SYNTHETIC FIBER REINFORCED CONCRETE PERFORMANCE AFTER PROLONGED ENVIRONMENTAL EXPOSURE UTILIZING THE MODIFIED INDIRECT TENSILE TEST

by

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This thesis was prepared under the direction of the candidate's thesis advisor, Dr. Francisco Presuel Moreno, Department of Ocean and Mechanical Engineering, and has been approved by all members of the supervisory committee. It was submitted to the faculty of the College of Engineering and Computer Science and was accepted in partial fulfillment of the requirements for the degree of Master of Science.

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ABSTRACT

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In order to study the mechanical performance of dry-cast synthetic fiber reinforced concrete (SynFRC), samples of varying geometry, fiber content, and environmental exposure were developed and tested using the modified indirect tensile test. The samples created consisted of three different thicknesses (with two different geometries), and six different fiber contents that differed in either type, or quantity, of fibers. Throughout the duration of this research, procedures for inflicting detrimental materials into the concrete samples were employed at a number of different environments by implementing accelerated rates of deterioration using geometric adjustments, increased temperature exposure, wetting/drying cycles, and preparation techniques. The SynFRC samples studied were immersed in a wide range of environments including: the exposure of samples to high humidity and calcium hydroxide environments, which served at the control group, while the sea water, low pH, and barge conditioning environments were used to depict the real world environments similar to what would be experienced in the

Florida ecosystem. As a result of this conditioning regime, the concrete was able to imitate the real-world effects that the environments would have inflicted if exposed for long durations after an exposure period of only 20-24 months. Having adequately conditioned the samples in their respective environments, they were then tested (and forensically investigated) using the modified indirect tensile testing method to gather data regarding each sample's toughness and load handling capability. By analyzing the results from each sample, the toughness was calculated by taking the area under the force displacement curve. From these toughness readings it was found that possible degradation occurred between the fiber-matrix interface of some of the concrete samples conditioned in the Barge environment. From these specimens that were immersed in the barge environment, a handful of them exhibited multiple episodes of strain softening characteristics within their force displacement curves. In regard to the fibers used within the samples, the PVA fibers tended to pull off more while the Tuff Strand SF fibers had the highest tendency to break (despite some of the fibers showing similar pull off and breaking failure characteristics). When it comes to the overall thickness of the sample, there was clear correlation between the increase in size and the increase in sample toughness, however the degree to which it correlates varies from sample to sample.

TESTING AND ANALYSIS OF NUMEROUS SYNTHETIC FIBER REINFORCED CONCRETE SAMPLE GEOMETRIES UNDER VARIOUS ENVIRONMENTAL CONDITIONS

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I. INTRODUCTION

Concrete is one of the most abundant and effective construction materials in the world. This ceramic composite is known for being extremely strong in compression, yet relatively weak in tension. For this reason, reinforcing mechanisms are added to concrete lattices to help strengthen the member and provide structural support. However, there are a number of issues accompanying the traditional forms of reinforcement (which utilize steel elements) regarding survivability, depending on the specimen's environment and concrete composition. When steel reinforced concrete is exposed to detrimental environments for extended periods of time, the reinforcing mechanisms can degrade and lose their strengthening characteristics as the chlorides that are absorbed into the concrete initiate and propagate the corrosion process. While this corrosion process initially enhances the reinforcing mechanisms, after significant cross section loss, the bond between the reinforcement the concrete weakens. Because of this issue, nonconventional means of reinforcement have begun to be studied and implemented in applications subject to extreme conditions. One of the alternate techniques of reinforcing concrete, in conjunction with these traditional methods, is the utilization of macro synthetic fibers (measuring lengths of 2.5-5 cm long) throughout the concrete lattice. Within the concrete, these fibers (depending on their volume within the cast) are able to potentially increase the fracture toughness, tensile and flexural strength, and crack resistance of the composite. Although this technique of implementing synthetic fiber reinforcement within concrete structures has been used throughout the years, it's reinforcement capabilities within dry-cast concrete pipes and culverts has yet to be studied. These applications of FRC (in concrete pipes particularly) are an area of special interest for this form of fiber reinforcement, as these structures could experience extremely harsh environments such as those observed in Florida's swamps and marine sites. For this reason, investigating the performance of different sample geometries consisting of different fiber contents, in environments that have low pH or high biological growth is important. This project aims to answer a number of these performance questions regarding synthetic fiber reinforced concrete as samples are exposed to environments that mimic these unforgiving conditions. Using exposure regimes such as the immersion of samples in the Intercostal waterway, potentially allows for the growth of microorganisms (fouling) and calcareous deposits (barnacles) to take place. Additionally, immersing samples in seawater, or seawater with a pH adjusted to a value of four, for extended durations can help replicate marine and swamp like conditions in which structures are exposed. In contrast, specimens immersed in calcium hydroxide solution, and exposed to high humidity environments act as control samples of which comparison can be based off of. By rigorously testing and analyzing the failure mechanisms of numerous types (and geometries) of fiber reinforced concrete exposed to a variety of environmental conditions, more can be understood about their performance characteristics. Utilizing a modified method of testing called the modified indirect tensile test, the concrete specimen prepared for analysis can help develop conclusions and pinpoint ideal applications for fiber reinforced concrete throughout the world.

II. THESIS OBJECTIVE

The main objective of this thesis is to present and document the methodology and results gathered through the analysis of the mechanical behavior of fiber reinforced concrete samples. Included in this document will be a complete overview of the preparation and conditioning regime that each tested FRC sample underwent, as well as the full testing procedure conducted on these specimens employing the modified indirect tension test. This thesis will also include a summary of the results and performance characteristics found through the application of this modified indirect tension testing procedure on the FRC samples that were exposed in the different conditioning environments, alongside the methodology used in processing and analyzing this data. These concrete samples with differing geometries and fiber contents that were exposed to High Humidity, immersed in Calcium Hydroxide, Sea Water, Low pH seawater, and Barge environments are presented and compared on a similar basis to help pronounce their differences in makeup and deterioration, helping to determine how these independent factors effects the samples toughness. By controlling the environmental conditions acting on the samples throughout this extended conditioning regime (which lasted anywhere from 20 to 24 months), a better understanding of the degree of deterioration on each sample, as well as how they failed can help to pinpoint the specific real-world applications that would be ideal for each fiber type. By comparing these testing results to those obtained through similar techniques, the results generated could be validated to help predict the performance of fiber reinforced concrete structures employed in similar applications.

III. LITERATURE REVIEW

III.I Concrete

Concrete is a construction material used throughout the world for a wide variety of applications. Comprised of coarse and fine mineral aggregates, hardened cement paste, and various additional admixtures (which are used to improve a number of the concretes properties) this brittle material is strong in compression yet weak in tension. In order to enhance concretes tensile strength, and overall structural stability, reinforcing mechanisms such as cables, bars, or fibers are added into the concrete matrix. While there has been an extensive number of studies regarding the properties and performance of these traditional reinforcement methodologies for concrete, concrete laden with fiber reinforcement and exposed to aggressive environments remains an area where additional research is needed.

III.II The Role of Fiber Reinforced Concrete

Fibers have been incorporated into concrete lattices because of their innate ability to increase the concretes performance upon the initiation of crack formation. These fibers help resist cracking and increase the concretes overall ductility [1]. In order to determine the fibers ability to increase the concretes ductility, the energy dissipation during failure is looked at. This characteristic for energy dissipation is what is known as the concrete's toughness. There are a number of techniques that have been introduced as means of calculating this toughness characteristic throughout the years, and many of these have been used to develop the testing regimen that was employed throughout this research, which will be discussed in a later section.

Synthetic fibers within concrete applications provide short, discontinuous, and randomly distributed reinforcement that are more closely spaced compared to the traditional reinforcement techniques. These fibers are beneficial in that they are relatively low cost, are less effected by detrimental environments, and can serve as an alternative to their steel reinforcing counterparts. While reinforcing concrete with steel bars or steel fibers, the ingress of chloride ions into the concrete can result in the buildup of corrosion product which can cause resultant cracking, spalling, or other forms of structural degradation. The use of synthetic fibers, such as those studied in this thesis, can eliminate these concerns for such severe corrosion degradation while providing similar advantageous structural enhancements.

