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Exploring the Properties of Fiber Reinforced Concrete

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ABSTRACT

Corrosion of steel reinforced concrete results in unsafe structures and significant economic costs. This project investigated using polymer, steel, and glass fibers in concrete to reduce corrosion by decreasing the permeability of concrete, which is the first line of defense against corrosion. The results suggested that polymer fibers resulted in high corrosion resistance, glass fibers increased flexural strength, and steel fibers improved yield strength but reduced fire resistance.

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AUTHORSHIP

Throughout this project, all of the team members contributed equally and were present during the mixing and testing of the samples. Team members were responsible for gathering information related to the fiber and test of their choice. Rita focused on the mix design and steel fibers, as well as the corrosion testing. In addition to looking into polymer fibers, Lauren also conducted the compression and furnace tests. RiAnna gathered information related to glass fibers and led the split tensile and four point bending tests. All of the team members helped to write and edit each section of the paper using feedback and direct revision methods. The feedback method entailed submitting drafts, making comments, and applying edits based on those comments. The direct revision method entailed making revisions directly to each other's sections.

Table of Contents

TABLE OF FIGURES AND TABLES

EXECUTIVE SUMMARY

Introduction & Literature Review

In the construction world, concrete is the most used material at over two billion tons (1.81 billion tonnes) produced annually. Concrete has many advantages including its low cost, availability of raw materials, high fire and weather resistance, and high compressive strength compared to wood. On the contrary, concrete lacks in tensile strength and ductility. Steel rebar is often incorporated into the matrix to increase the tensile strength of the concrete. Although the rebar provides tensile strength, the wide use of steel leads to a susceptibility to corrosion, leading to concrete failure. Globally, the estimated cost of corrosion was $2.5 trillion in 2013, which was more than 3% of the global gross domestic product.

Some techniques to solve the issue of corrosion have been tested. Coating the rebar in a sealant (such as epoxy) is an application that is currently used. While the coating helps prevent the rebar from corroding, coating the rebar creates a smooth surface that weakens the adhesion between the concrete and the rebar. It is also much less effective if it is chipped.

Because corrosion is still a prevalent issue, other solutions are needed. One possible solution is fiber reinforced concrete. Some studies have shown that fibers can reduce crack widths within a concrete sample, which is an integral part in the deterioration of concrete because cracks allow corrosive materials to reach the rebar.

Besides corrosion resistance, fibers can improve other properties of concrete including the ability to induce a strain hardening behavior where the post cracking tensile stress is higher than its tensile strength. Concrete that exhibits this behavior is referred to as an Engineered Cementitious Composite (ECC). The behavior of ECCs is desirable because when a crack in concrete occurs, the load from the matrix can be transferred to the fibers, increasing the amount of energy needed for the concrete to fail.

A variety of fiber shapes and sizes creates a wide range of applications. Longer fibers are ideal for flexural testing because the long fibers are able to link together, creating a stronger bond and preventing additional bending. Many fibers are straight in shape, but it is common to see metals fibers that have hooks at the ends because this helps them lock into the concrete. Other benefits of fibers in concrete include increasing ductility and reducing crack width, which is dependent on an even distribution of fibers. The material properties of the fibers are important to keep in mind when designing a mixture. Among the types of fibers available, steel, polymer, and glass are the most commonly used.

The idea of adding polymer fibers to concrete attracted a wide variety of people because chemists and engineers in the early 1900's believed that the combination of polymer fibers and concrete composite materials would result in a crack and impact resistant concrete that would be low in cost. When fibers are added in a mixture, the fibers are able to reduce plastic shrinkage by blocking any crack paths by reinforcing the concrete together and reducing the water from escaping through any openings. Polymer fibers are also known to make the concrete impact resistant which is the ability to consume energy.

Steel fibers in fiber reinforced concrete have the unique property of having different shapes like crimps and hooked ends that can help improve the bond between the concrete and the fiber. The deformed shape helps the concrete composite have a strain hardening behavior because it takes more energy to pull the fiber out if it is well embedded in the concrete. With steel's high yield strength, steel fibers can replace structural reinforcing rebar like stirrups to help with relieving reinforcement congestion and increase the ability to use concrete in smaller spaces in which it would be hard to fit a large number of stirrups. The use of a hybrid concrete that incorporates both steel fibers and steel rebar can also help with corrosion resistance. Replacing the stirrups with fibers reduces the amount of steel objects in contact with each other, and therefore minimizes the process of galvanic corrosion.

Early experimentation with glass fiber reinforced concrete was unsuccessful because the type of glass that was used degraded when exposed to the high alkali matrix of the concrete. An alkali resistant glass that contained zirconia was experimented with and has been used since the 1970s. Over the past 40 years, studies have shown that the addition of glass fibers can increase the tensile and compressive strengths of concrete. A single glass fiber that is used in concrete can have anywhere from 50 to 200 strands, which increases the ductility because the matrix only bonds to the outer strands. Unlike steel fibers, corrosion of glass fibers is not a concern when using them in a concrete mix.

Methodology

The polymer fibers used in this project were Polyvinyl Alcohol (PVA) fibers that were 0.0039 in. (100 microns) in diameter and 0.5 in. (13 mm) in length. Stainless steel crimped fibers were used with a nominal size of 0.020 in. x 0.033 in. (0.508 mm x 0.8382 mm) and 1 in. (26 mm) in length. The glass fibers were AR glass with 0.0007 in. (18 microns) in diameters and 1 in. (26 mm) in length.

The mix proportions consisted of 45.6 wt.% ordinary portland cement, 21.3 wt.% fine aggregate, 16 wt.% of fly ash, 15.5 wt.% of water, 0.4 wt.% superplasticizer and 1.3 wt.% of the polymer, steel, or glass fibers. The temperature was taken immediately after mixing, two minutes later, and after the mixture had been placed in the molds as a quality control test. After an initial curing period of 24 hours, the samples were demolded and placed in the curing room for two weeks. A variety of tests were conducted including split tensile, compression, four point flexural, furnace testing, and accelerated corrosion on mortar samples with added fibers (referred to as polymer, steel, and glass fiber samples).

Split tensile tests were performed on four 2 in. x 4 in. (5.08 cm x 10.16 cm) cylindrical samples of each type of fiber and controls. A load of 15,000 lbf/min was applied and the tensile strength was calculated. The failure pattern was also assessed to determine whether fibers broke in half or pulled out from the cross section.

In industry, the results of compression tests are generally used to indicate which mixtures are suitable for structures. For testing, sample diameters were measured and insured that they did not differ by more than 2%. Four samples were placed in the load frame and when cracks began to form, the load stopped and the compressive strength was calculated.

The four point bending test was chosen to determine the flexural strength of the samples. A load of 0.02 in./min (0.508 mm/min) was applied to 3 in. x 3 in. x 18 in. (7.62 cm x 7.62 cm x 45.72 cm) beams and the flexural strength was determined. Fiber adhesion to the matrix was also assessed in this test.

Furnace testing showed the effects of concrete strength after exposure to heat. Three 2 in. (5.08 cm) cubes were placed in the furnace at a temperature of 1,200 °F (649 °C) for one hour. After the hour of heating, the samples cooled for an additional 90 minutes and were then tested for strength.

Accelerated corrosion testing was done with 4 in. x 8 in. (10.16 cm x 20.32 cm) cylindrical samples that were prepared with No. 3 rebar embedded in the concrete mix that was held 0.75 in. (1.91 cm) from the bottom of the mold. The sample was submerged into a 5 wt. % sodium chloride solution which had a 13.5 V current running through it. A computer program logged the resistance of the concrete and stopped when there was a significant loss in electrical resistance to indicate that the concrete had cracked.

Results and Discussion

The initial proportions of the mix design resulted in a segregated mix. This segregation was attributed to the high fly ash content and was remedied by replacing half of the fly ash with cement by volume. There were also issues with the workability of the mix, which resulted in two broken mixing paddles. In order to address this issue, the fibers were added to the mixture last to avoid the clumping that was breaking the paddles.

It was evident from the cross sections of the split tensile tests that the samples had even distributions of fibers throughout, however, the steel fibers were sparse compared to the glass and polymer fiber samples. The thick consistency of the mix may have helped to prevent the fibers from settling. The fibers had pulled out from the matrix rather than splitting, showing that the fibers had sufficient strength but needed better adhesion to the matrix to transfer the load. All fiber reinforced samples failed at higher peak loads than the controls. However, the polymer and glass samples held higher peak loads than the steel samples and the control samples; they were higher than the steel by more than 65% and higher than the controls by 110%.

From the compression test, it was concluded that the overall compressive strength for all of the samples were on the higher side compared to industry standards. The strength of the mortar may have been due to the water to cement (w:c) ratio. The standard w:c ratio is 0.40 but the ratio used for testing was 0.33. The steel fibers also had the highest compressive strength. This may be because the type of steel fiber used was very easy to disperse. Crimped steel fibers are able to reach their maximum potential with strength because they are able to bend and yield in concrete.

