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Development of Self-Stressing Ultra High-Performance Concrete using Expansive Chemical Admixtures

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Development of Self-Stressing Ultra High-Performance Concrete using Expansive Chemical Admixtures

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Abstract

This study investigated the effects of expansive chemical admixtures on ultra-high performance concrete (UHPC) and self-stressing mechanisms. A literature review was performed to determine different types of expansive admixtures for feasibility of the self-prestressing concept. Ultimately it was decided that type-k cement, made by combining *Komponent* admixture with conventional UHPC, was the most suitable option due to its effects on wet and hardened concrete properties. Mix designs with varying amounts of *Komponent* were developed to test the effects the admixture had on various properties. Tested properties included, workability, compressive strength, expansion, short-term shrinkage, long-term shrinkage, and developed prestress. The development and testing of mix designs showed that the addition of the *Komponent* admixture decreased workability due to faster absorption of water. Compression strength testing showed that increasing the amount of the admixture increased the later age compressive strength of the UHPC. Increased compressive strength is also due to the high-water absorption characteristics of type-k cement. Various mix designs were tested using vibrating wire strain gauges on concrete cylinders during the curing phase. These tests confirmed the hypothesis that increasing the amount of chemical admixture increases the amount of measured strain developed as the concrete hardened. To test the long-term shrinkage behavior, elongation prism tests were performed on all mix designs. The results showed that the addition of chemical admixture had no effect on the shrinkage behavior after ten days. Chemical prestress was measured directly using a rod plate test specimen during the curing phase. The results of this test showed a cyclic correlation that indicated a small amount of prestress was developed after 7 days.

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1. Introduction

Ultra-high performance concrete (UHPC) was developed in France in the 1990s [1], and differs from conventional concrete in many characteristics. These characteristics include compressive strength, workability, ductility, and resistance to environmental impacts. UHPC is often used for the restoration or repair of damaged existing structures. A common application is the repair of corroded steel bridge girder ends at expansion joints [1]. Since these joints are often exposed to environmental corrosion, the durable UHPC is a suitable solution to restoration of bridge members [1]. Another bridge application for UHPC is deck overlays. Currently, UHPC is being used all over the world in restoring deteriorating bridge decks. These overlays are superior to conventional overlays due to increased strength, low permeability, and strong bond to the existing concrete. UHPC is also a better protector of the steel deck, preventing the intrusion of harmful chemicals, salts or freeze-thaw cycling [1]. Currently, UHPC's usage is limited due to the high cost. In construction, UHPC is mostly used to reinforce an existing concrete or steel member [12]. With new construction, UHPC is not as economical.

Reinforcement is essential for any concrete member subjected to flexural loading. Reinforced concrete not only facilitates better stability and flexible design, but also optimization of material [2]. The optimization of material properties leads to more economical designs. When a reinforced concrete member is subjected to flexural loading, the materials are optimized by the geometry of the member cross section. The reinforcing steel is placed in the tensile face of the cross section and takes the tensile forces. The concrete occupies the remainder of the cross section and carries the compressive forces in the compressive face [2]. Steel reinforcement can go a step further and induce stresses in the cross section before any load is applied. This idea is referred to as "prestressing." Prestressing a concrete member is advantageous when dealing with heavy loads that would induce high tensile forces in a structural concrete member. When prestressing a concrete beam, a common practice is to use post-tensioning steel tendons. These tendons are fed through the entire length of the member and are anchored at each end of the beam. After the concrete member has cured, the tendons are mechanically pulled and stretched at the ends to induce tension in the steel throughout the length of the beam. The tendons are reattached at the anchorage devices at the ends of the beam, and bearing stresses are developed. These bearing stresses induce compressive stress into the member. This compressive stress will counteract the tensile forces in the tensile face that are imposed by the loads [2]. Prestressing concrete members is a common practice used in many types of construction.

While prestressing concrete is common practice in the use of conventional concrete, the application of this technology to UHPC is less common. Finite element modeling research shows that prestressed concrete beams have superior flexural responses to blast loading [3]. UHPC already has uses in bunker and blast resistant structure construction [1]. If these UHPC members were prestressed, they would be better suited to resist these dynamic loads.

Most methods of prestressing concrete require mechanical manipulation of materials to achieve prestress in the member [2]. This research takes a different approach that requires the use of chemical admixtures to induce compressive stresses in the member. The way this can be achieved is by introducing expansive agents in a UHPC mix design. These expansive agents are produced by the hydration of expansive admixtures during the curing phase of the concrete. As the concrete cures, the agents expand to induce stress on the concrete matrix [4]. If the concrete is restrained, internal stresses are developed, and a measurable amount of prestress can be induced. Expansive admixtures can also affect other properties of UHPC such as compressive capacity, workability, and curing [4]. Chemical prestressing may be a new pathway to more economical and sustainable structural design methods.

2. Literature Review

To achieve the task of developing chemically induced prestress, a literature review was performed exploring various types of expansive admixtures and their chemical products. Expansive admixtures are mixed with cement to create expansive cements. During the mixing and curing phase, these expansive cements hydrate to form expansive agents. These agents are produced as the concrete cures and are the expansive mechanisms that can achieve prestress [4]. This mechanism can be seen in Figure 1. Expansive admixtures produce three main types of expansive agents: monosulfate, calcium hydroxide, and most importantly, ettringite. The Tokyo Institute of Technology researched these expansive agents and their chemical processes [4].

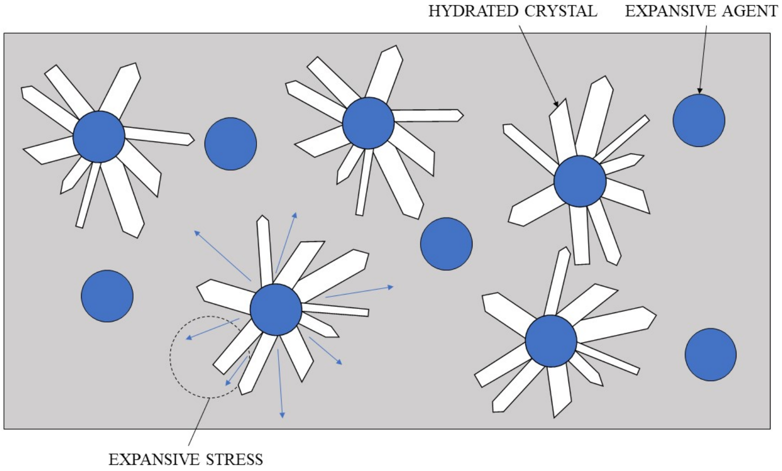


Figure 1. Cement matrix with expansive agents producing stress.

The study [4] concluded that, in terms of particle volume increase, ettringite was the most expansive agent produced by the expansive admixtures. The ratio of volume change for the hydrated particle was 9.3 for ettringite, 4.1 for monosulfate, and 1.9 for calcium hydroxide. From this research, it is conclusive that in order to produce the most compressive force from expansive ingredients, ettringite hydrates must be formed in the concrete matrix.

According to the American Concrete Institute (ACI), there are three different types of common expansive cements: ‘M type’, ‘S type’, and ‘K type’ [4]. These cement blends utilize the chemical processes of hydration to produce expansive agents during the curing process.

2.1 Expansive Cement Types

Type-M cement consists of portland cement mixed with alumina cement and gypsum [4]. The most common application for this cement is in masonry mortar. This mortar is the highest strength mortar used in masonry applications with a compressive strength up to 2500 psi [5]. Research experiments have shown that this type of cement is successful in generating compressive forces in the curing phase. In 1978, research by the Joint Highway Research Project at Purdue University proved this by creating restrained molds for the concrete [6]. The schematic consisted of a 3” x 3” x 11” rectangular specimen encasing an unbonded restrained rod covered by a rubber sleeve. The mold created a uniaxially restrained beam with an electrical resistance gauge inside to measure the stress of the rod. This stress was multiplied by the area ratio of steel to concrete. The specimens achieved self-stress up to 300 psi in 14 days [6].

