the slabs to cure properly which would allow normal expansion. However, the slab with the Novocon XR fibers seemed less affected by the cold temperatures. This could be due to the introduction of fibers into the mixture might affect the concrete chemistry and allow expansion to occur at a lower temperature. However, the exact reason as to why the slabs expansion was not as expected is unknown.

One interesting trend that developed was the magnitude of the overall expansion of the slab with fibers. The overall magnitude increased significantly which suggests that in larger scale implementation of the 25% expansive mineral admixture with fibers allows for the expansion to become less affected by the restraint of the fibers. However, this trend cannot be stated with certainty due to the slab with no reinforcement not expanding to the expected levels. In Figure 58, the longitudinal tip expansion of the slab with fibers is compared with the C-878 data for the same fiber type, but the C-878 data for the 25% expansive mineral admixture is shown as a baseline of what the expected expansion was for the slab with no reinforcement.

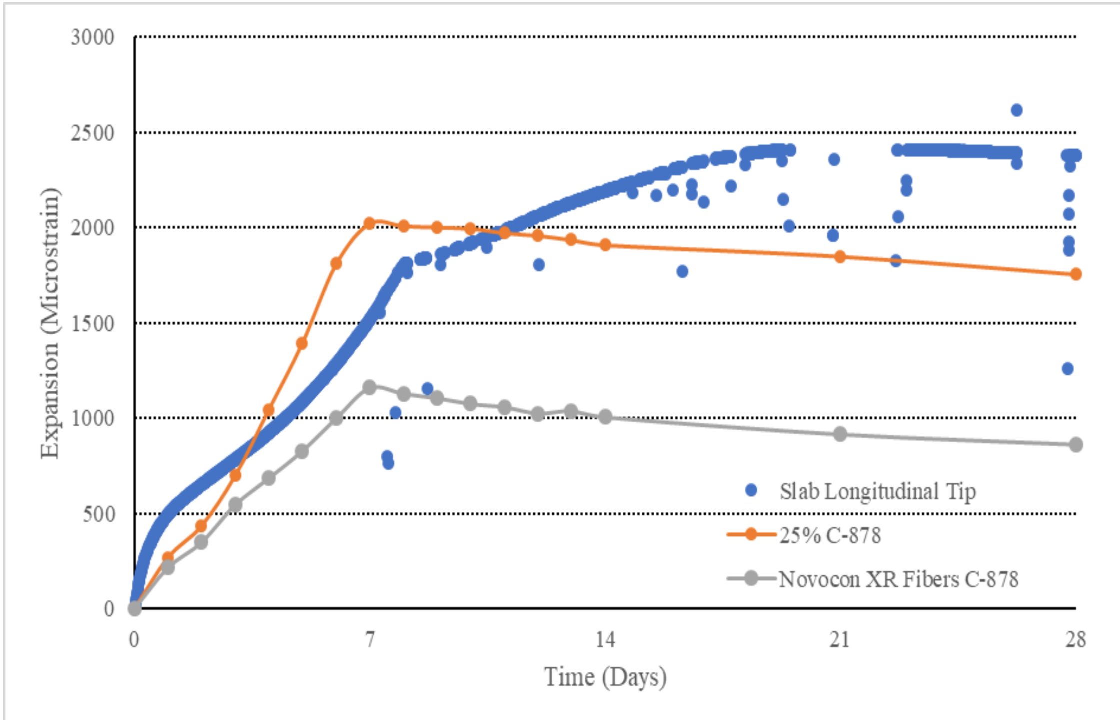

Figure 58, 25% Expansive Mineral Admixture C-878, Novocon XR C-878, and Slab with Fibers Longitudinal Tip Expansion