When cracking occurs on a concrete structure reinforced with synthetic fiber, the load transfers the applied stresses to the fibers and the fiber matrix interface [2]. These fibers initially provide a significant crack closing pressure that helps to prevent the further growth of the crack, or nucleation of new cracks throughout the structure. It has been shown that the addition of synthetic fibers throughout concrete structures has significantly increased their performance. In an article discussing the toughness of fiber-reinforced concrete [1] it was found that before cracking (pre-peak) the responses of concrete without fiber reinforcement resembled those with the fibers present. However, upon cracking occurring (post-peak) the fiber reinforced concrete samples exhibited a hardening type behavior. In this study, after cracking, (when the samples had crack opening displacement of 400μm) the samples with no fibers were only capable of withstanding maximum loads that were approximately 50% of what was observed to cause the first crack, while FRC samples could withstand loads around 100-180% of what was present upon cracking. This depicts the importance and influence that fiber reinforcement can have on the strength and durability of concrete.

The effects fibers have within concrete samples can be enhanced through the addition of fly ash (such as what was done throughout the preparation of the samples used in this research). It was found that when FRC includes a high volume of fly ash (in this case 235 kg per cubic meter of concrete, which was one third of the total fine aggregate by volume), the efficiency of the fiber reinforcement is increased [3]. For instance, when polypropylene fibers were encased in this specified (235 kg per cubic meter of concrete) high fly ash quantity concrete, the compressive and tensile strengths increased by 50%. This improvement in the performance of fibers in high fly ash concrete is attributed to the pozzolanic reaction of the fly ash, which replaces the preferentially oriented crystalline layer of calcium hydroxide in the interface with denser hydration products. This modification and densification of the microstructure occurs at the area that is about 20-40 µm thick between the matrix and the fibers known as the interfacial transition zone (ITZ)[3]. This pozzolanic reaction provides more strength to the matrix, and greater bonding between the matrix and the fibers. The combined beneficial effects of the fly ash and the fiber reinforcements can increase the concretes overall load bearing capabilities. It was found that when comparing the effects of fly ash in FRC, samples with fly ash present had compressive and tensile strengths of more than double those observed in samples without fly ash [3]. Due to these beneficial influences of fly ash in FRC samples, the specimen prepared for this research incorporate 23% fly ash F as a cement replacement with no fine aggregates to help pronounce the performance of the fiber reinforcements.

An assumption of this research is that the fibers within the concrete structure are assumed to be uniformly distributed and will act elastically up until their failure. As the applied force during testing is transferred from these fibers and the fiber matrix through a sheering force, deformation will begin to take place at the fiber interface [4]. This research will look into the failure mechanisms and characteristics, through the forensic analysis of the samples upon the conclusion of the modified indirect tensile testing, based on a variety of factors such as fiber make up and environmental exposure.

III.III Method of Testing

It has been noted that there are a number of shortcomings in the old testing methods of synthetic fiber reinforced concrete samples, such as the 3 point bending and the splitting tension test. Exhibited by these methods, is a need for better load application and control, due to the desired localization of damage along fracture plane and softening response (rather than the elastic-plastic type observed). Of these methods, during a splitting tension test, the state of the stress in the vicinity of the loading does not allow for a fiber dominated post cracking response. Additionally, these traditional methods are unsuitable for the testing of fiber-reinforced concrete because upon fracture, the stress and stress distributions are unknown, exemplifying the need for a better solution. It has been shown, however, that stable FRC tests can be performed by restricting the loading area and controlling the deformation across the crack plane. It is for this reason why a modified indirect tension testing (MIDT), which is a combination of the splitting tension test [1] and the Brazilian test approach [2][5], along with alterations proposed by Roque [2] such as adding a hole in the center of each specimen, will be the method of analysis used throughout this research.

The modified indirect tension testing method grants the ability to determine the uniform stress/strain distribution on a uniformly degraded cross-section of a fiber reinforced concrete structure [5]. A depiction of the indirect tensile testing method employed on a cylindrical sample can be seen in Figure 1 below.

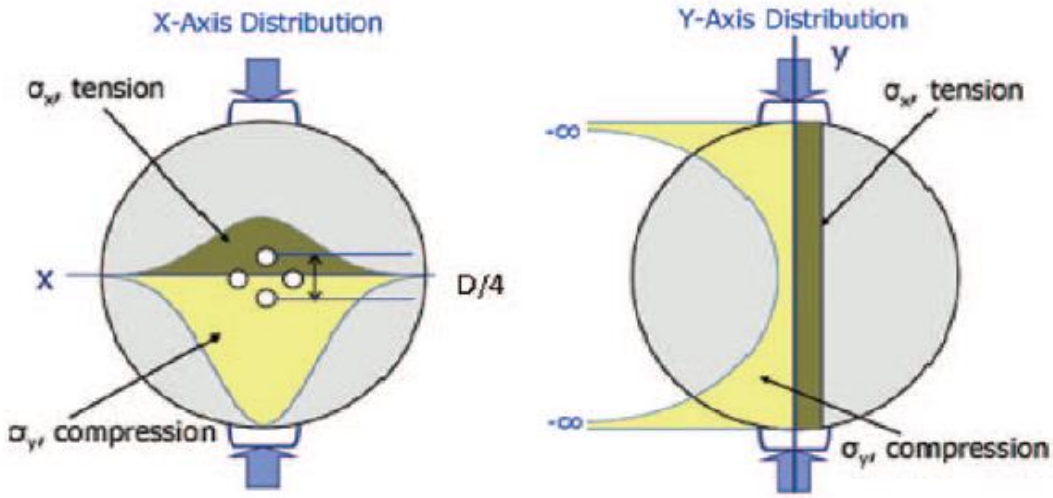


Figure 1-Theoretical Stress Distribution of Cylindrical IDT Sample [2].

It can be seen that the theoretical stress on this diametral plane is uniform near the specimen's center. However, the larger the specimen's thickness, the more this uniform horizontal tensile stress strays from this relationship as specimen may begin to exhibit bulging on its face or edges. The advantage to this method of analysis for concrete specimen is that the fracture plane is known before testing so fracture limits and displacement gauges can be installed on the specified planes [2]. At these predetermined locations the crack opening displacement (COD) can be measured to help in determining the samples toughness, as it is known to be the area under the load-COD curve until a specified COD limit [1]. In a similar testing procedure as the aforementioned process, another study applying load along two diametrically opposite generatrices to create a biaxial stress state within a cylinder created a similar theoretical stress distribution diagram which can be seen in Figure 2.

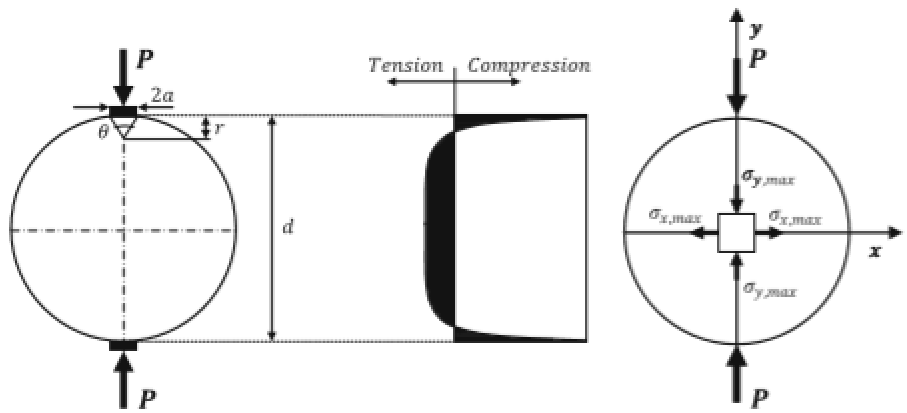


Figure 2-Diametral Compression Cylindrical Stresses [6].

This paper describing the indirect tensile test by means of a modified Brazilian test [6], specifies the importance of insuring that your samples has a flush, perfectly centered, and in uniform contact with the load applying faces for ideal results. From these diagrams shown in Figures 1 and 2 depicting the stress states present within cylindrical samples subject to the indirect tensile test, it can be seen that a uniform tension is applied across the fracture plane. It is for this reason why this method of analysis is used throughout the duration of this research regarding the toughness of fiber reinforced concrete samples.

When comparing the cylindrical samples to the square shaped concrete, the stress distributions along the vertical plane show similar behavior. It was found that the same stress distribution along the vertical plane in the center of the specimen was observed for both concrete geometries [2]. A depiction of the two stress distributions can be seen in Figure 3.