Type-S cement consists of portland cement mixed with tricalcium aluminate (C_3A) and gypsum [4]. This cement is also used mostly for masonry applications. It is considered medium strength with a compressive capacity of 1800 psi [5]. Due to the lower strength, this cement type was not considered for this project.

Type-K cement consists of portland cement mixed with anhydrous haunye, gypsum, and quick lime [4]. This cement used to have some application in masonry but is now considered outdated for that industry. As a mortar, type-K cement creates a mix with undesirable workability and yields a low strength [5]. Nowadays, type-K cement is used with conventional concrete to develop a mix design that is less susceptible to shrinkage and cracking. When the additive is combined with conventional concrete, compressive strengths of 4500 psi can be achieved at 28 days [7]. Compressive strengths are increased due to the acceleration of cement hydration caused by the expansive cement [10]. Because of these properties, type-K cement was chosen to be the expansive admixture of use for this project.

2.2 Expansive Admixtures with UHPC Research

While various experiments have been performed testing expansive admixtures with conventional concrete, research is limited in their uses with ultra-high performance concrete. The Wuhan University of Technology recently tested the effects of expansive agents on UHPC for concrete-filled steel tube applications [8]. In this study, steel tubes were filled with UHPC that contained a CaO based expansive admixture. This expansive admixture produces the expansive agent $Ca(OH)_2$ [8]. After various curing periods, the effects on the specimens' physical, chemical, and mechanical properties were noted.

This study also examined the effects of saturated lightweight aggregate (LWA) on the expansive nature of the mix designs. To do so, mix designs were developed containing different amounts of expansive admixture while maintaining a constant amount of LWA. These designs were compared to a control design with no amount of expansive admixture nor LWA. Each UHPC mixture was poured into 4-inch diameter tube with strain gauges measuring both circumferential and axial strains. It was concluded that the additional expansive admixture produces more expansion when LWA is present and assisting in the hydration process [8].

The study also concluded that adding expansive admixtures increases early compressive strength. When compared to the control group, a 12% addition of expansive admixture increased the 3-day compressive strength by 14%. However, the trend subsides as more expansive admixture is added. At the 28-day mark, the specimens with the expansive admixture had a lower compressive strength than the control group [8].

The reaction of the expansive admixture is dependent on the amount of surrounding water while curing [8]. The amount of surrounding water in the UHPC is improved by adding saturated aggregate. The degree of the reaction of the admixture is essential in producing expansive agents that cause volumetric expansion. A limitation of this study was the type of expansive admixture they used. The main expansive product was $Ca(OH)_2$. This agent is produced by the CaO particle during the hydration process. This reactant to product volume ratio is only 1.9 [4]. Type K cement, however, uses anhydrous calcium sulfoaluminate to produce calcium sulfoaluminate (ettringite). This reactant to product volume ratio is 9.3 and displays a much higher potential in producing prestress [7,4]. For this research, type-K cement was made by combining *Komponent* additive with a UHPC premix. To mitigate shrinkage, the manufacturer of *Komponent* admixture recommends a 15-17% replacement of cementitious materials with the additive [10].

3. Experimental Study & Setup

The UHPC used in this study was Lafarge Ductal Gray Premix®. This premix contains mostly quartz and cementitious materials [9]. To make UHPC with this premix, only water, fibers, and high range water reducer (HRWR) needed to be added. To test the effects of the expansive admixture on the UHPC alone, fibers were not used in this research. Since this premix contains cement already, *Komponent* additive was combined with the premix to produce a type k cement blend. Plastol SPC was used as the high range water reducer.

3.1 Development of Mix Designs

The experimental study began with the development of mix designs. These mixes were designed to test the effects of the *Komponent* admixture alone on UHPC properties. To achieve its intended use, creating shrinkage compensating concrete, it is recommended to replace 15-17% of cementitious material with the *Komponent* additive [10]. This percentage was recommended by the manufacturer for the purpose of shrinkage mitigation and not necessarily expansion. To ensure the attainment of prestress, some of the developed mix designs contained a larger amount of *Komponent* admixture than the recommended quantity. Many iterations were made to these mix designs. These changes were made to achieve the desired consistency of the fresh UHPC. The resultant mix designs can be seen in Table 1.

Table 1. UHPC mix designs with EA.

Designation[1]	**Ductal Dry Mix**[2] **[lbs]**	**Water [g]**	**HRWR**[3] **[g]**	***Komponent* Admixture**[4] **[lbs]**	**Estimated w/cm Ratio**[5]
Control	10.0	250	62.0	0	15.7%
Mix - 15	10.0	266	66.0	0.618	15.8%
Mix - 17.5	10.0	269	66.8	0.742	15.8%
Mix - 20	10.0	350	67.5	0.875	20.3%
Mix - 22.5	10.0	355	68.5	1.016	20.3%

1. The mix designation number represents the percent of expansive admixture by weight when compared to the total cementitious material content.
2. The dry mix is Ductal Dark Grey manufactured by Lafarge.
3. The high range water reducer is Plastol SPC manufactured by Euclid Chemical.
4. The expansive admixture is Komponent manufactured by CTS Cement.
5. The estimated ratio presumes the premix to contain 35% cementitious materials by weight.

3.2 Mixing Procedure

To maintain consistency, two standard mixing procedures were created. The first standard mix procedure yields a 10-pound quantity of UHPC. This procedure consists of a high shear mixer at a constant speed, mixing for up to ten minutes. The second standard mixing procedure yields a 25-pound quantity of UHPC. This procedure uses the same high shear mixer, but at varying speeds. The mixing starts at a low stirring speed while ingredients are being added. Once all the ingredients are in the mixer, the stirring speed is increased. The wet UHPC continues to mix until the desired consistency is achieved. This procedure also takes about 10 minutes. These standardized mixing procedures can be seen in the appendix.

3.3 Compression Tests

An important task of this research is to test the effects of *Komponent* on the compressive strength of the concrete. Typically, the hydration of the cement is accelerated due to the expansive admixture. This can lead to higher early strengths [10]. Compression tests were performed in accordance with ASTM C109 [14]. Two-inch cubes were formed and crushed at varying ages. These strength values were used for the calculation of the modulus of elasticity.

3.4 Vibrating Wire Tests

To verify that the *Komponent* admixture was capable of developing prestress in the UHPC, vibrating wire strain gauges were used to measure the elongation of a concrete specimen throughout the curing process. Each specimen consisted of a 4-in x 8-in cylindrical concrete mold with a Geokon 4200 internal strain gauge suspended in the center of the mold, see Figure 2. The gauges can measure strain via the vibrating wire principle. Each gauge contains a steel wire that is tensioned between the two end blocks. When concrete is poured into the mold, these end blocks bond firmly to the UHPC. Throughout the curing process, deformations in the concrete cause the end blocks to move in relation to another, which alters the strain in the steel wire. This strain is measured as a change in the resonant frequency of vibration in the wire [11]. These gauges were connected to a data logger to measure microstrain with time. Once the concrete was poured, the specimens were placed in a moisture room. After

7 days, the molds were carefully removed, and the specimens were placed in a dry room for an additional 21 days. The procedure for this experiment can be found in the appendix. Since expansive admixtures generally react at early age, most of the expansion should take place before the 7-day mark. Since the molds were initially restrained in the radial direction, the specimens could only elongate in the axial direction.

Figure 2. Specimen molds with suspended gauges.

In addition to the control mix design, the test was performed on Mix-20 and Mix-22.5. These mix designs were chosen because they contain a higher amount of admixture than most of the other designs. The goal was to see maximum deformations in the specimens that contained the admixture. These deformations can be used to estimate the level of prestress in the specimens.

