THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

MITIGATION OF SHRINKAGE CRACKING IN CONCRETE WITH A MAGNESIUM OXIDE ADMIXTURE

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Abstract

Early-age shrinkage cracking in concrete is one of the most detrimental events that occur in portland cement-based concrete. However, chemical admixtures can mitigate this type of cracking. One common admixture is magnesium oxide, which exists in a powder form and is expansive when reacting with water, which helps to offset early-age shrinkage. This work aimed to test a newly developed magnesium oxide-based expansive admixture and its ability to mitigate shrinkage cracking. Tests were conducted measuring restrained shrinkage (ASTM C 1581-2016), linear shrinkage (ASTM C 157-2016) and compressive strength (ASTM C 1314-2016) on portland cement-based mortar specimens.

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Chapter 1

Introduction

Concrete can be used for almost all types of structural elements, as well as pavements, sidewalks, and architectural features in almost all types of engineering projects. However, concrete often experiences a significant problem: susceptibility to cracking. As with any material, cracking leads to a reduction in material durability. Most cement-based materials will experience a small amount of micro-cracking. Macro-cracking (that which can be seen with the naked eye) may pose a threat to the structural integrity of such materials, or at least cause an observing bystander to be alarmed. Decreases in structural integrity due to cracking creates a potential for massive losses of life and resources. A secondary part of the cracking problem is that of aesthetics. Cracked concrete simply has a poor aesthetic appearance, which will cause dissatisfaction in owners and investors. Cracked concrete could also cause alarm within the general public with respect to the integrity of some structures.

Concrete cracking occurs because of an increase in tensile stress which exceeds the concretes tensile strength [6]. Tensile stresses develop in concrete can be due to a variety of causes. Thermal or physical contraction/expansion of the materials within the concrete (which may occur during curing or use), the intrusion of harmful ions, or of tensile loading during use are the most common causes of tensile stress in concrete. If the resultant of these stresses exceeds the concrete’s tensile strength, cracking will occur.

This paper will focus mainly on the mitigation of cracking due to physical expansion/contraction during the curing of freshly mixed concrete. The hydration reaction between water and portland cement is an exothermic process. During this process, heat is created. Larger volumes of concrete will experience larger effects than smaller volumes, as more overall heat is created in larger scale hydration reactions, and more time is needed for this heat to dissipate. However, approximately fifteen (15) minutes after the hydration reaction begins, the concrete rapidly cools. Another temperature spike is experienced around two (2) hours after the reaction occurs (See Figure 1 Below).

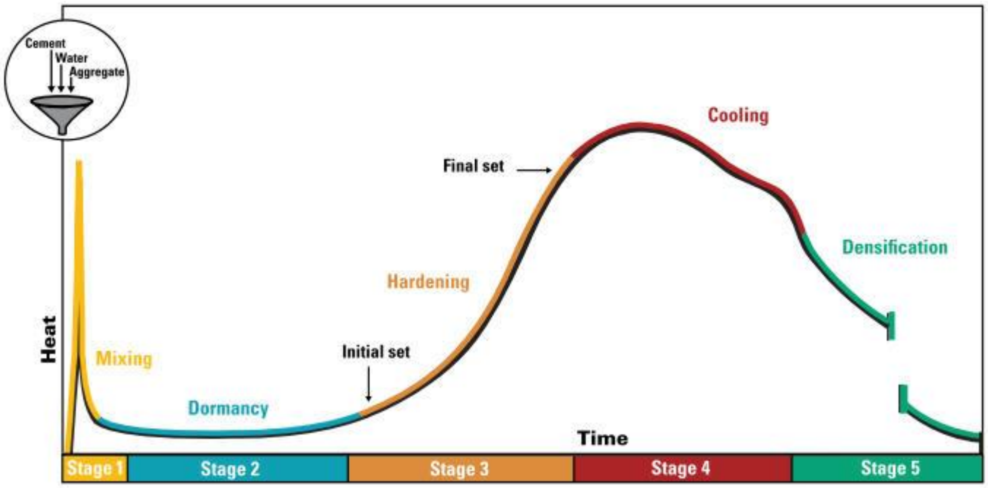


Figure 1: Graphical depiction of concrete heat evolution over time (Image courtesy of Alkon Connect)

During stages two (dormancy) and three (initial set, hardening, and final set), concrete is not fully cured, and its overall strength is quite low. At this time, tensile stresses begin to develop while the concrete’s strength remains quite low; this leads to a higher probability of cracking. Physical contraction (shrinkage) is a critical cause of early-age cracking, and it is this the mitigation of this type of cracking that this study aims to investigate.

To prevent early-age shrinkage cracking physical expansion of admixtures within the concrete mix can be used to offset the overall strain experienced by the concrete mix, therefore reducing tensile stresses with the goal of lowering tensile stress to a value that is less than the concrete’s tensile strength.

The method of shrinkage-cracking mitigation investigated is a magnesium oxide-based chemical admixture. To test the effectiveness of magnesium oxide, the investigator used the

Standard Test Method for Determining Age at Cracking and Induced Tensile Stress Characteristics of Mortar and Concrete under Restrained Shrinkage (ASTM C1581-2016), the Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete (ASTM C157-2016), and the Standard Test Method for Compressive Strength of Masonry Prisms (ASTM C1314-2016). The restrained shrinkage test was used to measure the effect of using the magnesium oxide admixture in concrete mixtures with respect to both the age of cracking and the induced tensile stresses. The mortar prisms and cubes were used to measure how the admixture affects the volumetric change and compressive strength, respectively, of cement mortar.

Chapter 2

Literature

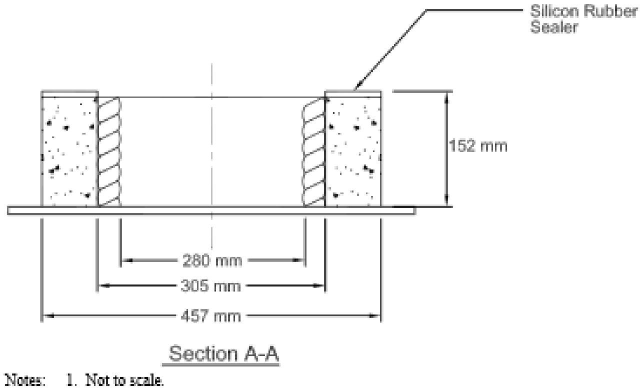
To begin reviewing the use of magnesium oxide in concrete, a short summary written by Chongjiang Du [5] will be examined. According to Du, magnesium oxide concrete was first developed over three decades ago by dam engineers in China, and is used extensively in Chinese-speaking regions of the world. The positive effect on shrinkage problems was discovered serendipitously. To date, over thirty dams have been constructed with magnesium oxide, with outstanding results. Magnesium oxide in concrete serves two purposes: it develops compressive stresses at early ages that will eventually offset tensile stresses that are developed, and; long term expansion that works against further cooling and thermal contraction. For the purposes of this paper, we are only interested in the advantages offered by the first effect.

Du then discussed the engineering properties of concrete with magnesium oxide admixture. The actual rate and final value of expansion in the early age will depend upon the specific makeup of the admixture used. He states that the tensile strain tolerances will increase by anywhere between 80 and 150 microstrain, although this is dependent upon the amount of magnesium oxide used and the temperature of the concrete at time of testing. Specifically, he lists that concrete at 30° C and 4.5% magnesium oxide will have a tensile strain tolerance increase of nineteen (19) percent.

However, Du also states that the compressive strength and modulus of elasticity in concrete that use magnesium oxide are increased to values higher than would be expected in typical Portland cement concrete. As discussed in Chapter 5: Discussion, the findings of this study contradict his claim.

Over the past several decades, much work has been done using the same test methods employed by this study to test various admixtures for use in concrete and cementitious materials. For the purposes of this study, a publication by Radlińska et. al. [6] has been chosen as the starting point for the literature review for concrete ring testing, as it provides a summary of recent developments and procedures regarding the concrete ring test.