As seen in Figure 58, the slab with fibers expanded a significant amount more than the corresponding C-878 data. The slab expanded more than the baseline of the 25% expansive mineral admixture C-878 data. This suggests that the previously stated trend of the large-scale effect of the slabs has merit. Prior work at Fears lab by Ramseyer et al. points out that the relative humidity under a slab is generally 100%. Since the relative humidity is 100%, there is moisture available for expansion curing. The magnitude of the scaling effect for the Novocon XR fiber was approximately doubling the original expansion. This increase in expansion creates more stress inside of the concrete, which would create more self-stress into the steel fibers. However, without knowing the true expansion of a large-scale slab with 25% expansive mineral admixture and no fibers, the exact amount of restraint of large scale specimens cannot be determined, which further indicates that another slab of 25% expansive mineral admixture is needed complete these suggested trends.

Chapter 6: Conclusions and Future Work

6.1 Conclusions

- Increasing the percentage of expansive mineral admixture increases the overall expansion of the concrete.
- At 14 and 28 days, the lowest percentage of expansive mineral admixture results in a higher compressive strength with a range of 1200 psi between the 21% through the 29% mixes.
- At 1 year, the lower percentage of expansive mineral admixture achieved the highest compressive strength, but the range between 21% through 29% was only 700 psi.
- Increasing percentage of expansive mineral admixture increases the amount of drying shrinkage.
- There is a jump at around 20% expansive mineral admixture that creates more aggressive expansion at higher percentages of expansive mineral admixture than those of less than 20%.
    - The cause of this behavior is unknown.
- The introduction of steel fibers increases the compressive strength of the 25% expansive mineral admixture concrete.
- At 14 days, the Novocon 1050 increased the compressive strength by 1200 psi, while the other three fibers increased the compressive strength by approximately 500 psi.
- At 28 days, the CTS Proprietary fibers increased the compressive strength the most for the four fiber types by approximately 1700 psi.

- The introduction of fibers decreased the amount of expansion in the 25% expansive mineral admixture.
- The CTS Proprietary fibers decreased the amount of expansion the least while the three other fibers decreased the expansion approximately the same amount.
- Both Novocon fibers and CTS Proprietary fibers allowed less drying shrinkage than the 25% expansive mineral admixture.
- The Dramix allowed a small increase in drying shrinkage.
- The introduction of fibers increased the MOR strength at 28 days in comparison to the 25% expansive mineral admixture MOR strength.
    - Dramix fibers increased the MOR strength the most with a 43.5% increase.
    - The CTS Proprietary and Novocon XR fibers increased the MOR strength by 32%.
    - The Novocon 1050 he increased the MOR strength by 11%.
- Standard VWSG's produce smooth curves for the expansion of concrete for percentages of expansive mineral admixture less than 23%.
- Extended range VWSG can be used to capture higher percentage expansive mineral admixture than the standard but the data set is not as clean as with a typical Portland cement concrete.
- Expansion of the slabs using 25% expansive mineral admixture concrete is larger than the corresponding C-878 samples.
- Expansion at the longitudinal tip was higher than at midspan for all three slabs types.

- Using No.5 reinforcing bar along the edges decreases expansion more than the Novocon XR fibers.

6.2 Future Work

- Construct slabs of different percentages of expansive mineral admixture to characterize the potential scaling or slab on ground effect has on the overall expansion.
- Repeat of phase I through III for different water to cement ratios.
- Understanding how high range water reducer effects the expansion of an expansive mineral admixture concrete mix.
- Repeat phase II through III for a different percentage of expansive mineral admixture.
- Characterizing the 20-22% expansive mineral admixture amount to understand what causes the more aggressive expansion at 21% and higher.
    - Examine the crystal structure for each percentage to see variations in the 20-22% range.
    - Compare the variations from the 20-22% to higher percentages of expansive mineral admixture (23-29%) to see what similarities and differences occur.