3.5 Hardened Concrete Length Change

To monitor the shrinkage behavior of the mix designs after curing, length change tests were performed in accordance with ASTM C157 [15]. Due to the lack of coarse aggregate in these mix designs, 1” x 1” x 11.25” concrete prisms were used for testing. Once the UHPC was placed in these molds, the specimens were covered and cured for three days at room temperature. After three days in the mold, the prisms were demolded and placed in a water and lime submersion tank for seven days. After a week in the tank, the specimens were removed from the tank to take initial length measurements, i.e. “day zero” readings. The specimens were then stored in a room temperature dry chamber. Lengths were measured using a comparator at days 3, 7, 14, 21 and 28 after submersion. These measurements were divided by the initial length to calculate shrinkage percentages. It is important to note that this test monitors the subsequent shrinkage after ten total days of curing, not initial shrinkage. In previous research, a common variable that affected the testing of expansive admixtures was shrinkage. Expansive admixtures are often used to combat shrinkage in concrete. However, shrinkage is an important behavior to monitor in relation to prestress. Expansive admixtures cause initial expansion when the internal humidity is high. At this stage, the expansion is greater than the initial autogenous shrinkage of the concrete. But due to the early developing nature of the expansive agents, shrinkage is still a factor of interest in the later ages of specimens. It is important to note how the *Komponent* admixture affects the shrinkage behavior in comparison to the control and other mix designs.

3.6 Rod Plate Test

To directly measure the amount of prestress developed in the UHPC, a rod plate testing apparatus was constructed. The setup consisted of a steel tube concrete mold with steel plates at each end. These plates were connected by a steel rod encompassed by PVC pipe. Two strain gauges were placed on the steel rod to measure strain induced by the expansive concrete, see Figure 3. A thermo-couple wire was placed inside the PVC to measure temperature as the concrete cured, these temperature readings assisted in the correction values for measured expansion. The strain is caused by the UHPC expanding and pushing on the plates in the axial direction. The forces are transferred to the rod via the nut and washer. Once the concrete was poured, the top nut was hand-tightened to induce an initial amount of tension in the rod and hold the apparatus together. The entire assembly was placed on its side to allow for plastic shrinkage in the direction of gravity, see Figure 4. As the concrete cured, the additional stresses caused by expansion were measured as additional strain in the steel rod. This allowed for a direct calculation of developed prestress.

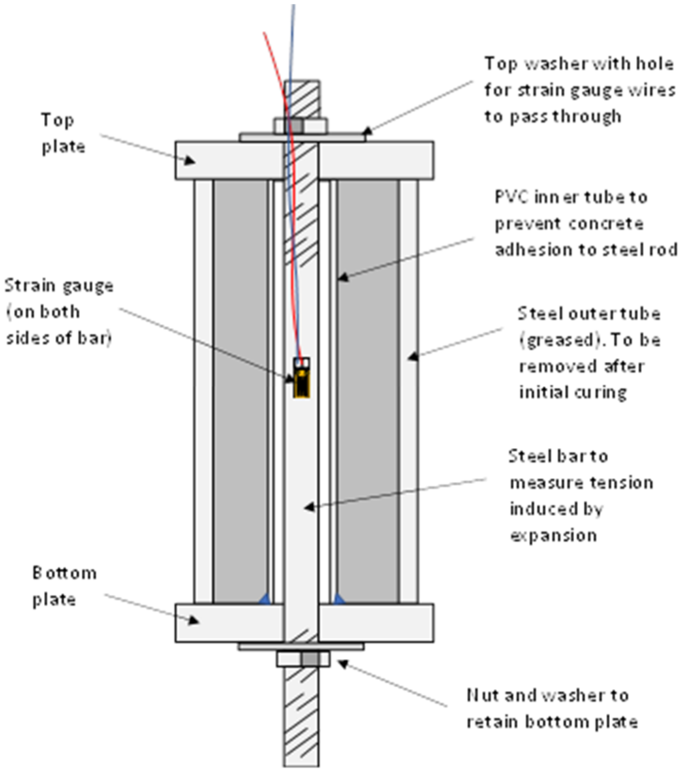


Figure 3. Rod plate test specimen schematic.

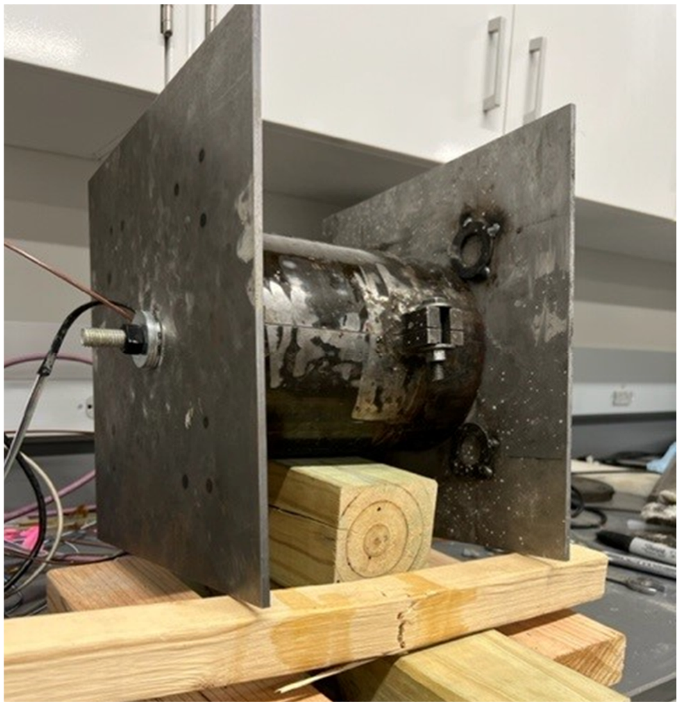


Figure 4. Rod plate test setup.

4. Experimental Results

4.1 Mixing Results

As the mix designs were developed, various effects were noticed due to the addition of the *Komponent* admixture. As the amount of admixture increased, the workability of the wet concrete decreased. This was due to the faster absorption of water by the expansive admixture. Due to this characteristic, the mix designs containing higher amounts of admixture have higher w/cm ratios.

4.2 Compressive Strength Results

Strength tests were performed on most of the developed mix designs. Over 70 cubes were poured and tested. The plot of average strengths can be seen in Figure 5. As evident by the summary of values in Table 2, the addition of the *Komponent* admixture caused an increase in compressive strength for UHPC. As predicted, the early age (7 day) cubes containing the expansive admixture obtained a higher compressive strength than the control group. A noticeable difference between mix designs was noted during the mixing process. The mixes that contained the expansive admixture began solidifying faster than the control mix. This was most likely due to the quick and efficient consumption of water by the admixture [10]. An unforeseen observation was that the strength increase carried through to the later ages. Not only were the early strengths higher in the expansive mix designs, but the later strengths as well. As the *Komponent* dosage increased, we can see increased strength at the age of 28 days. Although the 7-day strengths did not show a correlation between the expansive mix designs, the later 28-day strengths show a direct correlation between admixture content and compressive strength. All mix designs were tested at the 7-day and 28-day ages. Due to excess number of specimens for the control and mix-22.5 designations, 14-day compressive strengths were recorded for these mix designs.