Throughout the last century, the ring test has become a common test method to observe the time until cracking for concrete specimens. Linear test methods have much simpler data analysis, but tend not to be used because the method of constraint for linear methods leads to issues with quality control. The ring test makes use of a steel ring to restrain free shrinkage of concrete, which results in the development of tensile stresses that ultimately lead to cracking. Over time, two main specifications regarding the ring test have been developed by AASHTO and ASTM which specify different dimensions for the steel ring molds and the volume of concrete used in the test. This experiment used only the AASHTO PP 34-99 (2004) and ASTM C1581-2016 specifications. However, custom mold dimensions may be used for a variety of test purposes. Below are schematics of AASHTO and ASTM dimensioned test apparatuses:



Notes: 1. Not to scale.
2. Assume a tolerance of ±5 mm throughout.

Figure 2: AASHTO Dimensions for Restrained Shrinkage Test Apparatus [1]

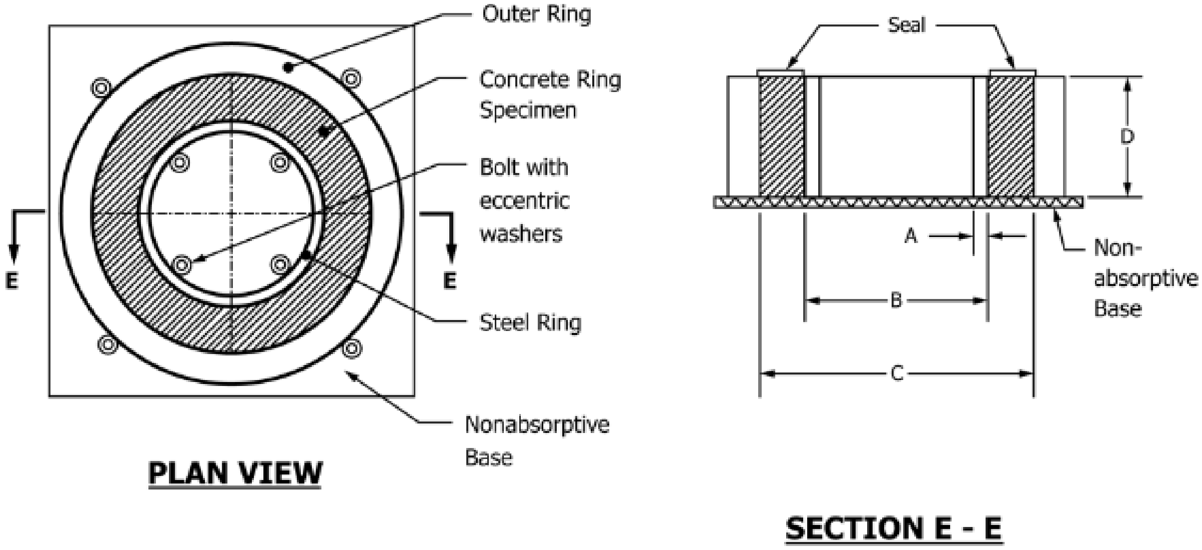


Figure Dimensions	SI Units	Inch-Pound Units
A	13 ± 1 mm	0.50 ± 0.05 in.
B	330 ± 3 mm	13.0 ± 0.12 in.
C	405 ± 3 mm	16.0 ± 0.12 in.
D	150 ± 6 mm	6.0 ± 0.25 in.

Figure 3: ASTM dimensions for Restrained Shrinkage Test Apparatus [2]

Initially, the ring test was only used for determining the time of cracking in concrete. However, as time moved forward and more technologies became readily available, the rings were instrumented with strain gages, so that the tensile stresses could be measured in addition to observing the time of cracking.

Over time, the ring test has become increasingly used to observe the effects of chemical admixtures, fiber reinforcements, the effects of creep and/or stress relaxation, the effects of specimen geometry on stress distributions and cracking, the influence of moisture, and the effect of constraint.

Chapter 3

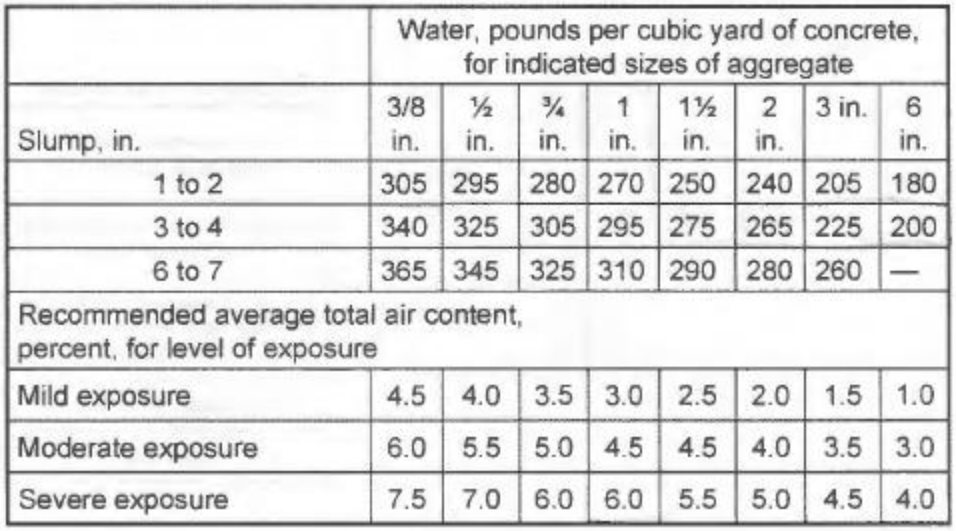
Methodology

3.1 Concrete Mix Design

For this project, a basic concrete mix design was developed using methodology presented in Homework #5: Concrete Mix Design – Material Science for Civil Engineers as taught by Dr. Aleksandra Radlińska at The Pennsylvania State University in the Spring 2016 semester [7]. The raw materials used were as follows: Lehigh Type I-II cement, Pennsylvania River Sand (also Tyrone Sand), #8 coarse aggregate from Union Furnace, distilled water, superplasticizer, and magnesium oxide admixture. The methodology used is a nine-step process, as summarized below (see Appendix A for the full mix design):

1. Gather the material information. Specific gravity of cement was assumed to be 3.15. Material unit weights and absorptions were determined by S. Bazer (M.S., The Pennsylvania State University) as per ASTM C128.
2. Select slump size. A maximum slump of four (4) inches was assumed, as per acceptable industry standards.
3. Determine max size aggregate (MSA). As per ASTM C1581 for the Restrained Ring Test, the MSA was taken as one-half (0.5) inch.
4. Determine water content. A water content at a batch weight of 325 pounds per cubic yard (pcy) was chosen as per the following table:

Table 1: Table for determining water content [7]

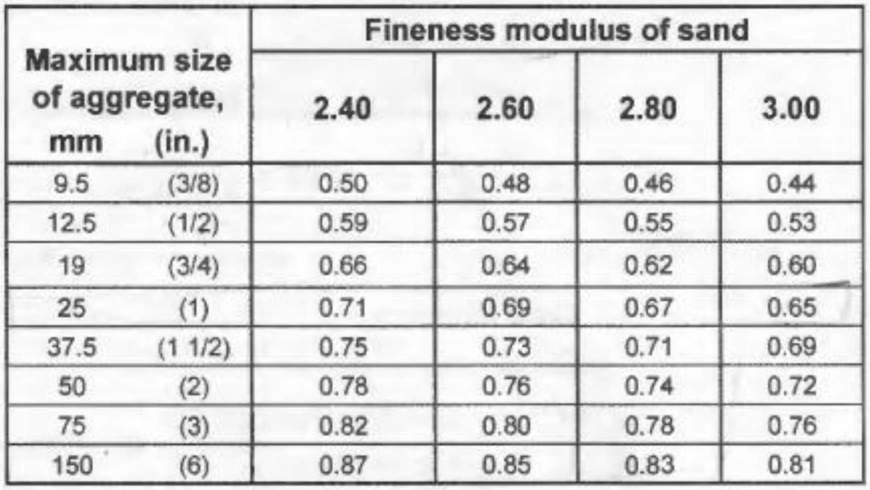


	Water, pounds per cubic yard of concrete, for indicated sizes of aggregate							
Slump, in.	3/8 in.	½ in.	¾ in.	1 in.	1½ in.	2 in.	3 in.	6 in.
1 to 2	305	295	280	270	250	240	205	180
3 to 4	340	325	305	295	275	265	225	200
6 to 7	365	345	325	310	290	280	260	—
Recommended average total air content, percent, for level of exposure								
Mild exposure	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0
Moderate exposure	6.0	5.5	5.0	4.5	4.5	4.0	3.5	3.0
Severe exposure	7.5	7.0	6.0	6.0	5.5	5.0	4.5	4.0