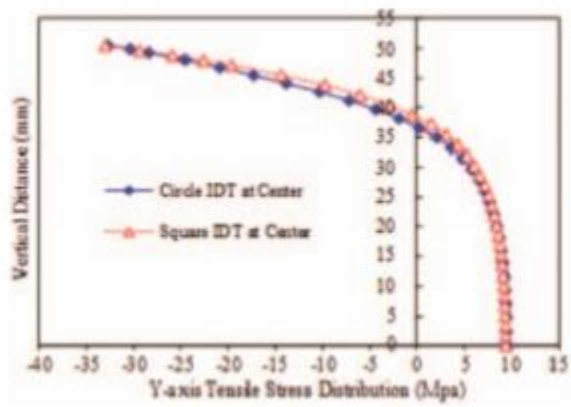


Figure 3-Square and Cylindrical Stress Distributions Using IDT [2].

Similar to the theoretical stress distribution diagrams presented above, a depiction of the stress distribution observed on a square sample can be seen in Figure 4.

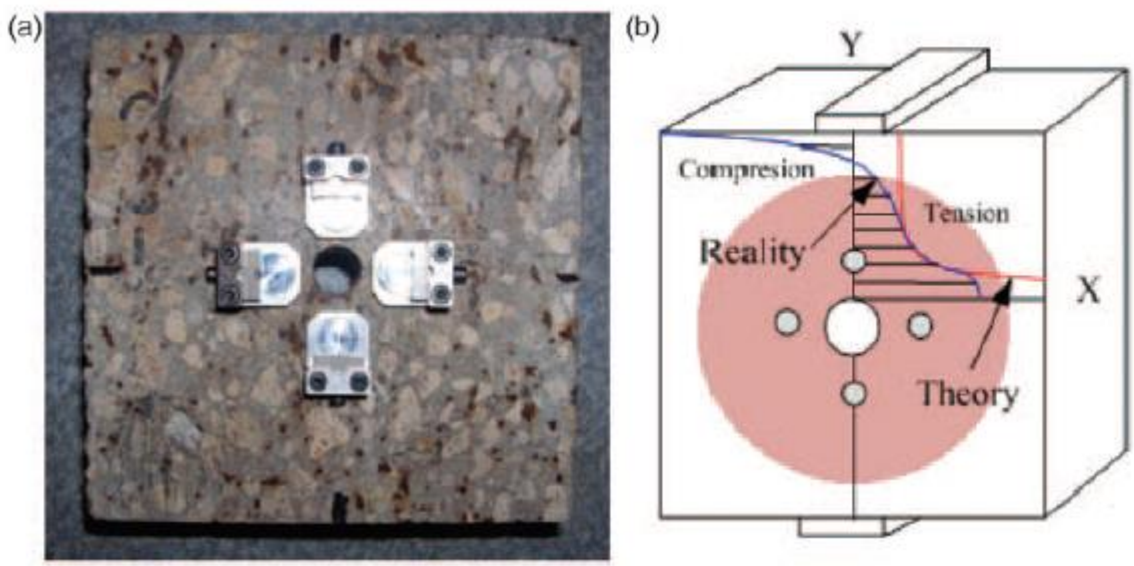


Figure 4-Square FRC Stress Distribution and Test Setup Using IDT [2].

Additional to the sample geometries and testing method alone, the presence of a 10 mm hole in the center of fiber reinforced concrete specimen helps enhance the testing results as well. This small hole running through the middle of the samples used in this report (proposed in the study by Kim and Roque [2]) serves as an additional means to concentrate the stresses observed during loading to the center of the sample along its fracture plane. This hole additionally serves as a method for allowing the ingress of deleterious materials which would further degrade the fiber or the fiber-concrete interface at this location of maximum stresses, permitting a more efficient means of observing the environment's effect on each sample. Implementing all of these methods of centralizing the uniform tension, along the samples fracture plane, helps to improve the consistency and accuracy of the indirect tensile test making it an extremely effective method to analyze the performance of fiber reinforced concrete.

III.IV Ingress of detrimental Materials

Concrete, and thus the reinforcing materials within the structure, are adversely affected by the influence of foreign materials infiltrating the composite. Deleterious materials are transported through concrete structures as a result of absorption, diffusion, and the permeability processes which can initiate the chemical and physical mechanisms for deterioration [5]. There are a number of chemical and physical means that control the degree of deleterious material transport into concrete. Examples of these influences that affect concrete deterioration include: the environmental condition, pore size distribution or structure (tourtosity and interconnectivity), solution characteristics, degree of concrete pore saturation, and temperature. It is for these reasons why when preparing the concrete specimen that are studied in this report, a consistent method of developing and conditioning each sample was followed. By implementing methods to increase the detrimental attack on each sample (such as heating the solution baths, and altering the sample's thicknesses), the conditioning time necessary to see the long-term effects that aggressive environments can have on fiber reinforced concrete is decreased.

When studying the detriment of concrete exposed to various conditions, it has been noted that the occurrence of wetting and drying processes result in the leaching of concrete and the accelerated ingress of the solutions (through absorption) into the concrete [5]. Because of this, it is important to determine the ideal wetting and drying cycle, as well as sample geometry, for the most efficient setup to inflict possible chemical or physical changes to the fiber-cement interface [5]. Attempting to streamline this conditioning regime, the studies performed by [2] noticed that the 12 hour cyclic wetting and drying conditioning utilized was insufficient for the ingress of detrimental conditions into the concrete samples. It is for this reason why the researchers altered their sample conditioning to seven days for wetting, and another seven days for drying to help increase the moisture transfer throughout these periods while avoiding the micro-damage and carbonation that could be a byproduct of extended conditioning periods. The addition of a heater and blower also allowed for additional ease of transferring moisture in and out of the concrete specimen. This research was able to determine that during this wetting and drying regime, the capillary action throughout the specimen would allow for 12.5mm penetration into the samples, indicating that a samples thickness of 25mm would allow for full saturation in the allotted 7 day wetting period.

In addition to the benefit regarding the localization of stresses along the center of the fracture plane, the implementation of a 10 mm through hole in the center of both the cylindrical and square samples also influenced the ingress of deleterious species/ions [2]. This centered hole would allow for increased surface areas capable of being exposed to the conditioning environment. The solution in which the concrete samples were exposed was able to access the center of the concrete and provide another location of which the ions could enter the concrete structure to fully saturate the specimen through its capillary action/diffusion.

IV. APPROACH

This section outlines both the preparation and experimental procedure that was performed in order to adequately test the wide variety of fiber reinforced concrete samples.

IV.I Sample Preparation

IV.I.I Developing the Samples

In order to produce a large variety of concrete samples a number of concrete mixes were prepared, poured and molded at the State Materials Office in incremental periods throughout April and May of 2017. To develop the vast quantity of samples required throughout this period, large quantities of concrete was constructed using limestone gravel, fine silica sand, Suwanne American cement, MasterGlenium admixture, and 23% fly ash type F (cement replacement). This specially made concrete had a low water to cement ratio in order to resemble the properties of dry-cast concrete. A typical Mix of concrete prepared for this experiment can be seen in Appendix B. In addition to these materials, four different types of synthetic fiber were mixed into this concrete, with special attention given to evenly distribute the fibers throughout the mixture. The type of fiber and their characteristics in each cast can be seen in Table 1.

Table 1-Sample Preparation Casting Information.

Sample Name	**Date Casted**	**Fiber Type**	**Material**	**Fiber Length (mm)**	**Cast (kg/ m^3)**
Mix 1	4/19/2017	MasterFiber MAC Matrix	Polypropylene	50	7.12

Mix 2	4/26/2017	Tuff Strand SF	Polypropylene/Polyethylene blend	51	7.12
Mix 3	5/10/2017	Tuff Strand SF	Polypropylene/Polyethylene blend	51	5.34
Mix 4	5/17/2017	MasterFiber MAC Matrix	Polypropylene	50	5.34
Mix 5	5/24/2017	MasterFiber 160CB	Chemically Enhanced Polypropylene	50	7.12
Mix 6	5/31/2017	PVA RF4000	Polyvinyl Alcohol (PVA)	30	8.90

A day after the concrete mixtures were poured into their casts (on their respective days), the molds were moved into a fog room for two weeks. The concrete blocks were then moved onto a covered patio. Upon reaching 56 days of age they were cut to their respective sample sizes. Three 10x10x38cm concrete beams taken from the concrete blocks were cut into 10x10x2.5 samples, as numerous square FRC samples were obtained. In addition to these square samples, 10 cm diameter cylindrical cores that were 20 cm tall were obtained from 20 cm tall concrete blocks. Six core samples per mix were then cut to size having thicknesses of 5 and 10 cm. The development of these different samples allows for the expansion of the testing procedure to incorporate varying geometries and their effects on the FRC toughness measurements. Upon cutting the samples to size, a 10 mm hole was drilled through the middle of every sample in order to facilitate the penetration of deleterious species (upon exposure in their respective environments) at the location where the greatest stresses would be concentrated to localize the position at which cracking would occur.