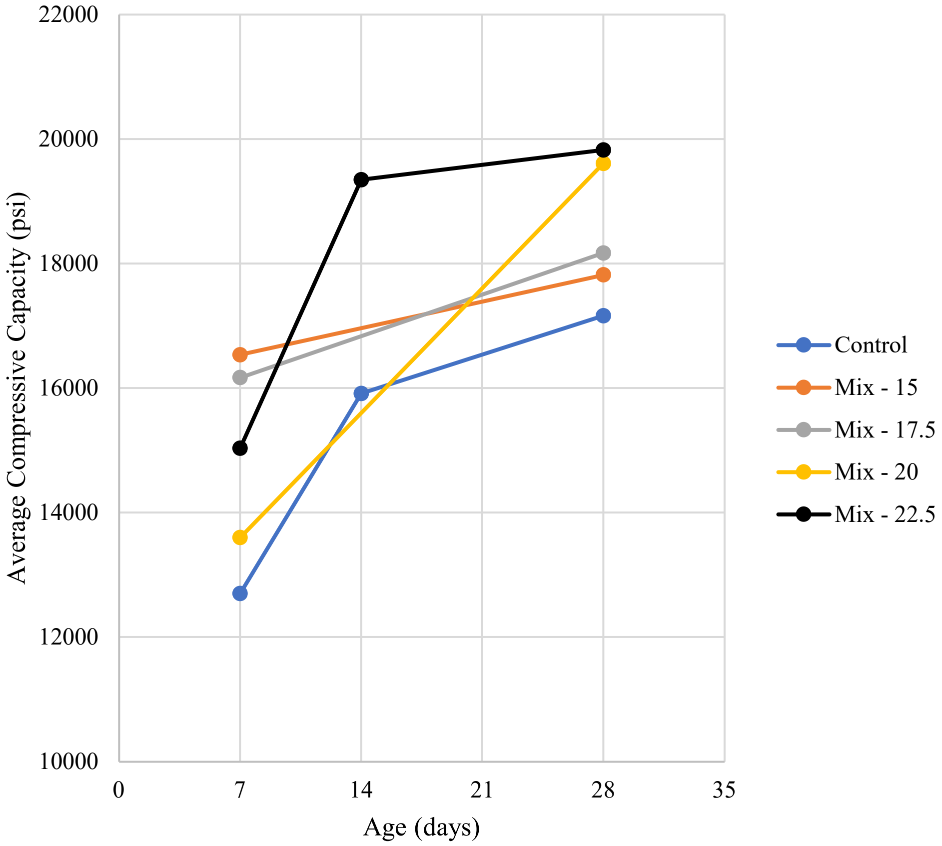


Figure 5. Compressive strength versus time with varying amounts of expansive admixture.

Table 2. Compressive strength results.

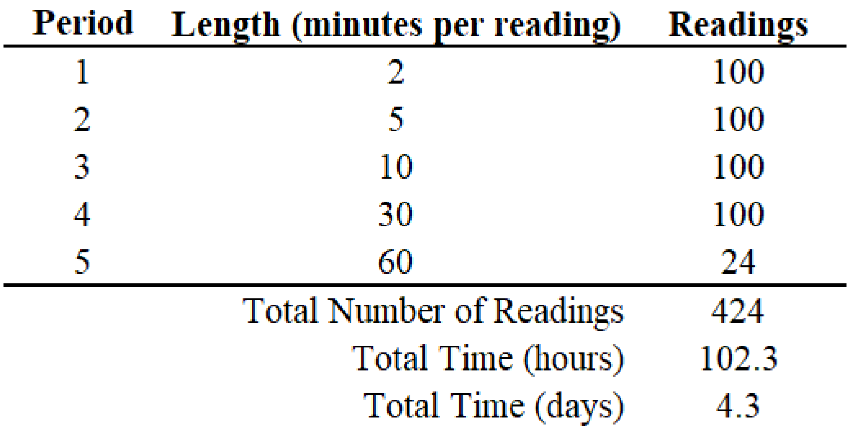
Designation[1]	7-Day [psi]	14-Day [psi]	28-Day [psi]
Control	12698	15914	17163
Mix - 15	16534	N/A	17818
Mix - 17.5	16167	N/A	18169
Mix - 20	13600	N/A	19607
Mix - 22.5	15033	19345	19824

[1] The mix designation number represents the percent of expansive admixture by weight when compared to the total cementitious material content.

4.3 Vibrating Wire Results

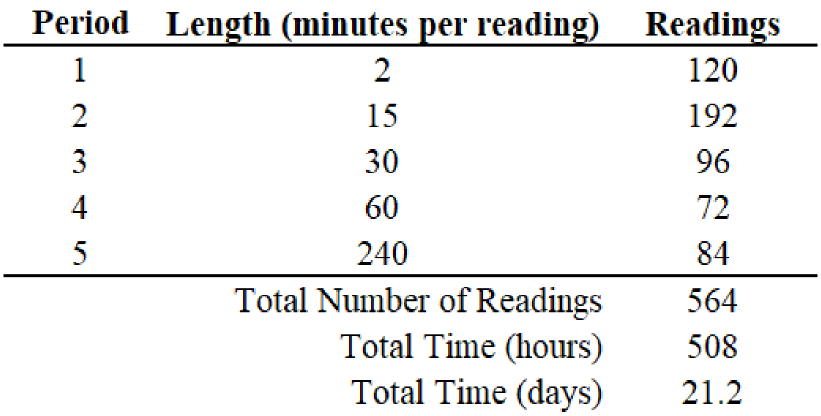
The vibrating wire gauge tests were run under two different data acquisition schedules. One schedule (Schedule A) was a short-term period that measured elongation for four days total. The other schedule (Schedule B) was a longer period that measured elongation for 21 days total. Both schedules would take more frequent readings during the curing phase. These schedules can be seen in figures 5 and 6. These schedules were developed to accurately map out the behavior of the UHPC and the expansive nature of the admixture. The most important window of time captured was the four to seven day period. During this time, most of the expansion and/or shrinkage took place in all mixes.

Table 3. Short term data schedule (Schedule A).



Period	Length (minutes per reading)	Readings
1	2	100
2	5	100
3	10	100
4	30	100
5	60	24
	Total Number of Readings	424
	Total Time (hours)	102.3
	Total Time (days)	4.3

Table 4. Long term data schedule (Schedule B).



Period	Length (minutes per reading)	Readings
1	2	120
2	15	192
3	30	96
4	60	72
5	240	84
	Total Number of Readings	564
	Total Time (hours)	508
	Total Time (days)	21.2

To monitor the short-term behavior of the specimens, the initial tests were run with Schedule A as the data acquisition timeline. To establish a baseline, the control specimen was tested first. It is important to note the shrinkage behavior of the ductal grey UHPC. As expected, the control specimen shrank the most in the first 30 hours and leveled out, see Figure 6. At the cutoff time of 100 hours, the shrinkage was about 0.015%. When compared to conventional concrete, this is a low amount of shrinkage. This amount of shrinkage is consistent with typical UHPC [1].

This experiment was repeated for Mix 22.5. Figure 6 shows the microstrain relative to the control specimen. It is important to note that due to the exposed top face of the concrete cylinder, initial plastic and autogenous shrinkage took place before the concrete started to expand. After this period of shrinkage, expansive agents began forming and expansion was measured. The data in Figure 6 uses corrected values that takes the point of zero strain at the time of which initial plastic shrinkage ceased. The measured expansion peaked at 0.0068% strain.