5. Determine the water to cement ratio (w/c). A w/c of 0.42 was selected.
6. Determine cement content. The water content divided by the w/c yields the cement content. For this mix design, cement content had a batch weight of 773.8 pcy. There were two types of expansive batches: five (5) percent of the cement weight was replaced with the magnesium oxide admixture, and; an amount equivalent to five (5) percent of the weight of cement of the magnesium oxide admixture was added to the total weight of cement. For those batches, the cement content batch weight was 735.11 pcy and 773.8 pcy, respectively, of cement, and the expansive admixture batch weight was 38.69 pcy;
7. Determine coarse aggregate content. For this step, one cubic yard is multiplied by a volume factor for coarse aggregate; the volume factor is a function of the fineness modulus of the fine aggregate being used and the MSA. For this design, the volume factor was 0.56, which when multiplied by one cubic yard yields 15.12 cubic feet. The design was altered to account for the expansive admixture batches. This is multiplied by the dry-rodded unit weight (DRUW) of the coarse aggregate to give a batch quantity in

pcy. For this mix, that batch weight was 1442.5 pcy. The volume factor was chosen by using the table below:

Table 2: Table for determining the volume factor of coarse aggregate based on MSA and Fineness modulus of sand [7]



Maximum size of aggregate, mm	(in.)	Fineness modulus of sand			
		2.40	2.60	2.80	3.00
9.5	(3/8)	0.50	0.48	0.46	0.44
12.5	(1/2)	0.59	0.57	0.55	0.53
19	(3/4)	0.66	0.64	0.62	0.60
25	(1)	0.71	0.69	0.67	0.65
37.5	(1 1/2)	0.75	0.73	0.71	0.69
50	(2)	0.78	0.76	0.74	0.72
75	(3)	0.82	0.80	0.78	0.76
150	(6)	0.87	0.85	0.83	0.81

8. Determine the fine aggregate content. Given the specific gravities and batch weights, volumes were calculated for all raw materials and subtracted from one cubic yard to give the requisite volume of sand. This volume was then multiplied by the unit weight of sand to give the requisite weight of sand for one cubic yard, which was taken as its batch weight. For this mix, that batch weight was 1294.1 pcy.
9. Final mix proportions and moisture content adjustment. All aggregates were used in an oven-dry (OD) state, and no moisture correction calculations were made. The final mix proportions are outlined below:

Table 3: Batch weights for normal and expansive concrete mix designs

MATERIAL	NON-EXPANSIVE BATCH WEIGHT (PCY)	5% REPLACED BATCH WEIGHT (PCY)	5% ADDED BATCH WEIGHT (PCY)
Cement	773.8	735.1	773.8
Water	325.0	325.0	325.0
Coarse Aggregate	1442.5	1442.5	1442.5
Fine Aggregate	1294.1	1294.1	1294.1
Super-Plasticizer	94.71 fl. oz.	89.97 fl. oz.	94.71 fl. oz.
Expansive Admixture	N/A	38.69	38.69

3.2 Mixing the Concrete

The concrete was mixed using a one and three-quarter (1.75) cubic foot capacity pan mixer, shown below:

Figure 2: Photograph of pan mixer used for concrete mixing (Civil Infrastructure Testing and Evaluation Center, The Pennsylvania State University)

The concrete was mixed with the following procedure:

1. Clean and dampen the pan and mixing paddles
2. Load coarse and fine aggregates
3. Begin mixing, add fifty (50) percent of the total water
4. After water is added, run mixer for thirty (30) seconds
5. Add all cement and magnesium oxide admixture (if applicable)
6. Add remaining water and superplasticizing admixture (if applicable)
7. After all materials are loaded, run the pan mixer for three (3) minutes
8. Stop the pan mixer for three (3) minutes
9. Run pan mixer for two (2) minutes

3.3 Mixing the Cement Mortar

The cement mortar was mixed using a twenty-quart capacity Hobart mixer. The cement mortar was prepared using the following procedure:

1. Place all mixing water in the bowl
2. Add all cement and magnesium oxide admixture (if applicable)
3. Start mixer at slow speed (140+/-5 r/min) for thirty (30) seconds
4. Add all sand over a thirty (30) second period
5. Stop mixer, change to medium speed (285+/-10 r/min) and run for thirty (30) seconds
6. Stop mixer, let mortar stand for ninety (90) seconds. For the first fifteen (15) seconds, scrape mortar on the sides of the bowl downward.
7. Run the mixer at medium speed (285+/-10 r/min) for sixty (60) seconds

A total of twenty-four (24) two-inch mortar cubes were cast for testing following ASTM C1314-2016: twelve (12) each for standard and expansive batches. The cubes were designated E1 through E12 and NE1 through NE12 for the expansive and standard batches, respectively. A total of nine (9) mortar prisms were cast for testing following ASTM C157-2016: five (5) for the expansive batch and four (4) for the standard batches. The prisms had dimensions of one inch by one inch by eleven inches. The prisms were designated E1P through E5P and NE1P through NE4P for the expansive and standard batches, respectively. Below is a photograph of typical test specimens for this type of test:

3.4 The Restrained Ring Test for Concrete

For this section of the experiment all practices followed the Standard Test Method for Determining Age at Cracking and Induced Tensile Stress Characteristics of Mortar and Concrete under Restrained Shrinkage ASTM C1581-2016. Ring molds with both ASTM and AASHTO specified dimensions were used. For all castings, ring molds were assembled and all sections of the ring molds that would be in contact with concrete were given a thin veneer of lubrication to aid in the removal of the ring mold parts at the appropriate times. For all castings, concrete was batched as described above in Chapter 1.2. After batching, the concrete was poured into two (2) equal sized layers within each of the three (3) molds and briefly vibrated to remove air voids. After all molds were filled, they were transported to an environmental chamber and were kept at twenty-three (23) degrees Celsius and fifty (50) percent relative humidity. After being placed in the environmental chamber, all rings were connected to a data acquisition system (DAS) that was attached to the wall immediately next to the environmental chamber. After connected to the

DAS, wetted burlap coverings were placed on the tops of the rings, and plastic coverings were placed over the burlap. This was done to avoid moisture loss during initial curing.

After being connected to the DAS, data acquisition began on a Dell computer. The program was set to record the strain every five (5) seconds. After twenty-four (24) hours, the program was paused to remove the burlap and plastic coverings and the outer ring mold part, and aluminum tape was placed over the top sections of all the rings (so that moisture could only enter/exit the rings on the outer face). The rings were checked periodically until the graph output displayed on the computer indicated that they had cracked. Data acquisition was then stopped and the rings were disconnected from the DAS. Visual inspection was given to ensure that the rings had cracked. The rings were then removed from the ring mold and disposed of. The data from the DAS was transported to another computer via flash drive and put into a Microsoft Excel file. In the Excel file, the raw data points were graphed.

For the Restrained Shrinkage Test, two (2) tests were done: one with three (3) molds of ASTM dimensions and one with three (3) molds of AAHSTO dimensions. Both tests were done only with concrete mixes without the expansive admixtures. Restrained Shrinkage Testing with the expansive admixture is future work that will be done. Figure 5 (below) presents a photograph of an ASTM dimension specimen after failure:

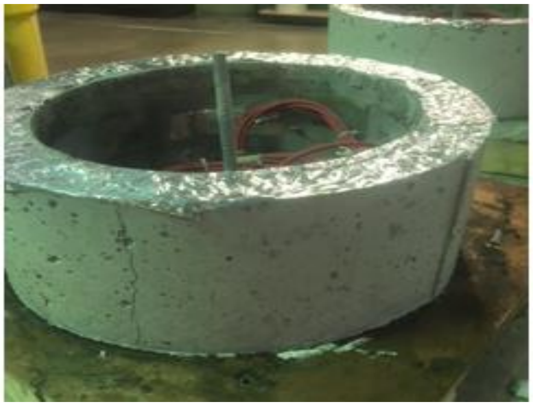


Figure 5: Typical Restrained Shrinkage Specimen after Failure

3.5 Compression Testing of Cement Mortar Cubes

For this section of the project all practices followed the Standard Test Method for Compressive Strength of Masonry Prisms ASTM C1314-2016. Measurements were taken at one (1), three (3), seven (7), and twenty-eight (28) days after initial casting. For the first seven days, all specimens were kept in a 100% humidity moist cure room. After seven days, specimens were kept in a 50% relative humidity (RH) room for the duration of their examination.