IV.I.II Environmental Exposure

Upon the development of these numerous concrete samples of varying fiber type, fiber quantity, and sample geometry, the next step was to expose the samples in environments that could be used to replicate the accelerated effects of the relevant environmental conditions. Utilizing these five different exposure procedures, insight on their effects on the performance of the fiber reinforcement could be developed. The exposure conditions included: High Humidity, Calcium Hydroxide, Sea Water, Sea water adjusted to Low pH (from this point forward referred to as low pH), and at the Barge immersed in intercoastal water (referred to as Barge) environments. Table 2 shown below provides a list of the number of samples tested per geometry in each environment, as well as the length of their exposure.

Table 2-Quantities of Each Geometry Sample Prepared in Each Environment

<table>
<tr><th>Geometry</th><th>Environment</th><th>Exposure Duration</th><th>Quantity</th><th>Total</th></tr>
<tr><td rowspan="5">1” Thick Square Specimen</td><td>High Humidity</td><td>20 months</td><td>26</td><td rowspan="5">91</td></tr>
<tr><td>Calcium Hydroxide</td><td>21 months</td><td>12</td></tr>
<tr><td>Sea Water</td><td>21 months</td><td>18</td></tr>
<tr><td>Low pH</td><td>22 months</td><td>18</td></tr>
<tr><td>Barge</td><td>22-23 months</td><td>18</td></tr>
<tr><td>2” Thick Cylindrical Specimen</td><td>Barge</td><td>22-23 months</td><td>22</td><td>22</td></tr>
<tr><td rowspan="3">4” Thick Cylindrical Specimen</td><td>High Humidity</td><td>21 months</td><td>12</td><td rowspan="3">61</td></tr>
<tr><td>Low pH</td><td>24 months</td><td>24</td></tr>
<tr><td>Barge</td><td>22-23 months</td><td>25</td></tr>
</table>

IV.I.II.I High Humidity Conditioning

To expose samples to high humidity environments, the concrete specimens were placed in a high humidity chamber and sprayed with water at incremental periods throughout the week. The concrete in this environment would sit on a mesh grate in order to prevent the samples from being submerged in the excess water, with the objective being to only hydrate the concrete’s surface. The high humidity chamber was capable of maintaining laboratory conditions while enveloping the samples with additional humidity introduced through the addition of water. A depiction of this humidity chamber can be seen in the Figure 5 below.

Figure 5-High Humidity Conditioning Chamber.

IV.I.II.II Calcium Hydroxide Conditioning

A different environment in which a handful of samples were exposed, was in a container of calcium hydroxide solution. Concealed in a high density polyethylene 30”x30”x18” container covered with insulation, the concrete specimen were submerged completely in the calcium hydroxide solution (prepared by adding 20 grams of Calcium Hydroxide to every liter of water). The samples in this environment sat on a raised grid in order to suspend them slightly in the tank so as to not occlude their bottom faces. The

Calcium Hydroxide solution in this insulation covered container was heated to a consistent temperature of 35º Celsius.

IV.I.II.III Sea Water Conditioning

Samples were also immersed in sea water in a similar insulated high density polyethylene container, however, this ones dimensions were 24”x24”x24”. Desiring to suspend the samples above the bottom of the container a raised meshed grid was inserted on which the samples could reside. In this sea water tank, the samples would undergo continuous cyclic wetting and drying cycles with each phase lasting 7 days. During the wetting process, sea water would be piped in from the Atlantic Ocean and heated to a temperature of 35º Celsius. During the drying process the saltwater would be drained from the tank, thus allowing the samples to dry as they are no longer immersed in the seawater.

IV.I.II.IV Low pH Conditioning

To condition the samples in low pH conditions, the concrete specimen were placed, yet again in another high density polyethylene container (30”x30”x18”) that utilized a raised mesh grid that would elevate the samples from the bottom of the container. Following the same wetting and drying regime as sea water, low pH solution was added every seven days and was immediately followed by seven days of drying the samples. During the last four to five months, fans were added into the conditioning tanks during the drying phase to help dry the samples with an increased airflow. This alternating wetting and drying process continued throughout the span of the experiment as the samples were conditioned for approximately two and a half years. During the wetting phase, a low pH solution was achieved by filling the container with sea water transported in from the Atlantic Ocean and treating it with sulfuric acid. In order to obtain adequate pH levels in this conditioning container (a pH of approximately 4.5), a pH meter was used daily to determine the H^+ concentration in the solution. To adjust the amounts of sulfuric acid daily (if the pH meter deemed the solution to be too alkaline) a beaker of 500 mL solution would be extracted from the tank. 20 mL of sulfuric acid would then be added to this beaker, and thus the beakers contents would be reintroduced into the tank, where pumps would help diffuse the higher acidity solution throughout the container. As this process decreases the pH readings, the tank would be monitored, and additional treatments of sulfuric acid would be added (ensuring that the past dosage had enough time to alter/influence the tank's pH). This process to decrease the tanks pH required about 60 mL of sulfuric acid daily and about 100 mL on the first day of the wetting cycle (when the tank was initially filled). Additionally, this low pH tank also included a heater, similar to that of the aforementioned sea water conditioning tank, that was used to bring the solutions temperature to 35º Celsius. It is important to note that this wetting procedure was altered after about two years of conditioning the samples with the introduction of an automatic dosing pump, which was able to stabilize the tanks pH values by providing diluted sulfuric acid doses of 5mL into the tank hourly. In addition to this auto dosing pump, a different pH monitor (the BlueLab guardian pH monitor) was used to easily measure the solution's pH. These additions to the conditioning setup allowed for more consistent low pH conditions throughout the remainder of the sample's exposure/conditioning.

IV.I.II.V Barge Conditioning

The final conditioning environment that was used throughout the sample preparation process, was the barge environment, where the samples were immersed in intercoastal waters. This exposure process allowed for the concrete samples to be exposed to the real world conditions experienced in the Intracoastal Waterway. In this environment, concrete specimen were placed in plastic milk crates, and covered with a meshed sheet that allowed the Intracoastal water to flow across the surface of the submerged samples, while still securing the samples inside the container. These milk crates were then tied to a barge that remained docked off the SeaTech seawall (in Dania Beach, FL) for the duration of approximately two years. These conditions allowed for the growth of marine organisms and calcareous deposits to form on the concretes surface and exemplified the conditions that would occur when FRC is placed in this type of environment. A depiction of the milk crates after retrieving the samples from the barge can be seen in Figure 6 bellow.

Figure 6-Barge Conditioned FRC Sample Container.

I.V.III Cleaning and Gluing the Samples

Upon removing the samples from their conditioning environments, the samples were left out for 3-4 days under lab conditions to allow for them to dry. The low pH and barge conditioned samples, however, had additional steps before drying could occur. For the low pH samples, once the specimen were removed from the solution bath, they were rinsed thoroughly with tap water to remove all the fine residue that covered the specimen's surface. A depiction of specimen that were rinsed as compared to unwashed specimen can be seen in Figure 7. In this image the specimen that were rinsed are shown by the red outline, allowing the stark difference in surface texture to clearly be seen.

Figure 7-Rinsed High Humidity Cylindrical FRC Samples.

Similarly, to these low pH samples, the barge conditioned concrete specimen also underwent an additional cleaning procedure before they were allowed to dry. After the samples immersed in the intercostal waterway were removed from their environment, they were rinsed off with sea water from the Atlantic Ocean to remove loosely attached organic material. The samples were then scraped with a metal spatula to remove any hard calcareous deposits from their surface (granting the samples a smooth exterior surface for accurate load testing) and rinsed once more in an Atlantic sea water bath. A depiction of the samples before and after this process can be seen in Figure 8.

Figure 8-Barge Conditioned Samples Before and After Cleaning.

Once the samples were dried (and cleaned in the case of the low pH and barge environments) the samples were then ready to have the steel extensometer gages glued to them. Each specimen was test fit into the gluing fixture to ensure that the centering rod would fit through the samples 10 mm hole. In the event that the hole did not fit, or had buildup that occurred during conditioning, the hole would be re-drilled to insure proper alignment. Utilizing the gluing fixture to standardize the gluing procedure, four metal gauges were attached in the vertical and horizontal directions, one inch apart from one another on the specimen's faces. Having adequately prepared these specimens, they were ready for testing.