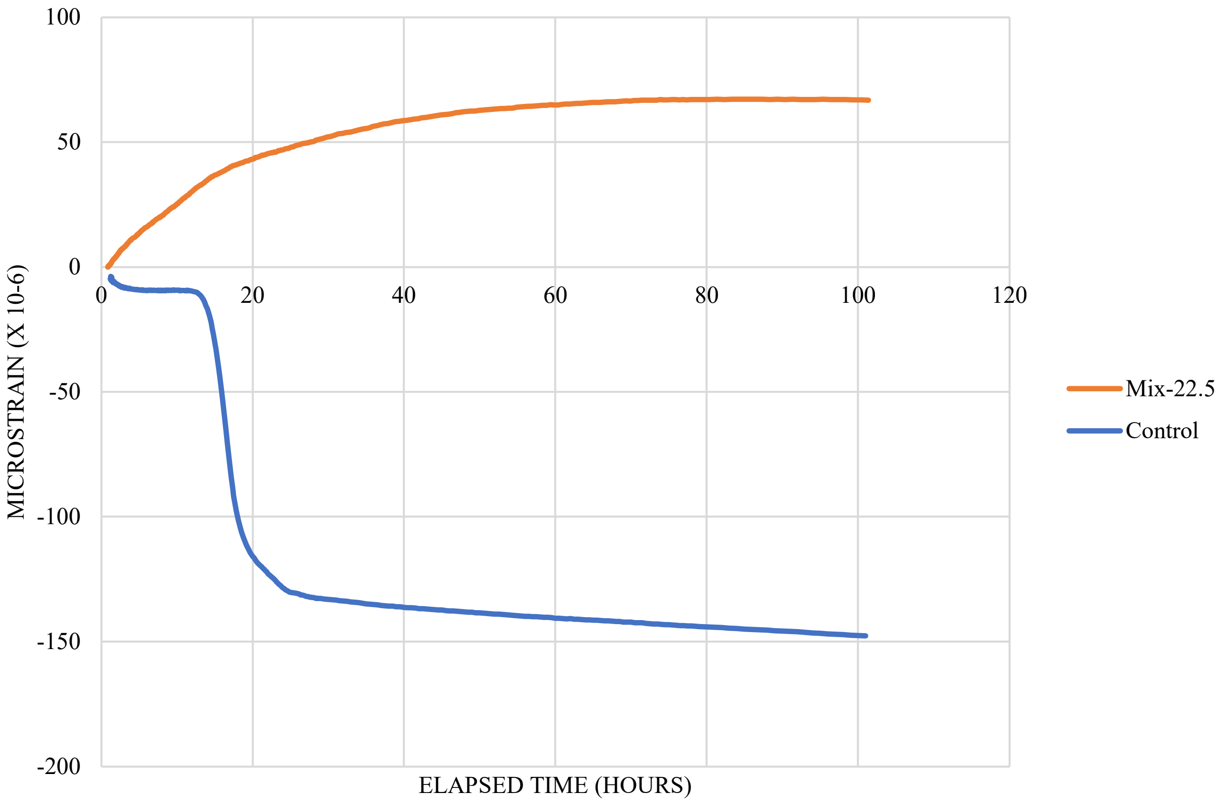


Figure 6. Vibrating wire plot, microstrain with time (Schedule A).

The procedure was replicated using the long-term schedule (Schedule B). This experiment tested a control, Mix-20 and Mix-22.5 mix designs. The objective of Schedule B is to map out the expansion behavior over a longer period. The stepwise procedure of this long-term experiment can be found in the appendix. These UHPC specimens also experienced initial plastic shrinkage prior to any expansion due to loss of water through the exposed top face. These values were omitted in the expansion plot but can be seen in Table 5. Figure 7 shows the combined plot of expansion for all tested specimens.

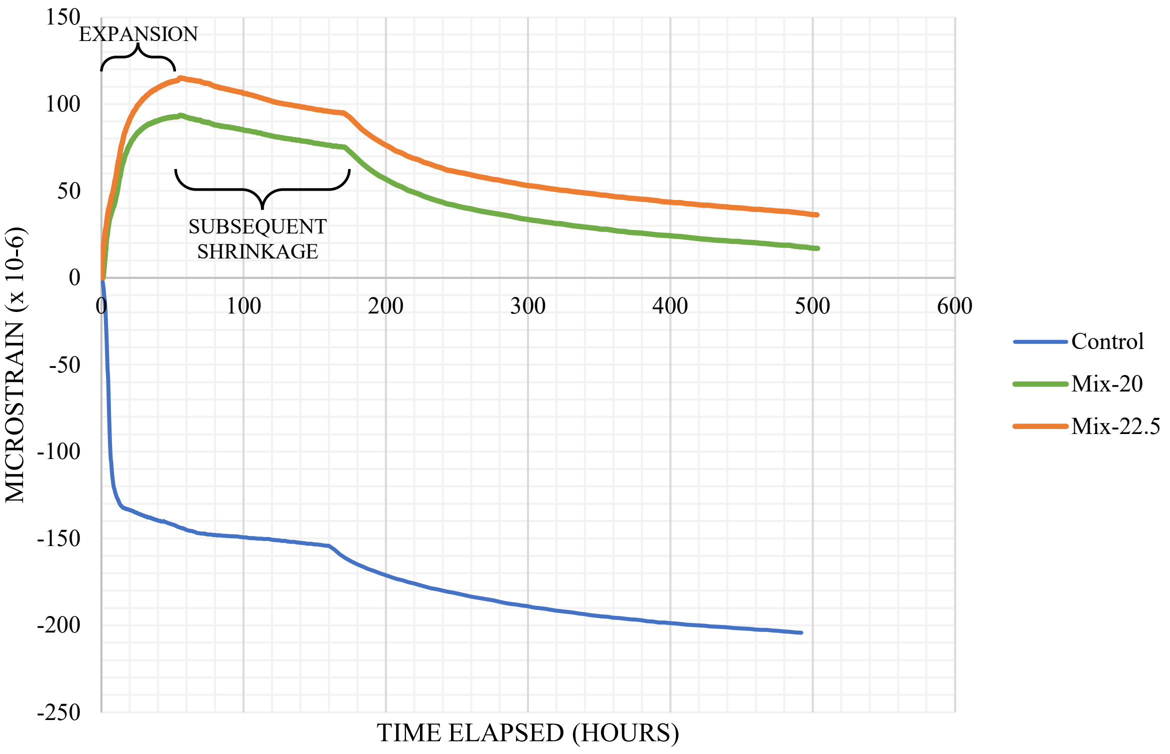


Figure 7. Vibrating wire plot, microstrain with time (Schedule B).

Results from the long-term tests show the cyclic shrinkage-expansion behavior of the mixes containing the expansive admixture. After initial setting, we see varying amounts of expansion that increases with increasing amounts of *Komponent* admixture. After the expansion peaks, we see consistent shrinkage for all mix desings. After the mold was removed at the 7-day mark, shrinkage accelerated and continued for the remaining weeks of the experiment. The control group experienced shrinkage behavior in a similar cyclic fashion. The initial shrinkage was rapid for about 24 hours after placement. After the concrete dried, the rate of shrinkage decreased until the mold was removed. Using the compressive strength at 7 days of these mix designs, we can calculate an estimate for peak developed prestress. Calculations for these values can be found in the appendix. Table 5 shows the results of these procedures.

Table 5. Summary of values (Schedule B).

Designation[1]	Peak Expansion[2] [%]	Subsequent Shrinkage[3] [%]	7-day Strength[4] [psi]	Estimated Prestress[5] [psi]
Control	N/A	-0.0026	12698	0
Mix - 20	0.0094	-0.0019	13600	547
Mix - 22.5	0.0115	-0.0020	15033	692

1. The mix designation number represents the percent of expansive admixture by weight when compared to the total cementitious material content.
2. Peak expansion represents the maximum change in length after initial shrinkage.
3. Subsequent shrinkage occurs after specimen reaches peak expansion. This amount of shrinkage is experienced prior to mold removal (7-days).
4. Average 7-day compressive strength capacities were used for the prestress estimation values.
5. The estimated prestress was based on a calculated modulus of elasticity of each specimen. The MOE formula was created by the U.S. Department of Transportation Federal Highway Administration. Refer to the appendix for calculation examples.

A discovered characteristic of this expansive admixture that may cause complications with the task of developing prestress is the shrinkage behavior caused by the *Komponent* admixture. As evidenced by Table 5, the shrinkage behavior of the specimens complicates the ability to achieve a predicted amount of prestress. Prior to autogenous shrinkage, we see varying amounts of expansion that positively correlate to the amount of expansive admixture used in the mix design. While the amount of expansion can be scaled, shrinkage will limit the ability of the expansive admixture to develop a net prestress in the specimen.

4.4 Hardened Concrete Length Change Results

Comparator measurements were taken for all mix designs. These measurements were taken over a 28-day period and were divided by the concrete prism’s initial length. A measured prism can be seen in Figure 8. The data was combined and plotted with specimen age. This plot can be seen in Figure 9. As seen by the data plot, the amount of *Komponent* admixture did not have any conclusive effect on the long-term shrinkage behavior of the UHPC. The length changes are consistent across the board. Also, the shrinkage behaviors of each mix design are similar at all intermediate ages. It is important to remember that the “day zero” reading occurred a total of ten days after mixing (three days in the mold, seven days in the submersion tank). Therefore, all expansion had occurred prior to day zero measurements. This plot shows the subsequent shrinkage that took place after ten days of curing.

Figure 8. Comparator measurement of cured UHPC prism.

