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FREEZE-THAW DURABILITY OF PVA FIBER REINFORCED MORTARS REPRESENTING IN-SITU CONDITIONS

by

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ABSTRACT

Masonry structures are susceptible to deterioration and mortar loss due to weathering. More flexible mortars have been developed for the repointing of unreinforced masonry structures to resist out-of-plane forces. To provide a more ductile mortar, the inclusion of polyvinyl alcohol (PVA) fibers has been introduced to increase the mechanical strength of the repointing mortar. The purpose of this study is to determine the freeze-thaw durability of PVA fiber reinforced mortars (FRM). The durability is determined by subjecting PVA FRM samples, described in a National Park Service database of sustainable FRM's, to rapid freeze-thaw cycles using a modified approach to the American Society for Testing and Materials (ASTM) C666 standard to represent in-situ conditions. Results of the experimental testing have determined the PVA mortars durable when exposed to freeze-thaw weathering durability. This investigation ensures that PVA FRM utilized in repair are sustainable and demonstrate an acceptable life expectancy.

Keywords: polyvinyl-alcohol, fiber, durability, mortars, freeze-thaw, in-situ.

CHAPTER 1: INTRODUCTION

1.0 BACKGROUND

Throughout history, the durability and splendor of masonry has played a vital role in the creation of structures. The Egyptian Pyramids, Roman Coliseum, and the Great Wall of China are examples of significant architectural achievements made possible through masonry. As a result of their durable nature, masonry structures have been constructed in a wide range of climates forcing them to experience a variety of environmental conditions. These conditions have a direct effect on the performance and sustainability of a masonry structure. The susceptibility of masonry to weathering, thermal expansion, thermal contraction, and fatigue are common issues engineers must face in order to ensure the longevity of mason work. Consequently, the growing desire to provide lasting structures has caused a push in research to provide new engineering materials which will increase the out-of-plane strength of un-reinforced masonry construction. Much of this research has been performed on the development of fiber-reinforced mortars (FRM). FRM are popularly utilized for repointing or repairing existing masonry structures. Numerous types of fiber are used in repair mortars. However, due to their relatively low cost and high out-of-plane load resistance, this study focuses on Polyvinyl Alcohol (PVA) fibers. PVA fibers are becoming a widely used additive for increasing the out-of-plane performance of mortars (Skourup & Erdogmus, 2010).

PVA fibers are utilized in structural applications as a method for controlling plastic shrinkage, thermal cracking, and improving abrasion resistance of mortars. These fibers are known for their high tensile strength and elastic modulus (Fukinishi, 1993); the elastic modulus represents the ability of a material to deform and recover without permanent deformation. As a result of their beneficial mechanical properties, PVA fibers are becoming an effective means to strengthen unreinforced cementitious materials. PVA fibers have been instituted to increase the ductility of unreinforced masonry walls by improving their out-of-plane bending capacities and their flexural resistance (Skourup & Erdogmus, 2010). Since mortars are stronger in compressive strength than in tensile strength, implementation of PVA fibers are ideal for improving the tensile strength of mortars. The high tensile strength properties of PVA as well as the high bond strength between the fiber and the mortar provide a beneficial addition to the out-of-plane load capacity of the composite mortar.

One of the features provided by inclusion of PVA fibers into the repair mortar mixture is an improvement at the joints for resisting out-of-plane loads through an increase in the tensile strength of the mortar when compared to non-FRM. This strength increase is vital for preventing mortar loss and improving sustainability of existing masonry structures. As PVA fibers are becoming more widely used in repairing structures, an increased understanding of their mechanical characteristics and resilience is necessary. It is the intention of this study to determine the freeze-thaw durability of PVA fiber reinforced mortars representing in-situ conditions as these FRM presently exist in the field. Future freeze-thaw durability studies of FRM and masonry prisms will benefit from this study as it presents a strategy for determining durability characteristics as they would be represented within a structure's natural environment. It is possible that the effects of including PVA fibers within the repair mortar can be beneficial or harmful to the mechanical integrity of the structure. The use of PVA fibers in structural applications warrants the need for accurately determining the long term durability of fiber reinforced mortars.

The durability of FRM pertains to the ability of a structure to maintain its original appearance, strength, and soundness for many years (Boynton & Gutschick, 1964). Engineers desire their materials to be able to withstand environmental conditions and weathering effects. The durability of a mortar is directly related to its permeability and the presence of cracks within the binder matrix (Lawler, 2001); in this study the binder matrix consists of the fiber and mortar mixture. Major issues with the inclusion of PVA fibers in the repair mortar exist. It is possible that the PVA fibers may increase the void spaces present within the mortar. Therefore, this would allow for excess moisture to penetrate into the mortar, causing it to be susceptible to freeze-thaw weathering and breakdown. PVA fibers are also known to absorb a small amount of moisture (Nycon, 2012). Although permeability of mortar is necessary, intake of too much moisture from the surrounding environment may cause undesired internal pressures to become present under freezing of the masonry.

Another point of interest lies within the mortar and brick interface. Analysis of FRM has been evaluated as a mortar component and not in combination with masonry units (Kosa, Naaman, & Hansen 1991; Wang & Li, 2005). When FRM are used in construction, large FRM blocks are non-existent. Durability tests on pure FRM prisms are not representative of conditions which are actually experienced by a structure. The amount of surface area present in a FRM block is much larger than the available surface area in a masonry joint. A representation of a smaller surface area in accelerated freeze and thaw testing may render the mortar less durable than previous studies have indicated.

If the in-situ placement of these mortars causes them to be more susceptible to breakdown, an interpretation of this alteration to the durability is desired.

Characterization of in-situ construction may provide an increase in void spaces in the brick and mortar prism due to workability and the inclusion of bricks. The inclusion of PVA fibers in a brick-and-mortar interface may have differing results than pure FRM prisms. This may incidentally cause the breakdown of the matrix after exposure to many freeze-thaw cycles. In addition to the possible increase in void space, the bond created between the PVA fibers and the masonry unit may weaken and cause a decrease in the ability of a material to deform under flexural stresses. By evaluating the freeze-thaw durability of PVA FRM with regard to in-situ conditions the effect of the long term weathering behavior of the PVA FRM mix is determined. The durability testing of the binder matrix is done utilizing a modified approach to the American Society for Testing and Materials C666 to represent in-situ conditions (ASTM, 2008).

FRM utilized in the repair of masonry structures are desired by engineers to satisfy a range of compatibility characteristics. This range includes aesthetic compatibility, an increase in out-of-plane strength, and mortar permeability. Additionally, the repointing mortar is desired to have a comparable compressive strength to that of the existing mortar. This will guarantee that the mortar is not stiffer than the brick, resulting in damage to the brick. This is extremely important in the repointing of historic mortar. Although it is costly, historic masonry is capable of being repaired with new mortar as long as the brick is not damaged (National Parks Service, 1998). This study provides insight into the benefits of utilizing PVA fiber reinforced mortars as a repair unit. By fully comprehending the freeze-thaw durability of PVA fiber reinforced mortars, it is possible to ensure that PVA FRM provide a long-lasting and safe structural application. As a result of this study, the long-term sustainability and durability of PVA FRM are determined.

A review of the existing literature points out that the freeze-thaw durability of PVA fiber reinforced cementitious composites has been performed prior to this study (Li, Horikoshi, Ogawa, Torigoe, & Saito, 2004; Wang & Li, 2006; Sahmaran, Lachemi, & Li, 2009). However, the durability has been determined utilizing ASTM C666, an omnidirectional procedure. Omnidirectional testing requires that the experimental specimens be exposed to freezing and thawing on all six faces simultaneously. A typical masonry structure will experience extreme weathering on a single face. An in-situ representation of the freeze and thaw durability of PVA FRM has not yet been conducted. Furthermore, durability testing has not been performed on masonry prism samples. By experimentally determining the freeze and thaw durability of a masonry prism, a representation of actual conditions can be replicated. The testing of the specimens before and after they have been subjected to accelerated freeze/thaw cyclic loading is done in accordance with applicable ASTM standards. At the conclusion of all durability testing, if a reduction in any of the strength capacities of the PVA FRM exists, the information will be provided to aid in the development, preservation, and rehabilitation of structures for future engineers.

1.1 PROBLEM STATEMENT

The purpose of this study is to determine the freeze-thaw durability of PVA FRM using a modified approach to existing ASTM standards. As PVA FRM are currently utilized for their capacity to increase flexural bond strength of unreinforced masonry, little information is known about their long-term durability. It has been assumed that the inclusion of PVA fibers within a brick-and-mortar interface may affect void spacing, moisture absorption, and bond strength of a masonry unit. This increase in void spaces may be amplified when the fibers are included within a brick and mortar interface. When a mortar is placed within a structure, in-situ conditions may consequently cause a problem with the bond between the brick and FRM. Furthermore, when representing in-situ conditions, the available surface area of the FRM for exposure is greatly reduced in comparison with previous tests performed on mortar cube specimens (Kosa and others, 1991). A smaller mortar surface area may be more vulnerable to spalling and deterioration. Consequently, if the findings of this study present no significant change in mechanical properties of the FRM after accelerated freeze-thaw testing, then the durability of the selected PVA FRM is deemed safe for structural applications.

The results of this study are limited to the determination of the in-situ freeze-thaw durability of a specific set of mixtures, brick and mixture prisms, and may not directly transfer to any combination of mortar and fiber mixture. The mixtures to be tested have been selected from a database made available through the National Parks Service (Armwood, Erdogmus, & Haider, 2011). If a reduction is found in the mechanical strength of the FRM, then the proposed reduction will only be accurate for the specific mixture of fiber content and mortar. The method of determining the freeze-thaw durability will be applicable to all mixtures of fiber reinforced mortars as well as brick and mortar prisms.

1.2 OBJECTIVES OF RESEARCH

The purpose of this research is to address numerous objectives pertaining to the freeze-thaw durability of PVA FRM. Attainment of these objectives will provide sufficient information regarding the freeze-thaw durability of PVA fiber reinforced mortars to confidently prescribe their use in construction. The objectives of this study are to:

1. Determine the moisture absorption rate of PVA fiber reinforced mortar cubes.
2. Determine the values for the percent length change of each specimen and the average percent length change for each group of specimens after exposure to freeze/thaw cyclic loading.
3. Determine mass loss or gain for PVA mortars subjected to freeze/thaw cyclic loading.
4. Determine the durability factor of each specimen and the average durability factor for each group of similar specimens after exposure to freeze/thaw cyclic loading.
5. Report the specified minimum relative dynamic modulus and maximum number of cycles which the mortar can resist freeze/thaw cyclic loading.
6. Report any defects in each specimen which may develop during testing.
7. Provide a better understanding of the freeze-thaw durability of polyvinyl alcohol fiber reinforced mortars within a brick-and-mortar interface.

1.3 RESEARCH TASKS

In order to achieve the objectives described above, the following tasks have been streamlined:

1. Generate a representative sample base of the FRM mix designs to represent a portion of the scope of the National Parks Service (NPS) FRM database. This database was developed to share the data and findings from a NPS funded project on the mechanical properties of FRM for masonry applications. The study was performed by Dr. Ece Erdogmus and her research team at the Peter Kiewit Institute on the Omaha campus of the University of Nebraska-Lincoln. The National Center for Preservation Technology and Training (NCPTT), grant number MT-2210-08-NC-03, funded the project.

2. Construct fiber reinforced mortar cubes in accordance with ASTM C109, Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (using 2 in. cube specimens). These cubes are utilized in accordance with ASTM C671, Standard Test Method for Critical Dilation of Concrete Specimens Subjected to Freezing. This enables the determination of a critical immersion time in water in which the cubes are determined to absorb the maximum amount of moisture. These calculations provide insight into the performance of the PVA FRM prior to freeze and thaw testing.

3. Objectives 3-6 are conducted in accordance with ASTM C666 with the exception of a few modifications intended to better represent in-situ conditions. The implementation of the freeze/thaw cycles are performed in a model number 6240-2 Caron freeze/thaw environmental chamber. This chamber allows for controlling a wide range of temperature and humidity settings as well as automatic cycling between set points which enables continuous simulation of the harsh conditions of rapid freezing and thawing. The specifications of this chamber are further discussed in Chapter 3.

4. Masonry prism compressive and flexural strength determinations are performed in accordance with the masonry prism compressive strength (ASTM C39) and the

masonry prism flexural strength (ASTM C1018) standards (ASTM C39, 2005; ASTM C1018, 1997).

5. For those samples where a reduction in strength occurs due to exposure to freeze/thaw cyclic loading, the amount of this reduction is determined.

6. The freeze-thaw durability of PVA fiber reinforced mortars within a brick and mortar interface is determined through derivation of a durability factor upon comparison of the performance of the specimens before and after exposure to freeze/thaw cyclic loading.

1.4 OVERVIEW OF THESIS

This thesis is divided into six chapters. The introduction (Chapter 1) is followed by a review of existing literature pertinent to this study (Chapter 2). Chapter 3 presents the methodology of this study. Presentation of the results of the freeze/thaw testing is given in Chapter 4. The experimental results are analyzed and discussed in Chapter 5. The sixth and final chapter in this thesis contains a summary of the results, conclusions, and suggestions for future work. A bibliography appears at the end of the thesis and is followed by a reference section of Appendices.

CHAPTER 2: LITERATURE REVIEW

2.0 INTRODUCTION

This chapter presents a summary of the existing published literature pertaining to durability studies of polyvinyl alcohol (PVA) fiber reinforced composites. The chapter is broken down into four sections. The first section presents information regarding the mechanical strength testing of PVA fiber reinforced mortars (FRM) and cementitious composites. The second section discusses pertinent research regarding the moisture absorption testing of PVA fiber reinforced mortars. The third section reviews various durability testing techniques which have been previously performed on PVA composites. The final section provides a summary of the existing published literature and conclusions which are necessary for deriving the experimental design for the freeze-thaw durability testing of the PVA FRM.

2.1 STRENGTH TESTING OF PVA FIBER REINFORCED MORTARS

The first step in understanding the behavior of PVA FRM is to characterize their basic strength properties. An in-depth interpretation of the advantages and disadvantages associated with the use of PVA fibers for masonry applications is necessary for this study as it will provide background information into the assumptions associated with the behavior of these FRM under extreme weather conditions. This also gives an interpretation of the significance of the use of PVA FRM by quantifying the advantages associated with their use and allows conclusions to be drawn about their effectiveness.

The development of recent research has enabled a basic understanding of the behavior of PVA FRM. One study which quantifies the mechanical strength parameters of PVA fiber reinforced mortars has been conducted by Skourup and Erdogmus (2010).

The purpose of their study is to determine the compressive, flexural, and flexural bond strength of PVA FRM. The strength characteristics of the FRM are directly dependent on the amount of fiber included in the mortar. It is determined that inclusion of too much or too little fiber content does not benefit the mortar. Because the strength of the mortar varies with fiber content, several different mix designs are created in which the size of the fiber and the amount of fibers are variables. This enables for the determination of the strength of the FRM as a function of the fiber content and makeup. Pure mortar prisms as well as masonry prisms are constructed in order to quantify the mechanical strength characteristics of PVA FRM. Using the ASTM manual (2007) as a guide for testing the mixes, the different samples are then subjected to compressive strength testing, flexural strength testing, and flexural bond strength testing. The overall results of these tests show an increase in ductility, toughness, and energy absorption for the FRM versus a typical Type N mortar with no fiber inclusion. Another benefit of the PVA FRM is that they did not positively or negatively impact the compressive strength of the mortar. These traits are all beneficial because they represent an increase in mechanical strength of the mortar which may be used for re-pointing of structures. More importantly, this increase occurs without altering the original compressive strength design of the mortar. However, it has been hypothesized that fiber dispersion in the mixture may form voids or disturbances in the mortar's matrix and can decrease the compressive resistance (Skourup & Erdogmus, 2010).

Formation of voids within the matrix is a key factor for deterioration of structural components as cracks or pore spaces collect moisture and are able to displace the mortar, thus causing tensile stresses on extreme matrix faces and leading to material loss (Lawler, 2001). FRM are constructed with a random association of the fibers within the mortar. This can cause development of excessive void spaces, which in turn may affect the long-term durability of the FRM.

In another study, the strength characteristics of PVA fiber reinforced mortars are evaluated utilizing a brick-and-mortar prism as well as a typical mortar specimen (Armwood and others, 2011). These masonry prisms are thought to better represent the behavior of FRM in the field. By constructing samples of Type N mortar mixed with varying PVA fiber length and content, the authors are able to determine the basic strength characteristics of the FRM in its natural setting. The results of this study determine the compressive strength of the mortar, the strength of the mortar in a 3-unit-stack masonry prism, the flexural strength of the mortar, and the flexural bond strength of the mortar in a 5-unit-stack masonry prism. The goal of their research is to limit the compressive strength of the mortar to a value lower than the brick unit while improving overall ductility, flexural capacity, and bond strength of the masonry system. As a result of their testing, it is determined that a consistent increase in flexural strength is observed for all Type N mortars combined with PVA fibers. The findings of the study are consistent with the results previously discussed by Skourup and Erdogmus (2010); the use of PVA FRM for masonry applications yields consistent increases in out-of-plane strength and ductility.

Similar studies regarding the strength performance of PVA fibers in engineered cementitious composites (ECC) have also been conducted (Wang & Li, 2005). Cementations composites consist of cement, sand, fly ash, and super plasticizer. As expected with the inclusion of PVA fibers in the mix design, these composites yield increases in tensile strength, crack width propagation resistance, flexural resistance, and compressive strength development. Structural ECC behave like high-strength concrete with nearly linear stress-strain behavior until failure. The mechanical properties and behavior of ECC are similar to FRM. Due to the absence of durability studies on FRM, ECC are useful for drawing similarities between ECC and FRM. As the specific durability studies of PVA FRM have not yet been conducted, comparisons are needed to be drawn between ECC and FRM in order to fully understand the freeze/thaw durability of FRM. The study conducted by Wang and Li (2005) helps to determine this relationship.

The results of several studies regarding the basic strength characteristics of PVA FRM and ECC have been discussed in the previous section. Overall, results show that the inclusion of PVA fibers within mortar as well as cementitious composites yields an increase in out-of-plane strength, ductility, and energy absorption. As the application of PVA fibers is becoming more widely apparent, these increases in strength need to be evaluated for longevity. Testing performed in this study leads to the determination of whether the advantages outweigh the disadvantages of PVA FRM and if they are feasible for long-term structural application.

2.2 MOISTURE IMMERSION TESTING

The apparent moisture absorption rate of PVA fiber reinforced mortars will play a vital role in determining their long-term freeze and thaw durability. This is due to the fact that moisture within the pore spaces of masonry is a major factor for the appearance of damage to the structure. If the effect of including PVA fibers within the mortar is found to increase the amount of moisture which is present within the joints of a masonry structure, then their use may be not as beneficial as they may appear.

The use of PVA fibers within a mortar matrix presents a few issues which need to be resolved. The first problem is the inevitable appearance of protruding fibers from the matrix outer face, commonly known as “whiskers.” The random orientation of fibers within the binder matrix causes them to protrude from the exterior face of the masonry joints. These “whiskers” appear during the construction of PVA FRMs and may increase the ability of the mortar to absorb moisture. An example of typical “whiskers” can be seen in Figure 2.1 below.

Figure 2.1 Typical Whiskers

The presence of these whiskers may cause unwanted moisture infiltration into the mortar. Justification of this phenomenon is derived from the fact that PVA fibers have less than a 1% by weight water absorption capacity (Nycon Incorporated, 2012). In general, by having a water absorption capacity, the PVA fibers are able to wick moisture from the surrounding environment and bring it into the mortar. The moisture absorption capacity of the PVA fibers may cause them to bring an excessive amount of water into the masonry, which will ultimately decrease its freeze and thaw durability.

Analysis of the degree of saturation of a mortar and a brick-and-mortar interface has been performed previously (Ritchie & Plewes, 1961). The purpose of their study is to determine the rain penetration of brick masonry walls for an array of differing brick and mortar structures. In their study, the authors construct masonry panels and subject them to a rainstorm in a pressurized simulation chamber. After rainstorm exposure, the panels are then evaluated for moisture penetration. As a result of the testing, it is concluded that the resistance of brickwork panels to moisture penetration varied greatly depending on the type of brick and mortar that was in combination. However, the major amount of absorption through the walls of the specimens occurred at the brick and mortar interface. The brick and mortar interface is a key point of interest for this thesis.

Currently, no research exists on the moisture absorption rate of PVA FRM. By conducting a study on the absorption rate of PVA FRM cubes and comparing their results with a typical mortar without fibers, a conclusion as to whether the effects of PVA fibers are beneficial or not will be determined. Previous research (Skourup & Erdogmus, 2010) has concluded that the inclusion of PVA fibers into a mortar may cause an increase in the void spaces present within the mortar. An increase in void spaces may ultimately cause an increase in the void spaces present at the critical brick-and-mortar interface. If this increase in voids occurs, then the bond between the brick and mortar may be altered. Coupling the increase in void spaces with the moisture absorption capacity of PVA fibers may yield a devastating effect to the freeze and thaw durability of the masonry. Regardless of the changes at the boundary between the brick and mortar interface, if the inclusion of PVA fibers causes an increase of moisture to be present within the mortar from their absorption characteristics, then their inclusion may not be as beneficial as expected. Investigation into the moisture absorption capacity of the PVA FRM selected for this study is necessary to understand the performance of the FRM. The entire methodology for determination of the moisture absorption capacity can be seen in Chapter 3. In the context of this study, absorption of extra moisture into the matrix will ultimately cause a less durable masonry mortar in regards to freeze/thaw cyclic exposure.

2.3 DURABILITY TESTING CONDITIONS

Numerous studies regarding the durability of PVA fiber reinforced materials have been performed prior to this study (Li, Horikoshi, Ogawa, Torigoe, & Saito, 2004; Wang & Li, 2006; Sahmaran, Lachemi, & Li, 2009). Different types of durability testing of fiber reinforced mortars exist, all of which can be determined according to numerous testing procedures. The three main durability tests that are applicable to PVA engineered composite mortars are hot water immersion, corrosion resistance, and freeze/thaw exposure. The majority of available published literature has sought to evaluate different aspects of the durability of PVA fiber reinforced compounds, such as extreme heat exposure, cyclic loading, and exposure to corrosive environmental conditions. However, few (Wang & Li, 2006; Sahmaran and others, 2009) have evaluated the freeze/thaw durability of a PVA fiber reinforced matrix. Of those few, none have sought to replicate in-situ conditions or the inclusion of the fibers in a brick-and-mortar interface. A review highlighting the relevant studies regarding the durability testing of PVA fiber reinforced materials are summarized in the following section.

2.3.1 Hot Water Immersion Testing

The hot water immersion test has been developed as a way to simulate exposure of a test specimen to a hot and humid environment. The purpose for performing this type of durability study is to determine whether or not PVA fibers will break down within the cement matrix after exposure to several cycles of extremely hot weather. The hot water immersion testing of PVA FRM has not yet been conducted. However, Li and others (2004) sought to investigate the durability of PVA reinforced cementitious composites through a hot water immersion test. The purpose of their study is to subject ECC to hot and humid environmental conditions and determine the changes in pullout behavior and tensile strain capacity associated with hot weather exposure. A similar study sought to investigate the bond strength between the fiber and the matrix as well as the apparent fiber strength after exposure to hot water immersion testing (Lepech & Li, 2005). Under exposure to these extreme heat conditions it is hypothesized that the fibers within the cementitious composite may be subjected to changes, the matrix may change, or the fiber-matrix interface may change. These changes may have a significant effect in modifying the performance of the structure (Li and others, 2004). Durability testing of PVA FRM under laboratory controlled conditions is helpful. However, when the fibers are constructed and introduced into environmental conditions, they may react unexpectedly. As a result of their study, Li and others (2004) as well as Lepech (2005) determine that long-term hot water immersion testing of the FRM composite leads to a reduction in the fiber strength as well as the tensile strain capacity of the ECC. This is a significant finding because it represents a reduction in the strength capacity of the PVA ECC. Since this reduction is known, structural integrity problems may be avoided by utilizing the long-term reduction in strain capacity during design.

A similar study sought to quantify the gains associated with PVA fiber inclusion (Horikoshi and others, 2005). The authors found that the tensile strain capacity of a mortar is increased by approximately 4.5 percent after the inclusion of PVA fibers within the mortar matrix. More significantly, after simulation of exposure to nearly 70 years of hot weather, hot water immersion testing reveals that the increase in tensile strain capacity is reduced to 2.7 percent. This reduction implies that the PVA fibers do increase the strength of the ECC. However, their long-term value of strain capacity must be used in structural applications.

Numerous researchers have found a reduction in the fiber strength as well as the tensile strain capacity of PVA ECC after exposure to hot water immersion testing (Horikoshi and others, 2005; Li and others, 2004; Lepech, 2005). Acknowledgement of apparent losses due to hot weather exposure reveals the importance for evaluating the durability of PVA fiber reinforced composites as they may react differently to differing environments.

2.3.2 Corrosive Testing

The purpose of performing corrosion testing on fiber reinforced materials is to determine whether they can effectively resist exposure to corrosive materials, such as deicing chemicals, salt, seawater, electric currents, and other corrosives, which may come in contact with the composite. One major reason for determining the corrosive resistance of PVA FRM or ECC is to quantify the resistance they provide to corrosion after the formation of cracking. The corrosion of reinforcing bars is one of the main causes for early deterioration of concrete structures; if the inclusion of PVA fibers can help to reduce the transport of corrosives into members, then their use will be highly beneficial in providing a sustainable structure.

PVA fiber by itself is known to be corrosive resistant (Fukinishi and others, 1993). The main interest in determining the corrosive resistance of PVA ECC is to account for the formation of voids within the cement matrix and quantify whether they have a significant impact on the performance of the material. One study which sought to investigate the corrosive resistance of PVA ECC has been conducted (Sahmaran, Li, & Andrade, 2008). In their study, the performance of PVA ECC is evaluated in terms of protection against corrosion of an interior steel reinforcing bar. ECC test specimens are constructed with a centrally placed steel bar. These specimens are then placed in a five percent NaCl solution and subjected to an electric current through the exposed steel bar. After exposure to nearly 300 hours of corrosion testing, ECC specimens exhibit a higher flexural capacity than that of the control mortar. However, a reduction in flexural capacity is noted after corrosion exposure. Overall, the authors suggest that the ECC must have a suggested corrosive environment service life to account for the flexural strength reduction which will occur.

The exposure of ECC to corrosive environments causes a reduction in flexural capacity. A generalization may similarly be applied to the behavior of PVA FRM when exposed to a corrosive environment. The results of previous studies have found significant reductions in strength capacity of PVA reinforced cementitious composites under exposure to hot weather and corrosion simulation. Even though no research exists on the performance of PVA FRM, their behavior can be assumed to perform much like an ECC. These findings for ECC reveal the necessity for determining the long-term durability of PVA FRM subjected to freeze/thaw cyclic loading. Current trends in research suggest that freeze/thaw exposure will cause a reduction in strength capacity as well.

2.3.3 Freeze/Thaw Testing

The standard freeze/thaw durability testing method as developed by ASTM C666 is characterized by two methods: (1) rapid freezing in water and thawing in water; and (2) rapid freezing in air and thawing in water. After selection of one of the above methods, experimental concrete or mortar matrix specimens are constructed. These specimens cannot be less than 3 inches nor more than 5 inches in width, depth, or diameter. Similarly they cannot be less than 11 inches nor more than 16 inches in length. The standardized makeup of each specimen requires them to be composed of concrete or mortar only, and they are required to have a finished face on all six sides of a specimen. This finished, or “tooled” face provides a clean and partially sealed surface for the experimental specimen much like that of the appearance of a completed structure. Following construction of experimental specimens, they are subjected to one of the two exposure methods described above; which impose freeze/thaw weathering on all six sides of the experimental specimens. ASTM C666 sets forth general guidelines regarding the length and number of freeze/thaw cycles to expose a specimen to extreme weathering conditions. These methods allow for complete saturation of the specimen and exposure to numerous freeze/thaw cycles. The testing then determines the dynamic modulus of the matrix as a way to quantify interior cracking and deterioration of the specimen. The response of the test specimens after exposure to accelerated harsh environmental conditions provides an understanding of their durability. Current research pertaining to the freeze/thaw durability testing on engineered cementitious composites is described below.

Due to their high permeability, cementitious materials are highly susceptible to breakdown as a result of exposure to freezing and thawing. As water penetrates into the pore spaces the concrete or mortar becomes saturated. Upon saturation, freezing causes the water to expand, distressing the cementitious material. After extended exposure to these stresses caused by freezing and thawing, concrete or mortar will be subjected to losses in material in the form of spalling or scaling of the surface. Spalling and scaling are noted as a loss of surface material due to weathering. This weakens the material, causing a reduction in the compressive and flexural strength of the binder matrix. The purpose for determining the freeze/thaw durability of cementitious materials is to quantify their ability to resist exposure to harsh environmental conditions. The freeze/thaw durability of a material is determined through rapid exposure of a test specimen to a specified number of freezing and thawing cycles. If the specimen experiences a reduction in strength at the conclusion of exposure, then this reduction is reported as design criteria for its structural use. A description of the procedure and results of previous freeze and thaw testing are discussed in the following section.

The freeze and thaw durability of PVA engineered cementitious composites has been previously determined (Wang & Li, 2006; Sahmaran, Lechemi, & Li, 2009). According to the ASTM C666 procedure, the determination of the resistance of concrete specimens to rapidly repeated cycles of freezing and thawing is most commonly used. The test specimens are constructed with adherence to ASTM C192/192M and then subjected to either freezing in air and thawing in water, or freezing in water and thawing in water.