IV.II Testing

In order for testing to begin, each prepared specimen was grouped based on its fiber content, and environmental exposure. The specimen from each group were then analyzed to see how they will be oriented during the indirect tensile test (making sure that the smoothest sides were the ones that would be in contact with the force application). The samples were then labeled, and the force directions were marked. The MTS Landmark Servohydraulic test system, the MTS Hydraulic Power Unit Control, the MTS Flex Test SE, and the computers that ran this testing equipment were all turned on and initialized. Depending on if the cylindrical or square samples were being tested, the Epsilon extensimeter software would be established to read 4 or 2 channels respectively, logging data at 40 ms intervals. Upon preparing the experimental equipment for testing, pictures were taken of the test sample, and the extensometer was attached to the glued metal gauges. The samples were then inserted (with the marked smoothest surfaces in the vertical orientation) into the T-brackets of the hydraulic machine. Here, two pressed cardboard strips were inserted between the T-bracket and the sample so that the load could be applied in a more uniform and controlled manner, as well as accommodating for the samples surface imperfections. A depiction of this experimental set up can be seen in Figure 9.

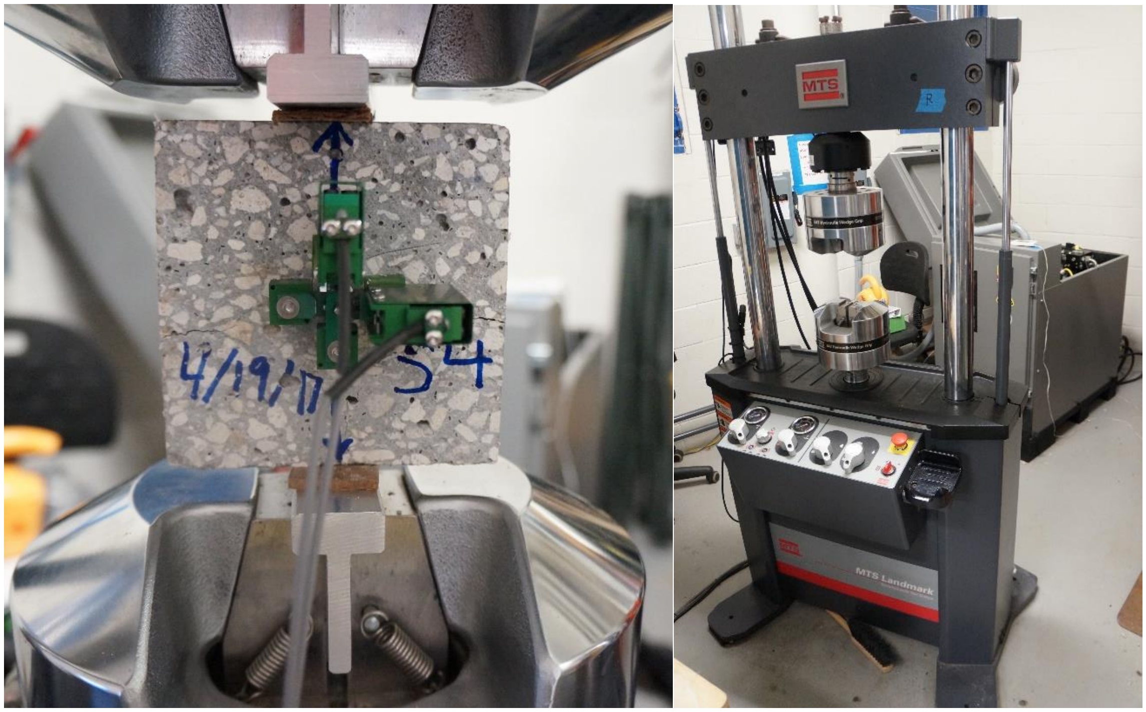


Figure 9-Experimental Setup ant Testing Apparatus.

The machine then began applying a compressive load along the vertical (diametrical) plane at a fixed displacement of 0.1016 mm/minute. Throughout this test, the MTS Landmark Servohydraulic test system would measure the load and displacement of the machine, while the attached Epsilon extensometers would log the displacement that was occurring on the samples (at the center) themselves. This was done so that the data sets could be analyzed in post processing to determine each samples toughness (like that performed in the study by Carmona [1]). This application of force continued until the sample began to fail, at this point the test would be stopped (at or slightly below the extensometers maximum displacement) in order to prevent the samples from completely failing, rupturing the fiber-matrix interaction, and potentially damaging the test equipment. The force and displacement information obtained during this procedure could then be used to process the data and provide more insight as to how each sample performed.

IV.III Analysis

IV.III.I Cross-Sectional Fiber Interaction

Upon running the modified indirect tensile test on the FRC concrete samples, images were taken of the cracked specimen. After obtaining this first image of the sample, the metal extensometer spacers were then removed, and another picture was taken. Once this photo had been obtained, the samples were then broken along the vertical (pre-cracked during testing) direction so that the samples cross section could be observed. Taking an additional image of the concrete specimen’s cross section, the sample was then analyzed to see how the fibers behaved during testing. A depiction of this specimen cross section can be seen in Figure 10.

Figure 10-Cross Section of Square Sample’s Fracture Plane.

Looking at the broken vertical cross-section of the sample, the amount of fibers protruding from the concrete (in the same direction as the horizontal axis) were observed to determine whether or not the primary method of failure was from breaking or from pulling out of the concrete lattice. A fiber was considered “pull-out” if it was still intact maintaining one uniform shape. On the other hand, fibers were considered to “break” when their ends appeared frayed, and the once singular fiber could be observed on both halves of the vertical cross section, seeming to have split (or broken) into two pieces. Fibers that ran along the same direction of the vertical axis of the concrete sample were noted as well. A pull-off in the vertical direction was observed if the fiber remained intact in the lattice while oriented vertical, and not protruding from the structure. It is important to note that the crevice of the pulled-off fiber can be seen on one half of the broken cross section while the unbroken fiber itself was on the other. Vertical breaks were observed when fibers oriented in the same direction as the crack appeared frayed with pieces of the fiber existing on both halves of the broken specimen. When vertical breaks were witnessed, the crevice created around the fiber had pieces of the broken fiber on both sides of the sample. After counting the number of horizontal and vertical pull-offs and breaks that occurred in each sample, the results were then tabulated for further analysis.

IV.III.I Load Displacement Curves

Taking the (force/load) data that was gathered from the MTS Landmark Servohydraulic system, and the Epsilon extensometers throughout the modified IDT testing procedures, a large gamut of graphs and data points were obtained. Upon importing the data from both measurements into excel and performing a number of conversions and equalization of the measurement values, two force versus displacement graphs were generated. The first of these graphs utilized the measurements from the MTS

Landmark Servohydraulic system for displacement and force representing the constant displacement applied by the machine.

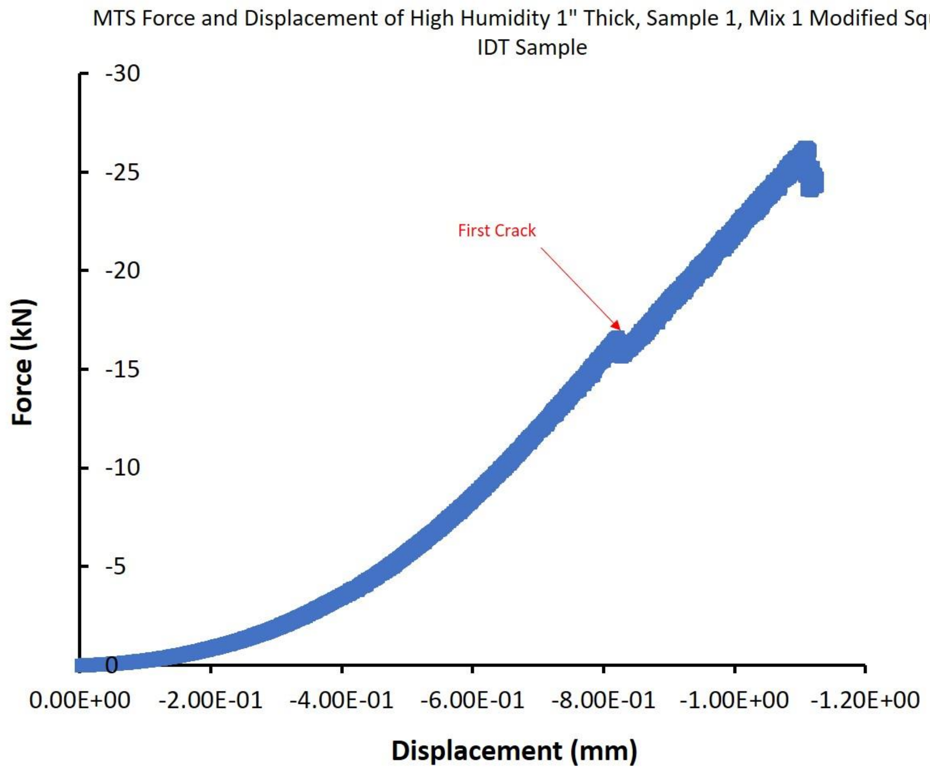


Figure 11-MTS Force and Displacement Curve.