The polymer and glass samples held approximately 19% higher peak loads during the four point bending test than the steel fiber samples. The controls had peak loads similar to the steel fiber samples. There were fewer fibers distributed throughout the failure plane of the steel fiber samples, which may have been the reason for the lower flexural strength. If there are not fibers at the point of maximum stress, then the fibers cannot help reinforce the mortar.

The results from the furnace testing showed that after exposure to heat of 1,200 °F (649 °C) for one hour, the controls and glass fiber samples had an increase in compressive strength while the steel and polymer fibers decreased in strength possibly due to the w:c ratio. The test also showed that the samples with steel fibers exhibited an explosive behavior within an hour, which was likely due to thermal expansion of the steel generating internal stresses. This behavior may have been due to the positioning of the fibers. Depending on the placement, the fibers can sometimes decrease or even increase the number of cracks in a sample.

The results from the accelerated corrosion testing indicated that the polymer fibers were the most successful of the fibers at resisting the corrosion of the embedded rebar. It was deduced that the high volume of fibers in the concrete helped create a more dense concrete that decreased permeability. On the other hand, the steel and glass fibers did not help with corrosion resistance and in fact ended up with corroded rebar after a shorter period than the control samples. Although the samples had failed through visual observation, the software did not read the expected 13.5 volts. Either this was caused by malfunctioning software or the fibers were able to hold the cracks together and resist the flow of the electrical current.

Conclusions/Recommendations

Strength, corrosion resistance, and fire resistance properties were assessed to compare polymer, steel, and glass fiber reinforced concrete to control mortar samples. The tests concluded that the benefits of the addition of fibers in concrete vary based on the type of fibers. It is recommended to use glass fibers when a higher flexural strength is desired, polymer fibers in locations that are prone to corrosive materials like chlorides because of the polymer’s high corrosion resistance, and steel fibers in structural applications due to steel’s high yield strength.

From the challenges experienced in this study, assessing the compressive strengths at multiple curing times to ensure the mix still meets industry standards is recommended. There should also be a standard for mixing fiber reinforced concrete to ensure consistency in research. Additionally, the utilization of equations for ECCs is recommended to ensure the correct fiber ratios for promoting multiple cracking and producing higher yield strengths.

1. INTRODUCTION

It is estimated that over two billion tons (1.81 billion tonnes) of concrete are produced each year globally and that number is only rising, making it the most used construction material today (Crow, 2008). Conventional concrete is typically reinforced by steel rebar to carry the tensile loads. Reinforced concrete provides a wide variety of benefits including high strength, durability, low maintenance, and low cost in comparison to other building materials like wood.

While reinforced concrete is very durable, the cause of its failure is often the corrosion of the embedded rebar. This corrosion causes cracking and spalling which leads to the deterioration of the whole concrete structure. A two-year study conducted by the United States Federal Highway Administration found that the estimated annual direct corrosion cost was $276 billion in 2002. That cost rose to $500 billion in 2013 and was estimated to keep growing. On a global scale, the cost of corrosion was estimated at $2.5 trillion in 2013, which was more than 3% of the global gross domestic product (NACE International, 2013).

Funds spent on corrosion continue to add to national debt each year. Additionally, corrosion results in unsafe structures, which raises the question of what can be done to put an end to the corrosion process. Stainless steel rebar is more resistant to corrosion, however, it is much more expensive when compared to conventional steel rebar. Coatings have also been used in construction by coating the bar in a type of sealant (commonly epoxy) which reduces the possibility of the rebar corroding. The epoxy is a smooth substance when it dries on the rebar and can reduce the strength of the bonds between the cement and rebar. If the coating is chipped, it becomes much less effective. While many proposed solutions are being explored, steel rebar corrosion remains a prevalent issue in the construction world.

Information regarding the effects of fiber reinforced concrete on corrosion is not readily available to the public. Many studies have shown that fibers can reduce crack widths. Crack width is an integral part of the deterioration of concrete because cracks allow corrosive materials to reach the rebar. Different types of fibers affect crack widths in different ways. It is not common knowledge which fibers specifically can reduce the corrosion process. Therefore, the goal of this project was to explore the properties of the most commonly used types of fibers, which are steel, polymer, and glass. Along with experimenting with corrosion, strength and fire tests were performed. If a given fiber drastically slows the corrosion of the rebar, it is important to ensure that the strength and fire resistance of that material is not compromised.

2. LITERATURE REVIEW

The use of concrete has evolved over the years as technology has advanced and the demand in the construction world for cheaper yet stronger materials continues to grow. A significant change that has greatly improved the strength of concrete is the addition of different types of reinforcement. Fiber reinforced concrete is among the more recently explored types of concrete and has been proven to have multiple benefits.

2.1 The History of Concrete

Aside from water, concrete is the most produced material in the world (WBCSD, 2009). It is a strong compound consisting of a mixture of cement, sand, aggregates, water, and admixtures. It has been a prominent building material for over a century because of the availability of low cost materials, its high fire and weather resistance, and its high compressive strength. Its high compressive strength makes concrete suitable for structures like columns and arches that are primarily subject to compressive loads (Darwin *et al.*, 2016).

However, concrete has disadvantages including its weak tensile strength, low ductility, and high weight to strength ratio. In order to address the low tensile strength, Joseph Monier invented reinforced concrete, which is a composite of concrete and steel rods. The rods are manufactured with exterior ridges that allow for interlocking so as not to slip past each other and increase frictional forces between the rebar and the concrete, creating another strengthening element. The steel bars are often placed near the bottom of the concrete forms because as loads are applied to the top, tension is created at the bottom. This top load idea is applicable to roads, bridges, buildings, dams, and other structures (Darwin *et al.*, 2016). While conventional rebar reinforced concrete has been a widely used material for many years and continues to be popular, efforts to find more lightweight, corrosion resistant materials are on the rise.

In the early 1960s, a group published a paper about the mechanics of crack arrest in concrete by using very closely placed steel wires as reinforcement. They found that a smaller spacing meant an increase in tensile strength (Romualdi and Batson, 1963). Their successful research sparked an interest in fiber reinforced concrete around the world (Zollo, 1996). Since then, many types of fibers have been subject to experimentation ranging from animal hair to synthetic polymers.

The idea of fiber reinforced concrete evolved even further in the early 1990s with the exploration of Engineered Cementitious Composites (ECC). ECCs are essentially highly ductile fiber reinforced concretes where the micromechanical interactions in the interfacial zone are engineered to produce desired properties including strain hardening behavior (Li, 2003). Strain hardening is desirable because the composite material ends up with a post cracking tensile stress that is higher than its tensile strength as well as a larger area under the stress-strain curve. The area under a stress-strain curve represents the amount of energy required for failure (Mier, 1986). Conventional fiber reinforced concrete is strain softening, so the post-cracking tensile stress is lower than its tensile strength but its stress-strain curve still has a larger area under the curve than concrete without fibers. Therefore, more energy is required to reach failure in fiber reinforced concrete than with concrete without fiber reinforcement.

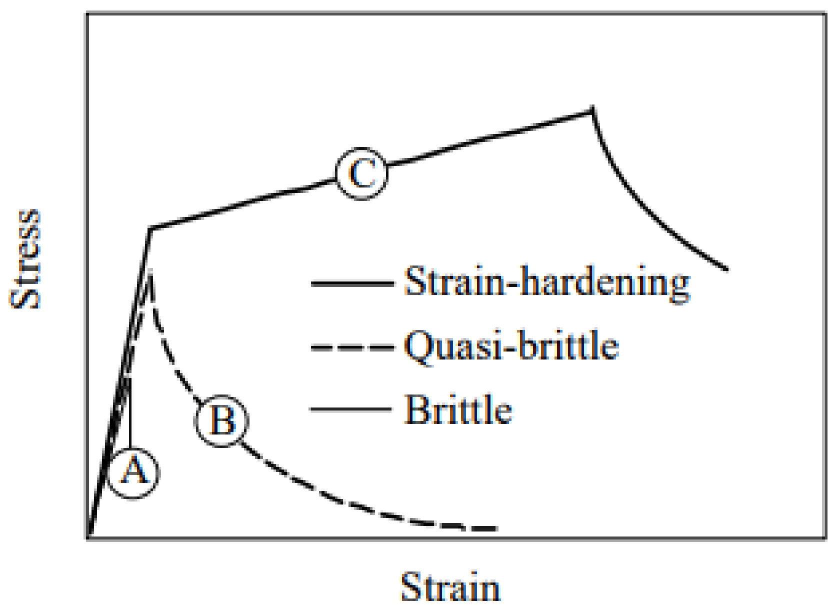

Figure 1: Stress strain curve showing brittle (A), strain softening (B) and strain hardening (C) behavior. Image courtesy of Victor Li, (1998)

Multiple cracking is necessary to create the desired strain hardening behavior making it a fundamental part of ECCs. In order to achieve multiple cracking, the strength of the fiber has to be higher than the strength of the matrix. This relationship can be modeled by the following formula:

$$J_b' = \sigma_o \delta_o - \int_0^{\delta_o} \sigma(\delta) d\delta \geq J_{tip} \approx \frac{K_m^2}{E_m}$$

J_b' = complementary energy

σ_0 = maximum bridging stress

δ_0 = crack opening corresponding to the maximum bridging stress.