Previous authors have sought to determine the freeze and thaw durability of PVA reinforced cementitious composites. One such study conducted by Wang and Li (2006) subjected fiber reinforced cementitious composite beam specimens containing two percent by volume PVA fibers to rapid freeze/thaw cyclic loading. Their study follows standard ASTM C666 with regards to rapid freezing and thawing in water. As specified, the authors allow their ECC beam specimens to cure 14 days prior to exposure to freezing and thawing. The dynamic modulus provides a relationship for the stress and strain behavior of the test specimen as a function of the number of freeze and thaw cycles which it has been exposed to. The authors report a description of the change in the dynamic modulus as a function of the number of freeze-thaw cycles which is shown in Figure 2.2.

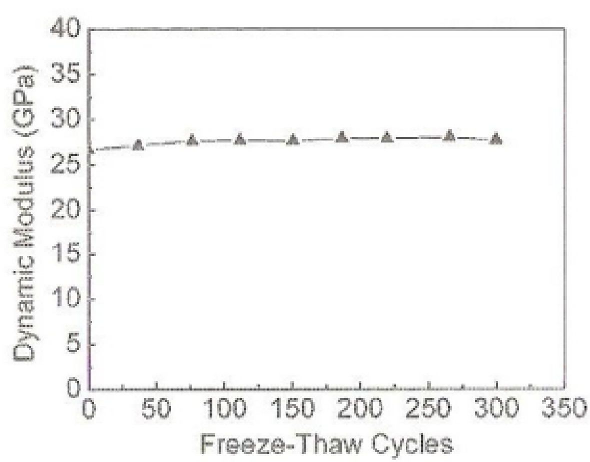

Figure 2.2 Dynamic Modulus vs. Freeze/Thaw Cycles

As can be interpreted from Figure 2.2, the dynamic modulus of the ECC remains virtually unaffected from exposure to rapid freeze and thaw exposure throughout the duration of the testing. In comparison to their control specimens constructed of non-air-entrained concrete, the ECC exhibited very durable behavior. The control specimens did not last more than 100 cycles before deterioration required their removal from testing. After completion of 300 cycles, the tensile strain capacity of the ECC experience a slight reduction when compared to specimens of the same age not subjected to freeze-thaw cycles. The strain capacity of specimens not subjected to freeze and thaw exposure is noted as 3 percent with a standard deviation of 0.5 percent. The reduction in strain capacity is noted as 2.8 percent with a standard deviation of 0.6 percent. Much like the results of the hot water immersion testing performed by Li and others (2006), and the corrosion testing performed by Sahmaran and others (2008), extreme exposure to freezing and thawing presents a reduction in mechanical strength of the ECC. This strain reduction capacity is significant proof of the necessity for in-situ evaluation of the PVA FRM. This will need to be conducted in a pure FRM prism as well as in a brick-and-mortar prism.

The results of the freeze-thaw testing performed by Wang and Li (2006) also determine the compressive strength of ECC specimens after exposure to freeze-and-thaw cycles. As expected, the specimens experience a reduction in compressive strength. When compared with ECC control specimens cured at room temperature of the same age, the ECC exhibit a 22 percent reduction in compressive strength after 300 cycles. This is representative of a very large reduction in strength that needs to be accounted for in initial design.

The freezing and thawing resistance of PVA composites has been evaluated in another study by Sahmaran, Lachemi, and Li (2009). In the study, an engineered cementitious composite is composed of PVA fiber reinforcing. This ECC matrix is then subjected to 300 cycles of accelerated freezing and thawing according to ASTM C666 (2007). The deterioration of specimens is determined by computation of mass loss. In order to determine the internal damage of specimens, the changes in pulse velocity through the ECC prism is measured. ASTM C666 specifies the use of the resonant frequency method rather than the pulse velocity method; however, the authors claim that previous research also allows the pulse velocity method for measuring the deterioration of specimens under freezing and thawing cycles. The findings of the researchers indicate that the prisms experience minimal internal mass losses due to freeze/thaw exposure. The prism surface is virtually undamaged. When compared with the control ECC matrix not containing PVA fibers, the PVA ECC exhibits excellent performance after 300 cycles. The control ECC matrix requires removal from the freeze and thaw testing chamber after 210 cycles. The condition of the PVA ECC after exposure to freeze and thaw cycles indicates a strong resistance to breakdown from freezing and thawing. The authors have found that the addition of PVA fiber to the ECC matrix causes an increase in the viscosity. This increase in viscosity increases the amount of entrapped air-voids inside the matrix. Sahmaran and others (2009) attribute the exceptional performance of their samples to the large pore size created by the inclusion of PVA fibers within the mortar. The reasoning behind this is the generalization that large pores are beneficial in providing freeze/thaw resistance (Hall & Hoff, 2002). The large pore spacing allows dissipation of stresses within the matrix. An effective pressure relieving strategy is to employ air-entrainment within mortars; the effect of the randomly distributed PVA fibers is assumed to form a network which enables entrained air bubbles to converge creating large entrapped air voids (Sahmaran and others, 2009). The results of their study conclude that the large accumulation of air voids within the PVA ECC provides exceptional freeze and thaw durability. Aside from the accumulation of large pore spaces, another contribution to the excellent freeze/thaw resistance of PVA ECC claimed by Sahmaran and others (2009) is that their high tensile strength and fracture resistance provide internal and external bridging of these pore spaces. This bridging resists the "spreading" of the mortar when internal expansion occurs during freezing. The bridging effect is believed to be the major resistor to deterioration during freeze and thaw cycles.

Aside from research composed in the laboratory on the freeze and thaw durability of PVA ECC, one study has been conducted to determine the in-situ ECC behavior (Li & Li, 2009). In the study, a small patch of PVA reinforced ECC is constructed as a repair on a bridge deck. Similarly, another portion of the bridge deck is repaired with a pre-packaged mixture of Portland cement and plaster of Paris. These repair patches are then subjected to identical vehicular loading as well as environmental loading over the course of four months of winter exposure in southern Michigan, U.S. Environmental loading consists of possible exposure to shrinkage, temperature change, freezing and thawing, chloride exposure, and salt-scaling. Upon loading, the ECC exhibit exceptional durability when compared with the Portland cement repair. No spalling or other deteriorations are found in the ECC patch; however, the control patch experiences severe deterioration with cracking larger than 3.5 millimeters. When the entire bridge deck is reconstructed two years later, the ECC experienced minor cracking. This study is significant because it describes the behavior of PVA ECC with respect to their field performance rather than their laboratory performance. As a result of their study, the in-situ performance of the

PVA ECC exhibits promising durability under exposure to harsh environmental conditions and heavy traffic loading.

2.4 SUMMARY

This chapter reviews the existing literature that is pertinent to the study of PVA FRM and cementitious composites. From this review, several points relevant to this study are extracted:

1. Incorporation of PVA fibers yields an increase in the out-of-plane resistance, crack width propagation resistance, flexural resistance, and does not have a direct effect on the compressive strength of a mortar.
2. Inclusion of PVA fibers may cause an increase in the moisture absorption capabilities of the mortar.
3. Inclusion of too little or too much fiber within the mix design does not benefit the mortar.
4. Exposure of PVA ECC to hot and humid environments as well as corrosive environments yields a reduction in flexural and compressive strength capacity. This reduction must be utilized in structural design of members.
5. Freeze-and-thaw testing has been conducted on PVA ECC. The results yield a decrease in strain capacity; however, the freeze and thaw durability testing has not been performed on PVA FRM.

Overall, the ASTM standard for evaluating freeze/thaw durability of mortars does not accurately represent all factors influencing the freezing and thawing of a structure. The apparent pitfalls associated with ASTM C666 (2007) reveal the importance for developing a standardized test to evaluate the freeze/thaw durability of a fiber reinforced mortar as a result of in-situ conditions. Based on the current research, the purpose of this study is to evaluate the freeze/thaw durability of PVA FRM. This is done utilizing a modified approach to ASTM C666 (2007) in order to represent in-situ conditions. This modified approach is presented in Chapter 3 of this study.

CHAPTER 3: FREEZE/THAW DURABILITY TESTING PROCEDURE

3.0 INTRODUCTION

The objective of this chapter is to define the experimental design procedure for the in-situ freeze and thaw durability of polyvinyl alcohol (PVA) fiber reinforced mortars (FRM). This is accomplished by modifying ASTM C666 (2012) in an attempt to more accurately represent environmental conditions. The proposed methodology for freeze and thaw testing and moisture absorption capacity is discussed in the following sections. Proposal of uncertainties associated with ASTM C666 as well as their corresponding remedies are presented in this chapter. Through providing justification for the changes necessary to accurately determine in-situ freeze and thaw durability of PVA FRM these modifications are validated.

A description of the masonry materials and their corresponding properties selected for obtaining the freeze and thaw durability of PVA FRM is also presented in this chapter. This provides background information regarding the behavior of the constructed test specimens. A description of the composition of the test specimens and their construction processes is provided at the conclusion of this section.

After the presentation of the design testing methodology, testing materials, testing material properties, and the construction methods, a detailed description of the experimental testing procedure is provided.

3.1 DISCUSSION OF TESTING METHODS

The purpose of this study is to evaluate the freeze/thaw durability of PVA FRM. As previously discussed in the literature review, there are many factors which may have an effect on the freeze/thaw durability of PVA FRM prisms. One of these is moisture absorption capacity, which is determined in conjunction with the freeze/thaw durability. A description of current experimental testing techniques and the necessity for changes within these techniques is given in this section.

3.1.1 Moisture Absorption

As a preliminary investigation into the freeze/thaw behavior of the masonry prisms, this study also seeks to determine the relationship between the amount of PVA fibers present in the mortar and the degree of saturation of the mortar. The literature review discusses the properties of the fibers as capable of absorbing moisture. Previous research has failed to comment on the moisture absorptive capabilities of PVA FRM. The ability to bring moisture into the mortar may saturate the masonry units. Saturation of a testing specimen is the key factor for deterioration under freeze and thaw cyclic loading. There exists a maximum degree of saturation that a specimen can undergo before the freezing will begin to cause structural damage (Ronning, 2001). A determination of this maximum degree of saturation can then be compared to the in-situ degree of saturation in order to determine whether frost damage will present an issue to the integrity of the structure. ASTM C642 (2012) provides a test method for determining the moisture absorption of a specimen. This method is directly related to the degree of saturation and is employed to determine the moisture absorption of PVA FRM.

ASTM Standard Test Method for Density, Absorption, and Voids in Hardened Concrete C642 (ASTM, 2012) is used for determining the moisture absorption of the mortar cube samples. ASTM C642 is used to determine the saturation characteristics of varying PVA FRM mix designs selected from the database developed by Erdogmus and others (2010). The use of ASTM C642 gives an estimate for the saturation characteristics of the mortar with and without the inclusion of PVA fibers. Interpretation of this data aids in the evaluation and behavior of the PVA FRM under freeze/thaw cyclic loading. The analysis of the saturation of the control mortar and the PVA FRM is conducted on 2-inch mortar cube samples. The full testing procedure is discussed in Section 3.3 under the moisture absorption experimental design heading.

3.1.2 Issues with Current Freeze/Thaw Testing

The current ASTM Standard C666 for has been summarized in Chapter 2. This section presents issues and alterations to current standards in order to represent in-situ conditions more accurately.

One major issue present with the ASTM C666 testing method is that it provides a durability rating for specimens created and contained within a laboratory, but it does not accurately represent in-situ conditions. The conditions as seen in the field may vary greatly due to specimen makeup, finishing, and freezing mode. The ASTM C666 test is the standardized and most widely accepted method for freeze/thaw durability testing of mortars in the United States. After reviewing this procedure, it is determined that strict adherence to the methodology of ASTM C666 does not adequately replicate the in-situ characteristics of a masonry structure. However, it is important to utilize standardized testing methods to render accurate and reproducible results. The purpose of this section is to present a suitable methodology for determining the in-situ freeze and thaw durability of PVA FRM. It is desired to maintain the generalizability of the proposed freeze/thaw testing. Therefore, for the purpose of this study, the ASTM C666 standardized test method for freeze-and-thaw durability of concrete members is modified to represent in-situ conditions. A brief list containing the modifications to ASTM C666 is given below:

1. Specimens are subjected to cyclic freeze/thaw loading on a single face rather than on all sides of a specimen.
2. Specimens for testing are not to be completely tooled on all sides.
3. Protruding "whiskers" present on specimens are not to be removed.
4. Specimens are constructed of brick-and-mortar prisms.
5. A durability rating of specimens is based upon strength testing before and after freeze/thaw exposure.

Accomplishing the above modifications provides a better representation of the in-situ freeze/thaw durability of the PVA FRM. The freeze/thaw testing of masonry mortars requires a complex analysis to duplicate in-situ conditions. Analysis of testing specimens cannot be expected to last the numerous years that it would take to replicate weathering conditions. As a result of time constraints, accelerated testing conditions are desired to represent the weathering that a structure would endure over time. This is done by simulating an aggressive weathering pattern on a test specimen, enabling the analysis of the durability of the mortar and brick to be obtained within a timely manner. In the case of determining freeze-and-thaw durability of testing specimens, rapid exposure to a freezing temperature followed by a thawing temperature simulates one cycle of experimental exposure.

Many factors arise when determining the in-situ weathering of a masonry structure. For example, the temperature present in a masonry structure is rarely uniform due to ambient temperatures that differ from the outside to the inside of a structure. Wall orientation and geographic location greatly influence the temperature changes within the brick and mortar (Ritchie & Davison, 1968). The presence of a temperature difference from one surface of a masonry wall to the opposite surface causes internal stress distributions to become apparent. Past research which has utilized ASTM C666 exposes test specimens to a uniform freezing and thawing temperature on all sides of the specimen. Temperature changes within the masonry structure directly influence the severity of the freeze/thaw cycles experienced by a masonry structure. Uniform loading does not accurately represent in-situ conditions. Because ASTM C666 exposes all specimens to a uniform temperature, it provides an unrealistic durability rating for its testing specimens. The effect of freezing and thawing on all six sides of a prism may help to alleviate the stress distributions that develop as a result of the temperature disparity throughout the specimen. Past research suggests that a masonry wall under normal operating conditions experiences freezing on only one face (Boynton & Gutschick, 1964). For determining the in-situ freeze and thaw durability of PVA FRM test specimens will be exposed on a single face.

Previously discussed literature describes freeze/thaw durability tests performed on PVA engineered cementitious composites (ECC) in accordance with ASTM C666. However effective, ASTM C666 presents many issues when analyzing the durability of fiber reinforced mortars. First, the test specimens are created as a pure mortar prism which is finished on all six faces. In practice, no portion of a structure is made up of a large “block” of mortar; it is included between the joints of masonry units as a way to adhere the structure together. When utilized in the joints of masonry units, a relatively small surface area is exposed to the elements. The smaller portion of mortar present with joints may or may not distribute thermal stresses differently than a larger mass of mortar. In order to accurately interpret in-situ conditions, testing specimens need to be representative of materials used for construction. Therefore, masonry prisms are used as the standardized testing specimen rather than the mortar prisms specified in ASTM C666.

The finishing effect on all sides of the test prism presents another issue. In modern construction, the mortar is completely finished or tooled. The effect of finishing decreases the amount of moisture that can seep into the mortar by providing an external water tight barrier (Simmons, 2011). This barrier does not allow the mortar to become saturated and effectively reduces the amount of damage that may be experienced due to interior freezing and expansion. The presence of fibers within the mortar does not allow for complete finishing of the outer surface. This is apparent through the presence of "whiskers." These protruding fibers extend from the mortar and may bring moisture into the mortar as previously discussed. This is possible as the fibers bridge pore spaces and allow moisture to travel inward. Increasing moisture within the specimen will cause it to be more susceptible to freeze/thaw breakdown.

Another issue with previous freeze/thaw durability testing is the lack of information on the inclusion of PVA FRM in a brick-and-mortar interface. The literature review has described current research as providing information on the freeze/thaw durability of PVA ECC as a mortar cube. However, a mortar cube does not provide an interpretation of the performance of the brick-and-mortar working together as one unit. PVA FRM are currently used in strengthening and repointing masonry structures. The purpose of this research is to provide an understanding of the in-situ performance of a PVA FRM. The bonding between the brick and mortar may cause unforeseen issues to freeze/thaw durability. An example of this may be an increase in pore spacing at the brick and mortar bond interface. An increase in void spaces presents an issue for freezing and thawing that may not be seen when testing pure mortar prisms. In order to provide a complete understanding of the in-situ performance of PVA FRM, the experimental samples must be representative of field placement. The following sections give an understanding of the materials and procedures for constructing the test specimens for determining the in-situ freeze and thaw durability of PVA FRM.

3.2 DESCRIPTION OF MATERIALS

This section provides a description of all the materials that are used in the experimental design of this thesis. A description of the mechanical properties of the materials is also included in this section. A general description of the tools and methods used for constructing test specimens is given at the conclusion of this section.

3.2.1 Materials

The materials selected for determination of the freeze/thaw durability of PVA FRM have been selected to closely resemble those used to develop the database developed by Erdogmus (2010). The materials used to make up the testing specimens are Type N mortar, PVA fibers, and standard solid construction bricks. A description of each of these materials and its properties is given below.

3.2.1.1 Type N Mortar

The mortar selected for use in determining the freeze-and-thaw durability in this study is a dry pre-blended mixture containing Portland cement, hydrated lime, and dried masonry sand. This mixture has been specialized by SPEC MIX© in order to meet ASTM C270 and ASTM C1714 requirements. The specific proportions of the mixture can be defined respectively as 1:1:6 Portland cement, hydrated lime, and dried masonry sand respectively.

Type N mortar is selected for combination with PVA fibers as a result of its low compressive strength. The use of a low compressive strength repair mortar rises from the desire to protect the integrity of the historic brick that the mortar is re-pointing. With a low compressive strength, the mortar will fail prior to the brick crushing. The 28 day compressive strength of the SPEC MIX© Type N mortar is estimated to be 1730 psi (SPEC DATA, 2012). The development of this mortar has been formulated for superior masonry bond, water retention, and shelf life. Additionally, this mortar is easily accessed and widely available for purchase across the United States.

3.2.1.2 Polyvinyl Alcohol Fiber

The benefits and pitfalls associated with the use of PVA fibers have been previously discussed in the literature review of this thesis. It is the desire of this experiment to evaluate the freeze and thaw durability of previously established mixtures of PVA fibers with Type N mortar. Therefore, two different fiber types are utilized in conjunction with the aforementioned Type N mortar. The fiber proportions are illustrated in Section 3.4. The two fiber types that have been suggested for use in masonry repair by Erdogmus (2010) are commonly referred to as RECS7 and RECS15.

The fibers used in this experiment have been obtained from NYCON Incorporated. PVA fibers are known for their remarkable ability to create a fully-engaged molecular bond with mortar and concrete that is 300 % greater than other fibers (NYCON, 2012). A visual interpretation of fiber size, length, and makeup for the RECS7 and RECS15 fibers is provided in Figure 3.1.

(a) (b)

Figure 3.1 PVA (a) RECS7 and (b) RECS15 Fiber Size

As can be seen from Figure 3.1, the RECS15 fibers have an increased diameter and length when compared to the RECS7 fibers. Differing fiber diameter and length may alter the fiber capability for bridging pore spaces and controlling thermal effects within the mortar. According to NYCON, the main purpose of PVA fibers is their capacity to control plastic shrinkage and thermal cracking. The ability to improve abrasion resistance of concrete or mortar is another benefit. For technical reference, Table 3.1 illustrates the physical and mechanical properties of the two fibers.

Table 3.1 Physical and Mechanical Properties of RECS7 and RECS15 Fiber

PVA Properties	RECS7	RECS15
Filament Diameter	5 Denier (24 Microns)	8 Denier (38 Microns)
Fiber Length	0.25 inches (6 mm)	0.375 inches (8 mm)
Specific Gravity	1.3	1.3
Tensile Strength	240 ksi	240 ksi
Flexural Strength	5500 ksi	5700 ksi
Melting Point	435 Fahrenheit	435 Fahrenheit
Water Absorption	Less than 1% by weight	Less than 1% by weight

Table 3.1 demonstrates the differences between the RECS7 and RECS15 fibers. Both of these fibers have exceptionally high tensile and flexural strength capacities as well as water absorption capabilities. The major difference between the RECS7 and RECS15 fibers is the fiber length and diameter.

3.2.1.3 Construction Brick

The selection of a suitable brick for the construction of masonry testing prisms in the freeze and thaw durability determination of this thesis relies greatly on availability. A solid core brick has been selected to replicate brick which would be found in historic masonry structures and is typical in unreinforced masonry construction. The solid core brick also allows for complete bonding of the mortar to the brick. This ensures the best results when testing flexural bond strength of the masonry prisms as the mortar will be in maximum contact with the brick.

The brick selected is a solid core concrete brick and has been developed by Oldcastle. This red concrete brick meets ASTM C90 specifications for use in construction of foundations or above grade masonry walls. The uniformity and shape of these bricks can be seen in Figure 3.2.

Figure 3.2 Oldcastle Concrete Brick

These concrete bricks are constructed from solid concrete with nominal dimensions of 3.75 inches x 2.25 inches x 7.75 inches. The estimated compressive strength of the brick is 1900 psi. These bricks have been selected because their compressive strength is larger than the compressive strength of the Type N mortar. This ensures that the mortar will fail in compression prior to the failure of the brick. In addition to their compressive strength, a concrete brick has been selected in lieu of a clay brick (typical of historic construction) due to the fact that concrete brick proves more durable when exposed to freeze/thaw weathering than a clay brick. This enables the study to evaluate the performance of the PVA mortar in a brick-and-mortar interface without issues that may arise due to break down of the brick.

3.2.2 Experimental Testing Specimens

In order to perform the freeze-and-thaw durability testing of PVA FRM, it is necessary to create specimens for experimental testing. For the purpose of this study, mortar cube specimens and masonry prism specimens are used. A description of their construction methods and experimental testing is given in the following section.

3.2.2.1 Mortar Cube Specimens

The mortar cube specimens are created in order to determine the moisture absorption rate of the PVA FRM with respect to plain Type N mortar. The construction of 2-inch mortar cubes is done in accordance with ASTM C109, The Standard Test Method for Compressive Strength of Hydraulic Cement Mortars Using 2-in. Cube Specimens (ASTM C109, 2012).

In order to create the 2-in. mortar cube specimens it becomes necessary to use standardized molds. These molds have been manufactured from stainless steel and constructed to ensure the uniform size and curing on all six sides of the cube specimen. A visual description of a typical beam mold is given in Figure 3.3.

Figure 3.3 2-in. Mortar Cube Mold

During construction, the cubes are constructed using two lifts. Each lift is tamped by hand using a rod 32 times to complete one round of tamping. After completion of four rounds of tamping per lift, the remaining void space in the mold compartment is then filled. The tamping of the second layer is completed in the same fashion as the first layer, except the tamping is done with a gloved finger rather than a rod. This tamping ensures that the specimens occupy the entire mold and adhere to the desired standardized size. Upon completion of the second round of tamping, any remaining mortar that is protruding from the top of the mold is cut off using a sawing motion with the straight edge of a trowel. The top of the mold is then placed to ensure no moving of the mortar. The complete mold is placed in a plastic bag to ensure no loss of moisture during the 28-day curing process.

3.2.2.2 Masonry Prism Specimens

The masonry prism specimens are constructed in order to determine the effect of in-situ freeze and thaw exposure on the PVA FRM. Construction of the masonry prism specimens consists of standardized 5-stack and 7-stack specimens.

The construction of a typical 5-stack specimen is described in ASTM C1314 Standard Test Method for Compressive Strength of Masonry Prisms (2012). In this standard, solid unit prisms are constructed utilizing a jig. The set up and use of the jig can be seen in Figure 3.4.

Figure 3.4 Experimental Jig

The use of a jig ensures plane surfaces on all sides of the specimen and contributes to the specimen being level; a key factor when applying an axial load to determine the compressive strength of the prism. The specimens are constructed by placing a brick at the base of the jig, then applying a layer of mortar slightly larger than 3/8 of an inch and placing another brick on top of the mortar. Tamping the brick into place is necessary to gain proper adhesion to the mortar. When constructing the prisms, tamping on the brick is utilized to obtain a standard mortar thickness of approximately 3/8 of an inch. After the specimen has been constructed in this manner, then the trowel is used to finish the edges of the mortar. Finishing the edges of the mortar provides an aesthetically pleasing specimen and helps to seal it from moisture entering or escaping the prism. A 7-stack masonry prism is constructed in the same manner as the 5-stack masonry prism. The 5-stack masonry prisms are used to calculate the compressive strength of the brick-and-mortar as they act together. The 7-stack masonry prisms are used to calculate the flexural bond strength of the masonry. A 7-stack specimen is required to gain the necessary length of a specimen because strength testing requires a constant moment to be produced within the center one-third span of the experimental specimen. Without the addition of two courses, specimens would be too short to provide a maximum moment in which the bond strength can be evaluated. Upon completion of the masonry specimens, they are placed in a plastic bag at room temperature (70 degrees Fahrenheit) to prevent moisture loss. The prisms are allowed to cure for 28 days prior to testing.

3.3 EXPERIMENTAL DESIGN

In this section, a detailed description of the experimental design for determining the moisture absorption capacity of PVA FRM is given. Following the description of the moisture absorption capacity is a description of the procedure for the in-situ freeze and thaw durability.

3.3.1 Experimental Design of Moisture Absorption Capacity

The moisture absorption capacity of PVA FRM is determined to illustrate the capacity of the mortar to absorb moisture. This is done in accordance with ASTM Standard C642 (2012). Additional steps are added to the implementation of this standard and are included in the description below.

ASTM C642 Standard Test Method for Density, Absorption, and Voids in Hardened Concrete is used for determining the absorption rate of PVA FRM. The moisture absorption of the mortar is calculated from experimental data performed on 2 in. mortar cubes. This is accomplished through three steps as outlined below:

1. Determine the dry mass of the testing specimen after completion of a 28 day curing cycle.

2. Completely immerse the specimen in water at approximately 21 C after drying. The immersion shall not last less than 48 hours; it is desired to interpret the absorption as a rate so the absorbed water weight will be taken as a function of time.
3. Illustrate the overall moisture absorption as a percent of total weight.

Completion of the outlined tasks gives a representation of the absorptive capacity of PVA FRM. As insight about the in-situ absorptive characteristics is desired, the mortar cubes are not oven dried prior to immersion. Oven drying of the specimens may give an inaccurate representation of the net amount of moisture that a PVA FRM is capable of absorbing. Another deviation from ASTM Standard C642 is the timing of the saturation. This enables an interpretation of the absorptive capabilities of the mortar and brick as an exposure rate. This is done to verify whether the inclusion of PVA fibers within the mortar may increase, decrease, or have no net effect on the absorptive rate of the mortar. Future research may be able to relate the exposure of an in-situ wall with the exposure rates determined here to calculate the net amount of absorbed moisture.

3.3.2 Experimental Design of Freeze and Thaw Testing

In this study, there are multiple aspects of the freezing-thawing testing that need to be modified to better represent in-situ conditions. Aspects to be modified are the preparation of the testing prisms, the freezing phase, and the thawing phase. Descriptions of the current standard, targets within the project to adhere to the standard, as well as the proposed modifications to the standard are contained in the following sections.

3.3.2.1 ASTM C666 Standard test method for resistance of concrete to rapid freezing and thawing.

Recall that ASTM C666 is characterized by two procedures: Procedure A which requires rapid freezing and thawing in water, and Procedure B which requires rapid freezing in air and thawing in water. The standard has a number of pre-determined requirements that are discussed in detail through the following sections. For the purposes of this experiment, modifications to Procedure B are utilized to carry out testing of the specimens.

3.3.2.2 Apparatus

According to ASTM C666, the freezing and thawing apparatus shall consist of a suitable chamber in which specimens may be subjected to the specified cycle. The chamber must be arranged in a manner which surrounds each specimen by a minimum of 1/32 of an inch of water and a maximum of 1/8 of an inch of water. The temperature of the chamber shall be uniform to 6 degrees Fahrenheit throughout the apparatus at any given time. Also, each specimen shall be supported in such a way that the temperature of the heat-exchanging medium will not will be transmitted directly through one face of the specimen.

In order to accomplish the tasks necessary for operation of the apparatus, a commercial freeze-and-thaw chamber is purchased from Caron Incorporated and is shown in Figure 3.5.

Figure 3.5 Experimental Freeze/Thaw Chamber

The specifications of the environmental chamber are presented in Appendix A of this thesis. This chamber is designed to create exposure to extreme environmental conditions and is able to accommodate the cyclic loading discussed later in this thesis. However, in order to replicate in-situ conditions, the specimens are subjected to water immersion on one face only and not on all sides as specified by ASTM C666. This is done to represent conditions experienced by an existing masonry structure (Ritchie & Plewes, 1961). The water exposure on one face is still limited to a minimum of 1/32 of an inch and a maximum of 1/8 of an inch. as described in ASTM C666. Furthermore, the horizontal airflow system within the chamber generates an evenly distributed temperature distribution across all shelf locations. With this design, uniformity of temperature is always maintained throughout the chamber to within 0.5 degrees Fahrenheit. The distribution of the airflow system also conforms to ASTM C666 as it exposes specimens to temperature loading equally on all faces. Following ASTM C666 with an alteration to the facial freezing represents in-situ conditions much better than saturation and freezing on all six sides of a masonry prism (Boynton & Gutschick, 1964).

In an attempt to maintain comparison between the methods of previous studies the mortar cube specimens are fully submersed and subjected to freezing on all six sides. This testing provides a “worst-case” scenario for the performance of the mortar under extreme freeze/thaw exposure.

3.3.2.3 Temperature-Measuring Equipment

ASTM C666 requires equipment for measuring the temperature at various points within the specimen chamber to an accuracy of 2 degrees Fahrenheit of actual temperature. The environmental chamber provides temperature sensors at several locations within the interior to digitally monitor temperature. Alarm settings are set to alert when the temperature of the chamber exceeds the parameters described in ASTM C666.