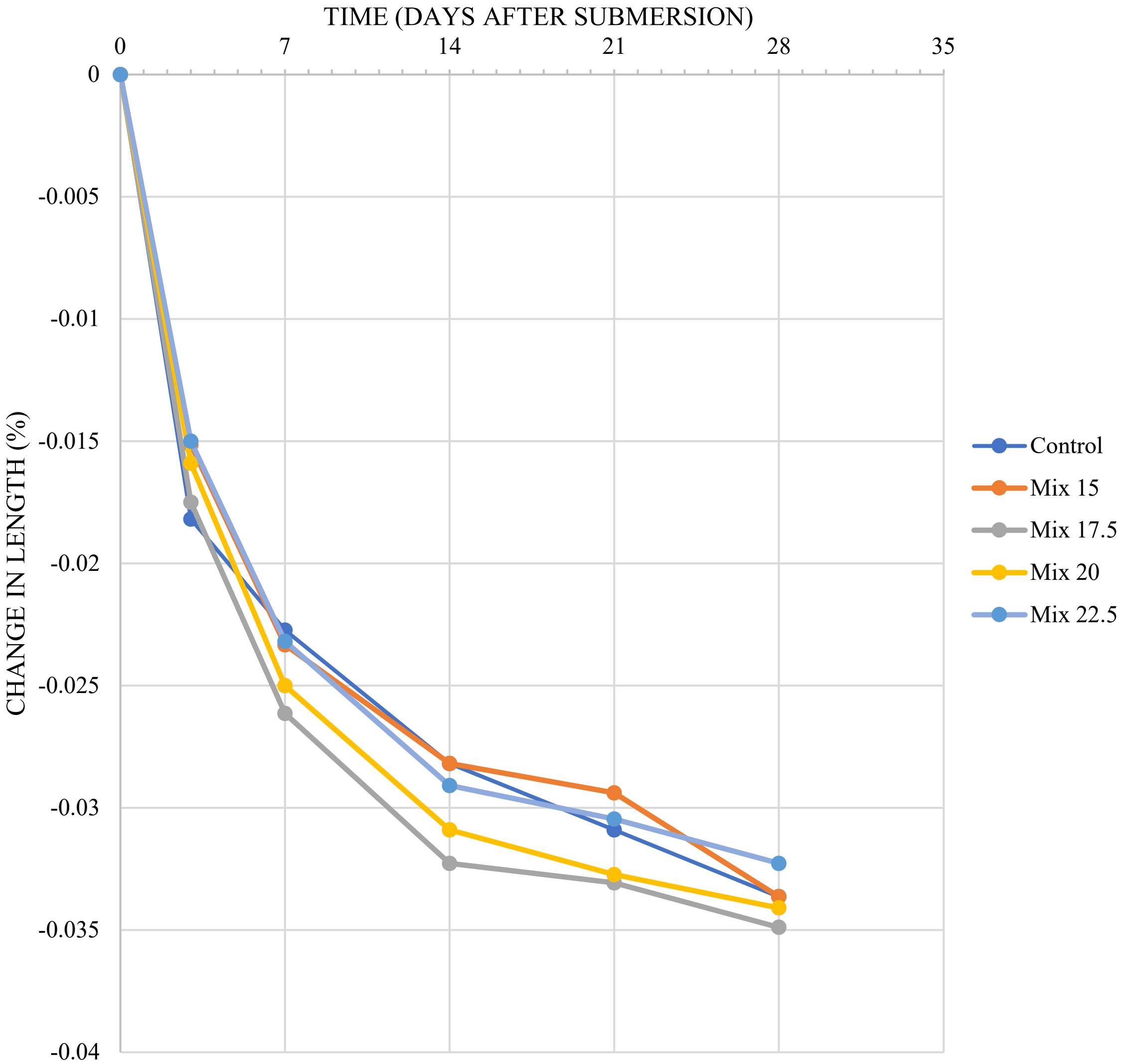


Figure 9. UHPC length change test results.

4.5 Rod-Plate Test Results

The rod-plate test was performed on mix-22.5, the mix design with the highest amount of expansive admixture. The temperature and strain were monitored over a 7-day period. The test was performed inside. A room temperature of 68°F was measured prior to testing. The water used in the specimen was measured to be 60°F. Once the concrete was poured into the mold and vibrated, the nuts were finger tightened and the apparatus was placed on its side. The initial temperature inside the PVC pipe was 79 degrees Fahrenheit. Figure 10 shows the specimen's change in temperature throughout the weeklong period. As evidenced by the plot, the UHPC experienced a quick increase in temperature during the first couple of hours of curing. After this stage, the temperature fell and oscillated around the 70 degree Fahrenheit mark. This oscillation in temperature is most likely due to daily cycles of room temperature in the lab.

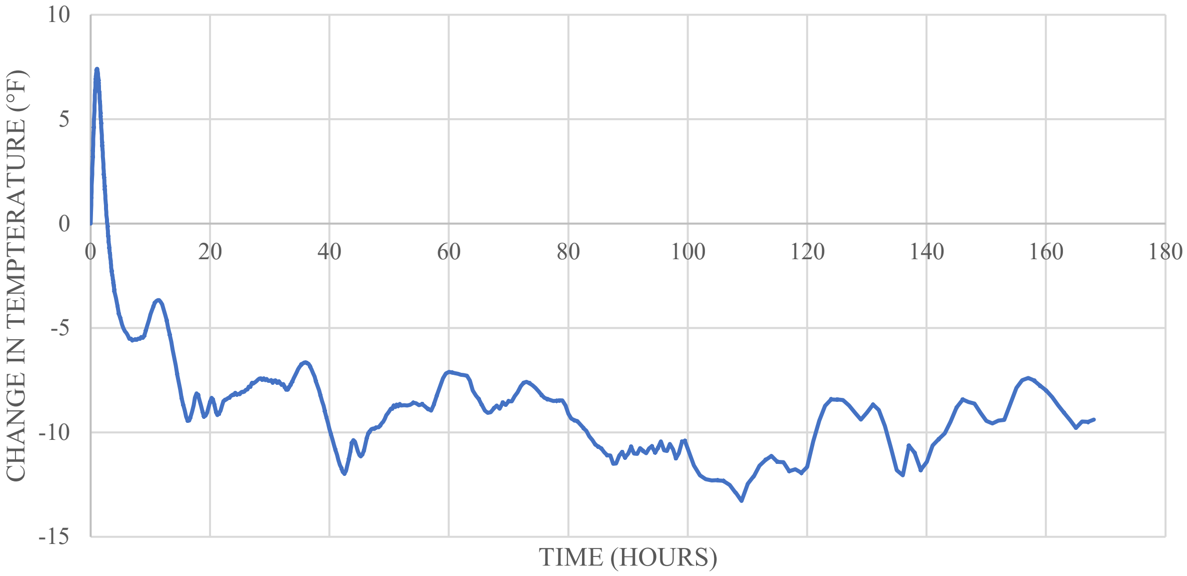


Figure 10. Temperature plot for Mix-22.5 during Rod-Plate Test.

The strain measurements from the two gauges were averaged and multiplied by the steel rod's modulus of elasticity to calculate the axial stress felt in the steel rod. The plot of this stress can be seen in Figure 11. Positive values indicate compressive stress in the steel rod while negative values indicate tensile stress. Like the behavior seen in the temperature plot, the rod stress experienced a quick increase in compressive stress during the first few hours and subsequently dropped. After this occurs, we can see a general trend of stress felt in the steel rod. This trend also shows oscillations influenced by daily temperature cycles. The data is limited in that the behavior is only monitored during a 7 day period. The stress felt in the steel rod is not stable after this amount of time. The tail end of the data shows ascending stress in an oscillating fashion. The rod plate test data shows that self-stressing mechanisms are taking place. However, the amount of prestress developed is not adequate for current uses of prestressed members.