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Appendices

Appendix I: Batch Sheets for Phase I

21% Komponent		Test:	My Research		8/16/2016
w/cm =	0.5		Sand % water =	1.538	start 8:15 AM
PC =	458.2	type I	Rock % water =	0.000	batch
RS =	0				stop 8:57 AM
Komp =	121.8				
FA =	0				

Sand SG	2.63	SSD=	0.70	b/bo =	0.65	Fineness Modulus = 2.5
Rock SG	2.68	SSD=	0.86	DRUW =	101.0	
H2O SG=	1.0					
C SG=	3.15					
RS SG=	2.88					
Komp SG	2.88					
FA SG=	2.58					

Moisture Content

Sand:	Wt (lb)		
Pan	0.39	Mc =	1.538
Pan + wet Sand	3.69		
Pan + dry Sand	3.64		
Aggregates:			
Pan	0.49	Mc =	0.000
Pan + wet Agg	4.52		
Pan + dry Agg	4.52		

	Theoretical Weight	Volume
Portland Cement	458.2	2.33
Rapid Set Cement	0	0.00
Komponent	121.8	0.68
Fly Ash	0	0.00
Water	290.0	4.65
Rock	1772.6	10.60
Air Entrapped 2%	0.0	0.54
DCI-chemical part	0.0	0.00
Sand	1346.4	8.20
Sum	3988.98576	27

		1 yd	2.25	cu ft		
Portland Cement		458.2	38.18	lb		
Rapid Set Cement		0.0	0.00	lb		
Komponent		121.8	10.15	lb		
Fly Ash		0.0	0.00	lb		
Coarse Aggregate, #67		1772.6	147.71	lb		
Fine Aggregate, Dover Sand		1367.2	113.93	lb		
Water		293.8	24.48	lb		
Air Ent. Admixture	oz	0.0	0.00	ml		
Citric Acid Retarder	lb	0.0	0.00	lb		
Glenium (MRWR)	oz	0.0	0.00	ml	oz/cwt	0.00
DCI (Accel w/ water)	oz	0.0	0.00	ml	oz/cwt	0.00

Concrete Temperature	74
Air Temperature	68
Humidity	83%
Air Content	1.20%
Slump	4
Unit Weight Pot Empty	7.76
Unit Weight Pot Full	44.56

Expected Unit Wt		147.74
Measured	36.8	147.20
Difference	%	0.37

23% Komponent

Test: **My Research** 8/16/2016

w/cm =	0.5			Sand % water =	1.538	start	9:08 AM
PC =	446.6	type I		Rock % water =	0.000	batch	
RS =	0					stop	9:52 AM
Komp =	133.4						
FA =	0						

Sand SG	2.63	SSD=	0.70	b/bo =	0.65	Fineness Modulus = 2.5
Rock SG:	2.68	SSD=	0.86	DRUW =	101.0	
H2O SG=	1.0					
C SG=	3.15					
RS SG=	2.88					
Komp SG	2.88					
FA SG=	2.58					

Moisture Content

Sand:	Wt (lb)		
Pan	0.39	Mc =	1.538
Pan + wet Sand	3.69		
Pan + dry Sand	3.64		
Aggregates:			
Pan	0.49	Mc =	0.000
Pan + wet Agg	4.52		
Pan + dry Agg	4.52		

	Theoretical Weight	Volume
Portland Cement	446.6	2.27
Rapid Set Cement	0	0.00
Komponent	133.4	0.74
Fly Ash	0	0.00
Water	290.0	4.65
Rock	1772.6	10.60
Air Entrapped 2%	0.0	0.54
DCI-chemical part	0.0	0.00
Sand	1345.5	8.20
Sum	3988.07779	27

		1yd	2.25	cu ft		
Portland Cement		446.6	37.22	lb		
Rapid Set Cement		0.0	0.00	lb		
Komponent		133.4	11.12	lb		
Fly Ash		0.0	0.00	lb		
Coarse Aggregate, #67		1772.6	147.71	lb		
Fine Aggregate, Dover Sand		1366.2	113.85	lb		
Water		293.8	24.48	lb		
Air Ent. Admixture	oz	0.0	0.00	ml		
Citric Acid Retarder	lb	0.0	0.00	lb		
Glenium (MRWR)	oz	0.0	0.00	ml	oz/cwt	0.00
DCI (Accel w/ water)	oz	0.0	0.00	ml	oz/cwt	0.00