3.3.2.4 Test Length Change Comparator

ASTM C666 requires all dial gage micrometers used for determining length changes in specimens to conform with ASTM Specification C490 prior to the start of measurements (ASTM, 2011). In order to meet these requirements, a standardized micrometer is utilized. This micrometer is capable of measuring dimensions to the nearest thousandth of an inch.

3.3.2.5 Scales

ASTM C666 requires that scales measuring the weight of samples must have a capacity of approximately 50% greater than the mass of the specimens, and be accurate to at least 0.01 pounds within the range of 10% of the specimen mass. For example, if an experimental specimen weighs twenty-five pounds, then the scales are required to detect changes in mass within a range of -2.49 pounds to 2.51 pounds. For the purpose of this experiment, an Adam CPW plus Portable Scale is utilized with a maximum capacity of 165 pounds and an accuracy of 0.05 pounds. This capacity and accuracy are within the allotted requirements for ASTM C666 (2012).

3.3.2.6 Tempering Tank

When specimens are not being subjected to freeze and thaw cycles, ASTM C666 requires that they be kept within a range of the target thaw temperature. This is done to ensure no additional damage is experienced by the specimens when they are not subjected to testing. The chamber must be able to maintain specimens within -2 degrees Fahrenheit and 4 degrees Fahrenheit of the target thaw temperature. Also, specimens are to be kept at the thawing temperature after exposure to freeze/thaw cycles. The chamber provided by Caron Incorporated, which has been previously discussed in the Apparatus section of this chapter, is utilized as the tempering tank while specimens are not subjected to freezing-and-thawing. All requirements for the tempering tank are met within the chamber.

3.3.2.7 Freezing and Thawing Cycle

ASTM C666 has specific details regarding the freezing and thawing cycles inflicted upon specimens. The position of specimens must be altered frequently to ensure that they are all subjected to extremes of the chamber. In the previously described apparatus, all specimens are subjected to uniform temperature ramping throughout the entire chamber. Therefore, rotation of positions within the chamber is not necessary.

The freezing and thawing cycle shall consist of alternately lowering the temperature of the specimens from 40 to 0 degrees Fahrenheit and back to 40 degrees

Fahrenheit. One cycle shall not be completed in less than 2 hours nor greater than 5 hours. The capabilities of the chamber allow for controlled ramping of a profile to conform to specifications within the standard. Completion of one cycle has been programmed for finish in 3 hours and 36 minutes. The standard also explains that the period of transition between freeze/thaw phases of the cycle shall not exceed 10 minutes. The automated program ensures that the transition period is less than ten minutes. The temperatures experienced by specimens within the chamber are represented in Figure 3.6.

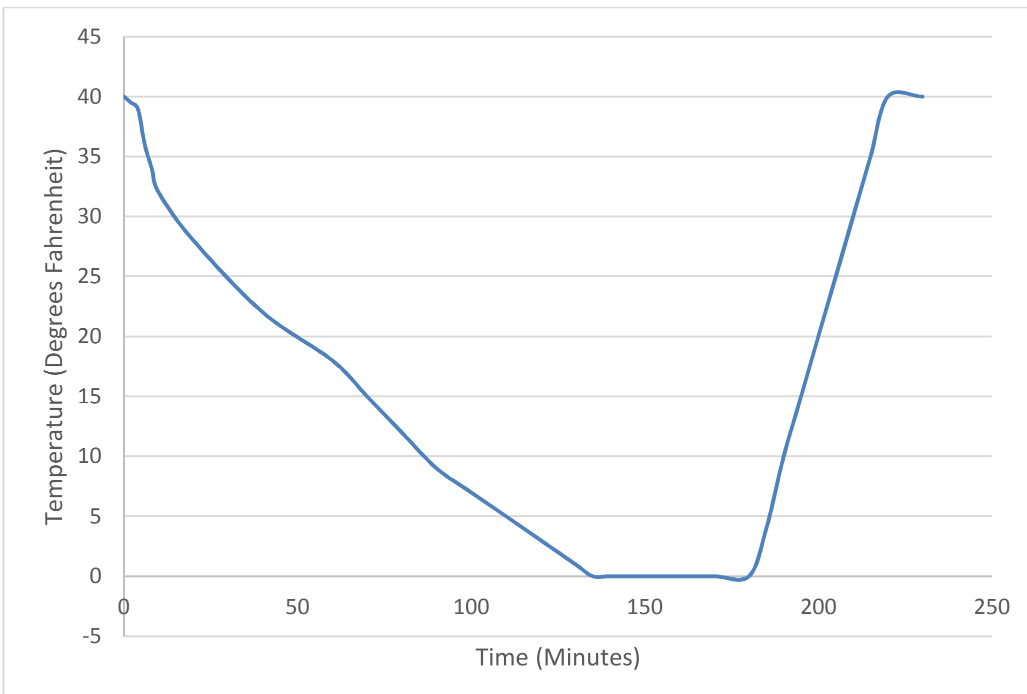

Figure 3.6 Typical Freeze/Thaw Cycle Profile

As can be seen from the figure, specimens within the chamber are accelerated to an internal temperature of zero degrees Fahrenheit. Once there, they are maintained at that temperature for approximately forty-five minutes before transitioning back to a temperature of forty degrees Fahrenheit. Furthermore, the difference between the temperature at the center of a specimen and its surface temperature does not exceed fifty degrees Fahrenheit at any given time. This is accounted for within the chamber. The interior sensors trigger an alarm system if temperature deviates from the target temperature by more than two degrees Fahrenheit.

3.3.2.8 Test Specimens

ASTM C666 describes typical specimens to be utilized for freeze/thaw testing. As described in the literature review, the preparation of the testing prisms need to be modified to represent in-situ conditions. Previous studies performed by Wang and Li (2006), and Sahmaran and others (2009) performed freeze/thaw testing on concrete prisms. The traditional prism consists of a typical prism of mortar, a specimen which is not representative of field conditions for a masonry structure. In the proposed method of study, masonry prisms and mortar cubes are used. The use of masonry prisms has been previously discussed in Section 3.3.2 of this thesis. The use of mortar cubes is done to allow the results to be compared with previous studies.

ASTM C666 requires that specimens for use shall be made and cured in accordance with ASTM standard C192/C192M (2012). Alteration to the standard is justified in the use of different specimens for in-situ determination. Masonry specimens are made in accordance with ASTM C270 (2012). Mortar cube specimens are made in accordance with ASTM C109 (2012).

Additionally, all specimens to be compared with each other initially shall be of the same nominal dimensions. Prior to testing, measurements are taken to ensure that all specimens are of the same nominal dimensions.

3.3.2.9 Procedure

ASTM C666 requires that all specimens be allowed to cure for 14 days prior to testing. This is done to ensure that specimens reach a degree of strength before extreme freeze/thaw exposure. Specimens tested in this study are allowed to cure for 28 days prior to testing. By allowing specimens to cure for 28 days, it can be assumed that they gain the proper amount of hydration to be representative of field strengths. After creation and curing of the specimens, they are placed in a container to represent in-situ conditions prior to placement within the chamber. As previously discussed, the freeze/thaw exposure is accomplished through exposure on a single face of the prism. An example of the masonry prism sample exposure and layout is given in Figure 3.7.

Figure 3.7 Masonry Prism Sample Freeze/Thaw Exposure

As shown in the figure, the masonry prism test specimens are exposed to moisture on a singular face at the bottom of the pan. Exposure to moisture on a single face simulates uni-directional freezing and thawing when induced to cyclic loading. The prisms are allowed to saturate one face of the prism prior to being brought to a temperature within -2 and +4 degrees Fahrenheit of the target thaw temperature. In order to get within the target temperature, the specimens are allowed to acclimate themselves within the chamber prior to initiation of cycles. During acclimation, specimens are contained in the sealed plastic bag to prevent against loss of moisture.

After exposure to 36 cycles, the specimens are removed in a thawed condition and tested for length change measurements. This procedure is repeated until the specimens have been subjected to 300 cycles or until they experience a 0.1% contraction in length change.

3.3.2.10 Calculations

ASTM C666 requires the measurement of the relative dynamic modulus of elasticity for each specimen. Determination of the compressive and flexural bond strength of the specimens before and after exposure is done to interpret the strength reduction rather than measuring the relative dynamic modulus of elasticity. This gives a better representation of what is expected of the masonry and mortar in the field. An overall durability factor is presented for compressive and flexural bond strength of the masonry prisms, and compressive strength of the mortar cubes. At the conclusion of the testing, the overall length change of specimens is presented in accordance with ASTM C666.

3.4 SUMMARY

All changes made to ASTM C666 are proposed to better represent the in-situ durability testing of PVA FRM. Throughout this chapter the experimental design of the project has been presented. All proposed alterations to the current standard have been addressed and justified in this chapter. At the completion of testing, a description of the moisture absorption capacity of the mortar and the freeze-and-thaw durability is provided.

CHAPTER 4: EXPERIMENTAL RESULTS

4.0 INTRODUCTION

The objective of this chapter is to present the experimental results of the moisture absorption and in-situ freeze/thaw durability of polyvinyl alcohol (PVA) fiber reinforced mortars (FRM). This chapter is broken down into three sections. A description of the properties of the mortar is given in the first section. The second section presents the results of the mortar moisture absorption rate. The final section presents the results of the freeze/thaw durability testing.

4.1 PROPERTIES OF THE MORTAR

In this section a complete description of the mix design of the Type N mortar is given. The proportions of mortar, cement, and fiber are given to describe the behavior of the mortar. The compressive and flexural bond strength properties of the Type N mortar are given prior to durability testing. The purpose for providing the strength characteristics of the mortar is to give an interpretation of the strength of the materials prior to exposure of freeze/thaw cyclic loading. The strength testing is performed in a Gilson MC-250P Concrete Compression Testing Machine as described in Chapter 3.

4.1.1 Experimental Mix Design

The experimental mix design segment of the results section provides a detailed description of the makeup of the FRM. This is done to ensure that its construction is reproducible and that its proportions are correct. As previously discussed, the FRM is made up of Type N pre-blended mortar mix, water, and two different lengths of PVA fibers. The exact mix proportions utilized to construct six 5-stack prisms, six 7-stack prisms, and six 2-in. mortar cubes can be seen in Table 4.1.

Table 4.1 Experimental FRM Mix Proportions

Mixture	Type N Mortar (g.)	Water (g.)	Fiber (g.)	
			RECS7	RECS15
Control Mixture	25,800	5,320	N/A	N/A
RECS7 (0.25%)	25,800	5,620	46	N/A
RECS7 (0.50%)	25,800	5,620	92	N/A
RECS15 (0.25%)	25,800	5,620	N/A	46
RECS15 (0.50%)	25,800	5,620	N/A	92
RECS7 (0.25%) + RECS15 (0.25%)	25,800	5,620	46	46

The quantity of fiber required for each mix design is calculated as a percentage of the mortar volume. By utilizing the density of the fibers, the correct weight of fiber is calculated and added to each individual mix.

The following sections present the characteristic strength properties of all experimental test specimens before and after exposure to freeze-and-thaw testing. An understanding of the basic compressive, flexural, and absorptive properties of the test specimens is necessary for a strength comparison to specimens after freeze/thaw testing.

4.1.2 Compressive Strength of 5-Stack Masonry Prism Specimens

The purpose of this section is to present the compressive strength of the 5-stack masonry prism specimens. In order to determine the effects that extreme unidirectional freeze-and-thaw weathering has on a masonry prism, the experimental compressive strength is determined before and after freeze-and-thaw exposure. The results and an overview of the masonry prism compressive strength tests are given in this section.

For the purpose of this study, all masonry prisms are tested for pre-freeze/thaw compressive strength at an age of 28 days. This allows for the prisms to achieve nearly 95% of their design strength prior to testing. Specimens exposed to the freeze/thaw weathering cycles are tested at an age of 100 days. These specimens are more mature than the pre-freeze/thaw test specimens due to the fact that 300 freeze/thaw cycles take approximately 75 days to complete. All specimens comprised of the same makeup and test procedure are evaluated for their strength at the same nominal age.

The compressive strength of the 5-stack masonry prisms is determined using a Gilson MC-250P Concrete Compression Testing Machine. In this machine the experimental specimens are axially loaded in accordance with ASTM C1314, Standard Test Method for Compressive Strength of Masonry Prisms (ASTM, 2012). In this method, the dimensions of the specimen are recorded and an axial load is transmitted throughout the specimen until failure. The ultimate load is recorded and the masonry compressive strength is calculated. The compressive strength of the masonry prism is calculated using Equation (1).

$$C = \frac{P}{(w \times b)} \quad (1)$$

Where:

C = Compressive strength of the prism

P = Ultimate load

w = Average width of the specimen

b = Average length of the specimen

The calculations for the compressive strength of the masonry prisms are shown in Appendix B.

In addition to the typical length measurements, the slenderness ratio for each specimen is also calculated and shown in Appendix B. According to ASTM C1314, the slenderness ratio has a direct impact on the specimen's compressive strength. As a way to mitigate errors associated with the slenderness ratio, ASTM C1314 introduces a height-to-thickness correction factor for calculating the masonry prism compressive strength. This correction factor is applied to the calculated compressive strength of the sample prism in order to determine the compressive strength of the masonry. The corrected average compressive strength of the pre-freeze/thaw 5-stack masonry prisms is calculated using strength data from an average of three experimental specimens and is displayed in Figure 4.1.

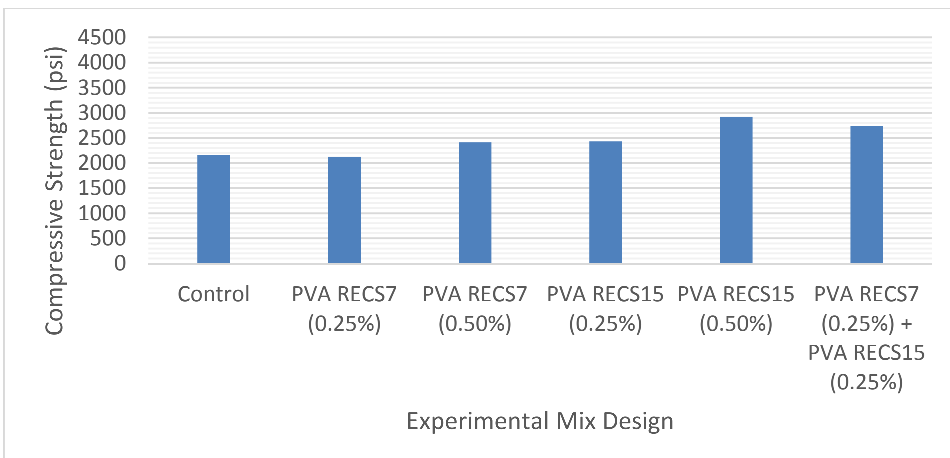

Figure 4.1 Pre-Freeze/Thaw Prism Corrected Compressive Strength

The calculated average compressive strength of specimens composed of different fiber quantities and lengths range from approximately 1900 psi to 2500 psi. As can be seen from Figure 4.1, once corrected, the compressive strength of the 5-stack prims yield a masonry compressive strength ranging from 2100 psi to 2900 psi. For 5-stack masonry specimens, the implementation of a correction factor for masonry increases the prism compressive strength by approximately 15 percent. The calculated standard deviation of the pre-freeze/thaw compressive strength testing is given in Figure 4.2.

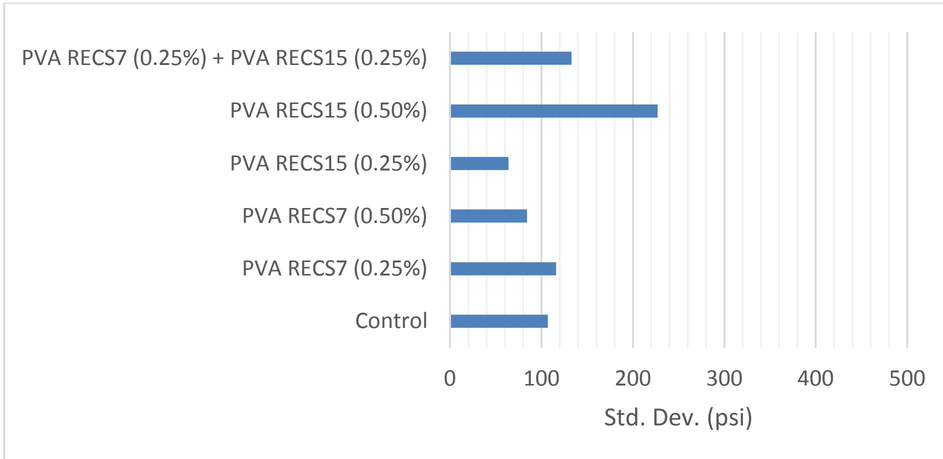

Figure 4.2 Pre-Freeze/Thaw Prism Compressive Standard Deviation

From Figure 4.2, it can be observed that the standard deviation of testing specimens did not fluctuate greatly between all mix designs. The exception to these results is the PVA RECS15 (0.50%) mix design; its sample standard deviation is nearly double that of all other mix designs. Figure 4.2 demonstrates an experimental range of all experimental samples in which the corrected compressive strengths range between 5 and 10 percent of their average corrected compressive strength. Observation of relatively small standard deviations shows that the experimental samples were all constructed similarly. Therefore, the sample standard deviations are small.

The compressive strength testing for the post-freeze/thaw specimens is conducted in the same manner as the pre-freeze/thaw exposure testing. The results of the post-freeze/thaw testing are shown in Figure 4.3.

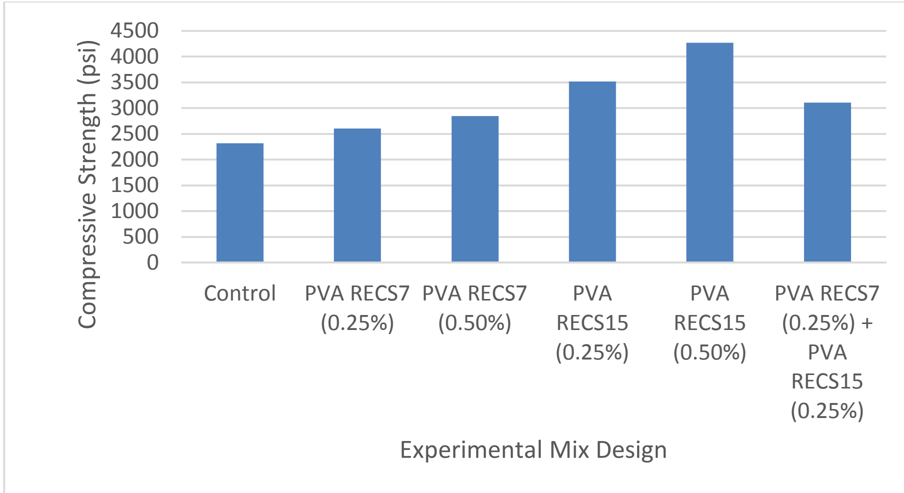

Figure 4.3 Post-Freeze/Thaw Prism Corrected Compressive Strength

From the 5-stack compressive strength calculations shown in Appendix B, it can be observed that the average compressive strength of specimens composed of different fiber quantities and lengths range from approximately 2250 psi to 3800 psi. The average compressive strength in combination with the correction factors provided in ASTM C1314 yields a masonry compressive strength ranging from approximately 2300 psi to 4300 psi. The standard deviation of the compressive testing for the post-freeze/thaw specimens is shown in Figure 4.4.

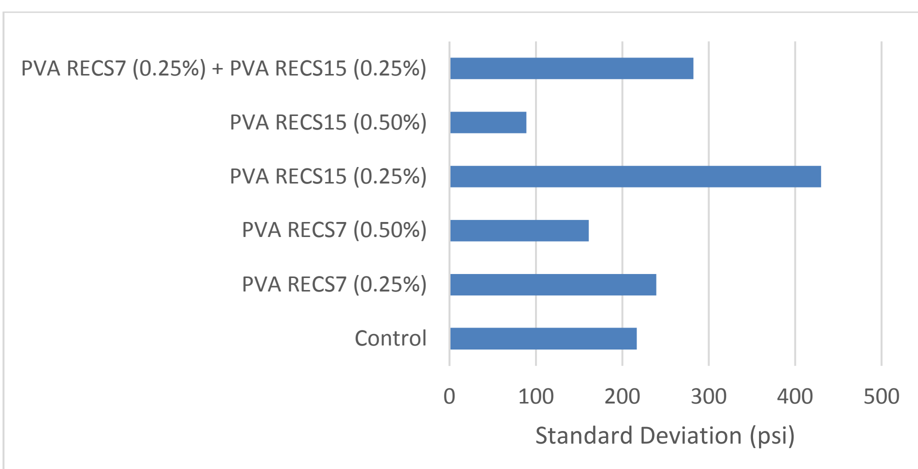

Figure 4.4 Post-Freeze/Thaw Compressive Standard Deviation

The standard deviation of testing specimens did not fluctuate greatly between all mix designs with the exception of the PVA RECS15 (0.25%) mix design

The compressive strength testing of the masonry specimens exhibits typical characteristic failure modes. These failure modes describe the strength parameters of the masonry specimens. The different classifications of a break are shown graphically in Figure 4.5.

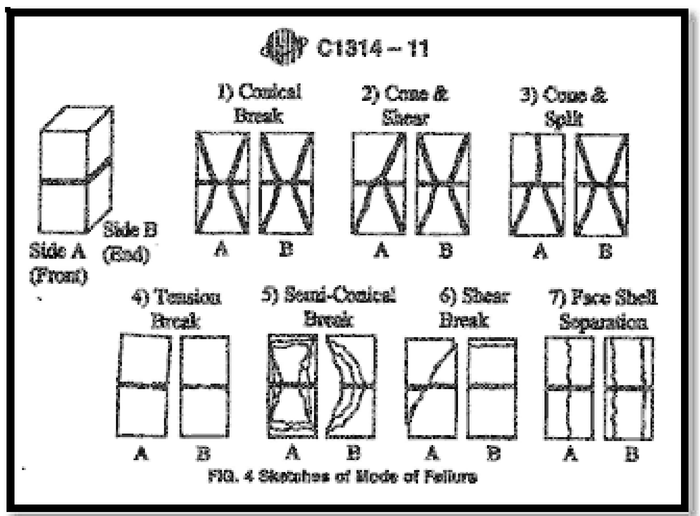

Figure 4.5 Sketches of Compressive Failure Mode (ASTM C1314, 2012)

Nearly all specimens prior to freeze-and-thaw exposure exhibit either a Type 2 Cone & Shear or a Type 3 Cone & Split failure mode. The specimens tested after completion of freeze/thaw exposure mainly exhibit either a Type 7 Face Shell Separation or a Type 2 Cone & Shear failure mode. The failure behavior of all experimentally tested specimens is discussed further in Section 5.1. Figure 4.6 shows photographs of the typical specimen breaks described above. In addition, images of the failure of all experimentally tested prisms can be seen in Appendix B.

a). Cone and Shear Failure Surface

b). Cone and Split Failure Surface

c). Face Shell Separation Failure

Figure 4.6 Typical Failure Surfaces of Experimental Specimens

The typical experimental test specimens exhibit failure as shown in Figure 4.6. The compressive strength testing of the experimental testing specimens provides an understanding of the strength characteristics of the experimental mortars. In summation, the pre-freeze/thaw compressive strength testing of various FRM prisms yields an average compressive strength of nominally the same value as the control. PVA FRM members did not experience a significant increase in strength when compared with the control mixture. The results of the experimental testing are summarized in Table 4.2.

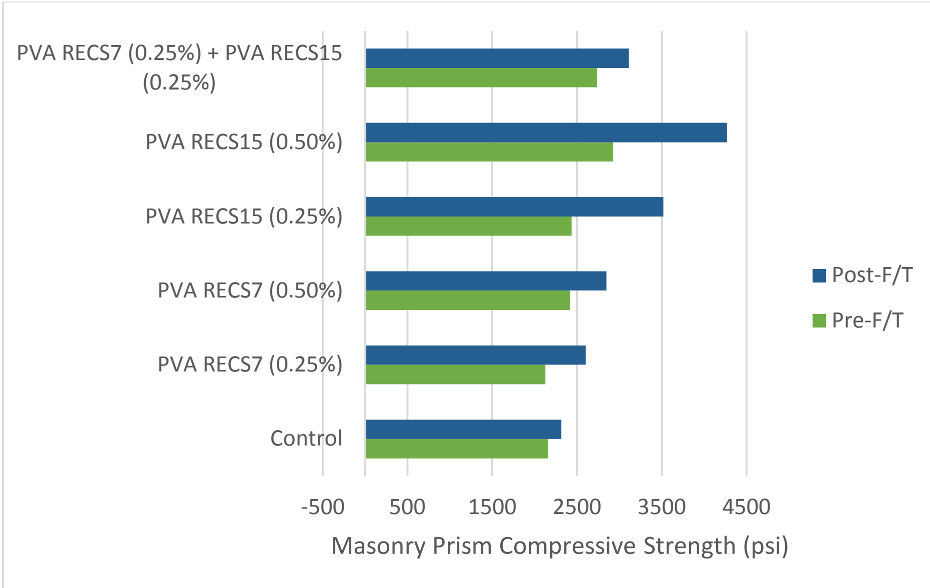

Figure 4.7 Prism Compressive Strength Testing Summary

The compressive strength of post-freeze and thaw experimental specimens appears to be higher than the compressive strength of pre-freeze and thaw specimens. Longer PVA fiber types included at a higher percent by volume are found to produce a slight increase in compressive strength. The masonry prism compressive strength testing yields specimens with consistent failure modes for their corresponding exposure. See Chapter 5 for the discussion of the experimental compressive strength testing results.

4.1.3 Compressive Strength of 2-in. Mortar Cube Specimens

The purpose of this section is to present the compressive strength of the 2-in. mortar cube specimens. In order to determine the effects that extreme freeze/thaw weathering has on a FRM, the experimental compressive strength is determined on specimens the same age as those exposed to extreme freeze and thaw weathering. Therefore, the average test age for specimens is approximately 100 days.

The compressive strength of the mortar cubes is determined using a Gilson MC-250P Concrete Compression Testing Machine. In this machine the experimental specimens are axially loaded in accordance with ASTM C109, Standard Test Method for Compressive Strength of Hydraulic Cement Mortars Using 2-in. Cube Specimens (ASTM, 2012). In this method, measurements of the dimensions of the specimen are recorded. Then an axial load is applied to the specimen until failure and the ultimate load is recorded. The compressive strength of the standard mortar cube is calculated using Equation (2).

$$f_m = \frac{P}{A} \quad (2)$$

Where:

f_m = Compressive strength (psi)

P = Total maximum load (lbf)

A = Area of loaded surface (sq. in.)

The length measurements for each specimen are taken with a standard caliper and are presented in Appendix E. The calculations for the compressive strength of the mortar cubes for each mix design are also contained in Appendix C. A summary of the results of the compressive strength testing is displayed in Table 4.2.

Table 4.2 Compressive Strength of 2-in. Mortar Cubes Pre-F/T Testing

Mix Design	**Control**	**PVA RECS7 (0.25%)**	**PVA RECS7 (0.50%)**	**PVA RECS15 (0.25%)**	**PVA RECS15 (0.50%)**	**PVA RECS7 (0.25%) + PVA RECS15 (0.25%)**
Mean Value (psi)	2355	2228	2557	2221	2375	1985
Standard Deviation (psi)	135	253	238	224	50	538

The experimental compressive strengths as shown in Table 4.2 are considerably larger than the specified minimum compressive strength by Spec Mix©. Typical pre-blended, commercial, Type N mortar can be expected to have a compressive strength of 750 psi. The experimental test results produces yield strengths nearly three times the expected minimum value. ASTM Standard C109 calls for 144 individual test specimens for each mix design. Due to limitations on time and available curing space, testing is made up of a much smaller batch of specimens. As a result of a smaller sample size, the observed standard deviation of test specimens does not lie within the desired range of values per ASTM C109.

Similar to the compressive strength testing of the 2-in. mortar cubes not exposed to weathering, the results of the compressive strength after freeze and thaw testing is shown in Table 4.3.

Table 4.3 Compressive Strength of 2-in. Mortar Cubes Post-F/T Testing

Mix Design	Control	PVA RECS7 (0.25%)	PVA RECS7 (0.50%)	PVA RECS15 (0.25%)	PVA RECS15 (0.50%)	PVA RECS7 (0.25%) + PVA RECS15 (0.25%)
Mean Value (psi)	1461	1717	2372	1817	2854	1584
Standard Deviation (psi)	742	152	323	358	330	26

Table 4.3 shows that the average mortar compressive strength of the various mix designs ranges from 1400 psi to 2900 psi. A wide range of compressive strengths is seen due to differences in the durability performance of the different PVA mix designs. With

the exception of the PVA RECS7 + RECS15 @ 0.25%, all specimens exhibit a large standard deviation.

A typical failure mode of the 2 in. mortar cube is shown in Figure 4.7. The observed failure mode of all the mortar specimens is similar in that they all exhibit crushing at failure.

Figure 4.8 Typical Mortar Cube Failure

When compared with the control mortar, it is observed that the mix designs containing PVA fibers exhibited greater toughness after formation of cracks. The presence of fibers inherently allowed for the mortar cubes to withstand an increase in axial load after cracking. Images of the failure of all specimens can be seen in Appendix B. A summarization of the pre and post freeze/thaw experimental mortar cube compressive strengths is shown in Figure 4.9.