J_{tip} = crack tip fracture toughness.

K_m = the fracture toughness

E_m = the matrix elastic modulus.

There are two parts to the equation. It is important to meet the first part of the equation because this ensures that multiple cracking will occur instead of a single localized fracture. This is based on the relationship displayed on a stress-strain curve. The complementary energy (J_b') is represented by the region to the left of the curve. The goal is to have a large area to the left of the curve because that means that there is more energy in the system. The relationship between the maximum bridging stress (σ_0) and the crack opening (δ_0) is derived by analyzing fracture mechanics like crack propagation along a fiber and the matrix to quantify and understand debonding (Li *et al*., 2001). The second part of the equation ensures that the fibers will be able to transfer the load from the matrix to the fibers when a crack does occur.

2.2 Fibers

According to a report from Zion Research, the market for fiber reinforced concrete was $1.87 billion in 2014 and is expected to grow. Fibers are beginning to become more popular because their variety of shapes and sizes creates a wider range of applications. Steel fibers are the most common claiming 45% of the fiber reinforced concrete market in 2014 (Joel, 2016). Typically, fibers come in precut lengths and diameters based on the desired results. Common sizes range from 0.5 in. to 3 in. (1.27 cm to 7.62 cm). Among the many fibers available, their properties vary and contribute differently to concrete. Depending on the fiber, it is better to have longer strands and more strands because the length of the fibers tend to perform differently with specific tests. Working with longer fibers in a flexural test is ideal because the long fibers are able to link together creating a stronger bond that can ultimately prevent any additional bending. Along with different sizes, it is also common to have different shapes of fibers. Many fibers are straight in shape, but it is common to see metals fibers that have hooks at the ends, forming a staple shape, because it helps them lock into the concrete.

The use of fibers within a concrete mix provides many benefits, including increasing ductility and reducing crack width. In terms of reducing crack width, the incorporation of fibers in concrete allows the fibers to carry some of the tensile forces that would normally only be carried by steel reinforcing bars. This results in a reduction of the steel stress in the reinforcing bars and results in a smaller crack width (Cederhout, 2010). Tara Rahmani explored this theory by conducting observational experiments on how fibers delayed crack formation during setting. It took over 110 minutes to have the first surface crack form in the mixture with the plastic fibers while it only took 90 minutes for the first crack to form in a conventional mixture. A mixture with the polymer fibers was able to last longer because the fibers provided water to the dry surfaces, which reduces cracks. Rhamani continued to run more tests and was able to conclude that adding 0.91 kg/m^3 (1.533 lb/yd^3) polymer fibers by hand into a concrete mixture it is able to decrease cracking by 40%-55% (Rahmani *et al.*, 2012).

Fibers are also known to help improve the ductility of concrete. Tests such as three point bending tests are commonly performed to show the strength after concrete has cracked. Fantilli *et al.* used a ductility index that was proportional to the difference between the ultimate load and the effective cracking load to show that an increase in fibers led to a more ductile specimen. (Fantilli *et al.*, 2016)

To develop a concrete mix with improved ductility and reduced crack widths, there are steps to be considered when mixing the fibers into the concrete to ensure the best performance. The fibers are more often used with smaller aggregate because large aggregates can prevent the fibers from dispersing at random. The viscosity of the mix must also be precise to keep the fibers suspended. If a mix is too viscous then fibers will stay near the top, and if a mix is not viscous enough then the fibers will sink to the bottom. The material properties of a fiber are important to consider when designing a mix. For example, most natural fibers are not ideal because they break down in concrete due to the alkalinity. The most common reinforcing fibers used today are polymer, steel, and glass.

2.2.1 Polymer Fibers

The earliest use of polymer fibers in concrete were publicized by the burgeoning petrochemical industry following World War II (Bakis, 2002). Chemists and engineers from the early 1900's believed that the combination of polymer fibers and concrete composite materials with mechanical properties including crack resistance and impact resistance would result in a low cost concrete (Bakis, 2002). Since then, the idea of adding polymer fibers to concrete has attracted a wide variety of people in the construction industry. For every polymer fiber, there are three different diameters to choose from that are: 0.0002 in. (7 microns), 0.0006 in. (15 microns), and 0.0039 in. (100 microns) and for the length: 0.25 in. (0.64 cm), 0.3125 in. (0.79 cm), and 0.5 in. (1.27 cm). If the fibers have a small diameter, they are more effective than the larger diameter fibers because the smaller diameter fiber provide a larger surface area over which the fibers can bond. Additionally, if the smaller and larger length fibers have the same fiber-volume ratio, then the smaller diameter fibers would provide more fibers in a given mixture creating a stronger tensile strength.

Plastic shrinkage appears during the first few hours after casting while the concrete is still in a plastic state and has not attained any significant strength (Rahmani *et al.*, 2012). Plastic shrinkage is a result from when water evaporates from a mixture, causing the concrete to weaken and eventually result in cracking. Mingli Cao tested that when polymer fibers are added to the mixture, the fibers are able to reduce the water evaporation by having the fibers control the bleeding channel (Cao, 2017). A bleeding channel is the process where all of the excess water is brought to the top surface through different paths (Uygunoglu, 2011). By incorporating polymer fibers into the mixture, the fibers are able to reduce the amount of water going to the top surface by reinforcing the concrete and disrupting the paths (Sadiqul Islam *et al.*, 2016).

Impact resistance is the ability of concrete to consume energy. Seeing as how conventional concrete is brittle, the ability to take in energy under multiple impact loads is very low. Alhozaimy *et al.* explored how polypropylene fibers, a type of polymer, interacts with pozzolans such as fly ash, silica fume, and slag to improve impact resistance when put in a mix together. They found that pozzolans reduced impact resistance in concrete because the pozzolans cause the concrete to become denser. Although the pozzolans form a stronger concrete there is still a reduction in toughness. Pozzolans reduced the failure impact resistance of conventional concrete by 28% - 42%. When the fibers were added, the first-crack impact resistance of the concrete increased by 78% - 151% (Alhozaimy *et al.*, 1996).

In addition to reducing plastic shrinkage and the impact resistance, polymer fibers are considered economical. Many engineers believe that polymer fiber is a cheaper alternative than steel fibers. In fact, Shi Yin compared plastic and steel fibers and showed that 37 lbs (16.78 kg) of plastic fibers is about $187 while steel fibers cost roughly $332 (Yin, 2015).

2.2.2 Steel Fibers

The study of steel fiber reinforced concrete started with experiments involving steel reinforcing materials like nails, pieces of cut wire and metal chips in 1910. Research was spearheaded by the United States in the early 1960s where the potential of steel fibers in concrete was evaluated. Since then, more research, development, and experimentation has led to an increase in the industrial application of steel fiber reinforced concrete (ACI Committee 554, 1982). Steel fibers are produced in many different forms ranging in length from 0.25 in. to 2.5 in. (0.6 cm to 6.4 cm) and in diameter from 0.02 in. to 0.04 in. (0.05 cm to 1.0 cm). These include straight and a variety of fibers with deformations including hooked end, irregular, crimped, stranded, twisted, and paddled. In commercial use, about 67% of fibers used are hook-end fibers. This can be attributed to the fact that deformations help improve the bond between the matrix and the fiber. In the case of straight fibers, the lack of deformations creates a strain softening behavior, which is similar to the response of concrete with no fibers. Fibers with deformations, however, display a strain hardening behavior where the maximum load is much higher (Pająk and Ponikiewski, 2013).

Figure 2: Different types of steel fiber deformations; hooked end, irregular, crimped, stranded, twisted, and paddled. Image courtesy of Holschemacher et al. (2010)

There are two types of failure when it comes to fiber reinforced concrete. Either the fibers break or they are pulled out of the concrete. It takes less energy to pull a fiber out than to break it. Therefore, it is more desirable to ensure that the mode of failure with fiber reinforced concrete is to be bent and break. This mode of failure is desirable because steel has a high yield strength meaning it can take a lot of strain without much increase in stress. Steel fibers with deformations like hooks and crimps help with getting the steel embedded into the concrete where they can bend and yield. The most desirable mode of failure is a combination of a well embedded fiber that takes a lot of energy to debond with the concrete and for the fiber to bend and yield so it can reach maximum potential. (Al-lami, 2015).