Before each length measurement, each specimen was wiped clean of excess moisture and particulate debris, and its mass was recorded. Three specimens for each batch was tested on each day: E1 through E3 and NE1 through NE3 were tested on day one (1) and so forth. The specimens were tested with a Boartt Longyear CM-625 hydraulic press machine. Each specimen was tested with loading at a rate of 50-100 pounds per square inch (psi) although the rate was kept mostly at 60-80 psi. Each specimen was tested with the side that had been exposed to the atmosphere during curing not touching either of the two loading plates during compression testing.

Failure was defined as the point at which the cube was supporting 50% of the peak load or when the cube could not sustain a positive loading rate. After the failure of each specimen, its peak load (lb) and peak strength (psi) were recorded. Photographs and/or videos were taken of each specimen, and then each specimen was properly disposed of. Analysis was then performed on all results via a Microsoft Excel Spreadsheet (see RESULTS). Figure 6 (below) presents a typical mortar cube specimen after failure.

Figure 6: Typical Mortar Specimen after Failure

3.6 Shrinkage Testing of Cement Mortar Prisms

For this section of the project, all practices followed the Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete ASTM C157-2016. Measurements were taken at one (1), three (3) or four (4), seven (7), fourteen (14) or sixteen (16), twenty-one (21), and twenty-eight (28) days after initial casting. For the first seven days, all specimens were kept in a 100% humidity moist cure room. After seven days, specimens were kept in a 50% relative humidity (RH) room for the duration of their examination. For three or four days and fourteen or seven days, the time of measurement changed due to shortened lab access during weekend hours.

Before each length measurement, each specimen was wiped clean of excess moisture and particulate debris, and its mass was recorded. The lengths were measured using a Humboldt comparator. A reference rod was placed in the restraints in the actuator, and the actuator was zeroed. The reference rod was then removed, which yielded a negative length reading. Each specimen was then placed in the actuator, and its length reading was recorded. After all specimens had been tested, they were returned to their assigned storage space. Analysis was then performed on all results in a Microsoft Excel spreadsheet (see RESULTS) adapted from a previous project. Below is a photograph of typical mortar prisms specimens.

Figure 7: Typical Mortar Prisms

Chapter 4

Results

The following is a series of graphs which present summaries of the results of all testing done during this project. Mortar Compressive Strength Results are presented first, followed by the Linear Shrinkage Results and the Restrained Shrinkage Results.

Figure 8 (below) displays the results for the ordinary portland cement mix, a mix with five (5) percent of the weight of portland cement replaced with the magnesium oxide admixture, and a weight of admixture added that is the equivalent of five (5) percent of the weight of portland cement. The measurements were taken at one (1), three (3) or four (4) (depending on laboratory hours of operation), seven (7), and twenty-eight (28) days after casting.

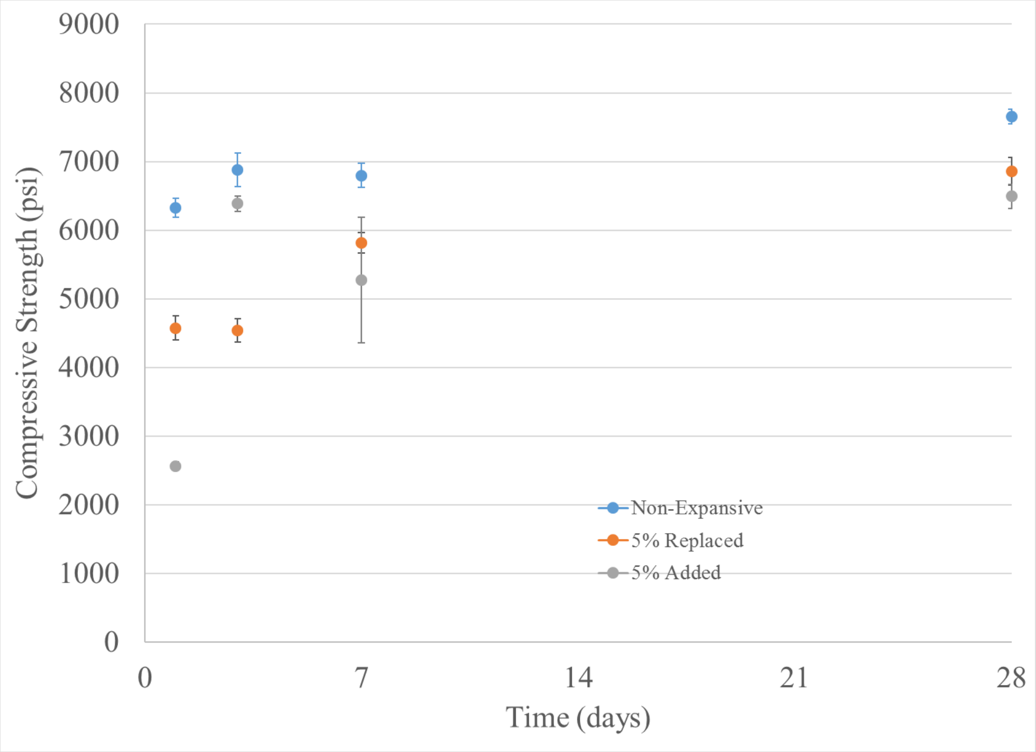


Figure 8: Compressive Strength of Mortar Cubes

Figure 9 (below) displays the results for for the ordinary portland cement mix, a mix with five (5) percent of the weight of portland cement replaced with the magnesium oxide admixture, and a weight of admixture added that is the equivalent of five (5) percent of the weight of portland cement. The measurements were taken at one (1), three(3) or four (4) (depending on laboratory hours of operation), seven(7), and twenty-eight (28) days after casting.

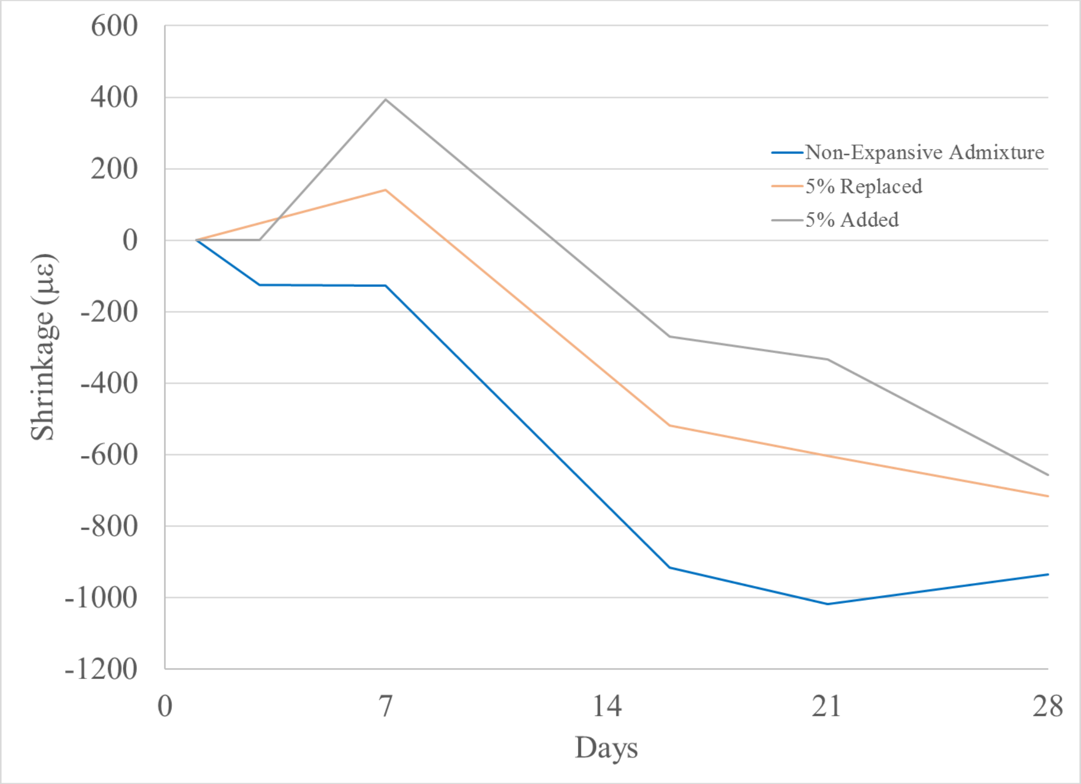


Figure 9: Mortar Prism Microtrain Results

Figures 10 and 11 (below) present the Restrained Shrinkage Test results for the ASTM and AASHTO dimensioned rings, respectively. For Figure 10, the average strain experienced by the third ring was omitted due to apparent strain gage malfunctions.