From this graph, the point at which each sample experienced its first crack was used to determine the corresponding force that caused this crack. This location of first crack is shown in Figure 11. It is at this location that the concrete matrix begins to crack, thus the load at this point is crucial for comparing the different specimens that were tested.

The second graph, on the other hand, utilized the same force values from the machine, but this time used the displacement readings from the extensometer along the horizontal axis. This graph was able to depict how the sample was displacing as a result of the applied force, and it is with this graph that a number of valuable data points related to the samples performance could be determined.

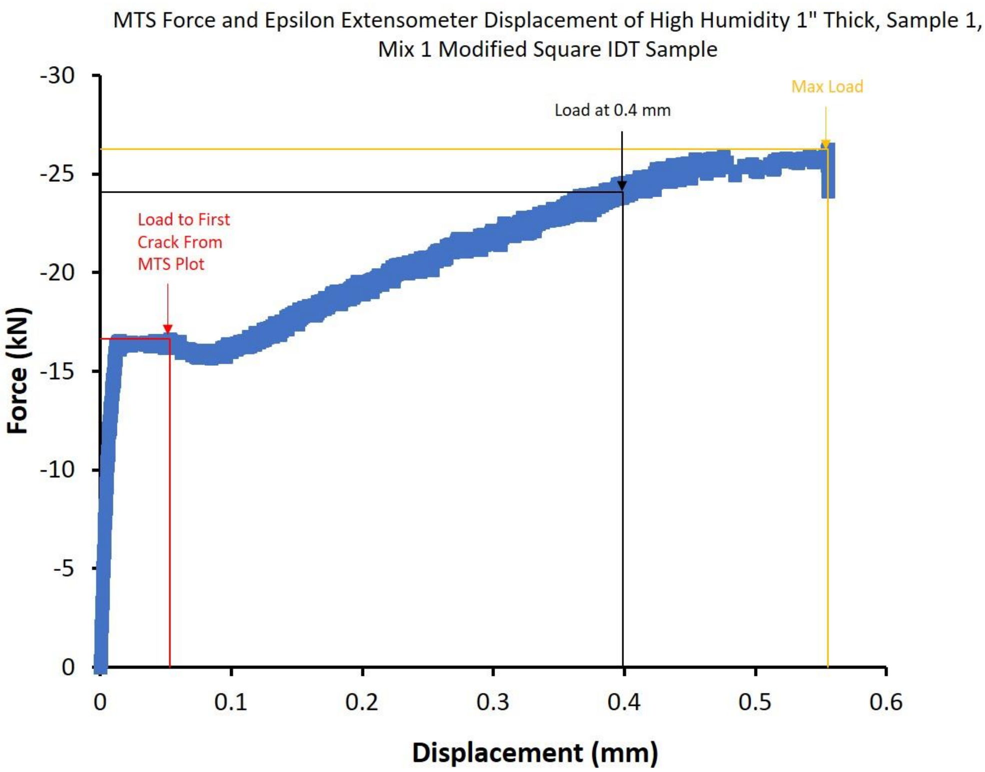


Figure 12-Epsilon Extensometer Force and Displacement Curve.

As shown by the plot in Figure 12, the displacement of the sample at the load to first crack, found in Figure 11, could be determined. Additionally, this plot was used to determine the load at an extensometer displacement of 0.4 mm, and the maximum load that the sample endured, as well as the corresponding extensometer displacement readings at these points. Developing further grounds for comparison, the plot shown in Figure 12 (that was generated for each sample tested) was used to determine the samples toughness by taking the area under the force-displacement curves. From these graphs, the total area under the curves were taken and recorded as the sample's toughness. It is important to note for this technique of measuring the samples toughness, that the total area under the curve was measured, rather than the area after first crack. This practice differs from that performed in similar studies; however, it was seen that up until first crack there is relatively little displacement witnessed by the specimen, and thus the toughness measurement was not greatly affected. The load applied up to first crack was also relatively similar for each sample of a given mix and geometry exposed to a given environment. Furthermore, by implementing a displacement range up to which the area under the curve was computed across all samples of similar geometry, the specimen area under the curve (toughness) could be compared based on a similar toughness characteristic. The displacement range that was selected for comparing the toughness of the samples tested in this study was from 0 mm to 0.4 mm horizontal displacement. These various data points gathered from the results of these tests were then tabulated, providing this characteristic data for each sample tested in one comprehensive document.

Upon generating these results for each sample, the effects of the environmental conditions and fiber content could be compared based on the specimen's performance during testing. From the compilation of this data into comprehensive graphs and charts, and performing cross comparison, a better understanding of the fiber-matrix interface could be determined for each of these independent testing variables.

V. RESULTS

This section displays a handful of the results that were obtained utilizing the modified indirect tensile test to observe the mechanical characteristics of fiber reinforced concrete samples varying in fiber content, exposure regime, and geometry from one another. By generating load-displacement graphs for each specimen that was prepared and tested, various load, displacement, and toughness data characteristics were recorded as shown by the methods outlined in Figures 11 and 12. These results were then tabulated and summarized as shown in the sections that follow.

V.I High Humidity Conditioned Specimen

The specimen exposed to the high humidity environment can be viewed somewhat as a control variable. In this conditioning regime, the reinforcing synthetic fibers were not subject to detrimental attack allowing them to serve as a good baseline for comparison. Of the samples emerged in this environment, those with a similar specimen thickness can be grouped and compared based on their load and toughness characteristics.

V.I.I 1 Inch Thick High Humidity Samples

For this high humidity conditioning regime four to five one-inch thick squares exposed for 20 months were available for each mix, and then tested using the modified indirect tensile testing method. The results presented in the following tables were obtained by averaging the measurements of each sample that was of the same geometry, mix, and environmental exposure. The performance characteristics of each individual sample from this group can be seen in Appendix C.

V.I.I.I High Humidity Test Loads for the 1" Thick FRC Specimen

The average maximum load, average load to first crack, and average load at a displacement of 0.4 mm, and their corresponding standard deviations, can be seen in Table 3 below.

Table 3-Load Characteristics from the Modified Indirect Tensile Testing of 1 Inch Thick Specimen Exposed to a High Humidity Environment.

Mix Name	Avg. Max Load (kN)	Avg. First Crack Load (kN)	Avg. Load at 0.4 mm (kN)	Max Load Std	First Crack Load Std	Load at 0.4 mm Std
Mix 1	-26.0	-17.4	-24.5	2.4	0.8	3.2
Mix 2	-24.5	-15.5	-21.6	1.6	2.8	2.3
Mix 3	-21.8	-16.7	-18.4	2.5	0.8	2.9
Mix 4	-20.9	-16.1	-16.9	2.0	0.7	2.0
Mix 5	-25.1	-17.4	-23.3	2.1	0.7	3.1
Mix 6	-23.6	-17.7	-21.0	2.8	0.2	2.8

V.I.I.II Test Toughness for the 1" Thick FRC Specimen Exposed to High Humidity

The toughness obtained from each sample's force-displacement curve generated from the modified indirect tensile test were also averaged and tabulated. In Table 4 below the average total area under the load displacement curve and the average area up to a sample displacement of 0.4 mm are provided. These measurements are accompanied by their corresponding standard deviations.

Table 4-Toughness Characteristics from the Modified Indirect Tensile Testing of 1 Inch Thick Specimen Exposed to a High Humidity Environment.