A study by You *et al.*, explored the effects of replacing structural reinforcement, specifically stirrups, with steel fiber reinforced concrete. In a conventional reinforced concrete beam, stirrups are placed to counter cracks that occur when the tensile strength of the concrete is exceeded. Steel fibers are able to hold these cracks together before the cracks become bigger and cause failure. They experimented with completely replacing stirrups with steel fibers but this led to a lower ultimate load capacity. They then only partially replaced the stirrups with steel fibers and this hybrid had a higher load capacity. With this hybrid, they explored the effect that the amount of fibers had on the beam to find that an increase in shear strength had a linear relationship to the increase of fibers. This was because the number of fibers crossing the interface of the shear crack increased and there is a lot of energy absorption in both debonding the fibers with the concrete and the high yield strength of the steel fibers. This hybrid can help with relieving reinforcement congestion and increase the ability to use concrete in smaller spaces where it would be hard to fit a large number of stirrups (You *et al.*, 2010).

Steel fiber reinforced concrete also helps with corrosion resistance. An oxide layer that forms during cement hydration protects the steel from reacting with oxygen and water, which causes rust. Corrosion that occurs at localized regions of steel is often due to the breakdown of this layer (Shores *et al*., 2017). Conventional concrete with rebar as the sole reinforcement usually shows signs of failure due to corrosion of the reinforcing rebar when rust pushes against the concrete creating large cracks (Wang *et al.*, 2017). Galvanic corrosion is an accelerated type of corrosion caused by two metals in contact with each other in a corrosive electrolyte environment like sodium chloride. This type of corrosion can be avoided by using steel fibers in addition to reinforcing rebar rather than stirrups because there are fewer stirrups in contact with the reinforcing rebar. In cases where the fibers go through galvanic corrosion due to contact with the reinforcing structural rebar, the volume of the fibers is so small that the stresses they enact on the concrete are smaller compared to the bursting stresses created by larger diameter stirrups (Tang, 2017).

Recent research suggests that steel fibers can also act as sacrificial anodes protecting the rebar and reducing or even stopping corrosion through different processes (Berrocal *et al*., 2016). Grubb *et al*. supported this theory by experimenting with cylindrical samples with steel rebar in the center. They submerged samples with and without steel fibers in a sodium chloride solution and found that the steel fiber reinforced mortar resisted the corrosion better than the mortar without fibers. They suggested that the formation of a passive layer for steel in a cement-based matrix is an oxygen intensive process, and therefore, the extensive amount of surface provided by the addition of steel fibers might act as localized sinks to draw oxygen away from the steel reinforcing bar.

2.2.3 Glass Fibers

Exploration of fiberglass reinforced concrete began in the late 1940s. However, the E-glass (which stands for "electrical grade" glass) that was used because of its high strength could not resist the high alkalinity within the matrix, which resulted in the degradation of the glass fibers. Fiberglass has a high silica content that reacts with the sodium and potassium hydroxides in the mortar, which causes the deterioration of the fibers and formation of a gel that can create swelling within the concrete. Once the force created by the swelling is greater than the tensile strength of the concrete, cracks will form and allow water in that will freeze and thaw creating even bigger cracks. The water can also carry substances that will accelerate corrosion. Eventually, these processes will result in the reduction of strength and deterioration of the concrete as a whole. In the 1970s, a new type of glass was used that produced better results in concrete. The solution was the addition of zirconia to the glass formula and the use of low alkali cement. Zirconia resists the alkalis with the cement instead of chemically reacting like the silica. These alkali resistant (AR) glass fibers are still the type that is currently used. For the past 40 years, glass fiber reinforced concrete has been used with minimal chemical destruction of the fibers (Palmer, 2015).

In addition to increasing concrete in ductility and reducing crack widths, glass fibers specifically have very high tensile strength, are considerably economical, and very lightweight. In a study by Kiran and Rao, conventional concrete was compared with concrete that had 5%, 6%, and 7% glass fiber added. On average, the samples with the glass fibers had 19% higher strength than the samples without fibers (Kiran and Rao, 2015). A single glass fiber that is used in concrete can have anywhere from 50 to 200 strands, which means the cementitious bonds are not attached to every strand of glass which results in the ductility drastically increasing. As the outer strands of the glass fiber are pulled, the inner strands may stay put creating a greater ability to deform (Palmer, 2015).

It has also been found that the addition of glass fibers increases the peak compressive load. Samples of glass fiber reinforced ceramic concrete with up to 2% fiber content had up to 19% higher peak compressive strength compared to samples without glass fibers (Tassew and Labell, 2014). Glass fibers are also more resistant to corrosion when compared to materials like steel because the iron in the steel corrodes when exposed to water and oxygen and glass does not. Corrosion is a key factor in the longevity of a concrete structure. As a material corrodes, a substance is produced (rust). That substance creates an excess volume that applies pressure to and debonds the concrete surrounding it. This leads to cracking that allows more environmental substances to permeate through the concrete. For example, once a crack forms water can fill that crack and freeze, which widens the crack or salt, can spread through the cracks, which accelerates the corrosion of the rebar. Eventually, the concrete will completely deteriorate.

The current research about fiber reinforced concrete shows that there is an opportunity for significant growth within this industry. Previous research has already identified strength and corrosion resistance as benefits of fiber reinforced concrete. To further explore the capabilities of plastic, steel, and glass fibers, a set of experiments was chosen to assess the strength, corrosion resistance, and fire resistance.

3. METHODOLOGY

The goal of the project was to assess the properties of different fibers and how they can affect concrete mixtures. To accomplish this goal, the following objectives were established:

- Create a mix design for the concrete with steel, glass, and polymer fibers
- Assess strength, corrosion, and fire resistance
- Provide recommendations for use

3.1 Create a mix design for the concrete with polymer, glass, and steel fibers

The polymer fibers used in this project were Polyvinyl Alcohol (PVA) fibers that were 0.0039 in. (100 microns) in diameter and 0.5 in. (13mm) in length. Stainless steel crimped fibers were used with a nominal size of 0.020 in. x 0.033 in. (0.508 mm x 0.8382 mm) and 1 in. (26 mm) in length. The glass fibers were AR glass with 0.0007 in. (18 microns) in diameters and 1 in. (26 mm) in length.

The mix design used in this project was adapted from Kan and Shi's design of ECC M45 (Kan & Shi, 2012). The original mix consisted of 27 wt.% ordinary portland cement, 22 wt.% fine aggregate, 33 wt.% of fly ash, 16 wt.% of water, 0.4 wt.% superplasticizer and 1.3 wt.% of the fibers. The initial mix with these quantities produced samples that did not harden and showed a segregation of materials. Due to the lower density of fly ash in comparison to the other materials in the mix, it was deduced that the light substance seen at the top of the sample was due to the high fly ash amount. The mix design was then modified to decrease the amount of fly ash by converting these values into a volume so that half of the fly ash in the mix design would be replaced by ordinary portland cement.

Figure 3: The initial samples showing the segregation. The light grey is the fly ash and the dark grey is the reacted cement and water.

The new mix consisted of 45.6 wt.% ordinary portland cement, 21.3 wt.% fine aggregate, 16 wt.% of fly ash, 15.5 wt.% of water, 0.4 wt.% superplasticizer, and 1.3 wt.% of the fibers. In order to prepare the mix, the superplasticizer was added to the water and mixed well to ensure even consistency. The cement, fly ash, and fine aggregate were first mixed for two minutes to make a consistent dry mix. This was placed in the mixer and water/superplasticizer was slowly poured as the mixer was running. When all of the water and superplasticizer were added, the mixer ran for an additional three minutes. After the mortar was completely mixed, the fibers were added gradually. Once all the fibers were incorporated, the mortar was mixed for an additional minute and the temperature of the batch was taken. The initial temperature was recorded, and another temperature reading was taken after two minutes as a quality control test. Molds specific to each of the tests were filled and hit with a rubber mallet to reduce the amount of air trapped in the sample. Once filled, the temperature of the mortar in the mold was taken and then covered with a plastic bag to induce a relatively stable moisture content for a 24-hour period. After the initial curing period, the samples were demolded and placed in the curing room. Two weeks after the pour date, the samples were removed from the curing room and tested.

Cement wt. %	Fibers (Steel, polymer and glass wt.%	Fly Ash wt.%	Fine Aggregate wt.%	Water wt.%	High Range water reducer (Superplasticizer) wt.%
43.5	1.3	16.5	22	16	0.4

Table 1: Concrete Mix Design

3.2 Assessing Strength, Corrosion and Fire Resistance

To understand which fibers worked well with the mix design, a variety of tests were conducted. These tests included: split tensile, compression, four point flexural, furnace testing, and accelerated corrosion.