Concrete Temperature	74
Air Temperature	72
Humidity	73%
Air Content	1.20%
Slump	4.5
Unit Weight Pot Empty	7.76
Unit Weight Pot Full	44.54

Expected Unit Wt		147.71
Measured	36.78	147.12
Difference	%	0.40

27% Komponent		Test:	My Research		9/2/2016				

w/cm =	0.5		Sand % water =	1.285	start	12:53 PM
PC =	423.4	type I	Rock % water =	0.000	batch	12:54 PM
RS =	0				stop	1:37 PM
Komp =	156.6					
FA =	0					

Moisture Content

Sand:	Wt (lb)		
Pan	0.4	Mc =	1.285
Pan + wet Sand	4.34		
Pan + dry Sand	4.29		
Aggregates:			
Pan	0.5	Mc =	0.000
Pan + wet Agg	4.82		
Pan + dry Agg	4.82		

Sand SG	2.63	SSD=	0.70	b/bo =	0.65	Fineness Modulus = 2.5
Rock SG	2.68	SSD=	0.86	DRUW =	101.0	
H2O SG=	1.0					
C SG=	3.15					
RS SG=	2.88					
Komp SG	2.88					
FA SG=	2.58					

	Theoretical Weight	Volume
Portland Cement	423.4	2.15
Rapid Set Cement	0	0.00
Komponent	156.6	0.87
Fly Ash	0	0.00
Water	290.0	4.65
Rock	1772.6	10.60
Air Entrapped 2%	0.0	0.54
DCI-chemical part	0.0	0.00
Sand	1343.7	8.19
Sum	3986.26184	27

		1 yd	2.25	cu ft		
Portland Cement		423.4	35.28	lb		
Rapid Set Cement		0.0	0.00	lb		
Komponent		156.6	13.05	lb		
Fly Ash		0.0	0.00	lb		
Coarse Aggregate, #67		1772.6	147.71	lb		
Fine Aggregate, Dover Sand		1361.0	113.42	lb		
Water		297.3	24.77	lb		
Air Ent. Admixture	oz	0.0	0.00	ml		
Citric Acid Retarder	lb	0.0	0.00	lb		
Glenium (MRWR)	oz	0.0	0.00	ml	oz/cwt	0.00
DCI (Accel w/ water)	oz	0.0	0.00	ml	oz/cwt	0.00

Concrete Temperature	80 F
Air Temperature	73 F
Humidity	88%
Air Content	1.10%
Slump	4"
Unit Weight Pot Empty	7.76
Unit Weight Pot Full	44.5

Expected Unit Wt		147.64
Measured	36.74	146.96
Difference	%	0.46

29% Komponent

Test: **My Research** 9/2/2016

w/cm =	0.5		Sand % water =	1.285	start	1:52 PM
PC =	411.8	type I	Rock % water =	0.000	batch	1:53 PM
RS =	0				stop	2:43 PM
Komp =	168.2					
FA =	0					

Sand SG	2.63	SSD=	0.70	b/bo =	0.65	Fineness Modulus = 2.5
Rock SG:	2.68	SSD=	0.86	DRUW =	101.0	
H2O SG=	1.0					
C SG=	3.15					
RS SG=	2.88					
Komp SG	2.88					
FA SG=	2.58					

Moisture Content

Sand:	Wt (lb)		
Pan	0.4	Mc =	1.285
Pan + wet Sand	4.34		
Pan + dry Sand	4.29		
Aggregates:			
Pan	0.5	Mc =	0.000
Pan + wet Agg	4.82		
Pan + dry Agg	4.82		