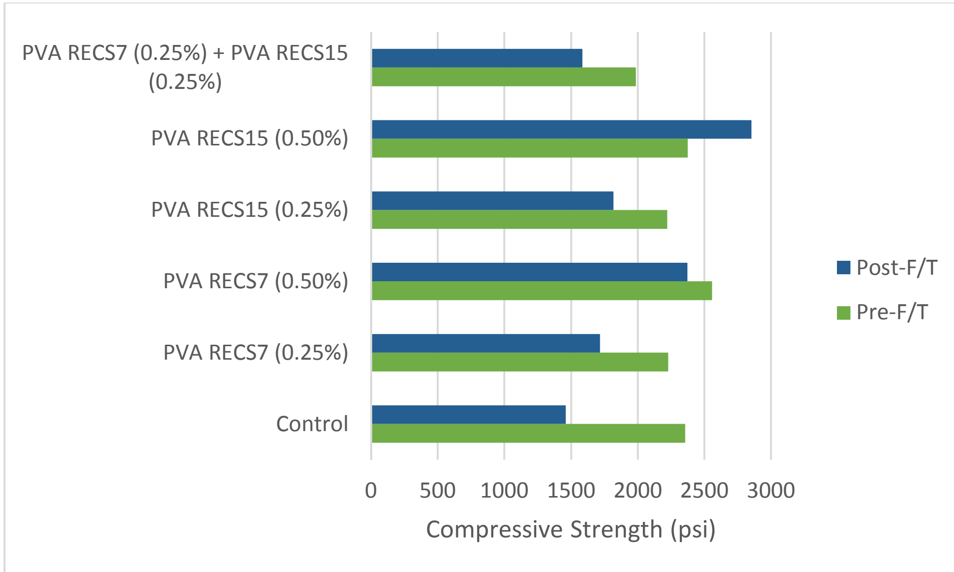

Figure 4.9 2-in. Mortar Cube Compressive Strength Summary

In summation, the pre-freeze/thaw compressive strength testing of various FRM prisms yields an average compressive strength of nominally the same value as the control. However, the experimental compressive strength is much higher than the expected value supplied by the mortar manufacturer. Specimens exposed to freeze/thaw weathering experience a reduction in compressive strength of approximately twenty percent. The control experienced an average reduction in strength of approximately thirty-eight percent. Overall, the PVA mortar specimens proved more durable when compared with the control mortar. Chapter 5 provides a detailed discussion of the experimental compressive strength testing results for the 2-in. mortar cubes.

4.1.4 Flexural Bond Strength of 7-Stack Masonry Specimens

The purpose of this section is to present the flexural bond strength of the 7-stack masonry prism specimens before and after cyclic freeze/thaw loading. In order to fully understand the effects that freeze/thaw weathering has on a FRM, the flexural bond strength is determined prior to freeze/thaw exposure. A separate sample of specimens created at the same time is then subjected 300 cycles of freeze/thaw weathering and the flexural bond is determined experimentally afterword.

The flexural bond strength of the masonry is determined using a Gilson MC-250P Concrete Compression Testing Machine. In this machine the experimental specimens are loaded in accordance with ASTM E518, Standard Test Methods for Flexural Bond Strength of Masonry (ASTM, 2012). The nominal dimensions and the weight of the specimen are recorded. A 3-point load is applied to the specimen to create a constant moment in the middle third of the span of the member until failure. An example of typical 3-point specimen loading can be seen in Figure 4.10.

Figure 4.10 3-Point Loading of Masonry for Flexural Bond Strength Testing

In specimens exposed to freeze and thaw weathering, the load is applied to the weathered face. This is done to simulate loading which is representative of in-situ conditions. After failure, the ultimate load is recorded. The flexural bond strength of the masonry prism is calculated using Equation (3).

$$R = \frac{(P + 0.75P_s)l}{bd^2} \quad (3)$$

Where:

R = Gross area modulus of rupture (psi)

P = Total maximum load (lbf)

P_s = Weight of specimen (lb)

L = Span (in.)

b = Average width of specimen (in.)

d = Average depth of specimen (in.)

The calculations for the flexural bond strength of the 7-stack masonry prisms prior to freeze and thaw exposure are contained in Appendix D. A summary of the results are displayed in Figure 4.11.

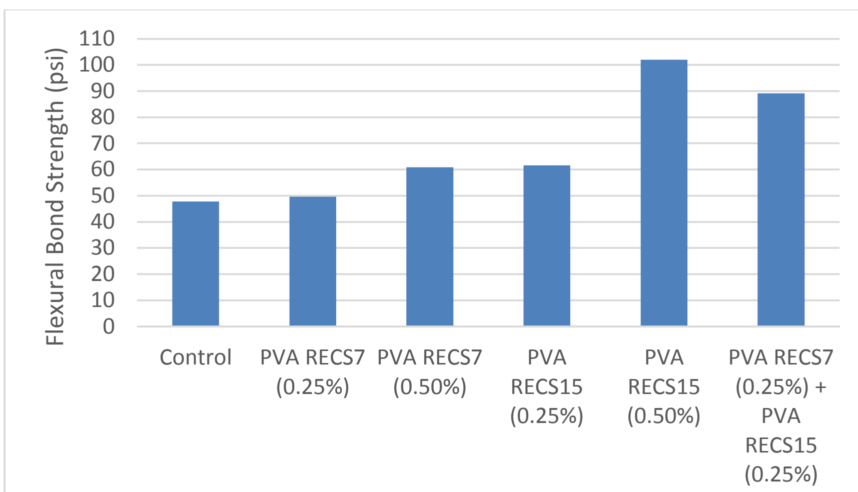

Figure 4.11 Flexural Bond Strength of 7-Stack Masonry Pre-F/T Testing

From Figure 4.11 it can be seen that the average flexural bond strength of the various mix designs ranges from approximately 50 psi to 100 psi. Testing of 3 specimens led to an average standard deviation of approximately 10 psi. The flexural performance of the mix designs containing PVA fibers consistently yields an increase in the flexural bond strength of the masonry specimens when compared with the control.

The flexural bond strength of all specimens is determined after cyclic freeze/thaw exposure. The flexural bond strength results for the various fiber reinforced mix designs after extreme weathering is given in Figure 4.12.

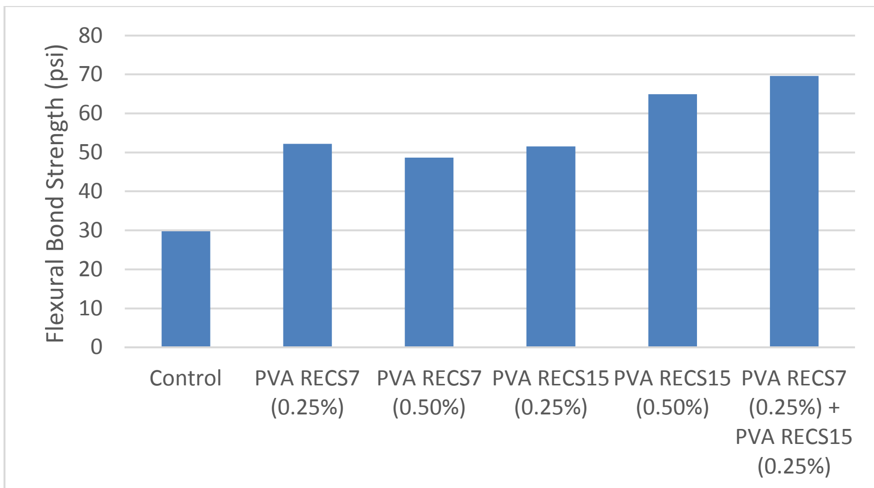

Figure 4.12 Flexural Bond Strength of 7-Stack Masonry Post-F/T testing

After exposure to freeze/thaw weathering, a consistent reduction in flexural strength is experienced in all mix designs. In conjunction with a decrease in flexural bond strength, the average standard deviation of all sample sets nearly doubled when compared to the specimens not exposed to weathering. Exposure to freeze/thaw weathering greatly decreases the reliability and flexural performance of the experimental specimens. The failure mode of all experimentally tested specimens was representative of a bond failure between the mortar and the brick. An example of the typical failure can be seen in Figure 4.13.

Figure 4.13 Flexural Bond Strength Failure

The results of the flexural bond strength testing yield values consistent with the expected strength of the mix design. Exposure to extreme weathering imposes a reduction in the bond strength between the mortar and the brick, as well as an increase in the inconsistency of the tested specimens. A summary of the reductions in flexural bond strength is shown in Figure 4.14.

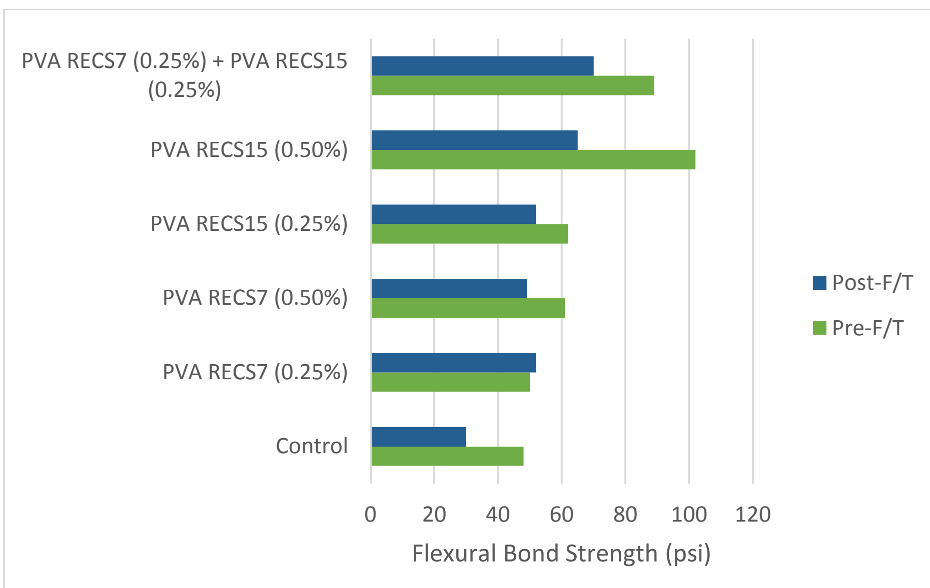

Figure 4.14 Flexural Bond Strength Summary

Figure 4.14 shows that the average PVA specimen experiences a reduction in strength ranging from twenty to thirty-six percent after freeze/thaw exposure. The control prisms experience a loss in strength of thirty-eight percent. All PVA specimens yield a superior flexural bond strength performance than the control when tested after exposure to freeze/thaw weathering on a single face. A complete description of the flexural bond strength of the masonry specimens is presented in Chapter 5.

4.1.5 Moisture Absorption Rate

The moisture absorption rate is determined for all mix designs on standard 2-in. mortar cubes. The literature review discusses the capability of PVA fibers to absorb and wick moisture into the mortar. This study determines the overall impact that the inclusion of PVA fibers within a mortar has on its moisture absorptive capabilities. The introduction of moisture into the mortar may be detrimental to the long-term strength under freeze/thaw exposure. The moisture absorptive capability of the mortar is determined using ASTM C642 Standard Test Method for Density, Absorption, and Voids in Hardened Concrete (ASTM, 2012). The total absorption is calculated by determining the dry weight of a specimen, completely immersing it, and determining the final weight at which it ceases to absorb moisture. Three samples from each mix design are immersed during testing. Each of their weights is measured to the nearest gram at time intervals given in Figure 4.15.

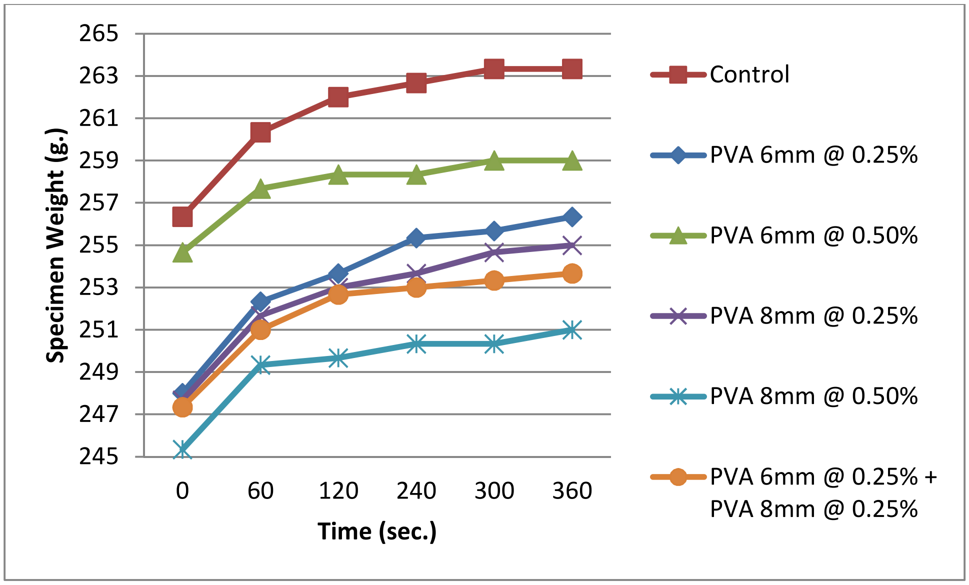

Figure 4.15 Moisture Absorption Rate vs. Time

Figure 4.14 illustrates the average absorption rate for each mix design. The calculations for the moisture absorption are contained in Appendix F. As can be seen from Figure 4.14, initially all mix designs absorb moisture at similar rates. Then, as the specimens become saturated, their absorption rates decrease as it approaches complete saturation. Testing is terminated at a time of 360 seconds as it was found that specimens ceased to accumulate moisture beyond this point. Upon comparison with the control mortar, the PVA mix designs are generally a lighter mix prior to testing. This is due to the replacement of mortar with much lighter PVA fibers during mixing. After immersion, it can be observed that the PVA FRM have a comparable amount of moisture absorption when compared with the control. Figure 4.16 below shows the average net absorption rate for each mix design.

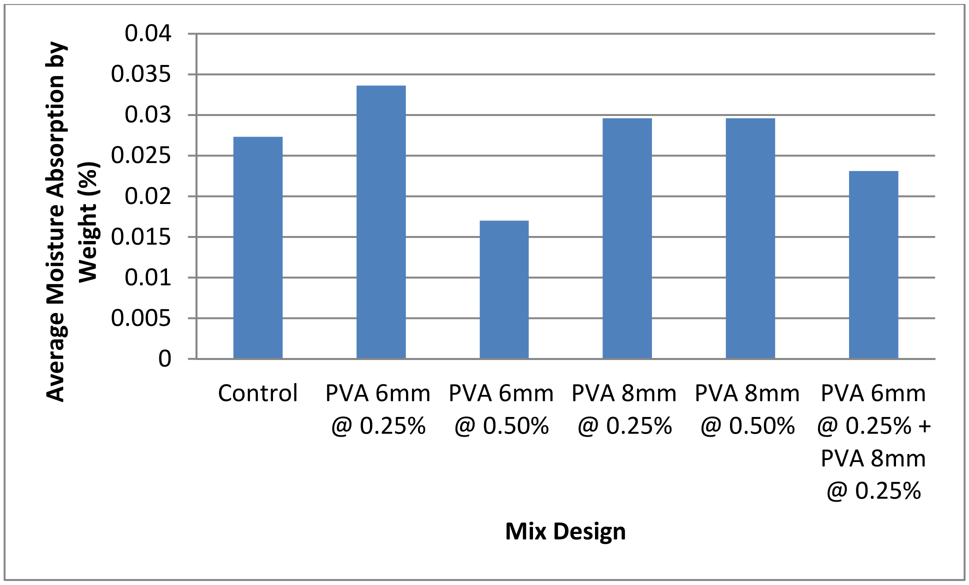

Figure 4.16 Average Moisture Absorption (%) Per Mix Design

The net moisture absorption for each mix design varies between 1.5 and 3.5 percent. The inclusion of PVA fibers within the mix does not appear to have a large effect on the absorptive capability of the mortar. However, a small amount of moisture within the mortar can expand under freezing conditions and cause undesired internal tensile forces. An analysis of the moisture absorption testing and comparison with current literature is provided in Chapter 5.

4.2 EXPERIMENTAL FREEZE-AND-THAW TESTING RESULTS

The purpose of this section is to provide a durability rating for the resistance of the PVA FRM specimens to repeated cycles of freezing and thawing. As discussed in the literature review, modifications are performed to ASTM C666, Procedure A, in order to represent in-situ conditions. The experimental tests performed in Section 4.1 are used to provide various durability ratings for the performance of the mortar after freeze/thaw exposure. A durability rating is presented for each mix design using the results of the masonry compression tests, flexural bond strength tests, and mortar cube compression tests. The durability rating provides a mathematical relationship of the various pre-and-post freeze/thaw strength testing. The durability rating of each mix design is determined using Equation (4).

$$DF = \frac{(P_i - P_f)}{P_i} \quad (4)$$

Where:

DF = Durability Factor

P_i = Average specimen strength prior to freeze-and-thaw exposure (psi)

P_f = Average specimen strength after freeze-and-thaw exposure (psi)

The durability factor provides an interpretation of the alteration of specimen strength after exposure to freeze/thaw weathering. If multiplied by 100, the durability factor can be idealized as a percent gain or loss for the experimental mix design. The calculations for the durability factors of the masonry are shown in Appendix F. The results of the testing are summarized in Table 4.4.

Table 4.4 Experimental Specimen Durability Factor

Mix Design	Prism Compressive Strength		Prism Flexural Bond Strength		Mortar Cube Compressive Strength	
Durability Factor (D.F)	**D.F.**	**(D.F.) / (D.F.1)**	**D.F.**	**(D.F.) / (D.F.1)**	**D.F.**	**(D.F.) / (D.F.1)**
Control (D.F.1)	-0.07	N/A	0.38	N/A	0.38	N/A
PVA RECS7 (0.25%)	-0.22	3.20	-0.04	-0.11	0.23	0.60
PVA RECS7 (0.50%)	-0.17	2.50	0.20	0.52	0.07	0.19
PVA RECS15 (0.25%)	-0.45	6.63	0.16	0.43	0.18	0.48
PVA RECS15 (0.50%)	-0.46	6.84	0.36	0.97	-0.20	-0.53
PVA RECS7 (0.25%) + PVA RECS15 (0.25%)	-0.13	1.96	0.21	0.57	0.20	0.53

The purpose of this study is to determine the in-situ freeze/thaw durability of PVA FRM specimens. From Table 4.5 it can be observed that exposure to freeze/thaw weathering did not produce a negative impact on the prism compressive strength. Recall from Chapter 2, Section 2.3.3 that laboratory freeze/thaw weathering has been previously performed on PVA FRM mortar prisms (Wang & Li, 2006). Their testing imposed freeze/thaw weathering on all six sides of the specimen, resulting in an average reduction in strength of approximately 22 percent. Similar to the results found by Wang & Li, mortar cube specimens exposed to freeze/thaw weathering on all six sides in this experiment also experienced a reduction in compressive strength of approximately 20 percent. However, throughout uni-directional exposure, the 5-stack masonry specimens did not experience a loss in compressive strength. Representation of the experimental specimens as they would be found in their natural environment did not produce a negative effect on the compressive strength after freeze/thaw exposure. From the results, it appears that testing of specimens as mortar prisms or cubes and exposing them to freeze/thaw on all sides may provide an exaggerated interpretation of their compressive strength performance. After freeze/thaw exposure, all mix designs experienced no reduction in compressive strength.

The 7-stack masonry specimens subjected to freeze-and-thaw exposure experienced an average reduction in flexural bond strength ranging from 10 to 40 percent. Previous studies have not been performed on the effects that freeze/thaw exposure poses on the flexural bond strength of the masonry prisms. However, freeze/thaw exposure is expected to produce a reduction in the strength performance of the brick and mortar. Discussion of the performance and durability ratings for experimental specimens is provided in Chapter 5.

In addition to the determination of a durability rating, the length change of each specimen is calculated after exposure to every 36 cycles. The purpose of determining the change in length of each specimen is to monitor its reaction to freeze/thaw weathering. If exposure to weathering causes abnormal shrinkage/elongation, the masonry specimens may crack and lose integrity. The length change is calculated using Equation (5).

$$l_c = \frac{(l_2 - l_1)}{l_1} x\, 100 \quad (5)$$

Where:

l_c = Length change of the specimen after C cycles of freezing and thawing (%)

l_2 = Length comparator reading after C cycles (in.)

l_1 = Length comparator reading at 0 cycles (in.)

The experimental specimens did not experience abnormal shrinkage/elongation throughout testing. The calculations for the length change of each specimen are contained in Appendix E of this report.

4.3 SUMMARY OF RESULTS

The experimental results of the 5-stack, 7-stack, 2-in. mortar cubes, moisture absorption, and length change measurements are contained in this chapter. Utilizing the proposed methodology to test in-situ PVA FRM exposed to freeze/thaw weathering, the selected PVA FRM mixes perform as well or better than the control mortar mix that does not contain PVA FRM. Overall, the 5-stack masonry specimens do not exhibit a loss in strength due to extreme freeze-and-thaw exposure when compared with specimens tested at 28 days. 5-stack masonry specimens exposed to uni-directional testing prove more durable than previous studies performed on mortar specimens. The results of the compressive strength of the 2-in. mortar cubes are in concurrence with findings in Section 2.3.3. The flexural capacity of the 7-stack specimen decreases when exposed to freeze/thaw weathering, but this decrease is significantly lower than the control mixture without PVA fiber. In addition, the specimens containing PVA fibers do not exhibit a significant change in moisture absorption rate when compared with the control containing no fibers. The nominal length change of the specimens throughout freeze/thaw testing did not exceed ASTM testing parameters.

CHAPTER 5: EXPERIMENTAL DISCUSSION

5.0 INTRODUCTION

The purpose of this study is to determine the in-situ freeze/thaw characteristics of polyvinyl alcohol (PVA) fiber reinforced mortars (FRM). This chapter discusses the results of the experimental testing, compares these results with pertinent previously conducted research, and develops conclusions regarding the research performed during this study. A summary containing the findings of this research and recommendations for future research is contained in Chapter 6.

5.1 EXPERIMENTAL MASONRY COMPRESSION TESTING

The results of the experimental masonry compressive testing is shown in Chapter 4, Section 4.1.2. As a result of the in-situ replicating freeze/thaw exposure, the test specimens did not exhibit a loss in strength. Theoretical verification of the compressive strength of the masonry prisms is made using standardized procedures developed by the International Building Code (International Building Code IBC, 2011).

According to the IBC, the combination of brick and mortar utilized in this thesis should produce masonry with an approximate minimum compressive strength of 1500 psi. The specifications set forth in the IBC can be seen in Table 5.1.

Table 5.1 Compressive Strength of Concrete Masonry (IBC Table 2105.2.2.1.2)

NET AREA COMPRESSIVE STRENGTH OF CONCRETE MASONRY UNITS (psi)		NET AREA COMPRESSIVE STRENGTH OF MASONRY (psi)[a]
Type M or S mortar	Type N mortar	
1,250	1,300	1,000
1,900	2,150	1,500
2,800	3,050	2,000
3,750	4,050	2,500
4,800	5,250	3,000

For SI: 1-inch = 25.4 mm, 1 pound per square inch = 0.00689 Mpa.

a. For units less than 4 inches in height, 85 percent of the values listed.

This table is used by engineers to prescribe the minimum compressive strength of masonry. Prescription of a minimum compressive strength ensures that construction will statistically produce a masonry compressive strength that is greater than, or equal to, the minimum strength. Therefore, the experimental results of the masonry prism compressive strength testing are expected to be slightly higher than an average compressive strength of 1500 psi. Further analysis of the experimental values yields an average factor of safety with respect to the IBC assumed minimum compressive strength of approximately 1.64. This represents a reasonable factor of safety associated with the material properties of masonry. Overall, the compressive strength of all test specimens, including the control mixture, is considerably larger than the expected strength.

A key element in the use of PVA FRM for the repointing of existing masonry structures is that previous research states that addition of fibers has no significant effect on mortar compressive strength (Skourup & Erdogmus, 2010). This enables flexural strengthening of a structure without altering original design compressive strength values. Alteration of original design compressive strength values may cause the historic brick to fail prior to the mortar, resulting in loss of the historic structure that repointing is trying to restore. The results of the experimental compressive strength testing prior to freeze/thaw testing of this study coincide with the results obtained by the study of Skourup & Erdogmus. As can be seen from Figure 4.3, the average compressive strength of the control, PVA RECS7 (0.25%), PVA RECS7 (0.50%), and PVA RECS15 (0.25%) are approximately the same. However, the inclusion of the slightly larger PVA RECS15 fibers at higher fiber content per volume produces a slight increase in the compressive strength. This result is corroborated by Skourup & Erdogmus as the FRM provides post-crack increases in ductility and toughness. The increase in ductility and toughness allows the masonry prism to ultimately take on additional load after development of a failure surface. As the masonry cracks the fibers are found to bridge these cracks and provide continued strength resulting in a slightly larger compressive strength.

Following experimental freeze/thaw exposure, nearly all specimens exhibit an increase in compressive strength. This may be due largely to the fact that specimens subjected to freeze/thaw exposure are contained in a humidity controlled environment throughout their testing. This controlled environment may allow specimens to completely hydrate and mature throughout testing. Resulting in specimens that have cured and are tested at a later date than the pre-freeze/thaw specimens tested at an age of 28 days. Specimens that are more mature, and have been allowed to hydrate for a longer period of time may exhibit greater compressive strength capacity than their pre-freeze/thaw counterparts.

5.2 EXPERIMENTAL MORTAR CUBE COMPRESSION TESTING

The experimental compressive strength associated with the 2-in. mortar cubes is much larger than the specified minimum compressive strength by Spec Mix©. According to Spec Mix©, the typical Type N mortar can be expected to have a minimum average compressive strength of 750 psi. Experimental test results yield strengths nearly three times the expected minimum value. There are a few variables that can explain the large discrepancy between the experimental results and the expected results. A portion of the increase in the compressive strength can be assumed to be due to a factor of safety associated with the Spec Mix© published values. The experimentally obtained strength is desired to be greater than the published strength to present a buffer for irregularities due to field placement. Another possible reason for the significant strength increase can be explained through previously published research. A study conducted by Drdacky and others titled Compression Tests on Non-standard Historic Mortar Specimens describes the increase in experimental compressive strength of non-standard specimens as slenderness ratio decreases (2008). The research conducted by Drdacky and others explains that mortar compressive strength decreases exponentially as slenderness ratio increases. The 2-in. mortar cube specimens tested in this experiment have a slenderness ratio of 1. Therefore, comparison of the compressive strength of the 2-in. mortar cubes with previous research conducted on FRM cylinders is expected to be in the range of 2 to 4 times higher than research conducted on 4x8 inch mortar cylinders.

The pre-freeze/thaw compressive strength testing of various FRM mortar cubes yields an average compressive strength slightly different than the control. However, large strength gains are not experienced, therefore verifying previous findings in which the inclusion of PVA fibers within the mortar does not significantly impact the compressive strength (Skourup & Erdogmus, 2010; Armwood and others, 2011). In the mortar cubes, longer PVA fiber types included at a higher percent by volume did not produce a significant increase in compressive strength. The experimental compressive strength of the 2-in. mortar cubes is 3-4 times higher than the specified manufacturer compressive strength. Low slenderness ratio of a mortar cubes when compared with a standard cylinder has been found to produce higher compressive strengths in past research.

Visual observation of the specimens containing PVA fiber throughout freeze/thaw exposure is also conducted. In general, the PVA FRM maintained general shape with less spalling of the mortar throughout testing when compared to the control not containing fibers. Images of the experimental specimens before and after exposure testing can be seen in Appendix C of this thesis.

5.3 EXPERIMENTAL FLEXURAL BOND STRENGTH TESTING

The results of the pre-freeze/thaw flexural bond strength testing are in concurrence with the results of previous findings. The inclusion of PVA fibers within the mortar provides an increase in the flexural bond strength of the masonry units. As described by Skourup and Erdogmus, microfiber mixtures or hybrid mixtures with the highest total volume fractions provide the best increase in flexural strength (2010). This can be seen as the strength of the PVA FRM RECS15 @ 0.50% is nearly double the strength of the control. The increase in flexural bond strength is the reason for introducing PVA fibers into the mortar. The findings of the pre-freeze/thaw testing show an increase in flexural bond strength for all PVA FRM. However, the results of the strength testing yield average flexural bond strengths less than the anticipated 75 psi as discussed in the literature review. This may be due to the fact that the brick and mortar did not display a significantly increased cohesion similar to previous research. Upon further analysis, previous literature portrayed a much larger standard deviation of the flexural bond strength determined for their experimental masonry specimens (Skourup & Erdogmus, 2010). Pertinent existing research tested only two specimens for each mix design; if a larger sample were tested the experimental data may suggest average flexural bond strengths closer to the experimental values obtained in this thesis. In general, a minimum of three specimens is recommended for the testing of each mix design. Tests performed on fewer specimens do not provide an accurate interpretation of the behavior of an experimental mix design; especially when the standard deviation of testing specimens ranges from two to four times the overall strength. The experimental results obtained in this thesis represent an accurate portrayal of the flexural bond strength of the PVA FRM mixtures.

5.4 MOISTURE ABSORPTION

The moisture absorption capacity of the experimental PVA FRM specimens is performed in this thesis. Previous research has not been conducted on the moisture absorptive capabilities of PVA FRM. However, the literature review describes the mechanical properties of the PVA fibers as being capable of absorbing moisture. The results of the moisture absorption testing do not provide a conclusive result in which the PVA FRM absorbs more moisture than the control mortar without fiber. Interpretation of the experimental results reveals no significant increase in the moisture absorptive capabilities of a mortar due to the inclusion of PVA fibers.

5.5 EXPERIMENTAL FREEZE/THAW TESTING

The results of the in-situ replicating experimental freeze/thaw provide an interpretation of the durability of a PVA FRM when exposed to freeze/thaw weathering. In this thesis, experimental values pertaining to the masonry prism compressive strength, mortar compressive strength, and masonry prism flexural bond strength are obtained by utilizing the modified ASTM C666 procedures described in Chapter 3.The pre-freeze/thaw compressive strength of various FRM prisms yield an average compressive strength that is nominally the same value as the control mixture. The results of the post-freeze/thaw prism compressive strength testing show a slight increase when compared with the pre-freeze/thaw results. This increase in strength is believed to be attributed to the longer cure time and to the fact that a slight decrease in adhesion between the mortar and brick limits the Poisson effects and reduces lateral stresses which may cause compressive failure more quickly (Kosa and others, 1991). The results of the masonry compressive strength testing show no decrease in compressive strength due to the inclusion of PVA fibers.