The split tensile test was chosen to assess the bonds of the fibers within the mortar samples along with the force required to split them. Four 2 in. x 4 in. (5.08 cm x 10.16 cm) cylindrical samples were molded and placed in the curing room for two weeks. Although an age of 28 days is the standard curing time for testing concrete samples based on ASTM Code 39 and 192, a two week period was chosen to speed up the process. As long as all samples cured for the same amount of time before testing, the data should be comparable and valid. After curing, areas of mortar that had overflowed, or mushroomed, over the top the mold were filed down using a sanding machine so that the samples could lay flat in the load frame. The sample was then loaded into the load frame. A load of 15,000 lbf/min (6804 kg/min) was applied. The maximum load at failure was recorded. The tensile strength was calculated using the following equation:

$$f_t = \frac{2P}{\pi DL}$$

P = peak load

D = diameter of the sample

L = length of the sample

The failure pattern was assessed to determine the reason for failure within the cylinder. By comparing both sides of the split cylinder, it can be observed if an aggregate or fiber split in half or if it pulled out from one side. This can provide insight into which materials were the first to fail.

Compression tests were a significant factor in testing the samples because the compression test represents which mixtures would be suitable for structures. In the construction industry, concrete should have a compressive strength of 24,700 - 33,400 psi (170 - 230 MPa) (Buzzini, 2016). To complete this test, there were measurements of the cylinder diameter at two locations: the mid height of each sample and the cross sectional area. This was done to ensure that the samples were acceptable to proceed to the next steps. To know if they were acceptable, the two diameters were not allowed to differ by more than 2%. The sample was centered on the load frame and a load between 20 and 50 psi (0.14 - 0.34 MPa) per second was applied continuously. When cracks within the sample began to form, the load stopped and the maximum load that was displayed on the machine was recorded. With these results, the compressive strength was calculated by dividing the maximum load by the average cross-sectional area.

It has been shown that fiber reinforced concrete directly influences the flexural strength of concrete; therefore, a four point bending test was chosen to compare the three fibers. Three 3 in. x 3 in. x 18 in. (7.62 cm x 7.62 cm x 45.72 cm) beams were molded in metal molds sprayed with a mold release. The beams were placed in the curing room for two weeks. Each beam was loaded onto the bearing blocks with two rollers on the bottom and two rollers on the top. The two on the top of the beam were set 1.5 in. (3.81 cm) inside the beam edge and the two bottom rollers were placed in the middle of the beam spaced evenly as to split the beam in thirds. A load was applied at 0.02 in./min (0.508 mm/min). At failure, the maximum load was recorded. The loads between the various samples were compared and the cracking patterns of the failed beam were assessed. Specifically, how the fibers performed within the cracks was observed (whether they broke or pulled out from the concrete).

Furnace testing was conducted to show how fibers affect the strength of concrete after exposure to heat. By collecting this information, the data can be used for structural safety testing. Three sets of mortar were tested. There were three types of each sample for a total of nine samples to be tested. All concrete samples had the same composition with the exception of the type of fibers used. The three 2 in. (5.08 cm) cube samples were placed in the furnace. The samples were exposed to 1,200 °F (649 °C) which is the typical temperature of a building fire. The samples remained in the furnace for one hour and then cooled for an additional 90 minutes. After cooling, the samples were tested for strength.

The accelerated corrosion test was conducted to test how fibers can be used in addition to structural reinforcement to reduce corrosion. It was set up with 4 in. x 8 in. (10.16 cm x 20.32 cm) cylindrical samples. They were prepared with a No. 3 rebar embedded in the concrete mix that was held 0.75 in. (1.91 cm) from the bottom of the mold and cured for two weeks. The mortar was submerged into a 5 wt.% sodium chloride solution with the waterline just below the top of the mortar. There are multiple ways for the solution to reach the rebar including a crack in the concrete and diffusion forced by the electric current. Two stainless steel plates were attached to negative leads and submerged in the solution. A positive lead was then attached to the rebar suspended above the surface. A current of 13.5 volts was applied to the system. A data logging program tracked the current in regular intervals. The corrosion activity was monitored daily for the samples based on the values of the electrical current passing through each sample. The readings were stopped when there was a significant loss in electrical resistance, which indicated that there had been a crack in the concrete (Ahmad, 2009).

Figure 4: Corrosion test setup that consists of two steel plates, the concrete sample and a salt water solution

4. RESULTS AND DISCUSSION

4.1 Mix Design

The first mix consisted of 27 wt.% of ordinary portland cement, 22 wt.% of fine aggregate, 33 wt.% of fly ash, 16 wt.% of water, 0.4 wt.% of superplasticizer, and 1.3 wt.% of polymer, glass or steel fibers. This design had too much fly ash that resulted in an increased setting time and segregation of materials. It was deduced that the fly ash was the cause of the increased setting time and the segregation of materials because the fly ash had a lower density than the rest of the materials used. Dave *et al.* also experienced an increase in setting time with mixtures that incorporated fly ash. Setting time is influenced by the process of cement hydration, which is a chemical reaction where chemical bonds are formed between cementitious materials and water molecules to become hydrates or hydration products. Fly ash is a pozzolan, which has a slow hydration process because as a silicate material, there is little alkali content to complete the cement hydration reaction (Dave *et al.*, 2017). It was also observed that there was a watery mixture at the top of each of the samples, initially attributed to the high water content. In order to ensure that there was no extra water in the mixture, from this point on the sand was placed in the oven at 100°F (37.8°C) for 24 hours before mixing to remove any moisture it may have absorbed from the air. The cement and fly ash were stored in airtight bins to present moisture absorption. Another explanation for the extra water could be that the increased fly ash reduced the amount of cement available to react with the water. The water and fly ash rose to the top while the reacted water and cement sank to the bottom. This was addressed by reducing the fly ash and increasing the amount of the cement in the mix.

Figure 5: Initial samples showing a watery and light grey substance that collected at the top

The second mix design was 45.6 wt.% ordinary portland cement, 21.3 wt.% fine aggregate, 16 wt.% fly ash, 15.5 wt.% water, 0.4 wt.% superplasticizer, and 1.3 wt.% polymer, glass or steel fibers. Superplasticizer is a very viscous material that may not have distributed evenly. Therefore, the mix was prepared by adding the superplasticizer to the water to ensure an even consistency. Then, all the fibers, cement, fly ash, and fine aggregate were mixed by hand to make a consistent dry mix. This was placed in the mixer and water was slowly poured as the mixer was running. This mix with a reduced fly ash content worked well with a small batch. However, when the quantities were scaled up, the mixing paddle from the Hobart 20 Quart Commercial Dough Mixer broke. Before the dry mixture could integrate with the liquid mixture, hard clumps were formed that the mixer could not break up. A new methodology was developed to pour the water faster and turn the speed of the mixer from “stir” to “one”. However, this method also broke the paddle.

Figure 6: Broken paddles from the Hobart 20 Quart Commercial Dough Mixer and intact paddle

Rather than add all of the fibers into the dry mix in the beginning, they were added gradually in the end to avoid the clumping. Instead of using the mixer, a hand held electric drill and mixing paddle were used. This worked well and created a consistent mix because there was the opportunity to centralize the paddle in locations where clumps had formed.

Figure 7: New mixing setup with a hand held electric drill and a mixing paddle

The temperature for each mix was taken immediately after mixing, two minutes after mixing, and when the mixture was in the mold. Figure 8 shows the temperatures for each of the mixes. The temperature of the mix varied because the temperature of the sand also varied. In some instances, the sand was mixed when it was right out of the oven so it was at 100°F (37.8°C). In others, the sand had been sitting at room temperature while the initial mixture was being poured into molds. A better method to ensure consistency would have been to allow the sand to cool down to room temperature. However, it was observed that using sand at a high temperature increased the workability of the mix. Companies like Shelby Materials use hot sand in cold temperatures to help speed up the hydration process of concrete, which requires heat. In order to gain the heat needed for hydration, there is the option of heating the water or the sand. Shelby materials chooses to heat the sand rather than water, one of the reasons being that water has a lower thermal conductivity than sand (Shelby Materials, n.d.). Therefore, although useful in many applications, this technique caused a spike in temperature for the samples where the sand had not cooled down yet, two minutes after mixing was done.