	Theoretical Weight	Volume
Portland Cement	411.8	2.10
Rapid Set Cement	0	0.00
Komponent	168.2	0.94
Fly Ash	0	0.00
Water	290.0	4.65
Rock	1772.6	10.60
Air Entrapped 2%	0.0	0.54
DCI-chemical part	0.0	0.00
Sand	1342.8	8.18
Sum	3985.35386	27

		1yd	2.25	cu ft		
Portland Cement		411.8	34.32	lb		
Rapid Set Cement		0.0	0.00	lb		
Komponent		168.2	14.02	lb		
Fly Ash		0.0	0.00	lb		
Coarse Aggregate, #67		1772.6	147.71	lb		
Fine Aggregate, Dover Sand		1360.1	113.34	lb		
Water		297.3	24.77	lb		
Air Ent. Admixture	oz	0.0	0.00	ml		
Citric Acid Retarder	lb	0.0	0.00	lb		
Glenium (MRWR)	oz	0.0	0.00	ml	oz/cwt	0.00
DCI (Accel w/ water)	oz	0.0	0.00	ml	oz/cwt	0.00

Concrete Temperature	80 F	Expected Unit Wt		147.61
Air Temperature	77 F	Measured	36.99	147.96
Humidity	65%	Difference	%	-0.24
Air Content	1.30%			
Slump	4 1/8"			
Unit Weight Pot Empty	7.76			
Unit Weight Pot Full	44.75			

Appendix II: Batch Sheets for Phase II

25% Komponent Novocon 1050 he Fibers

Test: **My Research** 6/26/2017

w/cm =	0.5		Sand % water =	1.977	start	8:58 AM
PC =	435	type I	Rock % water =	0.000	batch	
RS =	0				stop	9:30 AM
Komp =	145					
FA =	0					

Moisture Content

Sand:	Wt (lb)		
Pan	0.49	Mc =	1.977
Pan + wet Sand	4.1		
Pan + dry Sand	4.03		
Aggregates:			
Pan	0.58	Mc =	0.000
Pan + wet Agg	3.81		
Pan + dry Agg	3.81		

Sand SG	2.63	SSD=	0.70	b/bo =	0.65	Fineness Modulus = 2.5
Rock SG	2.68	SSD=	0.86	DRUW =	101.0	
H2O SG=	1.0					
C SG=	3.15					
RS SG=	2.88					
Komp SG	2.88					
FA SG=	2.58					

	Theoretical Weight	Volume
Portland Cement	435.0	2.21
Rapid Set Cement	0	0.00
Komponent	145	0.81
Fly Ash	0	0.00
Water	290.0	4.65
Rock	1772.6	10.60
Air Entrapped 2%	0.0	0.54
DCI-chemical part	0.0	0.00
Sand	1344.6	8.19
Sum	3987.169812	27

		1yd	5	cu ft
Portland Cement		435.0	80.56	lb
Rapid Set Cement		0.0	0.00	lb
Komponent		145.0	26.85	lb
Fly Ash		0.0	0.00	lb
Coarse Aggregate, #67		1772.6	328.25	lb
Fine Aggregate, Dover Sand		1371.2	253.93	lb
Water		287.7	53.28	lb
Air Ent. Admixture	oz	0.0	0.00	ml
Citric Acid Retarder	lb	0.0	0.00	lb
Glenium (MRWR)	oz	0.0	0.00	ml
DCI (Accel w/ water)	oz	0.0	0.00	ml

Percent of Fibers	3.3333	lb/ft^3
Amount of Fibers	16.667	lbs
oz/cwt =	0.00	
oz/cwt =	0.00	

Concrete Temperature	79
Air Temperature	82
Humidity	56%
Air Content	1.80%
Slump	3/4"
Unit Weight Pot Empty	7.76
Unit Weight Pot Full	45.31