The results of the mortar cube compressive strength testing before and after freeze/thaw exposure are representative of the results found by previous research. Specimens not exposed to freeze/thaw weathering do not exhibit a significant change in their compressive strength. Specimens exposed to freeze/thaw weathering experience a large reduction in compressive strength when compared to non-weathered specimens. All specimens have been found to portray a similar (crushing) mode of failure. Specimens containing PVA fiber exhibit a greater resilience and resistance to failure after cracking had occurred within the mortar.

CHAPTER 6: SUMMARY

6.0 INTRODUCTION

The purpose of this chapter is to summarize the results of the experimental freeze/thaw testing. In addition to summarization of the experimental results, provisions and recommendations for future research are presented.

6.1 SUMMARY OF MASONRY PRISM COMPRESSIVE TESTING

The pre-freeze/thaw compressive strength of the experimental PVA FRM do not experience a significant increase in strength when compared with the control prisms. After exposure to uni-directional freeze/thaw weathering, prism compressive strength is not significantly impacted by the inclusion of PVA fibers. Comparison of masonry prism compressive strength testing to mortar prism testing after freeze/thaw exposure yields a realistic representation of the expected durability of PVA FRM.

6.2 SUMMARY OF MORTAR CUBE COMPRESSIVE TESTING

The results of the pre-freeze/thaw 2-in. mortar cube compressive strength are consistent with the findings of previous research as they do not produce a significant change to the compressive strength of the mortar. Visual observation of specimens containing PVA fiber illustrate an increase in resistance to spalling and exterior cracking when compared to the control mixture. Overall, the mortar cube compressive strength results are much higher than expected for all specimens. Full exposure to freeze/thaw weathering produces more severe spalling when compared to the in-situ testing. No loss in strength due the inclusion of PVA fibers is observed throughout the freeze/thaw testing.

6.3 SUMMARY OF MASONRY PRISM FLEXURAL BOND STRENGTH TESTING

The flexural capacity of the 7-stack masonry prisms experience a decrease after exposure to the freeze/thaw testing. This decrease is significantly lower than the decrease experienced with the control mixture not containing PVA fibers, resulting in a more durable mix design. Based on these results, the inclusion of PVA fibers into the mix increases the durability and resiliency of the mortar and brick assemblages when compared to non PVA FRM mixes.

6.4 SUMMARY OF MORTAR CUBE MOISTURE ABSORPTION

Experimental research has found that the inclusion of PVA fibers does not significantly increase the moisture absorptive capabilities of PVA FRM.

6.5 SUMMARY OF EXPERIMENTAL FREEZE/THAW TESTING

The results of the masonry prism flexural bond strength testing reveal a consistent increase in flexural bond strength for the mix designs containing PVA fibers. After exposure to extreme freeze/thaw weathering, a consistent reduction in flexural strength is experienced by the majority of the mix designs. In addition to a consistent reduction in strength, the average sample standard deviation of each mix design nearly double when compared to specimens not exposed to weathering. Exposure to uni-directional freeze/thaw weathering imposes a reduction in the bond strength between the mortar and brick interface, as well as an increase in the inconsistency of the tested specimens. Overall, the PVA FRM prisms experience a smaller reduction in strength than the control not containing PVA fiber. Results of the experimental testing illustrate that the inclusion of PVA fibers within a mortar produces a more durable and resilient mortar to in-situ replicated freeze/thaw exposure.

6.6 SUMMARY OF CURRENT AND PAST RESEARCH

Previous research has determined the freeze/thaw durability of PVA mortar prisms exposed to weathering on all sides of a prism (Wang & Li, 2006). The findings of this thesis explain that PVA FRM as a repair mortar are not currently being tested in a manner similar to their field application. When a brick-and-mortar prism is freeze/thaw durability tested to represent in-situ conditions, specimens do not experience a reduction in compressive strength. As the engineering field advances, professionals are constantly developing and improving upon standards to become more accurate and efficient in design. There exists two improvements to be made to current freeze/thaw testing techniques:

1. Experimental freeze/thaw testing needs to be performed on masonry prism specimens in lieu of pure mortar prisms.
2. Freeze/thaw exposure needs to be imposed on a single face of a prism to represent the actual weathering a structure will experience.

Once these two changes are implemented, current freeze/thaw techniques will present more viable results consistent with performance specimens will yield in the field.

6.7 FURTHER RESEARCH RECOMMENDATIONS

Based on the results, the inclusion of PVA fibers into the mortar increases the durability and resiliency of the mortar and brick assemblages when compared to non PVA FRM mixes. Therefore, their utilization in future construction and masonry rehabilitation projects is recommended. However, this study only contains information on specific mix designs that have been experimentally tested. The principles and methods used to test specimens provide an accurate representation of in-situ freeze/thaw exposure. The results of this experiment cannot be assumed to be representative of other fiber types. As a result of this study, the following future research is recommended to provide overall generalizations and a greater understanding of FRM:

1. Freeze/thaw exposure of various mix designs containing different fiber types.
2. Comparison of actual in-situ testing with the replicated methodology developed in this study.
3. Presentation of an ASTM Standard for the in-situ freeze/thaw durability testing of masonry.

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APPENDIX A

CARON FREEZE/THAW CHAMBER SPECIFICATIONS

FEATURES & BENEFITS

AT A GLANCE STANDARD FEATURES

Caron's Freeze/Thaw Chambers precisely control a wide range of temperature and (optional) humidity settings. This broad range encompasses nearly every ambient environment on earth. Automatic, versatile and programmable cycling between setpoints enables continuous simulation of the harsh conditions of freezing and thawing for rapid testing. These demanding temperature and humidity cycling studies require accurate control of thermal conditions, and are best served by our chambers.

Our chambers will accomodate a wide range of freeze/thaw studies, including pharmaceutical drug studies, concrete and asphalt testing, coating and adhesive testing, outdoor weathering tests, stress testing and more! Our product offering includes two sizes of large capacity, reach-in units. Our products are not only consistently reliable, but offer best in class customer friendly features and unique energy efficient components.

- The wide temperature range of -25°C to 70°C and optional humidity range from 20% to 98% offers the flexibility to simulate a broad range of environmental conditions.
- Deluxe controller includes ramp and soak to cycle freezing and thawing for repeatable, accurate studies. Our controller can perform 4 programs, 40 individual steps, an infinite number of loops and a ramp based on any time or rate.
- Caron offers an optional factory calibration of the controller and will program it to your specific profile, which makes installation and start up easy.
- **gROD**™, Refrigeration on Demand, efficiently manages power consumption and saves electricity.
- Caron's humidified Freeze/Thaw Chambers, Models 6220 and 6240, feature **gVapor**™, which delivers controlled humidity vapor on an as needed basis without wasting energy or producing heat.
- The deluxe controller comes standard with analog outputs and RS-485 communications and connects the unit directly to an in-house monitoring system.
- The glass doors are heated, triple-pane and argon filled, which minimizes condensation for a clear view of your samples inside.
- Caron's carefully designed horizontal airflow system generates gentle and evenly distributed airflow across all shelf locations. Temperature uniformity and rapid recovery are always maintained, even under heavy loads.
- These chambers are designed with high R, CFC-free foam insulation, making them energy efficient.
- In the event of a power failure, non-volatile memory allows the chamber to return to its original setpoint when power is restored.
- Setpoint deviation alarm visually and audibly alerts you of a problem with the convenient option to silence the audible alarm.
- Dual display of temperature and humidity allows you to visualize instantaneous setpoint and operating conditions. Setpoints are easily adjusted by simply pressing the up or down arrow keys.
- The stainless steel shelves are adjustable and perforated, making them easy to clean and highly resistant to corrosion. These shelves also slide, so whether testing samples or heavy equipment, it is easy to locate all product inside.
- The interior is comprised of corrosion-resistant stainless steel and is quickly removed without tools, allowing you to reconfigure the interior.
- Our ergonomic, limolicious door handle is an attractive, modern design, and allows you to easily access the inside of your chamber.
- Two access ports make validation easy and provide you with convenient access to connect wires and instrumentation.
- A wide range of accessories are available, allowing you to modify the chamber to your specific application requirements.

EARTH FRIENDLY TECHNOLOGIES

OUR EXCLUSIVE INNOVATIONS

Caron developed earth friendly technologies into the design of our chambers. Our green innovations work together to contribute to energy efficiency and cost savings with cutting-edge unique technologies.

gROD

- **gROD**™ is Caron's Refrigeration on Demand controlled refrigeration, and it efficiently manages power consumption and saves electricity.
- Unlike competitive units that run refrigeration constantly to maintain required setpoints, **gROD**™ only operates the refrigeration system when it is needed to maintain the temperature setpoint.

gVapor (humidified chambers only, Models 6220 and 6240)

- **gVapor**™ injects humidity only as needed, without utilizing steam to create humidity, using much less energy than other technologies.
- Unlike competitive units that incorporate energy inefficient steam generators to control and create humidity, **gVapor**™ atomizes water into humidity vapor in small, controlled amounts.
- **gVapor**™ quickly recovers humidity after door openings.

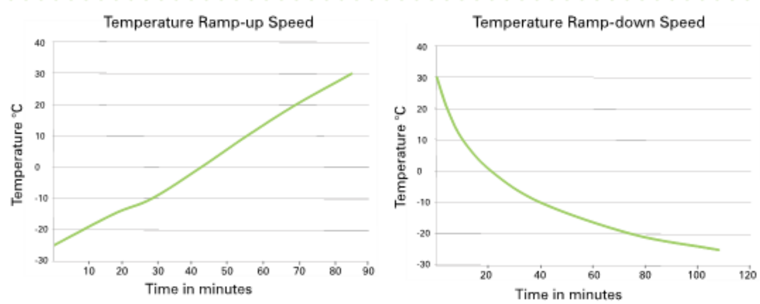
Other earth friendly, cost saving design features

- The chambers are insulated with energy efficient high R, CFC-free foam, contributing to high thermal retention, and tightly controlling the conditions inside the chamber. Heat loss is significantly eliminated, which places less demand on your laboratory's air conditioning unit.
- All units have a heated, triple pane, argon filled glass door, which meets the new Department of Energy standard for refrigerated equipment. The energy efficient door heater also minimizes condensation on the door for a clear view of your product and aids in temperature recovery.

Optional Condensate Recirculating System

- Caron's optional earth friendly water recycling/purification system (Model CRSY102) is available to provide a pure water source to your humidified chamber.
- The CRSY102 will convert tap water into purified water, eliminating the need to purchase more expensive water purification systems or maintain a supply of distilled or deionized water.
- It connects directly to the chamber and recycles the used water, continuously conditioning it, eliminating the need for a floor drain.
- One CRSY102 will supply purified water to two chambers.

Condensate Recirculating System



Quick ramp-up and ramp-down speeds represented in graphs.

SPECIFICATIONS & OPTIONAL ACCESSORIES

Model Number	6220-2	6220-3	6221-2	6221-3	6240-2	6240-3	6241-2	6241-3
Temperature Range	-25°C to 70°C							
Temperature Control	±0.1°C							
Temperature Uniformity at 20°C	±0.3°C							
Temperature Sensor	3-wire RTD							
Humidity Range	20 to 98% RH		N/A		20 to 98% RH		N/A	
Humidity Control	±3% RH		N/A		±3% RH		N/A	
Humidity Sensor	Capacitive		N/A		Capacitive		N/A	
Interior Dimensions	32" W x 27" D x 52.7" H (81.3 cm x 68.6 cm x 133.9 cm)				32" W x 27" D x 65.7" H (81.3 cm x 68.6 cm x 166.9 cm)			
Interior Construction	Type 304, 2B Finish, Solid Stainless Steel							
Exterior Dimensions	35.5" W x 33.3" D* x 77.1" H (90.2 cm x 84.6 cm x 195.8 cm)				35.5" W x 33.3" D* x 90.1" H (90.2 cm x 84.6 cm x 228.9 cm)			
Exterior Construction	Cold Rolled Steel, Powder Coated							
Work Space	25 cu. ft. (708 Liters)				33 cu. ft. (934 Liters)			
# of Shelves	4 Standard; 25 Maximum				5 Standard; 31 Maximum			
Shelf Construction	Type 304, Perforated Stainless Steel, Electropolished							
Shelf Dimensions	29.25" W x 24.45" D (74.3 cm x 62.1 cm)							
Electrical	208/230V 60 Hz 12A	230V 50 Hz 12A	208/230V 60 Hz 12A	230V 50 Hz 12A	208/230V 60 Hz 12A	230V 50 Hz 12A	208/230V 60 Hz 12A	230V 50 Hz 12A
Shipping Weight lbs.	775	875**	775	875**	800	1,100 **	800	1,100 **
Shipping Weight kg.	352	397**	352	397**	363	499**	363	499**

NOTE: Specifications are subject to change without notice. Specifications are based on 20°C ambient and standard voltage. Humidity non-condensing. *Add 2.75" for handle. **Includes export shipping crate.

DESCRIPTION	6220	6221	6240	6241
Remote alarm contacts. Provides NO and NC dry contacts for alarms.	ALRM301			
Condensate Recirculating System.	CRSY102	N/A	CRSY102	N/A
Solid insulated door.	DOOR302		DOOR306	
Heatless dryer package, purge air system. Allows for operation of the chamber at lower humidity levels (2% RH).	DRYR301	N/A	DRYR301	N/A
LED lighting system with timer for day/night simulations.	LGHT302			
Single interior GFI duplex outlet fused at 2A. Humidity levels cannot exceed 90% RH.	OUTL301			
Phenolic coated coils.	PCEC306	PCEC305	PCEC306	PCEC306
Built-in recorder; thermal printer, 10", 7 day, 24 hour.	RCDR304	RCDR303	RCDR304	RCDR303
Side-mounted recorder; thermal printer, 12", 7 day, 24 hour.	RCDR315	RCDR314	RCDR315	RCDR314
Stainless steel shaker support system capable of supporting 150 pound shakers.	SHKR301-2 (2 tier)		SHKR303-2 (3 tier)	
Heavy duty perforated shelf kit to replace standard shelving.	SHLF313		SHLF318	

For additional accessories, visit www.caronproducts.com.

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www.caronproducts.com
sales@caronproducts.com

CARON
Opening Doors for Scientists

CARON FREEZE/THAW CHAMBER PROFILE PROGRAM

Profile 1	**DISPLAY PARAMETER**	**DISPLAY VARIABLE**
Step 1	P1	1
	S.typ	ti
	t.sp1	-30
	hour	0
	min	0
	sec	0
	ent1	off
	ent2	off
Step 2	P1	2
	S.typ	Soah
	hour	3
	min	0
	sec	0
	ent1	off
	ent2	off
Step 3	P1	3
	S.typ	t1
	t.sp1	5
	hour	0
	min	0
	sec	0
	ent1	off
	ent2	off
Step 4	P1	4
	S.typ	Soah
	hour	0
	min	36
	sec	0
	ent1	off
	ent2	off
Step 5	P1	5
	S.typ	JL
	JS	1
	JC	36
	ent1	off
	ent2	off
Step 6	P1	6
	S.typ	END
	END	User

Step 7	P1	7
	S.typ	USTP

The testing for our chamber requires being able to take the chamber from a temperature of 4 C down to a temperature of -18 C in a time frame of 1 hour. Specifications of the chamber state that we can accomplish this in approximately 50 minutes. Then, soak the chamber at -18 C for 5 minutes and ramp the temperature back up to 4 C in the same 50 minutes. Soak it at 4 C for 5 minutes, and then repeat the cycle. Overall time for completion of one cycle should be approximately 2 hours.

Chamber cannot accomplish this speed when fully loaded. Must increase soak time in order to achieve full freezing and thawing.

APPENDIX B

Pre-F/T Compressive Strength of Masonry Prisms

weight of top plate = 10.6 lb

Control	H			L			W			Load (lb)	Strength (psi)	Description	Standard Deviation	hp/tp
1	7.471	7.461	7.606	13.197	13.234	13.209	3.645	3.665	3.654	49591	1806	2). Cone + Shear	106.9116	3.615469
AVERAGE		7.513			13.213			3.655						
2	7.658	7.656	7.599	12.907	12.890	12.930	3.638	3.655	3.677	55581	1990	1). Conical		3.530264
AVERAGE		7.638			12.909			3.657						
3	7.446	7.434	7.542	13.334	13.315	13.377	3.704	3.632	3.651	54541	1993	3). Cone + Split		3.643033
AVERAGE		7.474			13.342			3.662						
PVA RECS7 (0.25%)														
1	7.540	7.591	7.575	13.264	13.304	13.240	3.675	3.649	3.643	49531	1790	2). Cone + Shear	115.9506	3.629798
AVERAGE		7.569			13.269			3.656						
2	7.524	7.504	7.614	13.205	13.240	13.173	3.642	3.664	3.632	55601	2021	5). Semi-conical		3.622052
AVERAGE		7.547			13.206			3.646						
3	7.588	7.577	7.600	13.296	13.284	13.288	3.685	3.641	3.653	52281	1883	5). Semi-conical		3.631296
AVERAGE		7.588			13.289			3.660						
PVA RECS7 (0.50%)														
1	7.322	7.236	7.299	13.38	13.34	13.261	3.476	3.557	3.478	54731	2144	3). Cone + Split	84.06978	3.803729
AVERAGE		7.286			13.327			3.504						
2	7.297	7.347	7.295	13.29	13.321	13.279	3.662	3.577	3.563	54011	2051	6). Shear Break		3.692835
AVERAGE		7.313			13.297			3.601						
3	7.314	7.282	7.445	13.345	13.379	13.403	3.585	3.554	3.558	58131	2219	2). Cone + Shear		3.751239
AVERAGE		7.347			13.376			3.566						
PVA RECS15 (0.25%)														
1	7.248	7.164	7.35	13.155	13.204	13.2	3.547	3.55	3.514	53401	2081	2). Cone + Shear	63.98993	3.728084
AVERAGE		7.254			13.186			3.537						
2	7.449	7.332	7.184	13.336	13.337	13.337	3.433	3.487	3.548	54951	2151	2). Cone + Shear		3.822125
AVERAGE		7.322			13.337			3.489						
3	7.338	7.365	7.292	13.331	13.353	13.317	3.401	3.47	3.524	56121	2209	2). Cone + Shear		3.8481

Pre-F/T Compressive Strength of Masonry Prisms

AVERAGE		7.332			13.334			3.465						

PVA RECS15 (0.50%)

1	7.144	7.267	7.297	12.957	12.887	12.845	3.213	3.303	3.348	66821	2809	2). Cone + Shear	226.9903	3.922242
		7.236			12.896			3.288						
2	7.219	7.331	7.216	13.21	13.191	13.092	3.42	3.338	3.331	57581	2360	3). Cone + Split		3.914461
		7.255			13.164			3.363						
3	7.401	7.214	7.493	13.291	13.264	13.172	3.487	3.423	3.525	64701	2524	2). Cone + Shear		3.807092
		7.369			13.242			3.478						

PVA RECS7 (0.25%) + PVA RECS15 (0.25%)

1	7.366	7.165	7.281	12.853	12.871	12.867	3.42	3.352	3.404	58351	2366	2). Cone + Shear	132.7811	3.792355
		7.271			12.864			3.392						
2	7.277	7.44	7.436	13.054	13.058	13.036	3.539	3.623	3.561	61371	2325	2). Cone + Shear		3.650844
		7.384			13.049			3.574						
3	7.276	7.476	7.547	13.13	13.171	13.098	3.487	3.461	3.368	65760.6	2573	6). Shear Break		3.819213
		7.433			13.133			3.439						

Average Prism Compressive Strength (psi)		Average Masonry Compressive Strength (psi)	
Control	1930	Control	2157
PVA RECS7 (0.25%)	1898	PVA RECS7 (0.25%)	2126
PVA RECS7 (0.50%)	2138	PVA RECS7 (0.50%)	2416
PVA RECS15 (0.25%)	2147	PVA RECS15 (0.25%)	2435
PVA RECS15 (0.50%)	2564	PVA RECS15 (0.50%)	2925
PVA RECS7 (0.25%) + PVA RECS15 (0.25%)	2421	PVA RECS7 (0.25%) + PVA RECS15 (0.25%)	2737
			2466

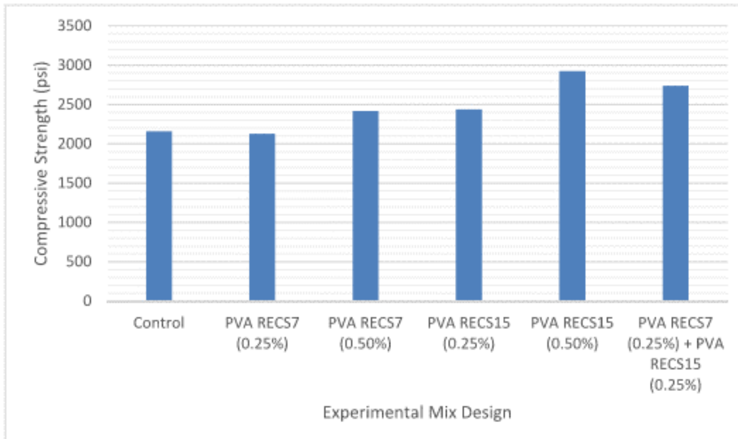
Pre-F/T Compressive Strength of Masonry Prisms

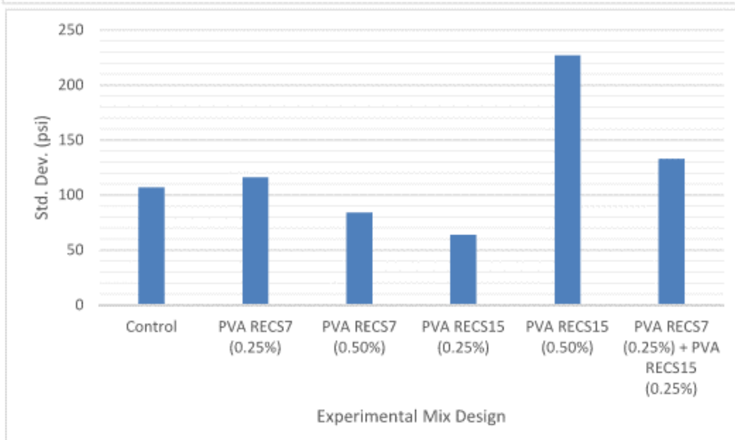
Correction Factor	Masonry Compressive Strength	
1.12	2021.527834	117.4605
1.11	2213.840837	
1.12	2234.529039	
1.12	2005.646881	129.232
1.12	2262.537739	
1.12	2109.433911	
1.13	2432.010425	100.5734
1.13	2308.435543	
1.13	2507.670963	
1.13	2348.213645	82.99603
1.14	2442.926534	
1.14	2513.625694	

Pre-F/T Compressive Strength of Masonry Prisms

1.14	3212.345686	262.649
1.14	2697.725717	
1.13	2863.776882	
1.13	2681.600007	163.5725
1.12	2608.993612	
1.14	2921.546861	

Pre-F/T Compressive Strength of Masonry Prisms



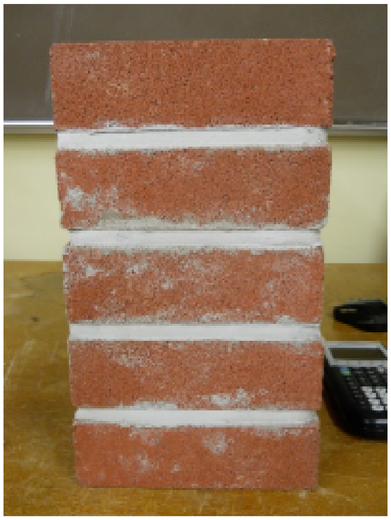


Pre-F/T Control Specimen # 1:

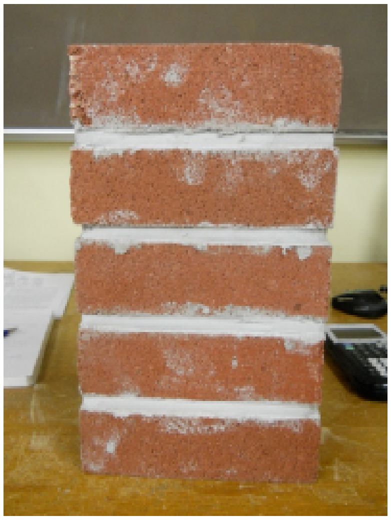
Pre-F/T Control Specimen # 2:

Pre-F/T Control Specimen # 3:

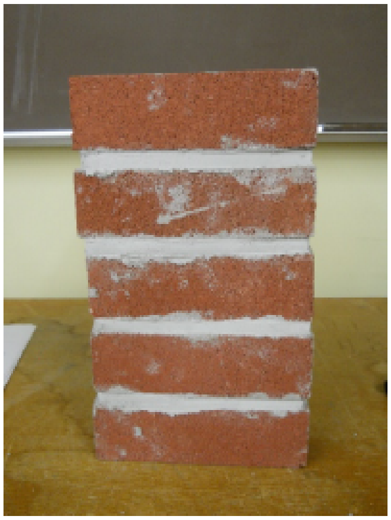
Pre-F/T PVA RECS7 (0.25%) # 1:



Pre-F/T PVA RECS7 (0.25%) # 2:



Pre-F/T PVA RECS7 (0.25%) # 3:



Pre-F/T PVA RECS7 (0.50%) # 1:

Pre-F/T PVA RECS7 (0.50%) # 2:


P 6Min
2 0.5%
MAX
PISTON
STROKE

Pre-F/T PVA RECS7 (0.50%) # 3:

Pre-F/T PVA RECS15 (0.25%) # 1:

Pre-F/T PVA RECS15 (0.25%) # 2:

Pre-F/T PVA RECS15 (0.25%) # 3:

Pre- F/T PVA RECS15 (0.50%) # 1:

Pre-F/T PVA RECS15 (0.50%) # 2:

Pre-F/T PVA RECS15 (0.50%) # 3:

Pre-F/T PVA RECS7 (0.25%) + RECS15 (0.25%) # 1:

Pre-F/T PVA RECS7 (0.25%) + RECS15 (0.25%) # 2:

Pre-F/T PVA RECS7 (0.25%) + RECS15 (0.25%) # 3:

Post- F/T Compressive Strength of Masonry Prisms

weight of top plate = 10.6 lb

Control		H			L			W		Load (lb)	Strength (psi)	Description	STD	hp/tp
1	7.389	7.469	7.440	13.538	13.586	13.572	3.481	3.625	3.607	58410	2201	2). Cone + Shear	216.782	3.798749
AVERAGE		7.433			13.565			3.571				7). Face Shell Sep.		
2	7.523	7.508	7.600	13.136	13.071	13.053	3.605	3.606	3.611	49150	1806	7). Face Shell Sep.		3.627795
AVERAGE		7.544			13.087			3.607						
3	7.509	7.456	7.447	13.150	13.219	13.209	3.577	3.543	3.576	57510	2159	5). Semi-Conical		3.700262
AVERAGE		7.471			13.193			3.565						

PVA RECS7 (0.25%)

1	7.350	7.171	7.341	13.350	13.320	13.283	3.496	3.427	3.600	52830	2067	2). Cone + Shear	239.3028	3.796731
AVERAGE		7.287			13.318			3.508				5). Semi-Conical		
2	7.367	7.114	7.525	13.140	13.139	13.118	3.507	3.607	3.625	60670	2311	3). Cone + Split		3.668591
AVERAGE		7.335			13.132			3.580						
3	7.394	7.433	7.508	13.352	13.298	13.275	3.625	3.510	3.581	67690	2545	2). Cone + Shear		3.725737
AVERAGE		7.445			13.308			3.572						

PVA RECS7 (0.50%)

1	7.427	7.425	7.349	13.606	13.638	13.550	3.483	3.454	3.545	60430	2337	7). Face Shell Sep.	161.2346	3.891815
AVERAGE		7.400			13.598			3.494						
2	7.383	7.467	7.387	13.425	13.391	13.364	3.498	3.489	3.513	65070	2508	7). Face Shell Sep.		3.826667
AVERAGE		7.412			13.393			3.500						
3	7.396	7.404	7.395	13.449	13.408	13.377	3.548	3.540	3.340	68390	2659	2). Cone + Shear		3.858266
AVERAGE		7.398			13.411			3.476						

PVA RECS15 (0.25%)

1	7.404	7.335	7.268	13.316	13.295	13.316	3.582	3.626	3.508	94390	3602	6). Shear Failure	429.9934	3.725924
AVERAGE		7.336			13.309			3.572						
2	7.278	7.424	7.432	13.247	13.231	13.216	3.560	3.538	3.482	72930	2803	7). Face Shell Sep.		3.751796
AVERAGE		7.378			13.231			3.527						
3	7.250	7.421	7.341	13.258	13.287	13.309	3.472	3.414	3.530	74590	2928	1). Conical		3.826229
AVERAGE		7.337			13.285			3.472						

Post- F/T Compressive Strength of Masonry Prisms

PVA RECS15 (0.50%)

1	7.280	7.270	7.450	13.100	13.040	13.000	3.190	3.400	3.410	90120	3687	2). Cone + Shear	89.10613	3.914
		7.333			13.047			3.333						
2	7.290	7.300	7.240	12.920	12.940	12.890	3.250	3.300	3.360	92280	3839	2). Cone + Shear		3.910192
		7.277			12.917			3.303						
3	7.200	7.280	7.150	13.100	13.080	13.020	3.240	3.420	3.400	89040	3683	2). Cone + Shear		3.89662
		7.210			13.067			3.353						

PVA RECS7 (0.25%) + PVA RECS15 (0.25%)