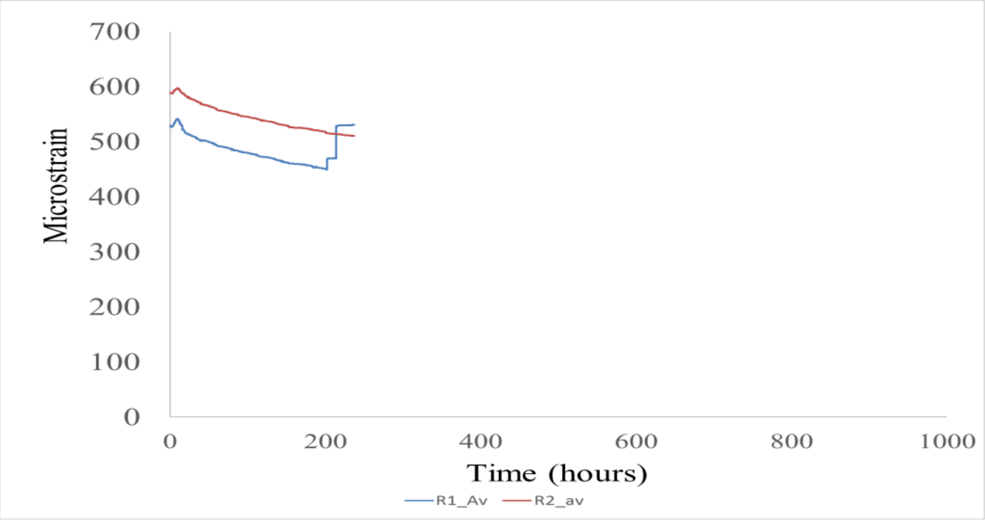


Figure 10: ASTM Non-Expansive Admixture Ring Average Microstrain Results

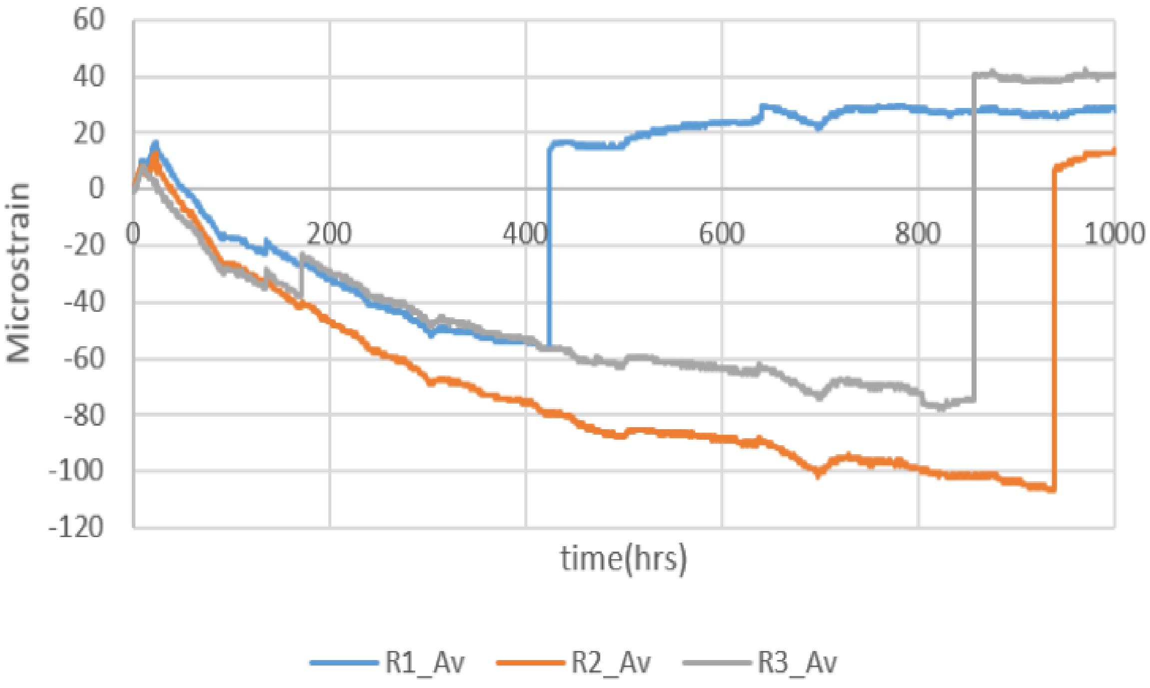


Figure 11: AASHTO Non-Expansive Admixture Ring Average Microstrain Results

Chapter 5

Discussion

5.1 Statistical Analysis of Data

No statistical analysis was done on the data for the concrete ring tests, as the raw data was simply too vast for such analysis to be practical. This paper presents the graphical results for the average of four (4) strain gages on each ring because this experiment is interested only in the approximate time for cracking. For the mortar prisms, a pre-made Excel spreadsheet that was supplied to the investigator from previous research teams was used for all analysis of the mortar prisms.

Limited statistical analysis was done on the compressive strength data for mortar cubes to determine which measurements for each day fell within the acceptable limits as per ASTM C1314. The acceptable range for all data points is within 3.6% of the average compressive strength for a given day. Any values outside of this range were omitted from the calculation of final average compressive strength (see Appendix B). Average Compressive Strength of Mortar Cubes (with the exception of Day Seven (7) for the 5% Addition mortar cube specimens) have higher statistical variance in the data set, as well as more individual data points that were discarded in the final results analysis.

For the non-expansive admixture, only two individual measurements were unacceptable, three for the five (5) percent replacement batch, and five (5) for the five (5) percent addition batch. This suggests that the addition of the admixture and the method of its inclusion (replacement or addition of equivalent cement weight) would create less predictability when used in large-scale concrete production, therefore leading to potentially under-strength concrete structures.

5.2 Effect of Admixture on Concrete Cracking Time

Due to constraints within the lab, only Retrained Shrinkage Tests without the expansive admixture were conducted. Testing was conducted with both ASTM and AAHSTO dimensioned ring molds. The results are presented in Section 4. Future testing will occur using the Restrained Shrinkage Test to examine the effect that the expansive admixture has on the concrete. The effect on how the strain levels in a mixture with magnesium oxide would compare to the specimens examined in this experiment cannot be commented on. However, there should be a much longer time to cracking than the ordinary mixes. This is because the admixture is designed to mitigate early-age cracking; if successful, cracking should happen at a later age.

5.3 Effect of Admixture on Mortar Compression Strength

Overall, the admixture appears to have an adverse effect on the compressive strength of mortar cubes, with the exception of the three (3) day strength reading. However, even at three (3) days, the compressive strength falls short of the non-expansive test data. Thus, it appears that the magnesium oxide admixture has adversely affects compressive strength. This, however, runs contrary to what Du claimed in his 2005 article. However, this is a new type of magnesium oxide admixture that is being developed, and therefore does not necessarily have to conform to behaviors previously observed in magnesium oxide admixtures.

This suggests that the actual compressive strength of the mortar cubes for day three (3) of this mix is much lower than reported; an increase in volume would cause the cube to exceed dimensions of two (2) inches that were used during compressive testing, which leads to a lower nominal compressive strength.