Expected Unit Wt		147.67
Measured	37.55	150.20
Difference	%	-1.71

25% Komponent Novocon XR Fibers		Test:	**My Research**		6/28/2017			**Moisture Content**		
w/cm =	0.5		Sand % water =	1.977	start	8:58 AM		Sand:	Wt (lb)	
PC =	435	type I	Rock % water =	0.955	batch			Pan	0.49	Mc = 1.977
RS =	0				stop	9:30 AM		Pan + wet Sand	4.1	
Komp =	145							Pan + dry Sand	4.03	
FA =	0							Aggregates:		
								Pan	0.58	Mc = 0.955
Sand SG	2.63	SSD= 0.70	b/bo = 0.65	Fineness Modulus = 2.5				Pan + wet Agg	3.75	
Rock SG	2.68	SSD= 0.86	DRUW = 101.0					Pan + dry Agg	3.72	
H2O SG=	1.0									
C SG=	3.15									
RS SG=	2.88									
Komp SG	2.88									
FA SG=	2.58									

	Theoretical Weight	Volume
Portland Cement	435.0	2.21
Rapid Set Cement	0	0.00
Komponent	145	0.81
Fly Ash	0	0.00
Water	290.0	4.65
Rock	1772.6	10.60
Air Entrapped 2%	0.0	0.54
DCI-chemical part	0.0	0.00
Sand	1344.6	8.19
Sum	3987.169812	27

		1 yd	5	cu ft				
Portland Cement		435.0	80.56	lb				
Rapid Set Cement		0.0	0.00	lb		Percent of Fibers	3.3333	lb/ft^3
Komponent		145.0	26.85	lb		Amount of Fibers	16.667	lbs
Fly Ash		0.0	0.00	lb				
Coarse Aggregate, #67		1789.5	331.39	lb				
Fine Aggregate, Dover Sand		1371.2	253.93	lb				
Water		270.8	50.14	lb				
Air Ent. Admixture	oz	0.0	0.00	ml				
Citric Acid Retarder	lb	0.0	0.00	lb				
Glenium (MRWR)	oz	0.0	0.00	ml	oz/cwt =	0.00		
DCI (Accel w/ water)	oz	0.0	0.00	ml	oz/cwt =	0.00		

Concrete Temperature	80	Expected Unit Wt		147.67
Air Temperature	77	Measured	36.98	147.92
Humidity	100%	Difference	%	-0.17
Air Content	1.90%			
Slump	1"			
Unit Weight Pot Empty	7.76			
Unit Weight Pot Full	44.74			

25% Komponent Dramix Fibers

Test: **My Research** 6/28/2017

w/cm =	0.5		Sand % water =	1.488	start	8:58 AM
PC =	435	type I	Rock % water =	0.662	batch	
RS =	0				stop	9:30 AM
Komp =	145					
FA =	0					

Moisture Content

Sand:	Wt (lb)		
Pan	0.49	Mc =	1.488
Pan + wet Sand	3.9		
Pan + dry Sand	3.85		
Aggregates:			
Pan	0.58	Mc =	0.662
Pan + wet Agg	3.62		
Pan + dry Agg	3.6		

Sand SG	2.63	SSD=	0.70	b/bo =	0.65	Fineness Modulus = 2.5
Rock SG:	2.68	SSD=	0.86	DRUW =	101.0	
H2O SG=	1.0					
C SG=	3.15					
RS SG=	2.88					
Komp SG:	2.88					
FA SG=	2.58					

	Theoretical Weight	Volume
Portland Cement	435.0	2.21
Rapid Set Cement	0	0.00
Komponent	145	0.81
Fly Ash	0	0.00
Water	290.0	4.65
Rock	1772.6	10.60
Air Entrapped 2%	0.0	0.54
DCI-chemical part	0.0	0.00
Sand	1344.6	8.19
Sum	3987.169812	27