1	7.700	7.180	7.260	12.900	12.900	12.920	3.229	3.320	3.340	67390	2770	2). Cone + Shear	282.4341	3.915462
		7.380			12.907			3.296						
2	7.200	7.120	7.320	12.780	12.820	12.780	3.380	3.320	3.480	59700	2439	3). Cone + Split		3.770138
		7.213			12.793			3.393						
3	7.480	7.200	7.340	12.880	12.920	12.900	3.480	3.380	3.340	74890	3001	6). Shear Break		3.794118
		7.340			12.900			3.400						

Average Compressive Strength (psi)

Control	2055
PVA RECS7 (0.25%)	2308
PVA RECS7 (0.50%)	2502
PVA RECS15 (0.25%)	3111
PVA RECS15 (0.50%)	3736
PVA RECS7 (0.25%) + PVA RECS15 (0.25%)	2737

Average Masonry Compressive Strength (psi)

Control	2317
PVA RECS7 (0.25%)	2603
PVA RECS7 (0.50%)	2848
PVA RECS15 (0.25%)	3519
PVA RECS15 (0.50%)	4269
PVA RECS7 (0.25%) + PVA RECS15 (0.25%)	3110

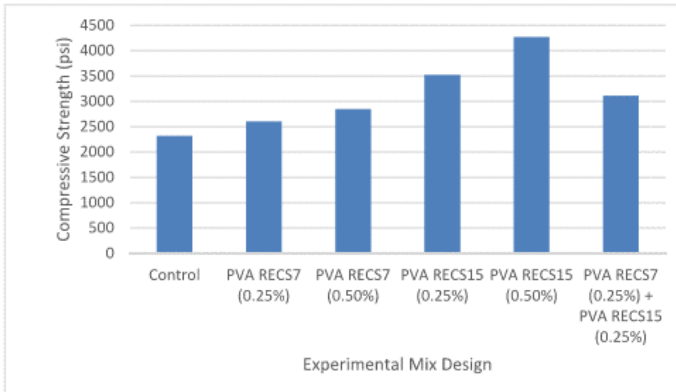
Post- F/T Compressive Strength of Masonry Prisms

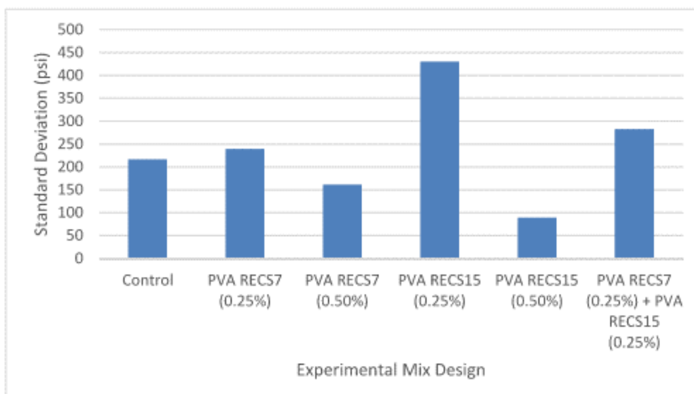
rection Fac	Compressive Strength	
1.13	2495.327	256.0429
1.12	2023.296	
1.13	2431.254	
1.13	2343.185	264.1448
1.12	2595.851	
1.13	2871.311	
1.14	2667.445	180.3423
1.14	2849.621	
1.14	3028.123	
1.13	4063.615	478.088
1.13	3167.647	
1.14	3326.431	

Post- F/T Compressive Strength of Masonry Prisms

1.14	4214.372	102.7501
1.14	4387.314	
1.14	4204.714	
1.14	3166.972	324.6297
1.13	2759.999	
1.13	3401.587	

Post- F/T Compressive Strength of Masonry Prisms

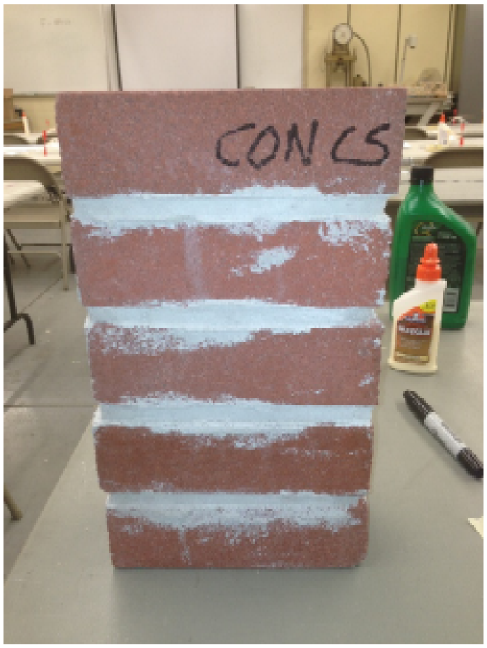




Post-F/T Control # 1 (A5):

Post-F/T Control # 2 (B5):

Post-F/T Control # 3 (C5):

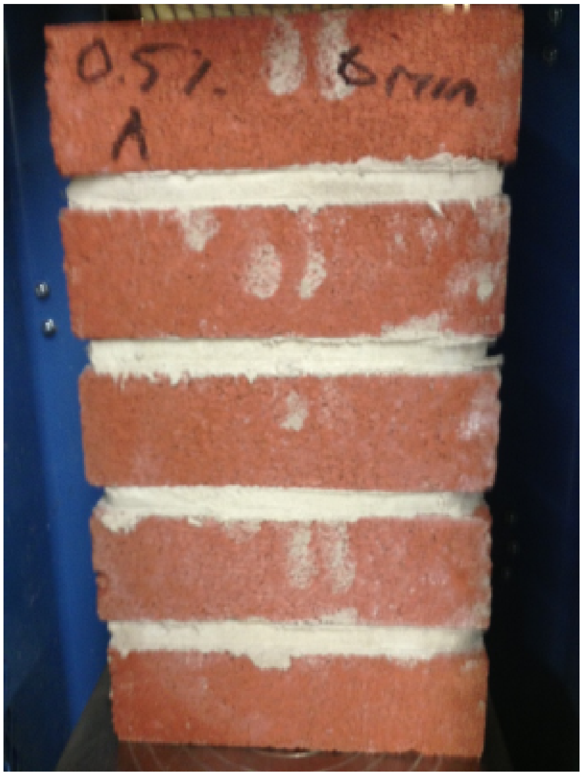


Post-F/T PVA RECS7 (0.25%) # 1 (A5):

Post-F/T PVA RECS7 (0.25%) # 2 (B5):

Post-F/T PVA RECS7 (0.25%) # 3 (C5):

Post-F/T PVA RECS7 (0.50%) # 1 (A5):



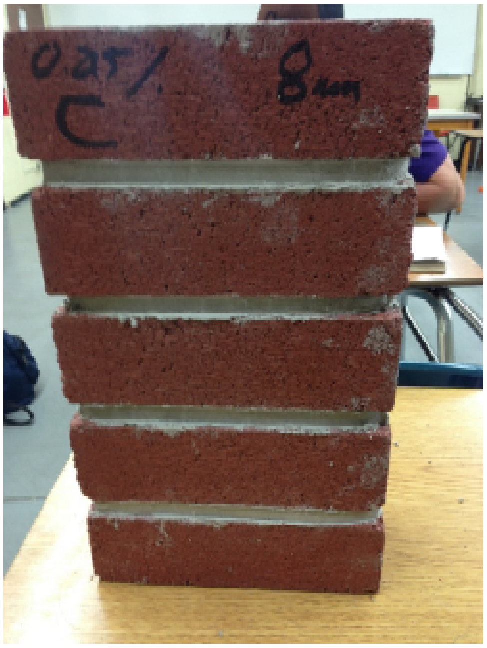
Post-F/T PVA RECS7 (0.50%) # 2 (B5):

Post-F/T PVA RECS7 (0.50%) # 3 (C5):

Post-F/T PVA RECS15 (0.25%) # 1 (A5):

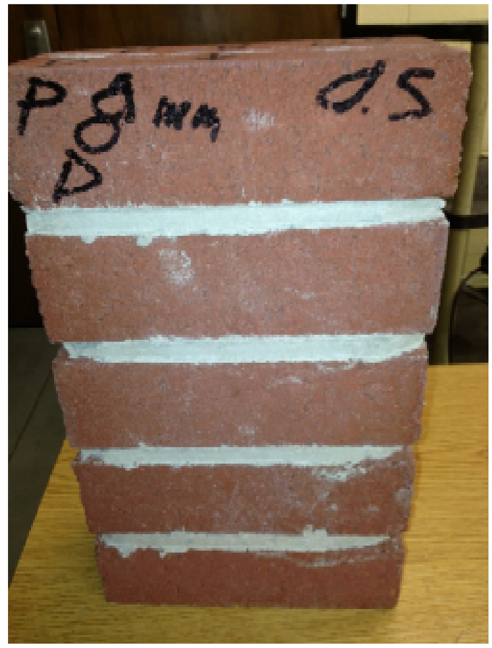
Post-F/T PVA RECS15 (0.25%) # 2 (B5):

Post-F/T PVA RECS15 (0.25%) # 3 (C5):

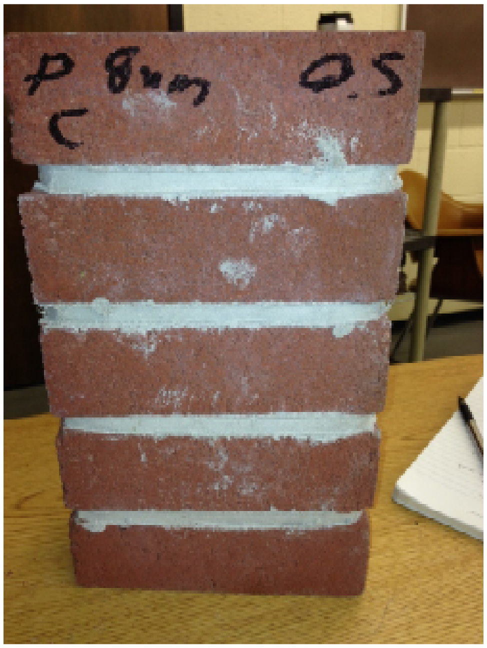


Post-F/T PVA RECS15 (0.50%) # 1 (A5):

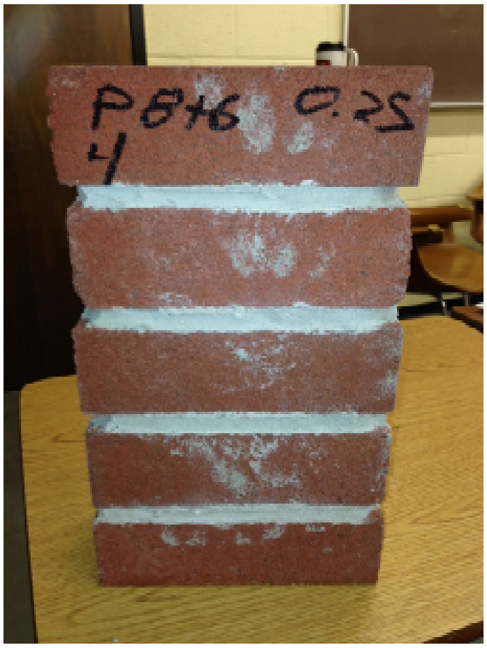
Post-F/T PVA RECS15 (0.50%) # 2 (B5):



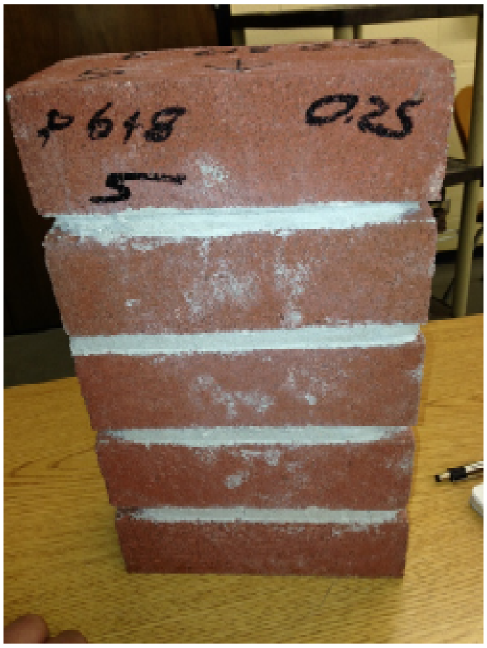
Post-F/T PVA RECS15 (0.50%) # 3 (C5):



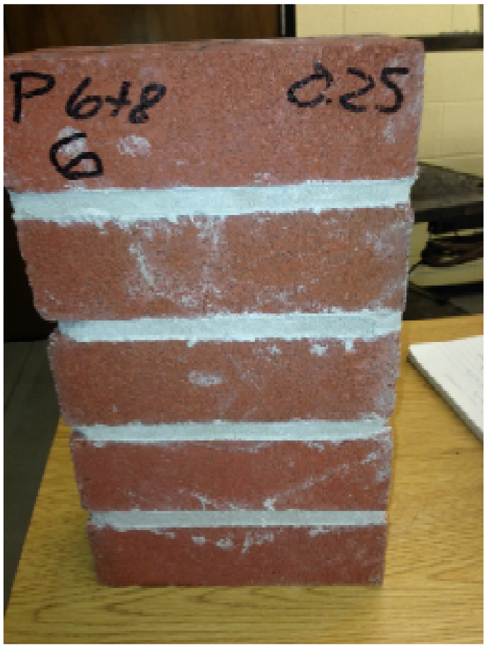
Post-F/T PVA RECS7 (0.25%) + RECS15 (0.25%) # 1 (A5):



Post-F/T PVA RECS7 (0.25%) + RECS15 (0.25%) # 2 (B5):



Post-F/T PVA RECS7 (0.25%) + RECS15 (0.25%) # 3 (C5):



APPENDIX C

Pre-F/T Compressive Strength of Mortar Cubes

weight of top plate = 10.6 lb

Control		H			L			W		Load (lb)	Strength (psi)	Description	STD
1	2.024	2.021	2.020	2.015	2.018	2.037	2.022	2.026	2.033	9700	2365		135.0213
AVERAGE		2.022			2.023			2.027					
2	2.041	2.030	2.001	2.026	1.979	2.010	2.005	2.030	1.994	10010	2484		
AVERAGE		2.024			2.005			2.010					
3	2.034	2.039	2.010	2.016	2.021	2.019	2.004	1.980	2.008	8930	2215		
AVERAGE		2.028			2.019			1.997					

PVA RECS7 (0.25%)

1	2.018	2.017	2.017	2.008	2.005	2.029	2.013	2.022	1.995	7850	1939		253.3855
AVERAGE		2.017			2.014			2.010					
2	2.009	2.006	2	2.019	2.015	2.003	2.02	2.03	2.002	9460	2330		
AVERAGE		2.005			2.012			2.017					
3	2.01	2.012	2.029	2.030	2.028	2.030	2.019	2.023	2.009	9880	2414		
AVERAGE		2.017			2.029			2.017					

PVA RECS7 (0.50%)

1	2.017	2.011	2.002	2.009	2.006	2.002	2.01	2.016	2.015	9980	2471		237.9194
AVERAGE		2.010			2.006			2.014					
2	2.025	2.028	2.015	2.021	2.025	2.03	2.021	2.024	2.04	9755	2375		
AVERAGE		2.023			2.025			2.028					
3	2.004	2.008	2.01	2	1.989	2.006	2.011	2.008	2.007	11345	2826		
AVERAGE		2.007			1.998			2.009					

PVA RECS15 (0.25%)

1	2.006	2.012	2.012	2.003	2	2.01	2.001	1.998	2.005	7900	1969		223.6687
AVERAGE		2.010			2.004			2.001					
2	2.009	2.011	2.004	2.005	2.011	2.012	2.025	2.024	2.021	9745	2397		
AVERAGE		2.008			2.009			2.023					
3	2.005	2.015	2.017	2.02	2.021	2.024	2.011	2.013	2.016	9350	2297		
AVERAGE		2.012			2.022			2.013					

Pre-F/T Compressive Strength of Mortar Cubes

PVA RECS15 (0.50%)

1	2.026	2.025	2.031	2.018	2.012	2.015	2.017	2.015	2.022	9890	2432		50.11915
		2.027			2.015			2.018					
2	2.007	2.017	2.015	2.024	2.022	2.01	2.028	2.011	2.015	9530	2339		
		2.013			2.019			2.018					
3	1.994	2.003	2.026	2	2.005	2.005	2.005	2.01	2.012	9470	2353		
		2.008			2.003			2.009					

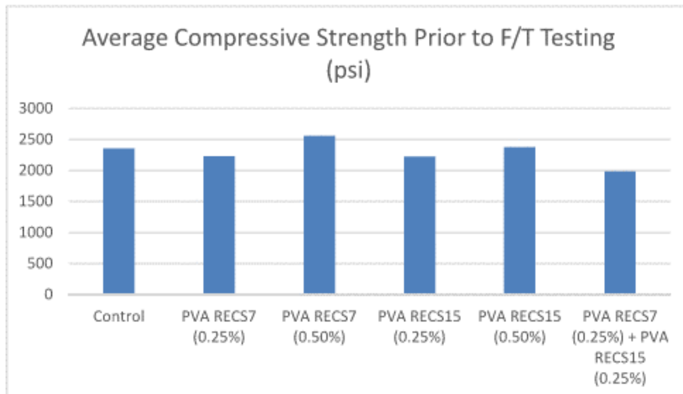
PVA RECS7 (0.25%) + PVA RECS15 (0.25%)

1	2.009	2.004	2.007	2.015	2.007	2.006	2.001	2.032	2.009	5570	1376		538.2561
		2.007			2.009			2.014					
2	2.009	2.005	2.004	1.99	2.004	1.992	1.986	2.003	2.012	9570	2398		
		2.006			1.995			2.000					
3	2.032	2.032	2.032	2.011	2.01	2.012	2.008	2.002	2.007	8800	2182		
		2.032			2.011			2.006					

Average Compressive Strength (psi)

Control	2355
PVA RECS7 (0.25%)	2228
PVA RECS7 (0.50%)	2557
PVA RECS15 (0.25%)	2221
PVA RECS15 (0.50%)	2375
PVA RECS7 (0.25%) + PVA RECS15 (0.25%)	1985

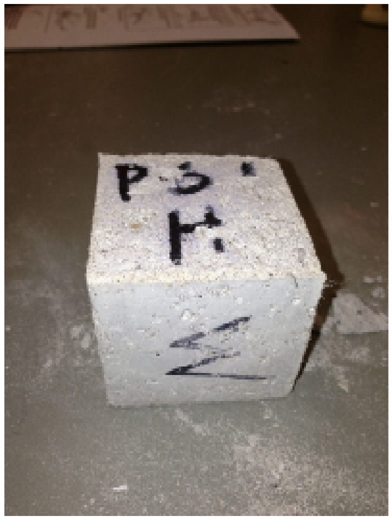
Pre-F/T Compressive Strength of Mortar Cubes

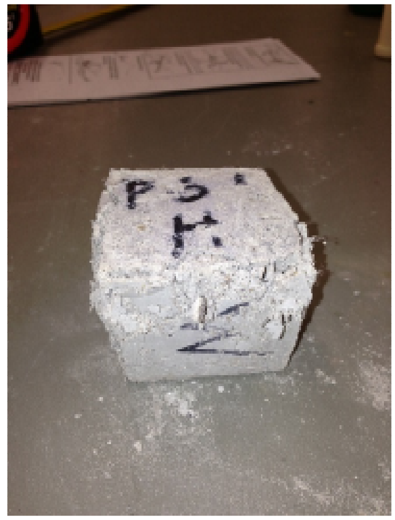


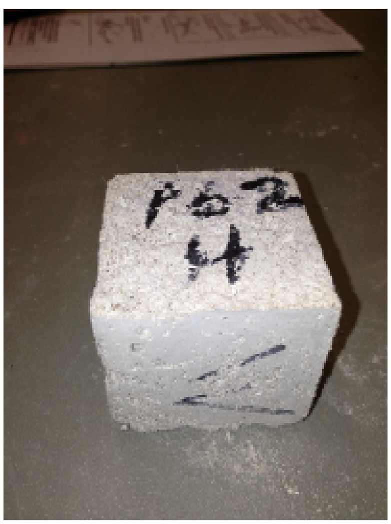
Control Mortar Cube Failure Pictures:

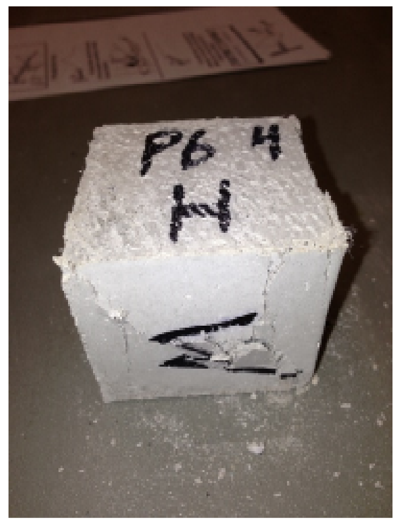


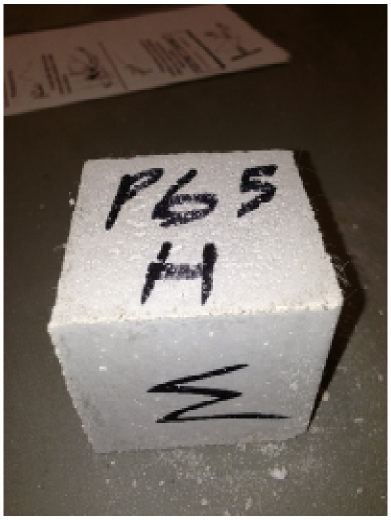

PVA RECS7 (0.25%) Mortar Cube Failure Pictures:







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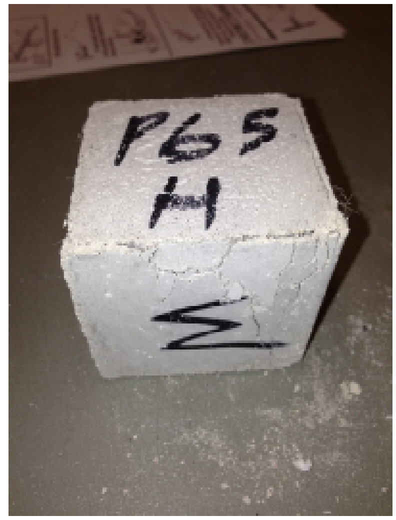
H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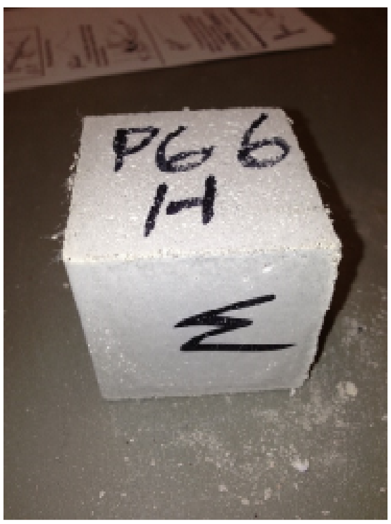
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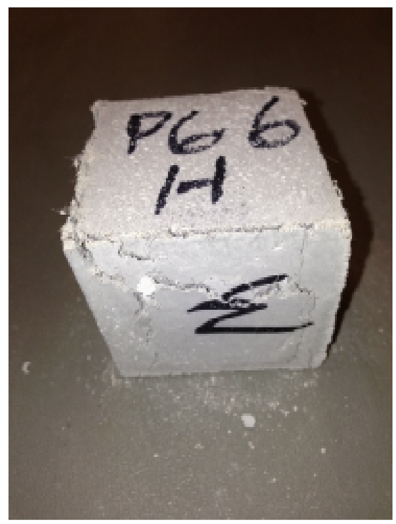
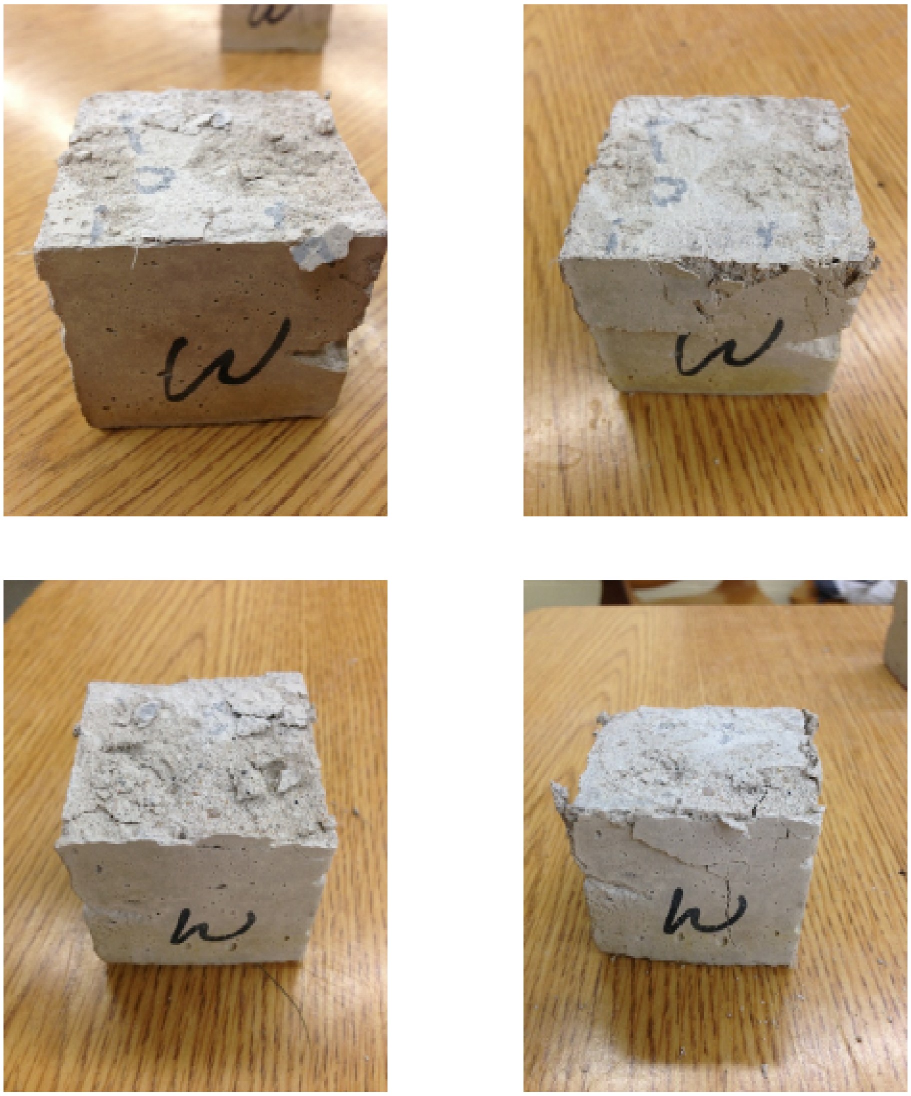
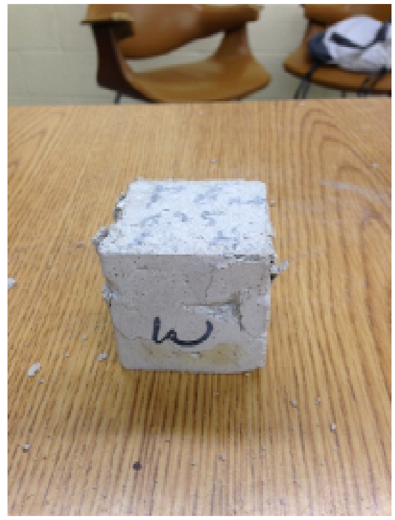
H


P66
H

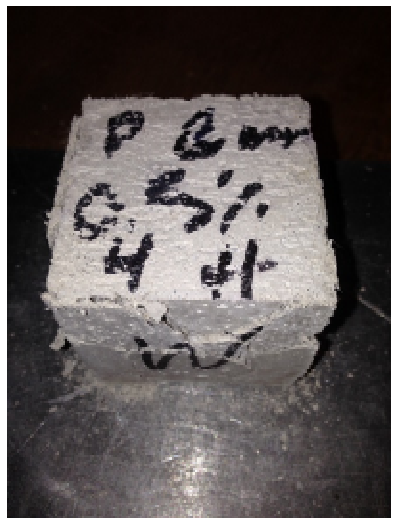
PVA RECS7 (0.50%) Mortar Cube Failure Pictures:

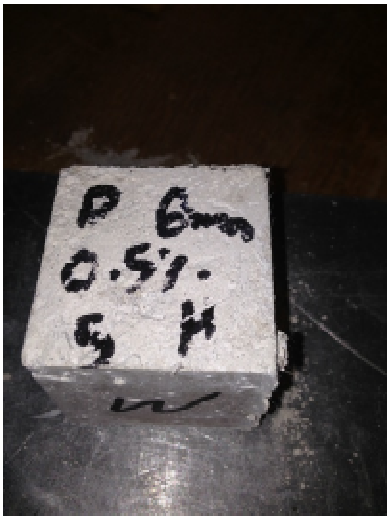
PVA RECS15 (0.25%) Mortar Cube Failure Pictures:



PVA RECS15 (0.50%) Mortar Cube Failure Pictures:

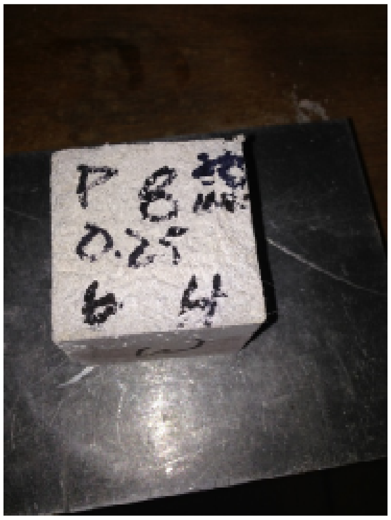


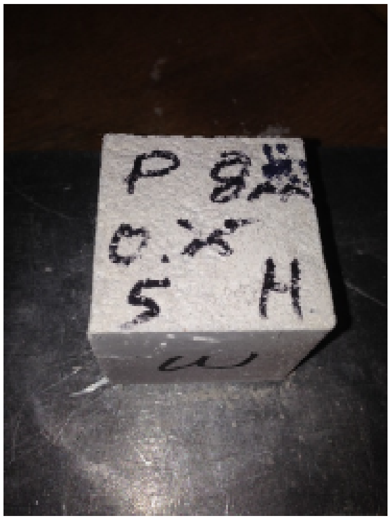

P 6mm
0.5%
H
W


P
0.5%
H


P 6mm
0.5%
H
W

PVA RECS7 (0.25%) + RECS15 (0.25%) Mortar Cube Failure Pictures:





Post-F/T Compressive Strength of Mortar Cubes

Control		H			L			W		Load (lb)	Strength (psi)	Description	STD
1	1.978	2.021	2.020	2.010	2.023	2.017	2.028	2.026	2.018	2580	632		742.1697
AVERAGE		2.006			2.017			2.024					
2	2.013	1.991	1.969	2.017	1.994	1.994	2.014	2.013	2.009	6800	1688		
AVERAGE		1.991			2.002			2.012					
3	2.024	1.984	2.018	2.023	2.020	2.020	2.015	2.011	2.010	8390	2063		
AVERAGE		2.009			2.021			2.012					

PVA RECS7 (0.25%)													
1	1.985	2.02	2.023	2.005	2.011	2.013	2.019	2.019	2.02	6770	1668		152.2579
AVERAGE		2.009			2.010			2.019					
2	2.02	2.019	1.993	1.995	2.010	1.997	2.019	2.019	2.024	6450	1595		
AVERAGE		2.011			2.001			2.021					
3	2.008	2.013	2.023	2.014	2.018	2.017	2.03	2.025	2.029	7720	1888		
AVERAGE		2.015			2.016			2.028					

PVA RECS7 (0.50%)													
1	2.018	2.012	1.999	2.01	2.009	2.007	1.995	1.995	1.991	8080	2018		323.4294
AVERAGE		2.010			2.009			1.994					
2	2.026	2.045	2.025	2.027	2.029	2.025	2.025	2.027	2.028	10890	2651		
AVERAGE		2.032			2.027			2.027					
3	2.011	2.012	2.022	2	1.999	2	1.995	1.998	2.005	9790	2449		
AVERAGE		2.015			2.000			1.999					

PVA RECS15 (0.25%)													
1	1.964	1.952	2.01	2.009	2.013	2.001	1.994	2	2.001	6230	1553		357.634
AVERAGE		1.975			2.008			1.998					
2	2.006	1.964	1.908	2.03	2.032	2.035	2.031	2.034	2.031	6910	1673		
AVERAGE		1.959			2.032			2.032					
3	2.022	2.031	2.035	2.014	2.02	2.014	2.018	2.018	2.007	9030	2224		
AVERAGE		2.029			2.016			2.014					

Post-F/T Compressive Strength of Mortar Cubes

PVA RECS15 (0.50%)

1	2.033	2.015	2.019	1.993	2.007	2.025	2.004	2.019	2.025	12190	3011		330.3552
		2.022			2.008			2.016					
2	2.01	2.003	2	2.033	2.013	1.978	2.003	2.005	2	12370	3076		
		2.004			2.008			2.003					
3	2.01	2.02	2.013	2.036	2.015	2.007	2.029	2.03	2.036	10150	2474		
		2.014			2.019			2.032					

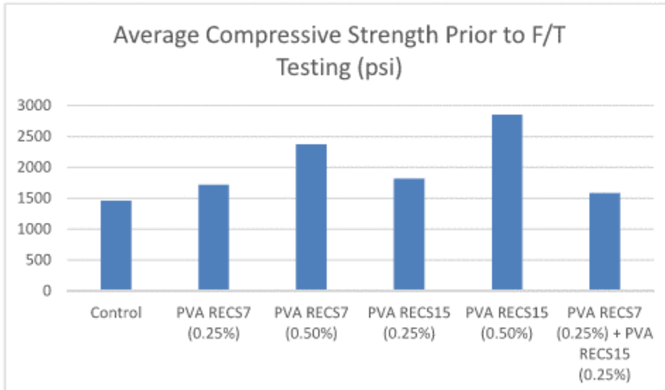
PVA RECS7 (0.25%) + PVA RECS15 (0.25%)

1	2.037	2.02	2.003	2.028	2.014	1.997	2.026	2.014	2.002	6470	1596		25.5253
		2.020			2.013			2.014					
2	2.036	2.038	2.019	2.04	2.026	2.043	2.036	2.042	2.04	6650	1601		
		2.031			2.036			2.039					
3	2.022	2.031	2.028	2.031	2.025	2.019	2.052	2.07	2.053	6480	1555		
		2.027			2.025			2.058					

Average Compressive Strength (psi)

Control	1461
PVA RECS7 (0.25%)	1717
PVA RECS7 (0.50%)	2372
PVA RECS15 (0.25%)	1817
PVA RECS15 (0.50%)	2854
PVA RECS7 (0.25%) + PVA RECS15 (0.25%)	1584

Post-F/T Compressive Strength of Mortar Cubes



APPENDIX D

Pre- F/T Flexural Strength of Masonry Prisms

weight of top plate = 13.12 lb

Control	H			L			W		Load (lb)	Strength (psi)	Weight (lb)	STD
1	18.543	18.560	18.526	7.409	7.507	7.543	3.588	3.621	3.643	170	36	37.75	10.79713
AVERAGE		18.543			7.486			3.617					
2	18.839	18.843	18.838	7.384	7.315	7.422	3.581	3.562	3.508	240	51	37.80	
AVERAGE		18.840			7.374			3.550					
3	13.775	13.753	13.787	7.508	7.319	7.445	3.496	3.565	3.525	410	57	28.00	
AVERAGE		13.772			7.424			3.529				Specimen debonded prior to testing	

PVA RECS7 (0.25%)

1	18.513	18.521	18.539	7.249	7.283	7.117	3.471	3.534	3.483	180	41	37.3	8.341591
AVERAGE		18.524			7.216			3.496					
2	18.657	18.689	18.639	7.297	7.335	7.269	3.370	3.521	3.429	260	58	37.5	
AVERAGE		18.662			7.300			3.440					
3	18.792	18.809	18.791	7.248	7.471	7.329	3.433	3.475	3.323	210	49	37.5	
AVERAGE		18.797			7.349			3.410					

PVA RECS7 (0.50%)

1	19.087	19.140	19.165	7.404	7.361	7.404	3.452	3.583	3.626	210	46	38.2	16.85758
AVERAGE		19.131			7.390			3.554					
2	19.326	19.336	19.290	7.408	7.527	7.472	3.496	3.512	3.505	260	57	39.2	
AVERAGE		19.317			7.469			3.504					
3	19.153	19.100	19.159	7.525	7.422	7.418	3.570	3.519	3.533	390	79	39.1	
AVERAGE		19.137			7.455			3.541					

PVA RECS15 (0.25%)

1	18.625	18.595	18.568	7.413	7.100	7.314	3.485	3.575	3.499	310	65	37.95	3.721365
AVERAGE		18.596			7.276			3.520					
2	18.568	18.539	18.474	7.355	7.345	7.296	3.600	3.583	3.649	320	62	37.55	
AVERAGE		18.527			7.332			3.611					
3	18.825	18.804	18.790	7.294	7.277	7.491	3.567	3.572	3.419	270	57	37.75	
AVERAGE		18.806			7.354			3.519					

Pre- F/T Flexural Strength of Masonry Prisms

PVA RECS15 (0.50%)

1	18.972	18.912	18.808	7.414	7.451	7.394	3.792	3.656	3.688	460	83	39.25	16.6373
		18.897			7.420			3.712					
2	18.824	18.759	18.759	7.711	7.518	7.462	3.560	3.498	3.538	570	109	39.15	
		18.781			7.564			3.532					
3	18.725	18.621	18.573	7.469	7.462	7.451	3.560	3.551	3.519	600	114	39.1	
		18.640			7.461			3.543					

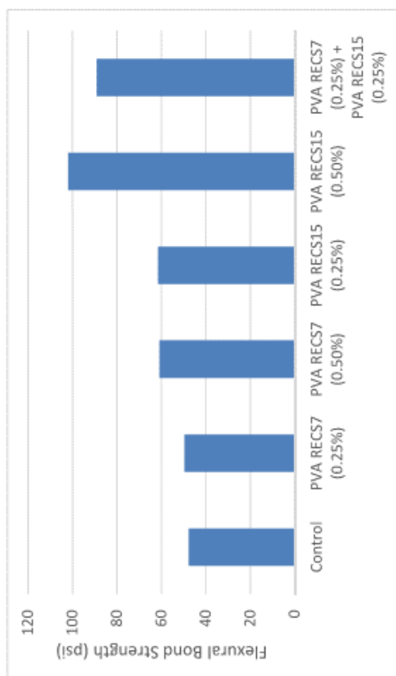
PVA RECS7 (0.25%) + PVA RECS15 (0.25%)

1	18.399	18.362	18.392	7.504	7.472	7.473	3.622	3.579	3.612	490	90	38.05	3.994652
		18.384			7.483			3.604					
2	18.124	18.159	18.171	7.388	7.554	7.531	3.622	3.579	3.612	470	85	37.75	
		18.151			7.491			3.604					
3	18.152	18.147	18.162	7.508	7.422	7.380	3.592	3.590	3.590	510	93	37.1	
		18.154			7.437			3.591					

Average Flexural Bond Strength (psi)

Control	48
PVA RECS7 (0.25%)	50
PVA RECS7 (0.50%)	61
PVA RECS15 (0.25%)	62
PVA RECS15 (0.50%)	102
PVA RECS7 (0.25%) + PVA RECS15 (0.25%)	89

Pre- F/T Flexural Strength of Masonry Prisms



Post-F/T Flexural Strength of Masonry Prisms

weight of top plate = 13.12 lb

Control		H			L			W		Load (lb)	Strength (psi)	Weight (lb)	STD
1	19.160	19.027	19.167	7.453	7.328	7.419	3.511	3.519	3.536	150	36	38.65	17.82245
AVERAGE		19.118			7.400			3.522					
2	18.919	18.9.4	18.911	7.507	7.597	7.467	3.540	3.486	3.560	200	44	38.70	
AVERAGE		18.915			7.524			3.529					
3	19.176	19.151	19.169	7.533	7.618	7.577	3.668	3.539	3.639	13	10	39.40	
AVERAGE		19.165			7.576			3.615					

PVA RECS7 (0.25%)

1	18.799	18.788	18.674	7.566	7.629	7.571	3.762	3.683	3.750	210	40	38.05	15.62319
AVERAGE		18.754			7.589			3.732					
2	18.674	18.708	18.707	7.341	7.263	7.383	3.560	3.563	0.577	160	70	38.3	
AVERAGE		18.696			7.329			2.567					
3	16.000	16.081	16.066	7.385	7.199	7.287	3.350	3.310	3.465	240	47	32.9	
AVERAGE		16.049			7.290			3.375					

PVA RECS7 (0.50%)

1	18.067	18.130	18.142	7.200	7.249	7.270	3.311	3.376	3.335	270	62	38.6	28.90676
AVERAGE		18.113			7.240			3.341					
2	15.476	15.503	15.516	7.507	7.309	7.400	3.504	3.451	3.468	60	15	38.95	
AVERAGE		15.498			7.405			3.474					
3	19.311	19.219	19.157	7.242	7.136	7.252	3.374	3.343	3.364	280	68	39.25	
AVERAGE		19.229			7.210			3.360					

PVA RECS15 (0.25%)

1	15.722	15.754	15.822	7.303	7.244	7.387	3.361	3.302	3.343	320	61	38.55	10.43807
AVERAGE		15.766			7.311			3.335					
2	18.917	18.912	18.878	7.427	7.439	7.464	3.532	3.451	3.463	240	53	38.8	
AVERAGE		18.902			7.443			3.482					
3	18.537	18.522	18.513	7.447	7.461	7.483	3.300	3.307	3.593	170	41	37.95	
AVERAGE		18.524			7.464			3.400					

Post-F/T Flexural Strength of Masonry Prisms

PVA RECS15 (0.50%)

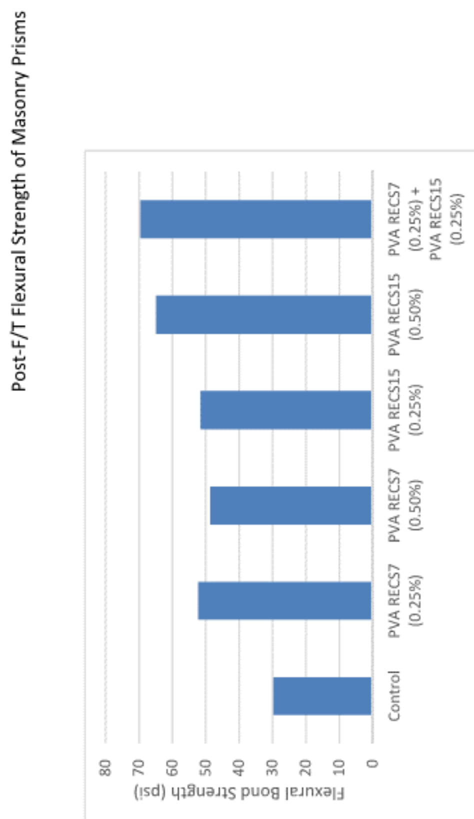
1	18.710	18.750	18.680	7.340	7.320	7.340	3.380	3.320	3.420	310	71	38.6	16.06512
		18.713			7.333			3.373					
2	18.550	18.600	18.620	7.310	7.280	7.300	3.380	3.420	3.480	200	47	38.1	
		18.590			7.297			3.427					
3	18.740	18.680	18.600	7.340	7.180	7.400	3.300	3.290	3.340	330	77	38.2	
		18.673			7.307			3.310					

PVA RECS7 (0.25%) + PVA RECS15 (0.25%)

1	18.440	18.450	18.400	7.140	7.280	7.300	3.440	3.540	3.420	360	76	38.85	13.80257
		18.430			7.240			3.467					
2	18.380	18.350	18.400	7.180	7.320	7.160	3.380	3.400	3.380	230	54	38.15	
		18.377			7.220			3.387					
3	18.320	18.400	18.420	7.220	7.290	7.280	3.400	3.420	3.340	360	79	38.45	
		18.380			7.263			3.387					

Average Flexural Bond Strength (psi)

Control	30
PVA RECS7 (0.25%)	52
PVA RECS7 (0.50%)	49
PVA RECS15 (0.25%)	52
PVA RECS15 (0.50%)	65
PVA RECS7 (0.25%) + PVA RECS15 (0.25%)	70


Post-F/T Flexural Strength of Masonry Prisms
Flexural Bond Strength (psi)
0
10
20
30
40
50
60
70
80
Control
PVA RECS7 (0.25%)
PVA RECS7 (0.50%)
PVA RECS15 (0.25%)
PVA RECS15 (0.50%)
PVA RECS7 (0.25%) + PVA RECS15 (0.25%)

Typical Failure Mode of Flexural Bond Strength Photographs:

APPENDIX E

MASONRY PRISMS

Freeze and Thaw Testing
Length Change Measurements

Specimen	Measurement			Measurement			Measurement			Measurement			Measurement		
	27-Mar		0 C	3-Apr		36 C	9-Apr		72 C	18-Apr		108 C	26-Apr		144 C
	H	L	W	H	L	W	H	L	W	H	L	W	H	L	W
Control A5	13.581	7.455	3.484	13.578	7.388	3.506	13.541	7.419	3.534	13.546	7.417	3.500	13.543	7.416	3.493
	13.582	7.459	3.648	13.598	7.459	3.630	13.553	7.444	3.631	13.554	7.539	3.629	13.556	7.448	3.626
	13.619	7.483	3.637	13.610	7.462	3.671	13.580	7.448	3.629	13.574	7.411	3.634	13.588	7.439	3.617
Control B5	13.097	7.538	3.638	13.053	7.549	3.624	13.044	7.527	3.616	13.048	7.527	3.606	13.055	7.520	3.609
	13.128	7.537	3.617	13.085	7.593	3.632	13.070	7.506	3.603	13.080	7.520	3.616	13.073	7.514	3.613
	13.124	7.605	3.655	13.075	7.606	3.641	13.069	7.604	3.618	13.072	7.628	3.634	13.062	7.609	3.613
Control C5	13.216	7.527	3.597	13.185	7.512	3.534	13.178	7.528	3.578	13.175	7.543	3.605	13.165	7.528	3.593
	13.230	7.483	3.567	13.226	7.437	3.542	13.223	7.438	3.561	13.238	7.495	3.563	13.206	7.482	3.542
	13.184	7.508	3.610	13.210	7.522	3.603	13.175	7.479	3.619	13.207	7.511	3.606	13.188	7.500	3.597
Control A7	19.344	7.625	3.723	19.112	7.488	3.553	19.140	7.454	3.505	19.117	7.436	3.554	19.138	7.454	3.561
	19.359	7.614	3.798	19.130	7.435	3.535	19.123	7.458	3.559	19.123	7.410	3.598	19.127	7.371	3.568
	19.359	7.695	3.787	19.113	7.500	3.560	19.100	7.507	3.601	19.083	7.491	3.567	19.086	7.504	3.550
Control B7	19.127	7.805	3.835	18.969	7.547	3.553	18.908	7.554	3.525	18.914	7.550	3.546	18.920	7.552	3.540
	19.139	7.796	3.812	18.938	7.553	3.604	18.928	7.532	3.569	18.934	7.618	3.492	18.934	7.616	3.541
	19.152	7.728	3.826	18.953	7.507	3.639	18.946	7.486	3.613	18.941	7.449	3.671	18.952	7.510	3.613
Control C7	19.411	7.731	3.905	19.179	7.746	3.823	19.200	7.553	3.670	19.200	7.541	3.663	19.207	7.530	3.677
	19.430	7.755	3.881	19.187	7.754	3.902	19.157	7.535	3.697	19.159	7.670	3.687	19.173	7.612	3.660
	19.398	7.814	3.867	19.153	7.819	3.843	19.138	7.612	3.650	19.135	7.635	3.658	19.138	7.622	3.627

MASONRY PRISMS

Freeze and Thaw Testing
Length Change Measurements

Specimen	Measurement			Measurement			Measurement			Measurement			Measurement		
	4-May		180 C	12-May		216 C	20-May		252 C	28-May		288 C	15-Jun		300 C
	H	L	W	H	L	W	H	L	W	H	L	W	H	L	W
Control A5	13.534	7.406	3.458	13.542	7.425	3.497	13.602	7.454	3.525	13.576	7.438	3.593	13.538	7.389	3.481
	13.540	7.501	3.640	13.553	7.456	3.624	13.588	7.456	3.616	13.548	7.449	3.578	13.586	7.469	3.625
	13.549	7.437	3.621	13.553	7.487	3.622	13.618	7.485	3.612	13.544	7.470	3.544	13.572	7.440	3.607
Control B5	13.056	7.524	3.623	13.046	7.534	3.606	13.070	7.572	3.640	13.063	7.520	3.569	13.136	7.523	3.605
	13.072	7.557	3.623	13.085	7.524	3.625	13.077	7.529	3.689	13.076	7.623	3.658	13.071	7.508	3.606
	13.057	7.628	3.613	13.096	7.618	3.636	13.098	7.005	3.614	13.049	7.556	3.675	13.053	7.600	3.611
Control C5	13.144	7.544	3.561	13.189	7.526	3.592	13.208	7.556	3.622	13.184	7.516	3.682	13.150	7.509	3.577
	13.212	7.499	3.533	13.214	7.428	3.550	13.219	7.545	3.500	13.212	7.457	3.655	13.219	7.456	3.543
	13.168	7.490	3.602	13.190	7.464	3.604	13.200	7.511	3.633	13.209	7.472	3.619	13.209	7.447	3.576
Control A7	19.123	7.440	3.520	19.113	7.447	3.536	19.110	7.456	3.527	19.103	7.443	3.577	19.160	7.453	3.511
	19.113	7.360	3.547	19.100	7.373	3.558	19.115	7.313	3.585	19.100	7.282	3.524	19.027	7.328	3.519
	19.080	7.472	3.548	19.081	7.483	3.581	19.102	7.482	3.592	19.103	7.462	3.538	19.167	7.419	3.536
Control B7	18.899	7.552	3.551	18.912	7.565	3.552	18.974	7.554	3.526	18.947	7.537	3.540	18.919	7.507	3.540
	18.920	7.595	3.532	18.934	7.607	3.499	18.948	7.619	3.506	18.937	7.612	3.645	18.934	7.597	3.486
	18.941	7.491	3.615	18.952	7.563	3.618	18.971	7.501	3.665	18.917	7.468	3.586	18.911	7.467	3.560
Control C7	19.168	7.564	3.671	19.180	7.584	3.674	19.221	7.540	3.615	19.135	7.492	3.644	19.176	7.533	3.668
	19.152	7.633	3.719	19.163	7.631	3.721	19.172	7.561	3.680	19.145	7.507	3.651	19.151	7.618	3.539
	19.126	7.617	3.629	19.131	7.609	3.647	19.152	7.610	3.699	19.172	7.595	3.736	19.169	7.577	3.639

MASONRY PRISMS

Freeze and Thaw Testing
Length Change Measurements

	Initial Weight (lb)	Final Weight (lb)
Control A5	27.15	27.45
Control B5	26.45	26.70
Control C5	26.60	26.80
Control A7	38.50	38.65
Control B7	38.55	38.70
Control C7	39.15	39.40
	3/27/2013	6/15/2013

Specimen	Measurement			Measurement			Measurement			Measurement			Measurement		
	27-Mar		0 C	3-Apr		36 C	9-Apr		72 C	4/18/2013		108 C	26-Apr		144 C
	H	L	W	H	L	W	H	L	W	H	L	W	H	L	W
PVA (6MM 0.25%) A5	13.303	7.338	3.547	13.342	7.391	3.625	13.335	7.365	3.512	13.349	7.528	3.500	13.377	7.328	3.513
	13.350	7.212	3.446	13.325	7.207	3.733	13.356	7.208	3.441	13.350	7.305	3.425	13.355	7.219	3.455
	13.351	7.348	3.626	13.291	7.357	3.615	13.280	7.350	3.613	13.288	7.324	3.584	13.282	7.408	3.621
PVA (6MM 0.25%) B5	13.159	7.404	3.611	13.153	7.391	3.566	13.159	7.454	3.581	13.136	7.368	3.603	13.150	7.459	3.663
	13.144	7.386	3.606	13.150	7.300	3.576	13.149	7.295	3.582	13.152	7.297	3.620	13.142	7.288	3.606
	13.143	7.542	3.671	13.119	7.544	3.622	13.114	7.532	3.659	13.121	7.543	3.671	13.114	7.533	3.657
PVA (6MM 0.25%) C5	13.275	7.398	3.562	13.295	7.407	3.626	13.334	7.415	3.562	13.302	7.380	3.531	13.324	7.394	3.545
	13.308	7.514	3.542	13.280	7.462	3.598	13.282	7.445	3.631	13.301	7.432	3.593	13.282	7.429	3.560
	13.345	7.557	3.572	13.275	7.549	3.557	13.265	7.541	3.594	13.271	7.546	3.590	13.269	7.543	3.586
PVA (6MM 0.25%) A7	18.992	7.549	3.746	18.817	7.601	3.757	18.777	7.560	3.739	18.777	7.605	3.739	18.776	7.551	3.694
	18.992	7.642	3.763	18.780	7.659	3.745	18.774	7.662	3.734	18.773	7.653	3.689	18.771	7.640	3.677
	19.006	7.541	3.749	18.814	7.588	3.759	18.794	7.575	3.761	18.791	7.586	3.739	18.787	7.578	3.768
PVA (6MM 0.25%) B7	18.913	7.600	3.885	18.675	7.335	3.528	18.672	7.373	3.532	18.666	7.346	3.544	18.675	7.321	3.528
	18.957	7.677	3.782	18.701	7.456	3.552	18.701	7.518	3.541	18.705	7.282	3.471	18.703	7.418	3.456
	18.925	7.719	3.744	18.721	7.427	3.544	18.727	7.455	3.538	18.719	7.406	3.546	18.705	7.519	3.555
PVA (6MM 0.25%) C7	16.291	7.499	3.738	15.991	7.443	3.700	16.005	7.407	3.689	15.975	7.429	3.616	15.975	7.415	3.603
	16.235	7.638	3.641	16.116	7.199	3.345	16.057	7.202	3.337	16.047	7.195	3.323	16.052	7.345	3.322
	16.195	7.566	3.684	16.077	7.360	3.470	16.080	7.403	3.454	16.073	7.340	3.448	16.076	7.461	3.469

Specimen	Measurement			Measurement			Measurement			Measurement			Measurement		
	4-May		180 C	12-May		216 C	20-May		252 C	28-May		288 C	15-Jun		300 C
	H	L	W	H	L	W	H	L	W	H	L	W	H	L	W
PVA (6MM 0.25%) A5	13.360	7.415	3.516	13.335	7.389	3.542	13.346	7.378	3.583	13.335	7.354	3.604	13.350	7.350	3.496
	13.335	7.184	3.431	13.316	7.168	3.438	13.331	7.156	3.474	13.311	7.169	3.589	13.320	7.171	3.427
	13.282	7.389	3.620	13.286	7.364	3.610	13.248	7.332	3.591	13.295	7.347	3.602	13.283	7.341	3.600
PVA (6MM 0.25%) B5	13.130	7.444	3.586	13.165	7.352	3.574	13.153	7.367	3.614	13.136	7.335	3.566	13.140	7.367	3.507
	13.132	7.287	3.605	13.130	7.288	3.592	13.172	7.318	3.610	13.152	7.289	3.548	13.139	7.114	3.607
	13.109	7.528	3.653	13.113	7.527	3.649	13.157	7.589	3.673	13.210	7.533	3.655	13.118	7.525	3.625
PVA (6MM 0.25%) C5	13.311	7.381	3.515	13.298	7.391	3.497	13.329	7.373	3.533	13.253	7.397	3.554	13.352	7.394	3.510
	13.275	7.407	3.576	13.270	7.440	3.572	13.285	7.405	3.584	13.246	7.425	3.537	13.298	7.433	3.581
	13.265	7.538	3.570	13.278	7.527	3.576	13.280	7.554	3.570	13.245	7.513	3.552	13.275	7.508	3.580
PVA (6MM 0.25%) A7	18.602	7.581	3.708	18.809	7.549	3.689	18.796	7.549	3.702	18.804	7.546	3.700	18.799	7.566	3.762
	18.600	7.666	3.764	18.773	7.638	3.764	18.790	7.621	3.712	18.786	7.566	3.663	18.779	7.629	3.683
	18.599	7.583	3.769	18.804	7.568	3.658	18.789	7.558	3.793	18.801	7.520	3.772	18.788	7.571	3.750
PVA (6MM 0.25%) B7	18.605	7.331	3.543	18.665	7.313	3.551	18.730	7.362	3.619	18.731	7.369	3.513	18.674	7.341	3.560
	18.582	7.263	3.465	18.719	7.266	3.516	18.809	7.254	3.485	18.722	7.241	3.493	18.708	7.263	3.563
	18.603	7.409	3.536	18.716	7.403	3.545	18.760	7.471	3.534	18.668	7.539	3.468	18.707	7.383	3.577
PVA (6MM 0.25%) C7	16.383	7.407	3.676	16.005	7.399	3.666	16.021	7.373	3.592	16.099	7.369	3.390	16.000	7.385	3.350
	16.466	7.207	3.355	16.054	7.205	3.326	16.036	7.208	3.580	16.053	7.197	3.299	16.081	7.199	3.310
	16.485	7.404	3.482	16.077	7.383	3.459	16.086	7.376	3.481	15.993	7.355	3.498	16.066	7.287	3.465

	Initial Weight (lb)	Final Weight (lb)
PVA (6MM 0.25%) A5	26.45	26.55
PVA (6MM 0.25%) B5	26.30	26.35
PVA (6MM 0.25%) C5	27.05	27.1
PVA (6MM 0.25%) A7	37.55	38.05
PVA (6MM 0.25%) B7	38.20	38.3
PVA (6MM 0.25%) C7	32.80	32.9
	3/27/2013	6/15/2013