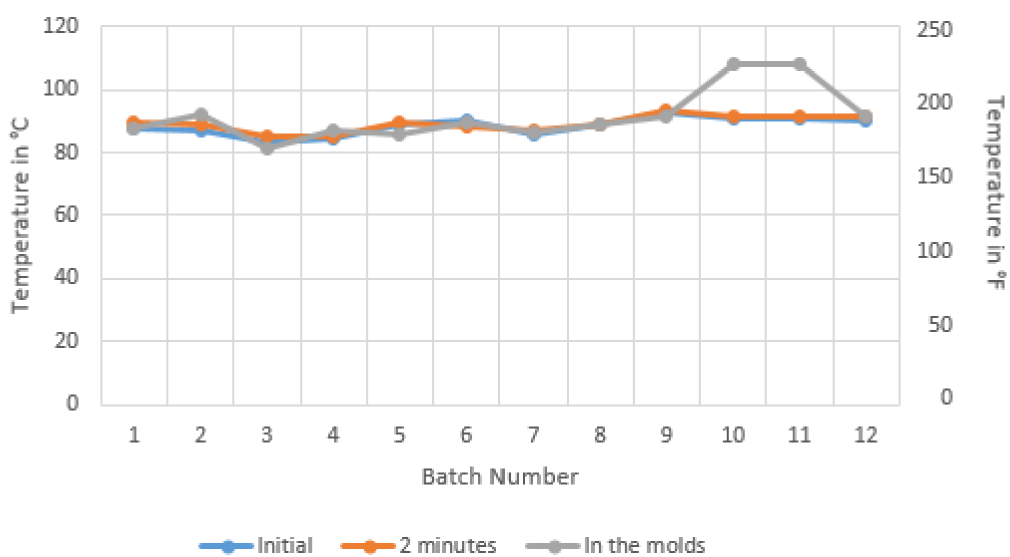

Figure 8: Graph showing that the temperature of each mix was mostly consistent except when the sand did not cool down enough

4.2 Assessing Strength, Corrosion and Fire Resistance

The split tensile strength test was important to assess not only the resistance to the tensile forces within the samples, but also to assess the distribution of the fibers throughout. All samples tested for split tensile strength were 2 in. x 4 in. (5.08 cm x 10.16 cm) cylinders tested 14 days after curing. Both the glass and polymer fiber samples appeared to have an even distribution of fibers throughout. The mix had a thick consistency that may have helped to prevent settling of the fibers. The steel fiber samples appeared to have an even and random distribution of fibers, however the volume of fibers was small. Fewer than 10 fibers were observed within the cross section created by the splitting from the test.

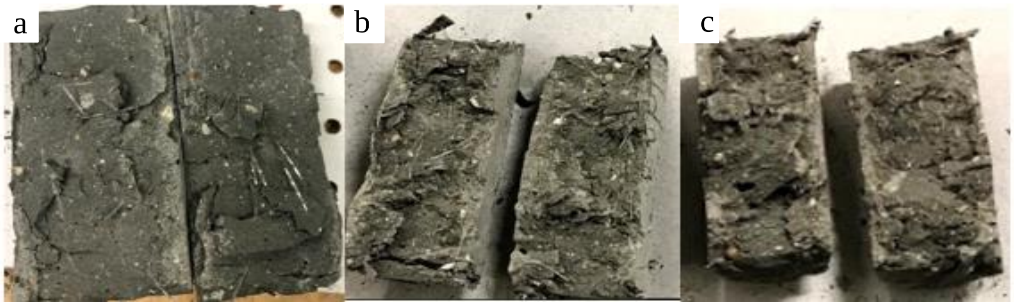

Figure 9: Cross sections of samples showing fiber distribution after split tensile test with a) steel fibers b) polymer fibers c) glass fibers

Regardless of the distribution of fibers, the polymer, steel, and glass fiber samples all failed at a higher average peak load than the control. However, the polymer and glass fiber samples held higher peak loads than the steel samples and the control samples; they were higher than the steel by more than 65% and higher than the controls by 110%. The standard deviations of the steel fiber samples and controls overlap. In a study by Kiran and Rao, they also found that adding fibers increased the split tensile strength when compared to samples without fibers. However, they tested samples with 0%, 5%, 6%, and 7% by weight of fibers and found that the increase in strength was not proportional to the amount of fibers (Kiran and Rao, 2015). It was observed that at 6% weight of fibers, a maximum strength was reached and then the strength began to decrease.

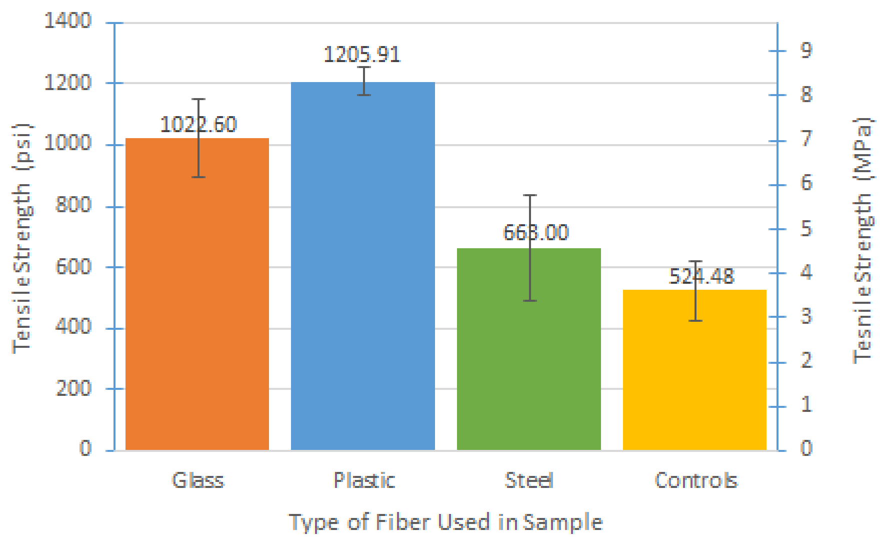

Figure 10: Comparison of the tensile strength

Some of the data gathered may have been influenced by various atypical factors. As explained in the methodology, mushrooming of the samples may have compromised some the strength because the edges had to be filed down in order to be placed flat in the load frame. It was observed that many of the fibers for all types had pulled out from one side of the sample when it split. If the fibers had better adhesion to the mortar, then the strengths may have been even higher. As explained in the background about multiple cracking, it appeared that the fibers had sufficient strength and it was the matrix to fiber adhesion that failed prematurely. The load was not able to be transferred to the fibers to achieve the fibers' ultimate strength. Better adhesion could be achieved by using fibers with a smaller diameter because they would have a higher surface area per volume. Increasing the volume of fibers may be another option to prevent the fibers from pulling out because that would distribute the load over a greater amount of fibers. Here, it can be concluded that adding fibers to the concrete does increase the split tensile strength. Because concrete has low tensile strength compared to compressive strength, this can be an influential property for designers to take into consideration.

As outlined in the methodology, compression tests were performed to determine if the sample had acceptable compressive strength. Each sample was measured for consistency and to verify that it was suitable for the test based on height and diameter. All samples for compression testing were 2 in. x 4 in. (5.08 cm x 10.16 cm) cylinders and tested 14 days after curing. From these tests, it was determined that overall the compressive strength for all of the samples were on the higher side and the standard deviations went as high as ± 1,500 psi (10.34 MPa). This may have been due to the water to cement (w:c) ratio. The ACI code states that for a minimum compressive strength of 5,000 psi (35 MPa) the standard w:c ratio should be 0.40 (Kosmatka *et al.*, 2016). It may have been possible that when creating the samples, there was a decrease in water content that resulted in a stronger mixture. This is because when water is added, the mixture is weakened.

The steel fibers also had the highest compressive strength of 9,476.5 ± 1,005.5 psi (65.3 ± 6.9 MPa) while the controls had the lowest compressive strength of 7,965.7 ± 1,488.3 psi (54.9 ± 10.3 MPa). Steel fibers may have had the largest compressive strength because the type of fiber used was crimped steel fibers, which are fibers that disperse easily. As mentioned in the Literature Review, crimped steel fibers help embed the steel into the concrete where they can bend and yield. By bending and yielding, the fibers are able to reach their full potential in terms of strength. For more accurate results, it is recommended to complete the test after 3, 7, and 28 days rather than just 14 days. Doing multiple tests will show if the compressive strength changes significantly between each test and if the sample still meets the industry standards. The ACI states that when doing compressive testing on day 3 and 7, the sample is acceptable if the average of all of the tests are equal or exceed the compressive strength value at 28 days. It also states that the two averages of compressive strength cannot fall below 500 psi (3.5 MPa) if the compressive strength is 5,000 psi (35 MPa) or less. If the compressive strength exceeds 5,000 psi (35 MPa) then the average cannot differ by more than 10%. In addition, seeing as steel had the highest compressive strength, redoing this test with the different forms of steel fibers (hooked end, irregular, crimped, stranded, twisted, and paddled) may produce results that show which type of steel fiber is suitable for structures.