Mix Name	Avg. Total Area (kN*mm)	Avg. Area at 0.4 mm (kN*mm)	Total Area Std	Area at 0.4 mm Std
Mix 1	-15.1	-10.4	5.2	4.3
Mix 2	-10.1	-7.3	1.2	0.6
Mix 3	-8.8	-6.9	0.7	0.5
Mix 4	-8.1	-6.3	1.2	0.3
Mix 5	-10.4	-7.9	0.7	0.7
Mix 6	-9.6	-7.4	0.5	0.4

V.I.II 4 Inch Thick Cylindrical High Humidity Samples

While conditioned in the same environment as the high humidity samples specified above, those that had a cylindrical geometry and were 4 inches thick were grouped, and the characteristic data obtained by the modified indirect tensile test can be seen in the tables that follow. For this grouping there were only two samples per mix, however extensometer readings were gathered from both the front and back of each specimen, resulting in additional data for analysis.

V.I.II.I High Humidity Test Loads for the 4" Thick Cylindrical FRC Specimen

The average maximum load, average load to first crack, and average load at a displacement of 0.4 mm at both the front and back extensometers, and their corresponding standard deviations, can be seen in Table 5 below.

Table 5-Load Characteristics from the Modified Indirect Tensile Testing of 4 Inch Thick Cylindrical Specimen Exposed to a High Humidity Environment.

Mix Name	Avg. Max Load (kN)	Avg. First Crack Load (kN)	Front Avg. Load at 0.4 mm (kN)	Back Avg. Load at 0.4 mm (kN)	Max Load Std	First Crack Load Std	Front Load at 0.4 mm Std	Back Load at 0.4 mm Std
Mix 1	-61.3	-50.8	-55.5	-52.3	11.2	0.3	7.0	3.5

Mix 2	-54.4	-45.8	-51.1	-49.6	18.4	6.3	14.3	12.2
Mix 3	-51.1	-50.0	-45.9	-48.0	0.9	2.2	2.2	5.2
Mix 4	-49.9	-46.6	-43.3	-44.6	3.3	1.4	3.2	4.6
Mix 5	-59.6	-51.2	-52.4	-51.8	8.0	0.7	8.1	7.3
Mix 6	-59.5	-53.7	-56.4	-55.4	1.3	0.0	2.6	4.2

V.I.II.II Test Toughness for the 4" Thick Cylindrical FRC Specimen Exposed to High Humidity

In Table 6 below, the average total area under the load displacement curve and the average area up to a sample displacement of 0.4 mm are provided using the measurements provided by both the front and back extensometers. These measurements are accompanied by their corresponding standard deviations.

Table 6-Toughness Characteristics from the Modified Indirect Tensile Testing of 4 Inch Thick Cylindrical Specimen Exposed to a High Humidity Environment.

Mix Name	Front Avg. Total Area	Back Avg. Total Area	Front Avg. Area at 0.4 mm	Back Avg. Area at 0.4 mm	Front Total Area Std	Back Total Area Std	Front Area at 0.4 mm Std	Back Area at 0.4 mm Std
*Note: Areas are given in (kN*mm)								
Mix 1	-41.4	-29.5	-20.0	-22.4	6.3	0.8	3.3	2.7
Mix 2	-43.5	-24.0	-21.4	-18.6	6.4	8.0	3.5	4.6
Mix 3	-44.0	-25.4	-20.1	-19.4	1.7	1.9	1.7	1.3
Mix 4	-38.1	-21.9	-18.3	-17.9	1.4	3.1	1.4	0.7
Mix 5	-29.8	-24.1	-16.8	-20.2	26.2	3.9	7.8	1.7
Mix 6	-52.7	-26.4	-21.9	-21.1	2.4	1.1	0.1	1.3

V.II Calcium Hydroxide Conditioned Specimens

Similar to the High Humidity conditioning environment, the samples exposed in the Calcium Hydroxide solution could be looked at as a control variable as well. Like in the High Humidity conditioning regime, the specimen submerged in the Calcium Hydroxide environment were not subject to detrimental attack and could be used as an additional baseline for comparison when looking at the influence that the environment has on the performance of the fiber reinforced concrete specimen. Of the specimens prepared during this research, only two square one-inch thick samples per mix were introduced into this conditioning environment, so there is no 2 or 4 inch thick cylindrical sample data.

V.II.I 1 Inch Thick Calcium Hydroxide Samples

For this conditioning environment, only two, one inch thick, square samples from each mix were submerged in the Calcium Hydroxide solution. Upon testing these samples utilizing the modified indirect tensile test, the results were averaged and can be found in the tables that follow. The performance characteristics of each individual sample from this group can be seen in Appendix C.

V.II.I.I Calcium Hydroxide Test Loads for the 1" Thick FRC Specimen

For these Calcium Hydroxide conditioned fiber reinforced concrete specimen, the average load characteristics measured during the modified indirect tensile test can be seen in Table 7 below. These results include the average maximum load, average load to first crack, and average load at a displacement of 0.4 mm, and their corresponding standard deviations.

Table 7-Load Characteristics from the Modified Indirect Tensile Testing of 1 Inch Thick Specimen Submerged in a Calcium Hydroxide Solution.

Mix Name	Avg. Max Load (kN)	Avg. First Crack Load (kN)	Avg. Load at 0.4 mm (kN)	Max Load Std	First Crack Load Std	Load at 0.4 mm Std
Mix 1	-27.3	-18.1	-25.3	1.3	1.2	0.7
Mix 2	-25.1	-16.5	-23.9	0.5	0.2	0.8
Mix 3	-23.7	-17.3	-18.2	1.3	0.2	0.9

Mix 4	-20.7	-16.0	-17.5	1.2	0.2	0.3
Mix 5	-20.3	-14.3	-17.8	0.7	2.4	2.6
Mix 6	-18.9	-16.1	-17.6	3.4	0.5	3.3

V.II.I.II Test Toughness for the 1" Thick FRC Specimen Exposed in the Calcium Hydroxide Solution

By developing the force-displacement curve for each Calcium Hydroxide conditioned sample that was tested using the modified indirect tensile test, the results were combined and averaged to determine the average total area under the load displacement curve and the average area up to a sample displacement of 0.4 mm. These measurements are accompanied by their corresponding standard deviations in Table 8.

Table 8-Toughness Characteristics from the Modified Indirect Tensile Testing of 1 Inch Thick Specimen Submerged in a Calcium Hydroxide Solution.

Mix Name	Avg. Total Area (kN*mm)	Avg. Area at 0.4 mm (kN*mm)	Total Area Std	Area at 0.4 mm Std
Mix 1	-20.6	-8.5	1.8	0.2
Mix 2	-19.3	-9.0	0.7	2.1
Mix 3	-17.5	-6.7	0.3	0.1
Mix 4	-13.3	-6.2	NA	NA
Mix 5	-16.8	-6.0	1.3	1.0
Mix 6	-15.3	-6.6	0.4	0.5

V.III Sea Water Conditioned Specimen

Throughout this research, only one-inch thick square FRC samples were subject to cyclic wetting and drying in the sea water solution. Therefore, only one geometry of concrete specimen from this conditioning regime was tested.

V.III.I 1 Inch Thick Sea Water Samples

From this Sea Water conditioning environment, there are three samples from each mix that were immersed for 21 months that were tested using the modified indirect testing method. By analyzing the results generated from this test, the individual data points for each sample were averaged to create a generalization that each group could be compared upon. These averaged values can be observed in the following tables. In Appendix C of this report, the individual performance of each specimen is reported.

V.III.I.I Sea Water Test Loads for the 1" Thick FRC Specimen

Using the mechanical performance data obtained from the modified indirect tensile test on the sea water exposed samples, the average values for the maximum load, first crack, and load at 0.4 mm displacement are reported with their appropriate standard deviation in Table 9 shown below.

Table 9-Load Characteristics from the Modified Indirect Tensile Testing of 1 Inch Thick Specimen Submerged in Sea Water.

Mix Name	Avg. Max Load (kN)	Avg. First Crack Load (kN)	Avg. Load at 0.4 mm (kN)	Max Load Std	First Crack Load Std	Load at 0.4 mm Std
Mix 1	-19.7	-17.0	-17.5	1.3	0.9	2.1
Mix 2	-22.5	-18.3	-21.5	3.7	1.7	3.3
Mix 3	-21.0	-17.8	-20.0	2.0	0.8	2.1
Mix 4	-21.0	-16.7	-19.5	1.4	0.6	1.3
Mix 5	-11.5	-17.5	-20.7	23.3	1.9	6.7
Mix 6	-21.3	-17.5	-19.7	2.1	2.2	1.7

V.III.I.II Test Toughness for the 1" Thick FRC Specimen Exposed to the Sea Water Environment

The testing results regarding the sample's toughness that were calculated from the force-displacement graphs for these sea water conditioned fiber reinforced concrete specimen are summarized in Table 10. This table includes the curves average total area, and the average area under the curve at a sample displacement of 0.4 mm. The average's standard deviations are also included.