For the mix with five (5) percent of the weight of cement replaced with magnesium oxide, the drop in compressive strength is to be expected, because less cement is available to hydrate, and therefore less bonding occurs between materials in the cement mix which would lead to decreased strength. However, it was expected that the mix with five (5) percent of the weight of cement of magnesium oxide added, the strengths would be higher than the non-expansive batch. One explanation for this may be that the water to cement ratio was not adjusted for adding the extra material; at a ratio of 0.42, it is possible that more material was added than could have been hydrated by the water added, so some cement may not have hydrated and/or some admixture may not have been activated.

Further, when considering the high amount of statistical variance in the data, some of this may be explained. With such high variance, and with some individual data points discarded for the analysis of the data, the actual compressive strengths of the mortar specimens may have been higher than reported, and therefore possibly higher than the strengths for standard portland cement.

However, the adverse effect on compressive strength is of slightly less importance than the dimensional change or the cracking time, for two main reasons: first, the final (twenty-eight (28) day) compressive strengths for al batches were above 6000 psi, which is still strong enough to withstand most normal loading conditions, and is well above industry standards; second, the compressive strength may yet be increased with the use of other types of admixtures. To this extent, further testing should be done to determine whether there is an optimal combination of admixtures to achieve low early-age shrinkage cracking without sacrificing compressive strengths.

5.4 Effect of Admixture on Mortar Dimension Change

Overall, the admixture had a positive effect on the final dimensional change of the mortar prism specimens. However, different uses of the admixture result in different amounts of expansion, which could themselves cause problem. If enough expansion occurs that the concrete sees an increase in permanent volume, compressive stresses could occur, which will also affect the concrete's performance.

This is particularly important for consideration during field applications. In many field situations, concrete and other cementitious materials are placed within a confined space. Unanticipated expansion within such spaces could result in stress distributions that lead to stress cracking, which negates the achievement of minimizing shrinkage cracking. Even if given proper expansion joints, the joints can become clogged with debris or otherwise not be large enough to accommodate this extra expansion.

The first few days of curing for any cementitious material are the most crucial for the material to cure properly and eventually achieve the performance parameters for which it was designed. Therefore, all stresses should be minimized to allow the material to cure properly and without the potential for this type of cracking.

5.5 Errors

There are a variety of errors that could have affected the results. The temperature and humidity in the lab space could not be controlled, and therefore every mixture made in this study was made under different environmental conditions. Further, the cleanliness and oiling of molds could not be ensured to be fully consistent between batches, which may have altered the initial curing process.

Although materials were precisely measured to within ten (10) grams of their calculated batch weight, some material was lost as dust particles when transferred from their storage containers into the mixing process. This was particularly a problem for the cementitious materials and fine aggregates. The superplasticizer that was added was measured to within ten (10) milliliters. This lack of precision would have further altered actual mix proportions between batches.

Because the admixture of interest had been newly developed, and the reactive properties of the materials used in the mixing of the specimens was not investigated, unknown reactions between the admixture and one or more materials in the base mix could have occurred that negatively affected the results for one or more tests conducted, which would have skewed the results (particularly the results for mortar compressive strength) away from the typical behavior of magnesium oxide admixtures.

Chapter 6

Conclusions

Cracking in concrete has always been a problem with the use of concrete as a construction material. Early-age shrinkage cracking is but one of several types of cracking that concrete may experience in its lifetime, but it remains one of the most difficult to control.

This study examined the time to cracking in concrete rings, the dimensional change in mortar prisms, and the compressive strength in mortar cubes in a standard OPC mix, a mix with five (5) percent of the weight of portland cement replaced with a magnesium oxide admixture, and a mix with a magnesium oxide admixture that was five (5) percent of the weight of cement. The study followed ASTM specifications for all experimental procedures.

The results of this study suggest that while the admixture has a slightly adverse effect on compressive strength (which is itself contrary to previously observed effects of magnesium oxide admixtures), this adversity is not significant and benefits are found in relative dimensional change in all specimens examined within this study. Twenty-eight (28) day compressive strengths of the mortar cubes vary from approximately 6000 to 8000 psi. Any decrease in compressive strength may be regained with other admixtures. Further, the overall dimensional change was smaller for specimens with the admixture than without, and an increase in volume was observed within the first fourteen days after casting.

With these in mind, the use of a magnesium oxide admixture is a good solution to the problem of early-age thermal shrinkage cracking in concrete. However, as mentioned in Chapter 5, further testing should be done to determine exactly how long the admixture delays cracking during the concrete ring test, and to see if this admixture is compatible with strength-enhancing admixtures. Also, further testing should be done with other percentages of the admixture used to determine the effects of adding the admixture in amounts other than five (5) percent of the weight of cement, and whether the effects scale linearly.

APPENDICES

Appendix A: Material Batching Calculations

The following nine steps were originally computed by hand on standard engineering paper using material properties measured in a laboratory setting and using course materials from CE 336 – Materials Science for Civil Engineers offered at The Pennsylvania State University during the Spring 2016 Semester. All material properties used in this investigation were determined before the investigation took place, and were all obtained using practices specified in applicable ASTM standards.

1. MATERIAL INFORMATION

   Cement: Type I-II Lehigh OPC, G = 3.15

   Coarse Agg. : G_{OD} = 2.701, G_{SSD} = 2.718, Abs. = 0.6%, DRUW = 95.4 pcf

   Fine Agg. : G_{OD} = 2.61, G_{SSD} = 2.62, Abs. = 0.3%, FM = 2.7

   Super – Plasticizing Admixture : 8 mL/kg cement = 0.1224 US fl. oz. / lb cement

   Expansive Admixture: Variable

2. SLUMP SELECTION

   Assume a maximum allowable slump of four (4) inches for design purposes

3. MAXIMUM SIZE AGGREGATE DETERMINATION

   Use MSA = one-half (0.5 or ½) inches as per ASTM C1581

4. WATER AND AIR CONTENT [5]

$$Water = 325\ pcy$$

$$Air = 5\%$$

5. WATER TO CEMENT RATIO DETERMINATION

$$\frac{w}{c} = 0.42$$

6. DETERMINING CEMENT CONTENT

$$C = \frac{W}{\frac{w}{c}} = \frac{325\,pcy}{0.42} = 773.8\,pcy$$

7. DETERMINE COARSE AGGREGATE CONTENT

$$Volume\ Factor = 0.56$$

$$(27\ cf) * (0.56) = 15.12\ cf$$

$$(15.12\ cf) * (95.4\ lb) = 1442.5\,pcf$$

8. DETERMINE FINE AGGREGATE CONTENT

$$Volume\ of\ Air: (27\ cf) * (0.05) = 1.35\ cf$$

$$Volume\ of\ Water : \frac{325lb}{62.4\,pcf} = 5.208\ cf$$

$$Volume\ of\ Cement : \frac{773.8lb}{3.15 * 62.4\,pcf} = 3.937\ cf$$

$$Volume\ of\ Coarse\ Aggregate : \frac{1442.5\ lb}{2.701 * 62.4\,pcf} = 8.559\ cf$$

$$Volume\ of\ Sand : (27 - 1.35 - 5.208 - 3.937 - 8.559)cf = 7.946\ cf$$

$$Weight\ of\ Sand : (7.946\ cf) * (2.61) * (62.4\ lb) = 1294.1\,pcf$$

9. FINAL MIX PROPORTIONS

Table 4: Full Batch Weights for concrete mixes

Material	Calculated Batch Weight (pcy)	Calculated Batch Weight (kg/m^3)	Non – Exp. Batch Weight (kg/m^3)	5% Replaced Batch Weight (kg/m^3)	5% Added Batch Weight (kg/m^3)
Cement	773.8	459.08	459.08	436.12	459.08
Water	325.0	192.82	192.82	192.82	192.82
Coarse Agg.	1442.5	855.80	855.80	855.80	855.80
Fine Agg.	1294.1	767.76	767.76	767.76	767.76
Super - P	0.1224 fl. oz./ lb cem	8 mL/kg cem	8 mL/kg cem	8 mL/kg cem	8 mL/kg cem
Exp. Admx.	-	-	-	22.95	22.95

Appendix B: Full Material Test Results

Table 5: Non-Expansive mortar cube compressive strength results.