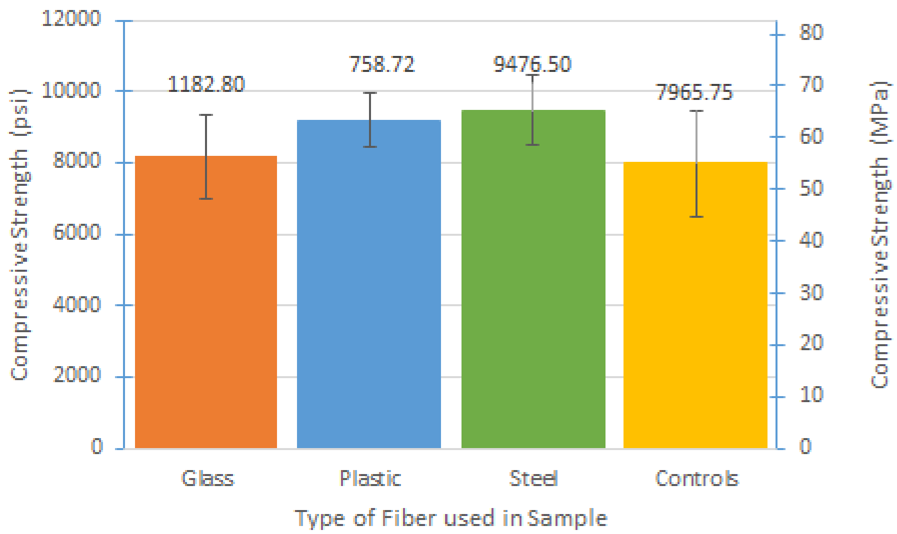

Figure 11: Comparison of compressive strength

All four point flexural tests were conducted 14 days after curing on 3 in. x 3 in. x 18 in. (7.62 cm x 7.62 cm x 45.72 cm) rectangular beams. Similar to the discussion of the split tensile test, the polymer and glass fiber samples appeared to have an even distribution throughout, and the steel fiber samples had a sparse distribution of fibers. All of the samples were made using the same mix design regardless of the type of test, so the dispersion of fibers throughout should have been the same across all samples of the same fiber.

The average flexural strength of the steel fiber samples was approximately 20% less than that of the polymer and glass samples. The flexural strengths of the steel samples were more similar to that of the control samples. The lower strength from the steel samples was likely caused by the lesser number of fibers distributed throughout the center of the sample where the beam split. If the fibers are not in the location of the maximum stress, then they are essentially negligible in carrying the flexural stress. Jang and Yun found that the flexural strength of steel fiber reinforced samples increased as volume of fibers increased. After the first crack, their data showed that flexural strength continued to increase. (Jang & Yun, 2018).

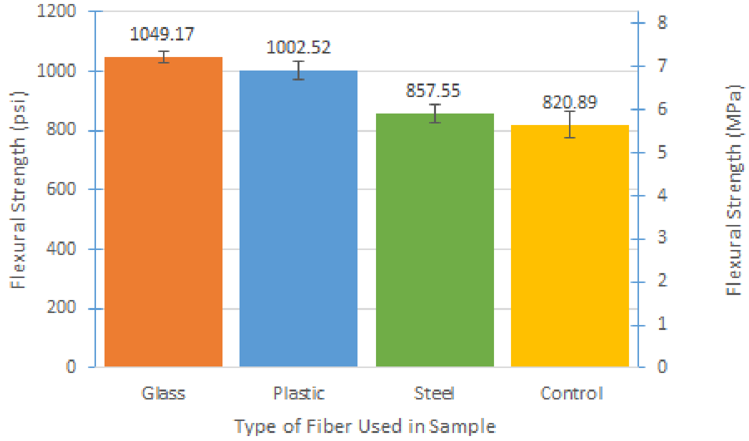

Figure 12: Comparison of the flexural strength

Furnace testing was performed to see how heat affects the strength of fiber reinforced concrete. For this test, three 2 in. (5.08 cm) cube samples were taken out of the curing room after 14 days and placed in the furnace. After exposure to the heat of 1,200 °F (649 °C) for one hour, the compressive strength in the controls and glass fiber samples increased while the steel and polymer fiber samples decreased. The controls also went from having the lowest compressive strength of 7,965.75 psi (54.92 MPa) to the highest strength of 9,572.00 psi (65.99 MPa) once exposed to heat. As previously mentioned in the results section of compression test, the increase in strength may have been due to the low w:c ratio.

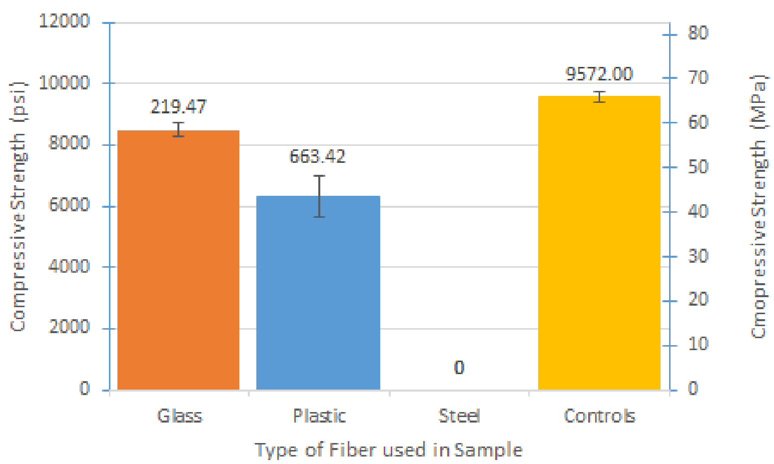

Figure 13: Comparison of compressive strengths after exposed to heat

When the samples containing steel fibers were exposed to the heat of 1,200 °F (649 °C) they were not able to survive the hour. The samples' explosive behavior in the furnace most likely occurred because thermal expansion of the fibers caused the fibers to expand. Li *et al.* tested fiber- reinforced composites that were exposed to high temperatures such as 392°F (200 °C), 752 (400°C), 600 °F (1,112 °C), and 1,472 °F (800 °C). There was a difference in the coefficient of thermal expansion between concrete and steel which caused internal stress on the sample resulting in failures (Li *et al.*, 2017). Many of the cracks also formed along the length of fibers rather than across the fibers, which could have had an effect on the samples. Depending on the placement of the fibers, they can sometimes increase or decrease the number of cracks. Plague *et al.* did a test on the influence of fiber types and fiber orientation on cracking. It was concluded that when the sample was cracked open and the fibers were between a 39 - 54 degree angle, the total number of cracks decreased up to 41% (Plague *et al.*, 2017).

Figure 14: Three 2 in. (5.08 cm) steel fiber cubes samples after exposure to heat

Accelerated corrosion testing was performed to see how fibers affected corrosion resistance in concrete with structural rebar. This was done with 4 in. x 8 in. (10.16 cm x 20.32 cm) cylindrical samples that were prepared with a No. 3 rebar embedded in the concrete mix that was held 0.75 in. (1.91 cm) from the bottom of the mold and cured for 14 days. The plastic samples were tested first and for the 10 days that the test was running, there was no failure of the sample because the rebar never corroded. This was determined by using a chisel and hammer to split open the sample and observe the state of the embedded rebar. It was expected for the samples to fail after a shorter period because Carpenter and Loucks conducted accelerated corrosion tests using the same procedure but with 2 in. x 4 in. (5.08 cm x 10.16 cm) cylinders. On average, samples with epoxy coating lasted 12.5 days and samples without lasted 1.5 days (Carpenter and Loucks, 2016). The glass samples were tested next and the test went on for a total of three days before there was any change in voltage for any of the samples. At three days there was a spike of about 3.8 volts, but if the sample had fully cracked it should have spiked to 13.5 volts. The test went on for an additional three days before corrosive material was seen around the rebar as well as in the water yet the software did not read 13.5 volts. The same behavior was seen with the steel fiber samples. Both the steel and glass fiber samples were removed from the salt solution and small cracks on the sample were observed. For the glass and steel samples, the bar had corroded.