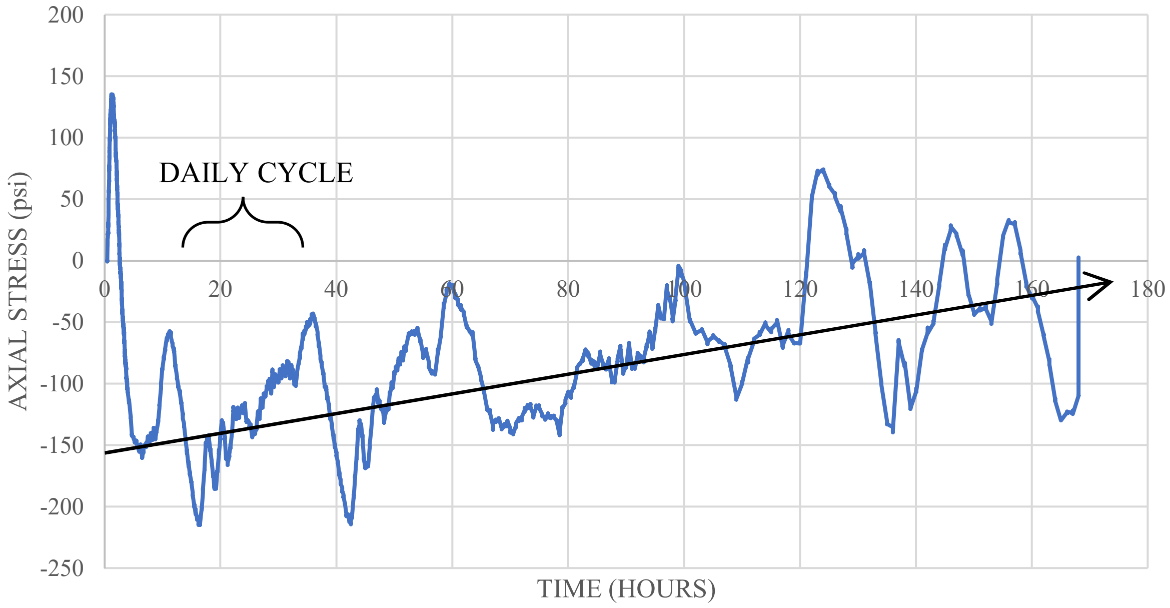


Figure 11. Rod stress plot for Mix-22.5 during Rod-Plate Test.

5. Conclusion

The goal of the study was to investigate the chemical admixture approach of self-stressing concrete, specifically, UHPC. During the literature review phase, a few expansive admixtures were investigated. The experimental study and setup included varying amounts of expansive additive to observe change in mix properties. The experimental results confirm some initial hypotheses while also presenting new questions and avenues for future research. From the experimental results, we can conclude the following:

1) Type-K cement (*Komponent* admixture) is the most suitable expansive admixture to achieve the desired characteristics of prestressed concrete members. Mix designs can be developed with varying amounts of admixture to test the effects of the concrete's behavior.
2) When all other quantities are held constant, increasing the amount of *Komponent* admixture increased the compressive strength of the UHPC at 28 days. This is most likely due to the admixture's consumption of water, resulting in a lower w/c ratio.
3) The *Komponent* admixture significantly reduces initial shrinkage in UHPC and causes elongation during the curing phase. More elongation is seen when the amount of *Komponent* admixture increases. This is due to the expansive admixture producing expansive agents during the hydration phase.
4) After the curing phase, the expansive admixture has no effect on the long term shrinkage behavior or UHPC.
5) The addition of *Komponent* admixture does induce self-stressing mechanisms in the concrete matrix. However, self-stress is evident through an increasing trend of oscillating values influenced by daily temperature cycles and the amount of stress developed is not substantial.

5.1 Future Research

For the purposes of future research in the development of self-prestressing concrete, expansive admixtures are a viable option to explore further. Once the technology is understood and perfected, developing prestressed members will require far less labor and skill when compared to the conventional mechanical method of prestressing members. From an industrial standpoint, chemical admixtures in mix designs can be as precise as needed and will yield consistent concrete properties. This study was able to prove that, in a given range, expansive admixtures can be scaled to achieve desired characteristics.

If further research was to be performed on type-k cement for the purpose of prestressing UHPC, additional admixtures should be used to control the initial and subsequent shrinkage behaviors. While the shrinkage behavior is relatively miniscule when compared to the overall specimen size, prestress development is heavily inhibited by the cyclic shrinkage behaviors.

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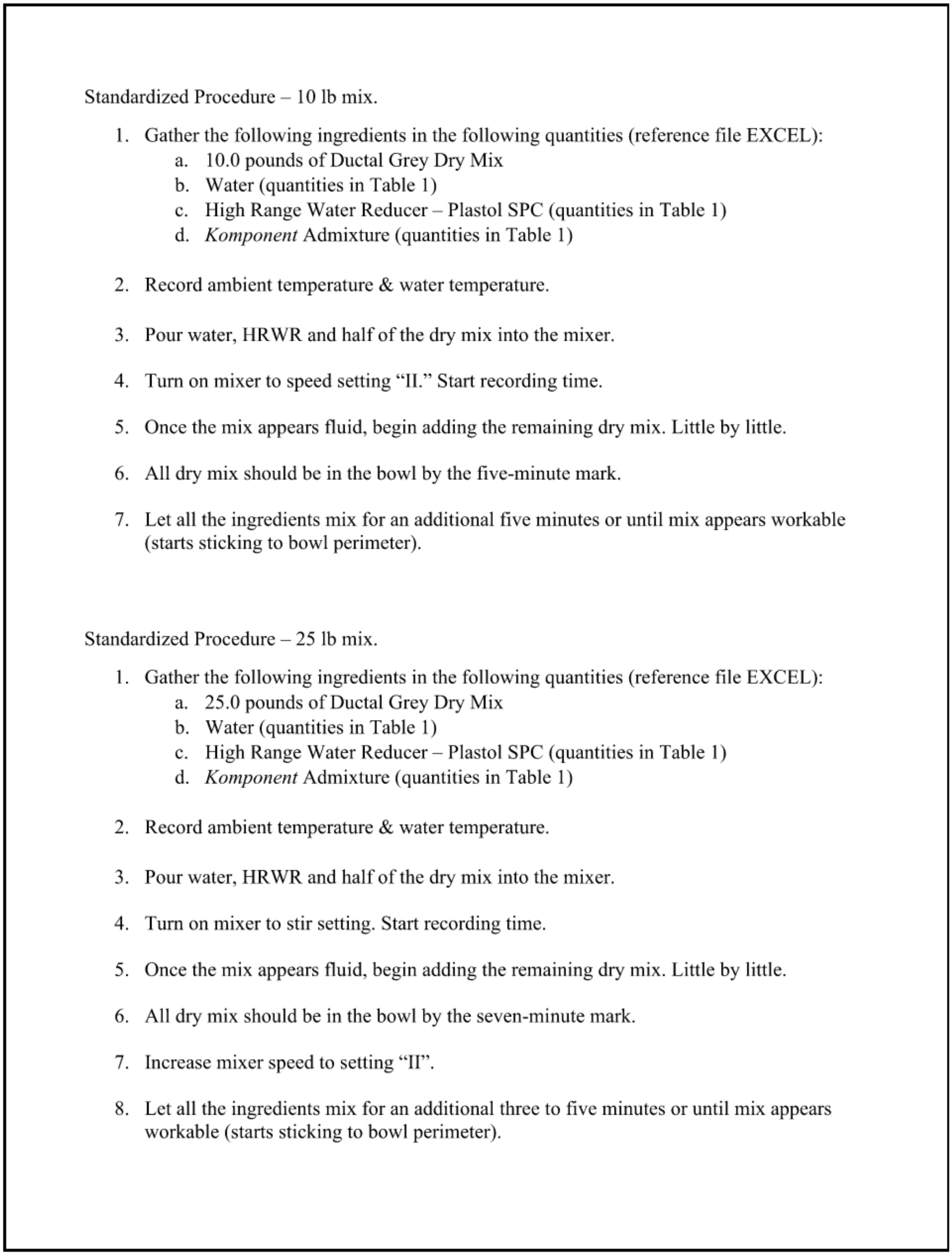
Appendix