Day	Specimen	Initial Mass (g)	Final Mass (g)	Mass Change	Load (lb)	Strength (psi)	Day Average Strength (psi)	SD	ACC.
1	NE1	298.0	298.0	0.000000%	25940.0	6486.0	6331.0	138.11	227.92
1	NE2	306.2	306.2	0.000000%	25150.0	6286.0			
1	NE3	297.5	297.5	0.000000%	24880.0	6221.0			
3	NE4	302.3	302.8	0.165399%	26060.0	6514.0	6686.5	243.95	240.71
3	NE5	305.1	305.6	0.163881%	27440.0	6859.0			
3	NE6	301.3	302.0	0.232327%	29010.0	7253.0			
7	NE7	295.6	297.0	0.473613%	27780.0	6946.0	6798.3	172.32	244.74
7	NE8	299.2	300.8	0.534759%	27360.0	6840.0			
7	NE9	300.1	301.2	0.366544%	26430.0	6609.0			
28	NE10	290.8	292.8	0.687758%	29110.0	7279.0	7846.0	104.65	282.46
28	NE11	294.5	296.6	0.713073%	31090.0	7772.0			
28	NE12	302.9	305.0	0.693298%	31680.0	7920.0			

Table 6: 5% Replacement mortar cube compressive strength results.

Day	Specimen	Initial Mass (g)	Final Mass (g)	Mass Change	Load (lb)	Strength (psi)	Day Average Strength (psi)	SD	ACC.
1	E1	296.4	296.4	0.000000%	17750.0	4392.0	4575.0	177.30	164.7
1	E2	298.2	298.2	0.000000%	18980.0	4746.0			
1	E3	296.2	296.2	0.000000%	18350.0	4587.0			
3	E4	298.3	298.8	0.167616%	15660.0	3915.0	4857.5	169.00	174.87
3	E5	304.2	304.8	0.197239%	19910.0	4977.0			
3	E6	298.4	299.2	0.268097%	18950.0	4738.0			
7	E7	284.0	285.4	0.492958%	22240.0	5559.0	5666.5	152.03	203.994
7	E8	289.3	290.8	0.518493%	23100.0	5774.0			
7	E9	294.9	296.7	0.610376%	24470.0	6117.0			
28	E10	289.1	292.4	1.141474%	28490.0	7141.0	6998.5	201.53	251.946
28	E11	298.1	301.2	1.039919%	27420.0	6856.0			
28	E12	287.6	290.6	1.043115%	26260.0	6565.0			

Table 7: 5% Addition mortar cube compressive strength results.

Day	Specimen	Initial Mass (g)	Final Mass (g)	Mass Change	Load (lb)	Strength (psi)	Day Average Strength (psi)	SD	ACC.
1	E1A	302.4	302.4	0.000000%	10445	2600	2566.67	57.74	92.4
1	E2A	304.9	304.9	0.000000%	10430	2600			
1	E3A	305.7	305.7	0.000000%	10030	2500			
4	E4A	296.6	299.6	1.011463%	23200	6000	6580	113.14	236.88
4	E5A	298.9	301.9	1.003680%	25250	6500			
4	E6A	298.9	301.8	0.970224%	22800	6660			
7	E7A	296.0	299.7	1.250000%	23300	5825	5177.5	915.70	186.39
7	E8A	296.1	299.6	1.182033%	18120	4530			
7	E9A	296.4	300.2	1.282051%	21900	5474			
28	E10A	297.8	302.0	1.410343%	24060	6014	6138	175.36	220.96
28	E11A	296.9	301.3	1.481980%	25050	6262			
28	E12A	301.2	305.4	1.394422%	28840	7210			

Table 8: Non-Expansive Mortar Prism linear shrinkage results

Day 1 - 11 October 2016													
Sample	Mass (g)	Zero	Length	Length-Zero		Δ Length	Microstrain	Average Microstrain (1`-3 Days)	Standard Deviation	Δ Mass		Day	Microstrain Average
NE1P	431.6	-0.2695	-0.0853	0.1842		-0.0012	-120	-125	19.14854216	0.005329008		1	0
NE2P	437.7	-0.2695	0.0328	0.3023		-0.001	-100			0.00456934		3	-125
NE3P	431.3	-0.2695	-0.0376	0.2319		-0.0014	-140			0.004637144		7	-127.5
NE4P	439.2	-0.2695	-0.0354	0.2341		-0.0014	-140			0.005919854		16	-915
												21	-1017.5
Day 3 - 13 October 2016												28	-935
Sample	Mass (g)	Zero	Length	Length-Zero		Δ Length	Microstrain	Average Microstrain (1-7 Days)	Standard Deviation				
NE1P	433.9	-0.2680	-0.0850	0.1830		-0.0012	-120	-127.5	15				
NE2P	439.7	-0.2680	0.0333	0.3013		-0.0011	-110						
NE3P	433.3	-0.2680	-0.0375	0.2305		-0.0014	-140						
NE4P	441.8	-0.2680	-0.0353	0.2327		-0.0014	-140						
Day 7 - 17 Otober 2016													
Sample	Mass (g)	Zero	Length	Length-Zero		Δ Length	Microstrain	Average Microstrain (1-16 Days)	Standard Deviation				
NE1P	434.9	-0.2681	-0.0851	0.1830		-0.0092	-920	-915	19.14854216				
NE2P	440.9	-0.2681	0.0331	0.3012		-0.009	-900						
NE3P	434.7	-0.2681	-0.0376	0.2305		-0.0094	-940						
NE4P	442.5	-0.2681	-0.0354	0.2327		-0.009	-900						
Day 16-26 October 2016													
Sample	Mass (g)	Zero	Length	Length-Zero		Δ Length	Microstrain	Average Microstrain (1-21 Days)	Standard Deviation				
NE1P	420.8	-0.2695	-0.0945	0.175		-0.0101	-1010	-1017.5	22.17355783				
NE2P	426	-0.2695	0.0238	0.2933		-0.0104	-1040						
NE3P	420.2	-0.2695	-0.047	0.2225		-0.0103	-1030						
NE4P	430.1	-0.2695	-0.0444	0.2251		-0.0099	-990						
Day 21-31 October 2016													
Sample	Mass(g)	Zero	Length	Length-Zero		Δ Length	Microstrain	Average Microstrain (1-28 Days)	Standard Deviation				
NE1P	419.4	-0.2695	-0.0954	0.1741		-0.0113	-1130	-935	377.0499525				
NE2P	425.4	-0.2695	0.0224	0.2919		-0.0037	-370						
NE3P	418.9	-0.2695	-0.0479	0.2216		-0.0114	-1140						
NE4P	428.8	-0.2695	-0.0453	0.2242		-0.011	-1100						
Day 28-7 November 2016													
Sample	Mass(g)	Zero	Length	Length-Zero									
NE1P	418.3	-0.2694	-0.0965	0.1729									
NE2P	424.2	-0.2694	0.0292	0.2986									
NE3P	417.8	-0.2694	-0.0489	0.2205									
NE4P	427.6	-0.2694	-0.0463	0.2231									