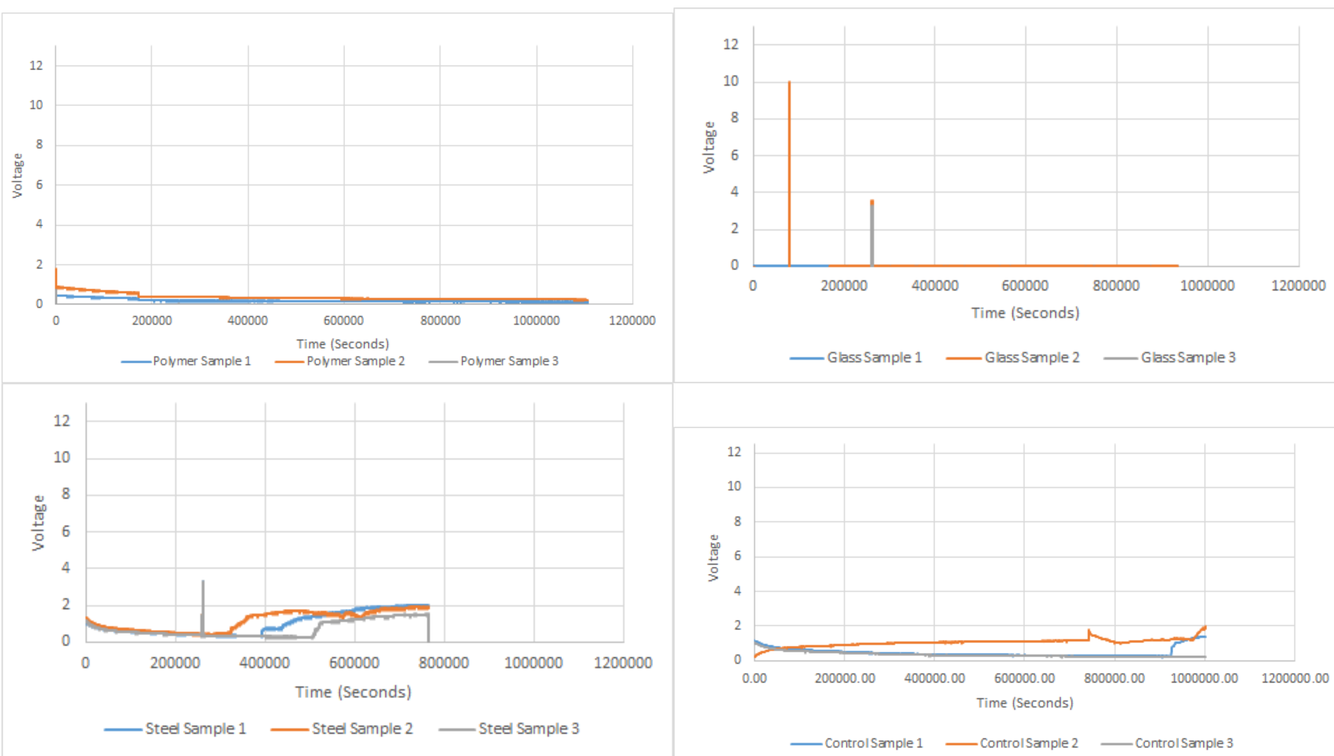

Figure 15: Corrosion testing graphs showing time (seconds) vs voltage for each of the samples

An important aspect of corrosion resistance and an indicator of concrete durability is the permeability of concrete (Song & Saraswathy, 2006). A study by Omoniyi and Akinyemi stated that the main factor that governs the permeability is the reduction of voids in the concrete. The study included bassage fibers to concrete, which helped reduce water permeability by filling those voids (Omoniyi and Akinyemi, 2013). The longer length of the steel and glass fiber samples in comparison to the polymer fibers may have created more voids in the mortar. In addition, if the concrete is denser, then there is less chance for water and other corrosive agents to reach the reinforcing rebar. This is evident in the samples without fibers because the samples were also able to resist corrosion for 8 days before a small change in voltage occurred for one of the samples. The other two samples did not fail until after 10 days.

Figure 16: Cross section of samples after corrosion testing showing that the rebar reinforced concrete sample with plastic fibers (a) did not corrode unlike the glass (b) and steel (c) samples

The results from the tests conducted in this study varied for each fiber. Therefore, there are different applications and recommendations for each fiber.

5. CONCLUSIONS/RECOMMENDATIONS

Strength, corrosion resistance, and fire resistance properties were assessed to compare polymer, steel, and glass fiber reinforced concrete along with control concrete samples. The results demonstrated that polymer fibers had a high corrosion resistance and a high tensile strength while glass fibers produced the highest flexural strength results. Tests conducted on the steel fibers were inconclusive based on the small volume of fibers used. However, it was found that the steel fibers were unable to withstand heat and caused the samples to deteriorate from the inside out. It can be concluded that the benefits of the addition of fibers in concrete vary based on the type of fiber. The following recommendations are made to be considered by designers and engineers:

- Glass fibers can be used when a higher flexural strength is desired. For example, large slabs and thin-shelled concrete are less resistant to bending because they can have a smaller thickness so fibers can help increase the strength.

- Polymer fibers would be beneficial in locations that are prone to corrosive materials because of the high corrosion resistance. Additionally, the polymer fibers would be ideal for pillars that are submerged in water such as bridges and dams.

- The use of steel fibers in concrete has potential in many structural applications because of the high yield strength of steel. However, caution should be used in areas that are prone to fire because the fibers can cause the concrete to experience explosive behavior.

Based on the challenges experienced in this study, it is recommended to develop a standard for mixing fiber reinforced concrete. This can be located in either the ASTM or ACI Standards to establish a consistent basis for research to be conducted. Although it is important to make sure that there is no extra water in the sand, all the materials used should be room temperature. It is also recommended to assess compressive strength on samples with more curing ages in order to ensure that the mix meets the industry's standards. Utilizing the equations used to make ECCs would have ensured that the volume of steel fibers used in the concrete mix was enough to induce multiple cracking and produce a higher yield strength. With these recommendations, more research can be conducted on the use of fibers in concrete to improve the mechanical properties and expand the applications of concrete in infrastructure.

DESIGN STATEMENT

Each Major Qualifying Project (MQP) at Worcester Polytechnic Institute (WPI) is required to include a description of how the project considered economic, environmental, sustainability, manufacturability, ethical, health and safety, social and political factors to meet Accreditation Board of Engineering and Technology (ABET) accreditation requirements. The design problem for this project was to assess the benefits of polymer, steel, and glass fibers in concrete. These fibers were chosen because they are the most common types used in fiber reinforced concrete.

Manufacturability in developing a concrete mix design is an essential factor in ensuring that there is an understanding of the process for others to replicate the mix design. During the project, the team first developed a mix design based on that used for Engineered Cementitious Composites. This mix had a high fly ash content that produced samples with an increased curing time where they had not set in 24 hours. It is important to have properly cured concrete because this allows for strength development. The second mix had a reduced fly ash content that produced samples that set in 24 hours. There were many iterations in creating the procedure for the mix design because there were many problems involving the workability of the mix. With the new mix design and a procedure that worked, a wide variety of tests were conducted including strength testing, furnace testing, and accelerated corrosion for each of type of fiber sample. Strength testing consisted of compressive, flexural, and tensile tests.

Compressive strength was tested to assess if the fiber reinforced specimen were strong enough for structural use. Each of the samples had high compressive strengths that were compared to the ASTM standards for compressive strength. Flexural strength was tested to observe the way the fibers affected crack formation and ductility. The results from this test were compared to the performance requirements for fiber reinforced concrete in ASTM C1116. Glass fibers can be used when a higher flexural strength is desired because they produced the highest flexural strength. For example, large slabs and thin-shelled concrete are less resistant to bending because they can have a smaller thickness so fibers can help increase the strength. Tensile strength was tested to explore the way that fibers used as reinforcement can affect tensile strength because concrete is known to be weak in tension.

Furnace testing was conducted to test compressive strength after heat exposure. Concrete's ability to maintain structural strength after heat exposure is important because if a fire were to occur in a building made of concrete, it should be able to stay up. Polymer and glass fiber samples were able to withstand the heat and actually had higher compressive strength. However, the difference in the thermal expansion of steel and concrete caused explosive behavior with the mortar where the steel fiber samples had fallen apart after the test. The use of steel fibers in concrete has the potential to be in many structural applications because of the high yield strength of steel. However, caution should be used in areas that are prone to fire because the steel fibers can cause the structure to collapse.

Finally, accelerated corrosion testing was conducted to assess how fibers affected corrosion resistance in rebar reinforced concrete. The importance of studying corrosion resistance is economically driven because the cost of corrosion grows steadily each year. The results from this test concluded that polymer fibers created a sample with high corrosion resistance. This makes polymer fibers beneficial in locations that are prone to corrosive materials such as pillars that are submerged in water to support bridges and dams.

PROFESSIONAL LICENSURE

The idea of a professional licensure is to protect the public by creating minimum standards that an engineer must obey. These standards include accepting and understanding both the technical and ethical responsibilities of an engineer. To understand the technical and ethical obligations, an engineer must have the desire and willingness to learn and do what is right, have basic communication skills, and the capability to resolve any issues.

To obtain a license, one must complete their degree from a four-year college or university and work under a professional engineer for a minimum of four years. Additionally, it is required to complete two competency exams, which includes the Fundamentals of Engineering (FE) and Principles and Practice of Engineering (PE) exams. The FE exam is a six hour, computer-based exam that tests students on material that was covered throughout their time in college or university. Some topics that are covered in this exam include fluid mechanics, structural analysis/design, construction, and geotechnical engineering. The PE exam is aimed at engineers that have had four years of post-graduate work in the specific sub-discipline of their choice. The exam is an eight-hour breadth and depth test. This means the first part of the test is open book and contains questions from the five different concentrations of civil engineering (construction, geotechnical, structural, transportation, and water resources/environmental) and the second part goes more in depth and focuses on the engineer's specific discipline. Once both the FE and PE test are completed, the engineer is a certified professional engineer and is able to obtain a professional license in their state. After receiving a professional license, the engineer still has requirements to keep the licensure. These requirements include maintaining and improving their skills through educational and professional opportunities. Some educational and professional opportunities can include partaking in classes, web seminars, and networking conferences.

As more people are going into the engineering industry, it is extremely important to understand the significance of having a professional license. If an individual has the desire to go into private practice or consulting, the PE is a requirement that is needed. Being a certified PE allows the public and other professionals to know that an individual has the credentials to sign, seal, and submit engineering plans and drawings for approval. Additionally, it shows that an individual is able to take on high level responsibilities and tasks because they have a deep understanding of materials in their specific discipline.

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