		1yd	5	cu ft			
Portland Cement		435.0	80.56	lb			
Rapid Set Cement		0.0	0.00	lb	Percent of Fibers	3.3333	lb/ft^3
Komponent		145.0	26.85	lb	Amount of Fibers	16.667	lbs
Fly Ash		0.0	0.00	lb			
Coarse Aggregate, #67		1784.3	330.42	lb			
Fine Aggregate, Dover Sand		1364.6	252.71	lb			
Water		282.8	52.37	lb			
Air Ent. Admixture	oz	0.0	0.00	ml			
Citric Acid Retarder	lb	0.0	0.00	lb			
Glenium (MRWR)	oz	45.0	0.00	ml	oz/cwt =	10.34	
DCI (Accel w/ water)	oz	0.0	0.00	ml	oz/cwt =	0.00	

Concrete Temperature	75	Expected Unit Wt		147.67
Air Temperature	72	Measured	36.7	146.80
Humidity	100%	Difference	%	0.59
Air Content	1.30%			
Slump	4"			
Unit Weight Pot Empty	7.76			
Unit Weight Pot Full	44.46			

Appendix III: Batch Sheets for Phase III

25% Komponent Slab Test: My Research

2/3/2018

No Reinforcement

w/cm =	0.5		Sand % water =	1.534	start	8:58 AM
PC =	435	type I	Rock % water =	0.556	batch	
RS =	0				stop	9:30 AM
Komp =	145					
FA =	0					

Moisture Content

Sand:	Wt (lb)		
Pan	0.49	Mc =	1.534
Pan + wet Sand	3.8		
Pan + dry Sand	3.75		
Aggregates:			
Pan	0.58	Mc =	0.556
Pan + wet Agg	4.2		
Pan + dry Agg	4.18		

Sand SG	2.63	SSD=	0.70	b/bo =	0.65	Fineness Modulus = 2.5
Rock SG	2.68	SSD=	0.86	DRUW =	101.0	
H2O SG=	1.0					
C SG=	3.15					
RS SG=	2.88					
Komp SG	2.88					
FA SG=	2.58					

	Theoretical Weight	Volume
Portland Cement	435.0	2.21
Rapid Set Cement	0	0.00
Komponent	145	0.81
Fly Ash	0	0.00
Water	290.0	4.65
Rock	1772.6	10.60
Air Entrapped 2%	0.0	0.54
DCI-chemical part	0.0	0.00
Sand	1344.6	8.19
Sum	3987.169812	27

		1yd	16.5	cu ft		
Portland Cement		435.0	265.83	lb		
Rapid Set Cement		0.0	0.00	lb		
Komponent		145.0	88.61	lb		
Fly Ash		0.0	0.00	lb		
Coarse Aggregate, #67		1782.4	1089.24	lb		
Fine Aggregate, Dover Sand		1365.2	834.32	lb		
Water		284.0	173.58	lb		
Air Ent. Admixture	oz	0.0	0.00	ml		
Citric Acid Retarder	lb	0.0	0.00	lb		
Glenium (MRWR)	oz	230.0	0.00	ml	oz/cwt =	52.87
DCI (Accel w/ water)	oz	0.0	0.00	ml	oz/cwt =	0.00

Concrete Temperature	79
Air Temperature	55
Humidity	57%
Air Content	NA
Slump	3.5"
Unit Weight Pot Empty	0
Unit Weight Pot Full	0

25% Komponent Slab No.5 Reinforcement

Test: **My Research** 2/3/2018

w/cm =	0.5		Sand % water =	1.534	start	8:58 AM
PC =	435	type I	Rock % water =	0.556	batch	
RS =	0				stop	9:30 AM
Komp =	145					
FA =	0					

Sand SG	2.63	SSD=	0.70	b/bo =	0.65	Fineness Modulus = 2.5
Rock SG	2.68	SSD=	0.86	DRUW =	101.0	
H2O SG=	1.0					
C SG=	3.15					
RS SG=	2.88					
Komp SG	2.88					
FA SG=	2.58					