Specimen	Measurement			Measurement			Measurement			Measurement			Measurement		
	2-Jun		0 C	11-Jun		36 C	18-Jun		72 C	24-Jun		108 C	2-Jul		144 C
	H	L	W	H	L	W	H	L	W	H	L	W	H	L	W
PVA (6MM 0.50%) A5	13.608	7.428	3.517	13.492	7.187	3.577	13.472	7.447	3.516	13.503	7.177	3.461	13.501	7.193	3.590
	13.554	7.460	3.460	13.533	7.371	3.575	13.513	7.355	3.505	13.541	7.391	3.516	13.537	7.383	3.553
	13.525	7.393	3.561	13.576	7.316	3.634	13.566	7.296	3.588	13.561	7.304	3.472	13.582	7.314	3.598
PVA (6MM 0.50%) B5	13.390	7.393	3.488	13.331	7.440	3.438	13.431	7.350	3.505	13.339	7.458	3.449	13.340	7.442	3.437
	13.379	7.562	3.544	13.348	7.364	3.411	13.459	7.459	3.509	13.360	7.416	3.415	13.349	7.383	3.426
	13.362	7.368	3.405	13.370	7.343	3.543	13.385	7.349	3.658	13.381	7.360	3.518	13.364	7.400	3.517
PVA (6MM 0.50%) C5	13.428	7.387	3.526	13.331	7.389	3.468	13.692	7.382	3.586	13.374	7.387	3.466	13.344	7.377	3.544
	13.411	7.398	3.517	13.414	7.212	3.508	13.628	7.202	3.523	13.382	7.241	3.517	13.370	7.274	3.509
	13.417	7.376	3.425	13.425	7.202	3.312	13.689	7.345	3.486	13.415	7.233	3.390	13.417	7.238	3.396
PVA (6MM 0.50%) A7	18.894	7.427	3.521	18.915	7.318	3.321	18.998	7.410	3.510	18.929	7.326	3.328	18.922	7.324	3.387
	18.905	7.471	3.569	18.895	7.440	3.438	18.934	7.472	3.552	18.911	7.445	3.462	18.889	7.420	3.449
	18.922	7.569	3.588	18.849	7.469	3.500	18.934	7.459	3.572	18.874	7.482	3.510	18.859	7.501	3.596
PVA (6MM 0.50%) B7	18.147	7.504	3.691	19.090	7.394	3.436	19.156	7.347	3.649	19.101	7.399	3.408	19.100	7.432	3.450
	18.143	7.373	3.473	19.110	7.319	3.426	19.127	7.322	3.478	19.128	7.211	3.457	19.125	7.226	3.464
	19.098	7.405	3.519	19.117	7.301	3.462	19.136	7.401	3.504	19.139	7.357	3.385	19.149	7.322	3.415
PVA (6MM 0.50%) C7	19.239	7.458	3.583	19.108	7.481	3.669	19.078	7.490	3.569	19.131	7.466	3.575	19.132	7.480	3.683
	19.175	7.438	3.571	19.172	7.361	3.456	19.132	7.328	3.558	19.177	7.382	3.504	19.168	7.373	3.452
	19.196	7.503	3.565	19.191	7.370	3.624	19.112	7.488	3.583	19.244	7.406	3.584	19.214	7.381	3.630

Specimen	Measurement			Measurement			Measurement			Measurement			Measurement		
	9-Jul		180 C	16-Jul		216 C	23-Jul		252 C	30-Jul		288 C	7-Aug		300 C
	H	L	W	H	L	W	H	L	W	H	L	W	H	L	W
PVA (6MM 0.50%) A5	13.523	7.114	3.565	13.516	7.158	3.551	13.524	7.207	3.575	13.508	7.157	3.554	13.606	7.427	3.483
	13.558	7.436	3.556	13.559	7.393	3.557	13.538	7.391	3.559	13.553	7.365	3.650	13.638	7.425	3.454
	13.602	7.302	3.589	13.626	7.282	3.558	13.591	7.296	3.594	13.605	7.289	3.576	13.550	7.349	3.545
PVA (6MM 0.50%) B5	13.338	7.443	3.442	13.346	7.443	3.455	13.352	7.456	3.449	13.344	7.467	3.393	13.425	7.383	3.498
	13.341	7.412	3.380	13.347	7.401	3.425	13.345	7.445	3.445	13.349	7.422	3.484	13.391	7.467	3.489
	13.350	7.361	3.545	13.366	7.424	3.529	13.379	7.388	3.562	13.363	7.394	3.505	13.364	7.387	3.513
PVA (6MM 0.50%) C5	13.352	7.360	3.528	13.356	7.363	3.521	13.356	7.388	3.528	13.353	7.355	3.573	13.449	7.396	3.548
	13.464	7.257	3.516	13.382	7.255	3.519	13.370	7.255	3.570	13.378	7.229	0.512	13.408	7.404	3.540
	13.410	7.219	3.449	13.439	7.270	3.423	13.421	7.311	3.403	13.441	7.240	3.403	13.377	7.395	3.340
PVA (6MM 0.50%) A7	18.925	7.334	3.377	18.924	7.362	3.449	18.867	7.343	3.450	18.924	7.341	3.443	18.067	7.200	3.311
	18.898	7.399	3.460	18.901	7.437	3.459	18.938	7.414	3.464	18.905	7.439	3.462	18.130	7.249	3.376
	18.861	7.453	3.501	18.865	7.495	3.502	18.943	7.496	3.483	18.887	7.543	3.491	18.142	7.270	3.335
PVA (6MM 0.50%) B7	19.108	7.438	3.415	19.116	7.426	3.437	19.111	7.418	3.442	19.110	7.417	3.426	15.476	7.507	3.504
	19.129	7.238	3.442	19.125	7.274	3.449	19.136	7.395	3.430	19.140	7.242	3.454	15.503	7.309	3.451
	19.133	7.345	3.352	19.166	7.361	3.383	19.143	7.334	3.440	19.138	7.401	3.408	15.516	7.400	3.468
PVA (6MM 0.50%) C7	19.126	7.460	3.679	19.146	7.484	3.676	19.118	7.470	3.696	19.134	7.489	3.677	19.311	7.242	3.374
	19.190	7.435	3.469	19.175	7.367	3.517	19.162	7.421	3.481	19.192	7.380	3.484	19.219	7.136	3.343
	19.204	7.398	3.603	19.209	7.383	3.659	19.200	7.378	3.632	19.201	7.385	3.654	19.157	7.252	3.364

	Initial Weight (lb)	Final Weight (lb)
PVA (6MM 0.50%) A5	27.25	27.35
PVA (6MM 0.50%) B5	27.40	27.5
PVA (6MM 0.50%) C5	26.50	26.4
PVA (6MM 0.50%) A7	38.45	38.6
PVA (6MM 0.50%) B7	38.90	38.95
PVA (6MM 0.50%) C7	39.20	39.25
	6/2/2013	8/7/2013

Specimen	Measurement			Measurement			Measurement			Measurement			Measurement		
	2-Jun		0 C	11-Jun		36 C	18-Jun		72 C	24-Jun		108 C	2-Jul		144 C
	H	L	W	H	L	W	H	L	W	H	L	W	H	L	W
PVA (6MM 0.50%) A5	13.311	7.393	3.569	13.247	7.285	3.372	13.378	7.411	3.600	13.243	7.319	3.338	13.247	7.298	3.377
	13.299	7.378	3.641	13.272	7.208	3.467	13.329	7.330	3.620	13.285	7.319	3.493	13.282	7.337	3.462
	13.277	7.352	3.575	13.282	7.224	3.506	13.381	7.248	3.569	13.290	7.361	3.520	13.290	7.230	3.587
PVA (6MM 0.50%) B5	13.259	7.284	3.522	13.210	7.231	3.527	13.259	7.278	3.527	13.211	7.465	3.466	13.211	7.632	3.522
	13.228	7.425	3.528	13.194	7.448	3.515	13.247	7.419	3.546	13.186	7.593	3.481	13.191	7.550	3.489
	13.213	7.444	3.516	13.197	7.427	3.529	13.236	7.435	3.523	13.234	7.624	3.572	13.215	7.620	3.513
PVA (6MM 0.50%) C5	13.256	7.297	3.481	13.256	7.244	3.413	13.319	7.244	3.543	13.281	7.463	3.430	13.281	7.386	3.434
	13.285	7.477	3.424	13.251	7.272	3.421	13.283	7.249	3.436	13.252	7.434	3.387	13.267	7.440	3.378
	13.291	7.324	3.552	13.224	7.282	3.456	13.276	7.262	3.431	13.253	7.362	3.503	13.239	7.347	3.484
PVA (6MM 0.50%) A7	18.762	7.343	3.517	18.758	7.150	3.477	18.753	7.302	3.530	18.779	7.146	3.445	18.777	7.141	3.428
	18.780	7.374	3.466	18.750	7.320	3.499	18.743	7.156	3.522	18.772	7.310	3.466	18.764	7.351	3.460
	18.797	7.424	3.510	18.728	7.315	3.495	18.801	7.165	3.578	18.756	7.319	3.525	18.745	7.228	3.444
PVA (6MM 0.50%) B7	18.903	7.503	3.519	18.838	7.143	3.502	18.904	7.418	3.526	18.863	7.222	3.444	18.842	7.210	3.399
	18.895	7.426	3.529	18.880	7.211	3.441	18.900	7.366	3.434	18.899	7.241	3.438	18.871	7.240	3.446
	18.875	7.302	3.553	18.882	7.372	3.397	18.890	7.460	3.555	18.898	7.393	3.496	18.893	7.342	3.515
PVA (6MM 0.50%) C7	18.544	7.519	3.532	18.465	7.446	3.531	18.473	7.310	3.531	18.288	7.282	3.347	18.488	7.479	3.557
	18.516	7.380	3.579	18.494	7.192	3.468	18.461	7.366	3.540	18.274	7.365	3.286	18.471	7.307	3.448
	18.510	7.437	3.577	18.460	7.254	3.452	18.399	7.361	3.363	18.275	7.345	3.272	18.462	7.350	3.492

Specimen	Measurement			Measurement			Measurement			Measurement			Measurement		
	9-Jul		180 C	16-Jul		216 C	23-Jul		252 C	30-Jul		288 C	7-Aug		300 C
	H	L	W	H	L	W	H	L	W	H	L	W	H	L	W
PVA (6MM 0.50%) A5	13.250	7.292	3.377	13.243	7.301	3.377	13.260	7.324	3.382	13.239	7.294	3.359	13.316	7.404	3.582
	13.259	7.283	3.475	13.276	7.316	3.487	13.272	7.351	3.501	13.262	7.314	3.474	13.295	7.335	3.626
	13.287	7.222	3.507	13.286	7.228	3.501	13.301	7.288	3.556	13.292	7.198	3.526	13.316	7.268	3.508
PVA (6MM 0.50%) B5	13.232	7.242	3.486	13.218	7.249	3.433	13.201	7.253	3.495	13.214	7.270	3.485	13.247	7.278	3.560
	13.191	7.436	3.475	13.204	7.390	3.480	13.190	7.378	3.512	13.184	7.355	3.486	13.231	7.424	3.538
	13.215	7.406	3.520	13.244	7.427	3.357	13.224	7.447	3.518	13.203	7.387	3.505	13.216	7.432	3.482
PVA (6MM 0.50%) C5	13.281	7.400	3.407	13.292	7.352	3.436	13.284	7.418	3.429	13.293	7.364	3.416	13.258	7.250	3.472
	13.283	7.412	3.378	13.263	7.408	3.376	13.246	7.399	3.422	13.268	7.410	3.400	13.287	7.421	3.414
	13.263	7.331	3.473	13.254	7.352	3.472	13.242	7.346	3.531	13.245	7.343	3.497	13.309	7.341	3.530
PVA (6MM 0.50%) A7	18.779	7.134	3.464	18.788	7.145	3.436	18.801	7.191	3.501	18.815	7.188	3.491	15.722	7.303	3.361
	18.785	7.360	3.441	18.789	7.341	3.490	18.779	7.359	3.452	18.842	7.308	3.475	15.754	7.244	3.302
	18.749	7.326	3.506	18.813	7.355	3.497	18.763	7.367	3.513	18.815	7.371	3.601	15.822	7.387	3.343
PVA (6MM 0.50%) B7	18.868	7.223	3.351	18.885	7.191	3.299	18.893	7.114	3.430	18.866	7.143	3.380	18.917	7.427	3.532
	18.881	7.264	3.439	18.918	7.261	3.474	18.882	7.246	3.449	18.897	7.493	3.465	18.912	7.439	3.451
	18.892	7.412	3.455	18.929	7.189	3.552	18.892	7.361	3.544	18.892	7.388	3.535	18.878	7.464	3.463
PVA (6MM 0.50%) C7	18.472	7.487	3.540	18.492	1.489	3.551	18.472	7.482	3.547	18.476	7.482	3.552	18.537	7.447	3.300
	18.469	7.275	3.465	18.471	7.273	3.443	18.463	7.273	3.458	18.460	7.259	3.464	18.522	7.461	3.307
	18.469	7.307	3.442	18.466	7.420	3.509	18.450	7.337	3.541	18.453	7.292	3.488	18.513	7.483	3.593

	Initial Weight (lb)	Final Weight (lb)
PVA (6MM 0.50%) A5	27.35	27.4
PVA (6MM 0.50%) B5	26.85	26.8
PVA (6MM 0.50%) C5	27.00	26.9
PVA (6MM 0.50%) A7	38.60	38.55
PVA (6MM 0.50%) B7	38.85	38.8
PVA (6MM 0.50%) C7	38.05	37.95
	6/2/2013	8/7/2013

Specimen	Measurement			Measurement			Measurement			Measurement			Measurement		
	17-Sep		0 C	24-Sep		36 C	3-Oct		72 C	10-Oct		108 C	17-Oct		144 C
	H	L	W	H	L	W	H	L	W	H	L	W	H	L	W
PVA (8MM 0.50%) A5	13.185	7.487	3.357	13.117	7.411	3.407	13.516	7.394	3.442	13.302	7.453	3.408	13.303	7.455	3.404
	13.240	7.443	3.585	13.051	7.507	3.419	13.588	7.490	3.478	13.246	7.504	3.635	13.249	7.507	3.591
	13.282	7.513	3.639	13.003	7.422	3.440	13.339	7.545	3.518	13.201	7.506	3.599	13.190	7.474	3.570
PVA (8MM 0.50%) B5	13.105	7.469	3.379	13.140	7.537	3.428	13.108	7.506	3.528	13.114	7.497	3.448	13.144	7.489	3.375
	13.129	7.524	3.475	13.124	7.548	3.477	13.133	7.537	3.521	13.137	7.518	3.654	13.138	7.507	3.395
	13.139	7.278	3.577	13.133	7.506	3.597	13.145	7.332	3.571	13.120	7.533	3.620	13.133	7.517	3.491
PVA (8MM 0.50%) C5	13.248	7.392	3.408	13.313	7.443	3.411	13.525	7.420	3.593	13.306	7.481	3.441	13.314	7.370	3.419
	13.271	7.441	3.639	13.280	7.385	3.660	13.310	7.420	3.609	13.286	7.429	3.664	13.275	7.473	3.665
	13.306	7.363	3.638	13.260	7.330	3.621	13.320	7.319	3.609	13.260	7.415	3.615	13.263	7.347	3.593
PVA (8MM 0.50%) A7	18.634	7.414	3.594	18.709	7.508	3.575	18.655	7.512	3.470	18.724	7.513	3.594	18.712	7.490	3.602
	18.722	7.455	3.584	18.706	7.452	3.580	18.719	7.566	3.542	18.688	7.521	3.583	18.690	7.541	3.654
	18.721	7.526	3.577	18.682	7.509	3.593	18.819	7.629	3.635	18.652	7.530	3.649	18.665	7.518	3.629
PVA (8MM 0.50%) B7	18.516	7.364	3.564	18.440	7.291	3.571	18.512	7.552	3.455	18.434	7.669	3.569	18.430	7.439	3.539
	18.479	7.447	3.519	18.485	7.502	3.507	18.497	7.620	3.564	18.460	7.475	3.533	18.498	7.396	3.498
	18.436	7.432	3.579	18.479	7.508	3.567	18.443	7.532	3.540	18.489	7.752	3.709	18.517	7.542	3.573
PVA (8MM 0.50%) C7	18.652	7.520	3.500	18.710	7.533	3.493	18.615	7.817	3.635	18.689	7.553	3.516	18.698	7.582	3.499
	18.654	7.442	3.520	18.648	7.334	3.507	18.655	7.439	3.535	18.673	7.466	3.526	18.639	7.516	3.494
	18.697	7.537	3.613	18.607	7.518	3.591	18.698	7.564	3.614	18.619	7.561	3.622	18.625	7.544	3.554

Specimen	Measurement			Measurement			Measurement			Measurement			Measurement		
	25-Oct		180 C	1-Nov		216 C	8-Nov		252 C	15-Nov		288 C	30-Nov		300 C
	H	L	W	H	L	W	H	L	W	H	L	W	H	L	W
PVA (8MM 0.50%) A5	13.306	7.453	3.413	13.320	7.540	3.410	13.300	7.480	3.380	13.310	7.470	3.390	13.100	7.280	3.190
	13.241	7.507	3.603	13.250	7.510	3.600	13.260	7.510	3.610	13.220	7.510	3.630	13.040	7.270	3.400
	13.192	7.543	3.640	13.200	7.490	3.600	13.200	7.510	3.630	13.210	7.530	3.620	13.000	7.450	3.410
PVA (8MM 0.50%) B5	13.143	7.493	3.395	13.150	7.520	3.400	13.150	7.510	3.480	13.130	7.500	3.410	12.920	7.290	3.250
	13.146	7.513	3.557	13.120	7.530	3.510	13.120	7.520	3.520	13.120	7.520	3.500	12.940	7.300	3.300
	13.128	7.469	3.552	13.120	7.500	3.580	13.110	7.500	3.590	13.140	7.430	3.520	12.890	7.240	3.360
PVA (8MM 0.50%) C5	13.314	7.426	3.433	13.310	7.420	3.450	13.310	7.480	3.490	13.310	7.490	3.480	13.100	7.200	3.240
	13.282	7.478	3.638	13.310	7.450	3.630	13.280	7.480	3.640	13.290	7.510	3.650	13.080	7.280	3.420
	13.269	7.422	3.549	13.280	7.390	3.590	13.280	7.420	3.700	13.270	7.400	3.630	13.020	7.150	3.400
PVA (8MM 0.50%) A7	18.720	7.553	3.600	18.740	7.510	3.600	18.750	7.510	3.590	18.750	7.510	3.600	18.710	7.340	3.380
	18.683	7.511	3.569	18.710	7.500	3.590	18.710	7.590	3.600	18.700	7.540	3.590	18.750	7.320	3.320
	18.663	7.733	3.610	18.690	7.580	3.630	18.630	7.550	3.660	18.660	7.540	3.620	18.680	7.340	3.420
PVA (8MM 0.50%) B7	18.426	7.493	3.682	18.470	7.680	3.600	18.430	7.580	3.600	18.420	7.580	3.580	18.550	7.310	3.380
	18.501	7.464	3.537	18.500	7.480	3.520	18.581	7.480	3.540	18.490	7.480	3.610	18.600	7.280	3.420
	18.510	7.552	3.606	18.510	7.610	3.630	18.510	7.570	3.610	18.500	7.590	3.690	18.620	7.300	3.480
PVA (8MM 0.50%) C7	18.706	7.535	3.509	18.610	7.590	3.610	18.700	7.550	3.520	18.720	7.570	3.510	18.740	7.340	3.300
	18.701	7.475	3.526	18.690	7.510	3.550	18.680	7.480	3.560	18.690	7.460	3.530	18.680	7.180	3.290
	18.648	7.521	3.554	18.710	7.570	3.630	18.610	7.580	3.590	18.630	7.550	3.590	18.600	7.400	3.340

	Initial Weight (lb)	Final Weight (lb)
PVA (8MM 0.50%) A5	26.65	26.7
PVA (8MM 0.50%) B5	26.25	26.3
PVA (8MM 0.50%) C5	27.00	27.1
PVA (8MM 0.50%) A7	38.60	38.6
PVA (8MM 0.50%) B7	38.15	38.1
PVA (8MM 0.50%) C7	38.10	38.2
	9/17/2013	11/30/2013

Specimen	Measurement			Measurement			Measurement			Measurement			Measurement		
	17-Sep		0 C	24-Sep		36 C	3-Oct		72 C	10-Oct		108 C	17-Oct		144 C
	H	L	W	H	L	W	H	L	W	H	L	W	H	L	W
PVA (6MM + 8MM @ 0.25%) A5	13.108	7.357	3.505	13.085	7.264	3.462	13.108	7.245	3.690	13.102	7.243	3.459	13.092	7.305	3.467
	13.102	7.550	3.513	13.097	7.407	3.516	13.095	7.480	3.598	13.100	7.481	3.524	13.091	7.533	3.536
	13.096	7.508	3.577	13.103	7.456	3.579	13.114	7.604	3.649	13.104	7.453	3.554	13.104	7.498	3.622
PVA (6MM + 8MM @ 0.25%) B5	13.001	7.337	3.572	12.943	7.383	3.631	12.988	7.377	3.470	12.990	7.420	3.539	12.930	7.436	3.603
	12.982	7.357	3.551	12.992	7.330	3.531	12.970	7.286	3.588	12.989	7.360	3.564	12.982	7.367	3.561
	12.941	7.452	3.617	13.002	7.605	3.682	12.936	7.644	3.429	13.009	7.554	3.557	12.996	7.551	3.580
PVA (6MM + 8MM @ 0.25%) C5	13.219	7.608	3.598	13.107	7.442	3.602	13.128	7.465	3.452	13.104	7.534	3.620	13.107	7.495	3.600
	13.127	7.402	3.520	13.121	7.475	3.530	13.100	7.421	3.573	13.117	7.502	3.566	13.107	7.408	3.544
	13.160	7.437	3.624	13.124	7.608	3.659	13.109	7.592	3.549	13.122	7.594	3.634	13.125	7.586	3.603
PVA (6MM + 8MM @ 0.25%) A7	18.489	7.282	3.673	18.472	7.463	3.630	18.487	7.518	3.598	18.462	7.413	3.630	18.454	7.430	3.634
	18.473	7.447	3.628	18.469	7.385	3.640	18.486	7.484	3.799	18.482	7.407	3.605	18.475	7.505	3.611
	18.455	7.514	3.645	18.488	7.528	3.638	18.463	7.531	3.582	18.489	7.514	3.675	18.481	7.513	3.639
PVA (6MM + 8MM @0.25%) B7	18.361	7.272	3.614	18.347	7.477	3.545	18.372	7.483	3.607	18.360	7.489	3.576	18.336	7.459	3.610
	18.337	7.549	3.583	18.337	7.493	3.583	18.323	7.453	3.663	18.323	7.488	3.620	18.322	7.567	3.641
	18.400	7.326	3.534	18.366	7.426	3.537	18.380	7.398	3.660	18.323	7.473	3.504	18.347	7.390	3.571
PVA (6MM + 8MM @ 0.25%) C7	18.392	7.389	3.616	18.340	7.412	3.608	18.396	7.425	3.602	18.380	7.469	3.631	18.382	7.510	3.618
	18.422	7.622	3.600	18.368	7.439	3.585	18.370	7.568	3.533	18.415	7.447	3.583	18.364	7.375	3.543
	18.397	7.472	3.574	18.400	7.459	3.577	18.354	7.483	3.574	18.448	7.542	3.680	18.341	7.467	3.560

Specimen	Measurement			Measurement			Measurement			Measurement			Measurement		
	25-Oct		180 C	1-Nov		216 C	8-Nov		252 C	15-Nov		288 C	30-Nov		300 C
	H	L	W	H	L	W	H	L	W	H	L	W	H	L	W
PVA (6MM + 8MM @ 0.25%) A5	13.100	7.280	3.510	13.110	7.290	3.510	13.090	7.300	3.500	13.110	7.290	3.580	12.900	7.700	3.229
	13.110	7.480	3.510	13.140	7.520	3.520	13.110	7.500	3.540	13.110	7.500	3.520	12.900	7.180	3.320
	13.120	7.480	3.600	13.140	7.580	3.590	13.110	7.610	3.600	13.110	7.480	3.560	12.920	7.260	3.340
PVA (6MM + 8MM @ 0.25%) B5	12.980	7.420	3.560	12.970	7.410	3.590	12.950	7.430	3.600	12.940	7.420	3.570	12.780	7.200	3.380
	13.000	7.390	3.580	13.010	7.380	3.550	13.000	7.350	3.590	13.010	7.470	3.580	12.820	7.120	3.320
	13.000	7.590	3.600	13.020	7.550	3.610	13.000	7.620	3.600	13.000	7.550	3.610	12.780	7.320	3.480
PVA (6MM + 8MM @ 0.25%) C5	13.110	7.510	3.600	13.120	7.510	3.650	13.120	7.520	3.610	13.110	7.680	3.620	12.880	7.480	3.380
	13.130	7.440	3.580	13.130	7.420	3.580	13.110	7.450	3.600	13.110	7.550	3.580	12.920	7.200	3.340
	13.120	7.590	3.610	13.150	7.590	3.610	13.120	7.590	3.600	13.100	7.560	3.600	12.900	7.340	3.400
PVA (6MM + 8MM @ 0.25%) A7	18.490	7.436	3.650	18.490	7.420	3.680	18.480	7.470	3.680	18.480	7.390	3.650	18.440	7.140	3.440
	18.500	7.400	3.620	18.510	7.410	3.680	18.500	7.400	3.610	18.490	7.420	3.620	18.450	7.280	3.540
	18.500	7.510	3.630	18.520	7.530	3.650	18.500	7.510	3.640	18.500	7.510	3.640	18.400	7.300	3.420
PVA (6MM + 8MM @0.25%) B7	18.390	7.493	3.680	18.340	7.500	3.600	18.350	7.480	3.590	18.370	7.480	3.590	18.380	7.180	3.380
	18.342	7.464	3.664	18.390	7.590	3.690	18.340	7.580	3.600	18.350	7.570	3.600	18.350	7.320	3.400
	18.380	7.451	3.655	18.390	7.410	3.560	18.350	7.400	3.600	18.340	7.390	3.610	18.400	7.160	3.380
PVA (6MM + 8MM @ 0.25%) C7	18.390	7.450	3.610	18.380	7.420	3.600	18.370	7.470	3.600	18.340	7.490	3.610	18.320	7.220	3.400
	18.400	7.490	3.600	18.390	7.460	3.600	18.400	7.420	3.610	18.400	7.410	3.590	18.400	7.290	3.420
	18.400	7.480	3.600	18.420	7.500	3.600	18.400	7.500	3.590	18.410	7.560	3.600	18.420	7.280	3.340

	Initial Weight (lb)	Final Weight (lb)
PVA (6MM + 8MM @ 0.25%) A5	27.40	27.35
PVA (6MM + 8MM @ 0.25%) B5	27.05	27
PVA (6MM + 8MM @ 0.25%) C5	27.40	27.5
PVA (6MM + 8MM @ 0.25%) A7	38.70	38.85
PVA (6MM + 8MM @ 0.25%) B7	38.10	38.15
PVA (6MM + 8MM @ 0.25%) C7	38.40	38.45
Date:	9/17/2013	11/30/2013

APPENDIX F

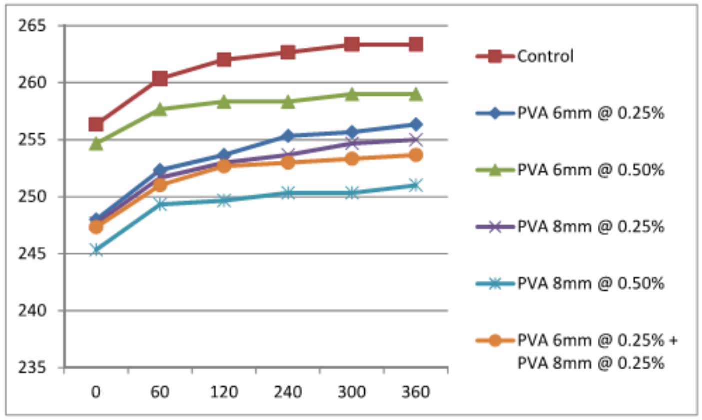
Moisture Absorption Rate

	TIME (SEC)						
Control	0	60	120	240	300	360	
1	262	267	268	269	269	269	WT (g)
2	253	256	258	258	259	259	WT (g)
3	254	258	260	261	262	262	WT (g)
	256.3333	260.3333	262	262.6667	263.3333	263.3333	
PVA 6mm @ 0.25%							
1	246	251	252	254	255	255	WT (g)
2	249	252	254	255	255	256	WT (g)
3	249	254	255	257	257	258	WT (g)
	248	252.3333	253.6667	255.3333	255.6667	256.3333	
PVA 6mm @ 0.50%							
1	255	258	258	258	259	259	WT (g)
2	259	262	263	263	263	263	WT (g)
3	250	253	254	254	255	255	WT (g)
	254.6667	257.6667	258.3333	258.3333	259	259	
PVA 8mm @ 0.25%							
1	247	251	252	253	254	254	WT (g)
2	250	254	256	256	257	258	WT (g)
3	246	250	251	252	253	253	WT (g)
	247.6667	251.6667	253	253.6667	254.6667	255	
PVA 8mm @ 0.50%							
1	244	248	248	249	249	250	WT (g)
2	246	250	251	251	251	252	WT (g)
3	246	250	250	251	251	251	WT (g)
	245.3333	249.3333	249.6667	250.3333	250.3333	251	
PVA 6mm @ 0.25% + PVA 8mm @ 0.25%							
1	246	249	251	251	252	252	WT (g)
2	247	251	253	253	253	253	WT (g)
3	249	253	254	255	255	256	WT (g)
	247.3333	251	252.6667	253	253.3333	253.6667	

Moisture Absorption Rate

Net Wt. Absorbed (g).	Average Percent Absorbed
7	
6	
8	
7	0.027308
9	
7	
9	
8.333333	0.033602
4	
4	
5	
4.333333	0.017016
7	
8	
7	
7.333333	0.02961
6	
6	
5	
5.666667	0.023098
6	
6	
7	
6.333333	0.025606

Moisture Absorption Rate



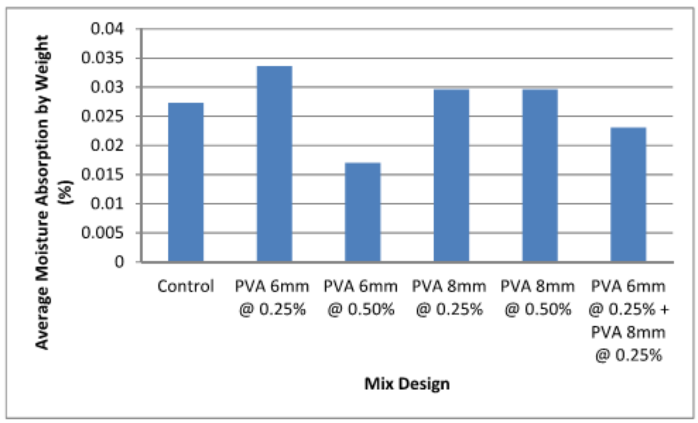


Image of Typical Moisture Absorption Testing