Table 9: 5% Replaced mortar prism linear shrinkage results

Day 1 - 11 October 2016														
Sample	Mass (g)	Zero	Length	Length-Zero		Δ Length	Microstrain	Average Microstrain (1`-3 Days	Standard Deviation	Δ Mass		Day	Microstrain Average	
E1P	429.5	-0.2695	-0.0606	0.2089		0.0011	110	48	46.5832588	0.009546		1	0	
E2P	427.2	-0.2695	-0.0654	0.2041		0.0005	50			0.008661		3	48	
E3P	437.2	-0.2695	-0.0339	0.2356		0.0004	40			0.009149		7	140	
E4P	419.5	-0.2695	-0.145	0.1245		0.0006	60			0.009774		16	-518	
E5P	434.3	-0.2695	-0.0582	0.2113		-0.0002	-20			0.00875		21	-604	
												28	-716	
Day 3 - 13 October 2016														
Sample	Mass (g)	Zero	Length	Length-Zero		Δ Length	Microstrain	Average Microstrain (1-7 Days)	Standard Deviation					
E1P	433.6	-0.2680	-0.0580	0.2100		0.0015	150	140	30.82207001					
E2P	430.9	-0.2680	-0.0634	0.2046		0.0012	120							
E3P	441.2	-0.2680	-0.0320	0.2360		0.0015	150							
E4P	423.6	-0.2680	-0.1429	0.1251		0.0018	180							
E5P	438.1	-0.2680	-0.0569	0.2111		0.001	100							
Day 7 - 17 Otober 2016														
Sample	Mass (g)	Zero	Length	Length-Zero		Δ Length	Microstrain	Average Microstrain (1-16 Days	Standard Deviation					
E1P	435.3	-0.2681	-0.0577	0.2104		-0.0051	-510	-518	27.74887385					
E2P	432.5	-0.2681	-0.0628	0.2053		-0.0054	-540							
E3P	442.2	-0.2681	-0.0310	0.2371		-0.0051	-510							
E4P	424.5	-0.2681	-0.1418	0.1263		-0.0048	-480							
E5P	439.5	-0.2681	-0.0558	0.2123		-0.0055	-550							
Day 16-26 October 2016														
Sample	Mass (g)	Zero	Length	Length-Zero		Δ Length	Microstrain	Average Microstrain (1-21 Days	Standard Deviation					
E1P	420.1	-0.2695	-0.0657	0.2038		-0.0059	-590	-604	32.09361307					
E2P	418	-0.2695	-0.0708	0.1987		-0.0063	-630							
E3P	427.8	-0.2695	-0.039	0.2305		-0.006	-600							
E4P	410.2	-0.2695	-0.1498	0.1197		-0.0056	-560							
E5P	424.5	-0.2695	-0.0637	0.2058		-0.0064	-640							
Day 21-31 October 2016														
Sample	Mass(g)	Zero	Length	Length-Zero		Δ Length	Microstrain	Average Microstrain (1-28 Days	Standard Deviation					
E1P	418.5	-0.2695	-0.0665	0.203		-0.007	-700	-716	39.11521443					
E2P	416.4	-0.2695	-0.0717	0.1978		-0.0077	-770							
E3P	426.3	-0.2695	-0.0399	0.2296		-0.007	-700							
E4P	408.7	-0.2695	-0.1506	0.1189		-0.0067	-670							
E5P	422.9	-0.2695	-0.0646	0.2049		-0.0074	-740							
Day 28-7 November 2016														
Sample	Mass(g)	Zero	Length	Length-Zero										
E1P	417.2	-0.2694	-0.0675	0.2019										
E2P	415.1	-0.2694	-0.073	0.1964										
E3P	425	-0.2694	-0.0408	0.2286										
E4P	407.5	-0.2694	-0.1516	0.1178										
E5P	421.6	-0.2694	-0.0655	0.2039										

Table 10: 5% Replaced mortar prism linear shrinkage results

Day 1 - 20 January 2017

Sample	Mass (g)	Zero	Length	Length-Zero		Δ Length	Microstrain	Average Microstrain (1`-3 Days)	Standard Deviation	Δ Mass		Day	Microstrain Average
E1PA	443.2	-0.2663	0.0005	0.2668		-0.0003	-30	-5.57066E-13	2878.446919	0.008348		1	0
E2PA	449.7	-0.2663	-0.017	0.2493		-0.0032	-320			0.007338		4	-5.6E-13
E3PA	446.3	-0.2663	-0.0355	0.2308		0.0701	7010	**		0.00717		7	393.3333
E4PA	432.7	-0.2663	0.154	0.4203		-0.0033	-330			0.007627		14	-270
E5PA	437.2	-0.2663	-0.0573	0.209		0.0021	210			0.006633		21	-333.333
E6PA	431.9	-0.2663	-0.0406	0.2257		0.0047	470			0.009261		28	-656.667

Day 4 - 23 January 2017

Sample	Mass (g)	Zero	Length	Length-Zero		Δ Length	Microstrain	Average Microstrain (1-7 Days)	Standard Deviation
E1PA	446.9	-0.2643	0.0022	0.2665		0.0072	720	393.3333333	470.2623381
E2PA	453.0	-0.2643	-0.0182	0.2461		-0.0021	-210		
E3PA	449.5	-0.2643	0.0366	0.3009		0.0041	410		
E4PA	436.0	-0.2643	0.1527	0.4170		-0.0012	-120		
E5PA	440.1	-0.2643	-0.0532	0.2111		0.0097	970		
E6PA	435.9	-0.2643	-0.0339	0.2304		0.0059	590		

Day 7 - 26 January 2017

Sample	Mass (g)	Zero	Length	Length-Zero		Δ Length	Microstrain	Average Microstrain (1-16 Days)	Standard Deviation
E1PA	448.1	-0.272	0.0020	0.2740		-0.0009	-90	-270	372.343927
E2PA	454.3	-0.272	-0.0248	0.2472		-0.0093	-930		
E3PA	450.9	-0.272	-0.0371	0.2349		-0.003	-300		
E4PA	437.2	-0.272	0.1471	0.4191		-0.0034	-340		
E5PA	441.9	-0.272	-0.0533	0.2187		0.0018	180		
E6PA	436.9	-0.272	-0.0404	0.2316		-0.0014	-140		

Day 14 - 2 February 2017

Sample	Mass (g)	Zero	Length	Length-Zero		Δ Length	Microstrain	Average Microstrain (1-21 Days)	Standard Deviation
E1PA	435.7	-0.2715	-0.0056	0.2659		-0.0042	-420	-333.3333333	218.235347
E2PA	442.1	-0.2715	-0.0315	0.24		-0.0045	-450		
E3PA	439.0	-0.2715	-0.0437	0.2278		-0.0039	-390		
E4PA	425.0	-0.2715	0.1454	0.4169		-0.0044	-440		
E5PA	430.3	-0.2715	-0.0607	0.2108		0.0011	110		
E6PA	424.9	-0.2715	-0.0472	0.2243		-0.0041	-410		

Day 21 - 9 February 2017

Sample	Mass(g)	Zero	Length	Length-Zero		Δ Length	Microstrain	Average Microstrain (1-28 Days)	Standard Deviation
E1PA	433.7	-0.2714	-0.0088	0.2626		-0.0054	-540	-656.6666667	179.2949153
E2PA	440.0	-0.2714	-0.0266	0.2448		-0.0083	-830		
E3PA	436.8	-0.2714	-0.0445	0.2269		-0.0081	-810		
E4PA	422.9	-0.2714	0.1445	0.4159		-0.0076	-760		
E5PA	428.0	-0.2714	-0.0613	0.2101		-0.0037	-370		
E6PA	422.8	-0.2714	-0.0498	0.2216		-0.0063	-630		

Day 28 - 16 February 2017

Sample	Mass(g)	Zero	Length	Length-Zero
E1PA	432.5	-0.2688	-0.0074	0.2614
E2PA	438.6	-0.2688	-0.0278	0.241
E3PA	435.4	-0.2688	-0.0461	0.2227
E4PA	421.5	-0.2688	0.1439	0.4127
E5PA	426.7	-0.2688	-0.0635	0.2053
E6PA	421.6	-0.2688	-0.0494	0.2194

**Values with a double asterisk were discarded for data analysis

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ACADEMIC VITA

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Undergraduate Major August 2013 - Present

B.S. in Civil Engineering with focus in Geotechnical and Materials Engineering, The Pennsylvania State University

Undergraduate Minor August 2013 - Present

Political Science, the Pennsylvania State University

Research Experience August 2016 - April 2017

The Cementitious Materials Research Group, The Pennsylvania State University Department of Civil and Environmental Engineering

Industry Experience

Geotechnical Engineering Intern, Gannet Fleming Inc. Pittsburgh PA	May – August 2016
Field Technician, Pennsylvania Soil&Rock Inc, Monroeville PA	June 2013 – August 2015

Academic Experience and Awards

Schreyer Scholar	May 2015 – Present
Vice President, Penn State ASCE	May 2016 – Present
Author for Penn State 2017 Mead Student Paper	November 2016 - Present
Chi Epsilon	December 2015 – Present
Penn State ACI	February 2016 – Present
ASCE Central Pennsylvania Student Award	November 2016
Pittsburgh ACI Founders Award	April 2017

Professional Memberships

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S.M. ACI