Moisture Content

Sand:	Wt (lb)		
Pan	0.49	Mc =	1.534
Pan + wet Sand	3.8		
Pan + dry Sand	3.75		
Aggregates:			
Pan	0.58	Mc =	0.556
Pan + wet Agg	4.2		
Pan + dry Agg	4.18		

	Theoretical Weight	Volume
Portland Cement	435.0	2.21
Rapid Set Cement	0	0.00
Komponent	145	0.81
Fly Ash	0	0.00
Water	290.0	4.65
Rock	1772.6	10.60
Air Entrapped 2%	0.0	0.54
DCI-chemical part	0.0	0.00
Sand	1344.6	8.19
Sum	3987.169812	27

		1 yd	16.5	cu ft		
Portland Cement		435.0	265.83	lb		
Rapid Set Cement		0.0	0.00	lb		
Komponent		145.0	88.61	lb		
Fly Ash		0.0	0.00	lb		
Coarse Aggregate, #67		1782.4	1089.24	lb		
Fine Aggregate, Dover Sand		1365.2	834.32	lb		
Water		284.0	173.58	lb		
Air Ent. Admixture	oz	0.0	0.00	ml		
Citric Acid Retarder	lb	0.0	0.00	lb		
Glenium (MRWR)	oz	230.0	0.00	ml	oz/cwt =	52.87
DCI (Accel w/ water)	oz	0.0	0.00	ml	oz/cwt =	0.00

Concrete Temperature	79
Air Temperature	55
Humidity	57%
Air Content	NA
Slump	4"
Unit Weight Pot Empty	0
Unit Weight Pot Full	0

25% Komponent Slab with Fibers		Test:	My Research		2/3/2018		
w/cm =	0.5		Sand % water =	1.534	start	8:58 AM	
PC =	435	type I	Rock % water =	0.556	batch		
RS =	0				stop	9:30 AM	
Komp =	145						
FA =	0						

Moisture Content

Sand:	Wt (lb)		
Pan	0.49	Mc =	1.534
Pan + wet Sand	3.8		
Pan + dry Sand	3.75		
Aggregates:			
Pan	0.58	Mc =	0.556
Pan + wet Agg	4.2		
Pan + dry Agg	4.18		

Sand SG	2.63	SSD=	0.70	b/bo =	0.65	Fineness Modulus = 2.5
Rock SG	2.68	SSD=	0.86	DRUW =	101.0	
H2O SG=	1.0					
C SG=	3.15					
RS SG=	2.88					
Komp SG	2.88					
FA SG=	2.58					

	Theoretical Weight	Volume
Portland Cement	435.0	2.21
Rapid Set Cement	0	0.00
Komponent	145	0.81
Fly Ash	0	0.00
Water	290.0	4.65
Rock	1772.6	10.60
Air Entrapped 2%	0.0	0.54
DCI-chemical part	0.0	0.00
Sand	1344.6	8.19
Sum	3987.169812	27

		1 yd	16.5	cu ft		
Portland Cement		435.0	265.83	lb		
Rapid Set Cement		0.0	0.00	lb	Percent of Fibers	3.3333 lb/ft^3
Komponent		145.0	88.61	lb	Amount of Fibers	55 lbs
Fly Ash		0.0	0.00	lb		
Coarse Aggregate, #67		1782.4	1089.24	lb		
Fine Aggregate, Dover Sand		1365.2	834.32	lb		
Water		284.0	173.58	lb		
Air Ent. Admixture	oz	0.0	0.00	ml		
Citric Acid Retarder	lb	0.0	0.00	lb		
Glenium (MRWR)	oz	250.0	0.00	ml	oz/cwt =	57.47
DCI (Accel w/ water)	oz	0.0	0.00	ml	oz/cwt =	0.00

Concrete Temperature	76
Air Temperature	55
Humidity	57%
Air Content	NA
Slump	2"
Unit Weight Pot Empty	0
Unit Weight Pot Full	0