A1. Standardized Mixing Procedure – High Shear Mixer



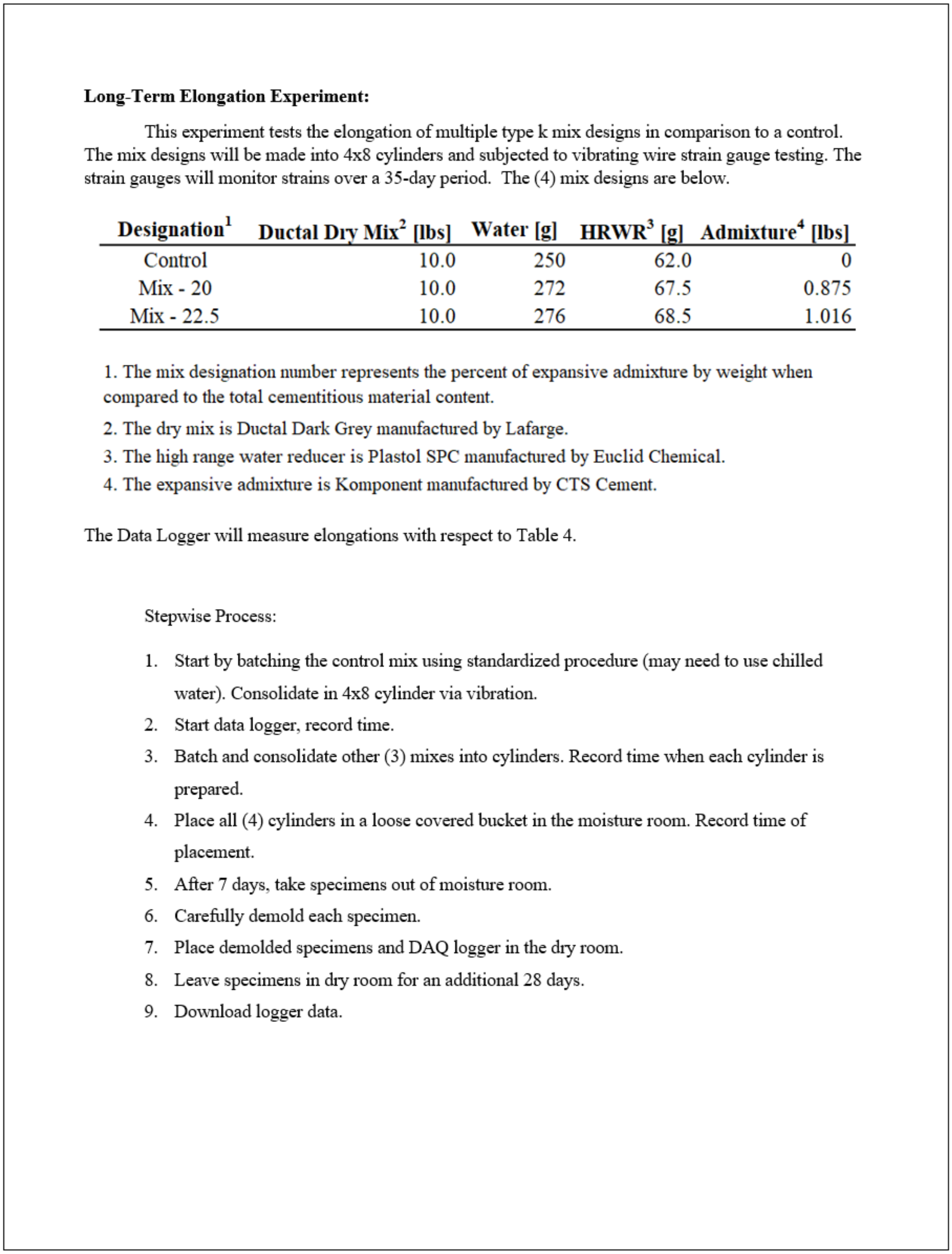
Standardized Procedure – 10 lb mix.

1. Gather the following ingredients in the following quantities (reference file EXCEL):
   a. 10.0 pounds of Ductal Grey Dry Mix
   b. Water (quantities in Table 1)
   c. High Range Water Reducer – Plastol SPC (quantities in Table 1)
   d. *Komponent* Admixture (quantities in Table 1)
2. Record ambient temperature & water temperature.
3. Pour water, HRWR and half of the dry mix into the mixer.
4. Turn on mixer to speed setting "II." Start recording time.
5. Once the mix appears fluid, begin adding the remaining dry mix. Little by little.
6. All dry mix should be in the bowl by the five-minute mark.
7. Let all the ingredients mix for an additional five minutes or until mix appears workable (starts sticking to bowl perimeter).

Standardized Procedure – 25 lb mix.

1. Gather the following ingredients in the following quantities (reference file EXCEL):
   a. 25.0 pounds of Ductal Grey Dry Mix
   b. Water (quantities in Table 1)
   c. High Range Water Reducer – Plastol SPC (quantities in Table 1)
   d. *Komponent* Admixture (quantities in Table 1)
2. Record ambient temperature & water temperature.
3. Pour water, HRWR and half of the dry mix into the mixer.
4. Turn on mixer to stir setting. Start recording time.
5. Once the mix appears fluid, begin adding the remaining dry mix. Little by little.
6. All dry mix should be in the bowl by the seven-minute mark.
7. Increase mixer speed to setting "II".
8. Let all the ingredients mix for an additional three to five minutes or until mix appears workable (starts sticking to bowl perimeter).

A2. Vibrating Wire Test Procedure



Long-Term Elongation Experiment:

This experiment tests the elongation of multiple type k mix designs in comparison to a control. The mix designs will be made into 4x8 cylinders and subjected to vibrating wire strain gauge testing. The strain gauges will monitor strains over a 35-day period. The (4) mix designs are below.

Designation[1]	Ductal Dry Mix[2] [lbs]	Water [g]	HRWR[3] [g]	Admixture[4] [lbs]
Control	10.0	250	62.0	0
Mix - 20	10.0	272	67.5	0.875
Mix - 22.5	10.0	276	68.5	1.016

1. The mix designation number represents the percent of expansive admixture by weight when compared to the total cementitious material content.
2. The dry mix is Ductal Dark Grey manufactured by Lafarge.
3. The high range water reducer is Plastol SPC manufactured by Euclid Chemical.
4. The expansive admixture is Komponent manufactured by CTS Cement.

The Data Logger will measure elongations with respect to Table 4.

Stepwise Process:

1. Start by batching the control mix using standardized procedure (may need to use chilled water). Consolidate in 4x8 cylinder via vibration.
2. Start data logger, record time.
3. Batch and consolidate other (3) mixes into cylinders. Record time when each cylinder is prepared.
4. Place all (4) cylinders in a loose covered bucket in the moisture room. Record time of placement.
5. After 7 days, take specimens out of moisture room.
6. Carefully demold each specimen.
7. Place demolded specimens and DAQ logger in the dry room.
8. Leave specimens in dry room for an additional 28 days.
9. Download logger data.

A3. Prestress Calculations using Vibrating Wire Data.

The USDOT Federal Highway Administration [13] gives us the following equation for modulus of elasticity for UHPC without coarse aggregate:

$$E_c = 525000 * \sqrt[3]{\frac{f'_c}{10}}$$

Where:

E_c is the modulus of elasticity in psi.

f'_c is the compressive strength in psi.

Using E_c & f'_c, estimated prestress can be calculated using the following equation:

$$\sigma = E_c * \delta$$

Where:

σ is the estimated prestress in psi.

δ is the measured strain in the UHPC.

Example Calculation for Estimated Prestress: Mix 22.5 (reference Table 5)

Compressive Strength, $f'_c = 15033$ psi

Peak Expansion, $\delta = 0.0115\%$

Find MOE:

$E_c = 525000 * \sqrt[3]{\frac{15033\ psi}{10}} = 60141154$ psi

Find estimated prestress:

$$\sigma = 6014154\ psi * \ 0.000115 = 692\ psi$$