Table 10-Toughness Characteristics from the Modified Indirect Tensile Testing of 1 Inch Thick Specimen Submerged in Sea Water.

Mix Name	Avg. Total Area (kN*mm)	Avg. Area at 0.4 mm (kN*mm)	Total Area Std	Area at 0.4 mm Std
Mix 1	-16.0	-6.6	1.4	0.5
Mix 2	-17.1	-7.7	1.7	0.9
Mix 3	-17.0	-7.2	3.2	0.2
Mix 4	-17.7	-7.0	0.1	0.5
Mix 5	-18.8	-7.9	5.4	2.0
Mix 6	-20.5	-7.3	3.2	0.5

V.IV Low pH Conditioned Specimen

In the Low pH conditioning regime, both one inch thick square fiber reinforced concrete samples, as well as four inch thick cylindrical samples underwent the cyclical wetting and drying. These samples were subsequently subject to the modified indirect tensile testing procedure to generate data regarding their mechanical characteristics. The summaries of these data characteristics for each geometry can be seen in the sections that follow.

V.IV.I 1 Inch Thick Low pH Samples

From the Low pH conditioning environment, 3 samples from each mix were tested in order to obtain the load and toughness data points that are presented in the following tables. Additional data such as the samples displacement readings, the individual load values, or the toughness calculations for each individual sample can be found in Appendix C.

V.IV.I.I Low pH Test Loads for the 1" Thick FRC Specimen

The average values for the maximum load, first crack load, and load at a displacement of 0.4 mm for each mix submerged in a Low pH solution can be found in Table 11. Additionally, included in this table is the standard deviations of each of these load measurements.

Table 11-Load Characteristics from the Modified Indirect Tensile Testing of 1 Inch Thick Specimen Submerged in a Low pH Solution.

Mix Name	Avg. Max Load (kN)	Avg. First Crack Load (kN)	Avg. Load at 0.4 mm (kN)	Max Load Std	First Crack Load Std	Load at 0.4 mm Std
Mix 1	-20.6	-16.8	-19.1	3.0	0.9	3.0
Mix 2	-22.6	-17.2	-21.2	2.7	0.7	2.9
Mix 3	-18.6	-18.0	-16.5	1.3	1.3	0.9
Mix 4	-25.3	-17.7	-22.7	1.9	0.7	0.6
Mix 5	-21.3	-17.1	-19.4	3.2	0.8	2.3
Mix 6	-20.9	-16.5	-18.9	2.4	0.7	2.8

V.IV.I.II Test Toughness for the 1" Thick FRC Specimen Exposed to the Low pH Environment

From this Low pH environment, the toughness characteristics of each sample were averaged and are presented in Table 12. This table presents the average total area measured under the force-displacement curve, and the average area under this curve at a displacement of 0.4 mm. This table also provides the standard deviations for these measurements.

Table 12-Toughness Characteristics from the Modified Indirect Tensile Testing of 1 Inch Thick Specimen Submerged in a Low pH Solution.

Mix Name	Avg. Total Area (kN*mm)	Avg. Area at 0.4 mm (kN*mm)	Total Area Std	Area at 0.4 mm Std
Mix 1	-18.4	-8.0	1.8	0.7
Mix 2	-15.8	-7.4	2.1	0.8
Mix 3	-13.1	-6.5	1.4	0.6
Mix 4	-17.6	-7.9	1.7	0.3
Mix 5	-17.1	-7.2	2.5	1.1
Mix 6	-14.2	-6.7	1.4	0.4

V.IV.II 4 Inch Thick Cylindrical Low pH Samples

In addition to the one inch thick square samples prepared in the Low pH solution, four inch thick cylindrical FRC samples were also conditioned and tested. For this sample geometry in this environment, there were four specimen per mix. When these FRC samples were tested utilizing the MIDT procedure, extensometers were fixed to each face of the cylinder. As a result, the characteristic mechanical performance data for both sides of the sample are provided in the subsequent tables. The expanded results showing the load, displacement, and toughness metrics for each sample can be found in Appendix C.

V.IV.II.I Low pH Test Loads for the 4" Thick Cylindrical FRC Specimen

The average load results from the modified indirect tensile test for the four inch thick cylindrical fiber reinforced concrete samples can be observed in Table 13. This table presents the average findings for each mix's maximum load, load to first crack, and load at a displacement of 0.4 mm at both the front and back extensometers. The corresponding standard deviations from each mix are also included.

Table 13-Load Characteristics from the Modified Indirect Tensile Testing of 4 Inch Thick Cylindrical Specimen Submerged in a Low pH Solution.

Mix Name	Avg. Max Load (kN)	Avg. First Crack Load (kN)	Front Avg. Load at 0.4 mm (kN)	Back Avg. Load at 0.4 mm (kN)	Max Load Std	First Crack Load Std	Front Load at 0.4 mm Std	Back Load at 0.4 mm Std
Mix 1	-69.9	-59.1	-59.7	-61.1	8.9	1.8	5.9	7.0
Mix 2	-58.7	-52.7	-52.6	-51.4	14.3	3.2	11.1	8.0
Mix 3	-55.2	-54.1	-50.2	-51.0	2.8	3.9	1.1	1.4
Mix 4	-54.4	-48.2	-49.8	-48.9	6.7	5.0	4.8	5.2
Mix 5	-61.6	-53.3	-52.1	-52.0	8.1	3.8	4.3	5.5
Mix 6	-62.4	-53.3	-56.1	-56.3	7.0	3.6	4.5	3.3

V.IV.II.II Test Toughness for the 4" Thick Cylindrical FRC Specimen Exposed to the Low pH Environment

Shown in Table 14 are the average total areas under the load displacement curve for each mix, and the average areas up to a sample displacement of 0.4 mm. For each of these area characteristics, the areas were calculated using measurements from both the front and back extensometers. These area values are accompanied in this table by their corresponding standard deviations.

Table 14-Toughness Characteristics from the Modified Indirect Tensile Testing of 4 Inch Thick Cylindrical Specimen Submerged in a Low pH Solution.

Mix Name	Front Avg. Total Area	Back Avg. Total Area	Front Avg. Area at 0.4 mm	Back Avg. Area at 0.4 mm	Front Total Area Std	Back Total Area Std	Front Area at 0.4 mm Std	Back Area at 0.4 mm Std
*Note: Areas are given in (kN*mm)								

Mix 1	-52.1	-31.1	-23.2	-23.7	5.0	3.0	1.4	1.3
Mix 2	-47.8	-27.4	-21.1	-20.6	9.2	3.0	2.0	1.4
Mix 3	-46.4	-26.4	-23.6	-21.8	1.1	2.5	4.0	2.4
Mix 4	-47.5	-25.0	-19.3	-19.7	6.4	2.9	1.9	1.5
Mix 5	-51.7	-27.5	-21.1	-21.4	6.0	5.1	1.7	2.4
Mix 6	-45.8	-30.0	-21.5	-21.6	4.0	5.5	1.5	0.8

V.V Barge Conditioned Specimen

Understanding that the barge environment would be one of the most adverse conditioning regimes employed, samples of all three geometries (one inch thick squares, two inch thick cylinders, and four inch thick cylinders) were conditioned and tested. Upon testing each sample in this environment, the specimen's individual mechanical characteristics that were measured were recorded. A summary of the load and toughness characteristics for each geometry and mix can be seen in the ensuing sections.

V.V.I 1 Inch Thick Barge Samples

Of the samples emerged in the barge environment, there were three one inch thick square FRC samples that were tested. Upon performing the modified indirect tensile test, the load, displacement, and toughness values for each sample were obtained and can be seen in Appendix C. By summarizing the loads and toughness's observed by each mix, the tables in the following sections were developed.

V.V.I.I Barge Test Loads for the 1" Thick FRC Specimen

In the table provided in this section (Table 15) the average maximum loads, first crack loads, and loads at a displacement of 0.4 mm for each mix conditioned on the barge can be found. The standard deviations of each of the averages is additionally included.

Table 15-Load Characteristics from the Modified Indirect Tensile Testing of 1 Inch Thick Specimen Exposed to Barge Conditioning.

Mix Name	Avg. Max Load (kN)	Avg. First Crack Load (kN)	Avg. Load at 0.4 mm (kN)	Max Load Std	First Crack Load Std	Load at 0.4 mm Std
Mix 1	-18.2	-17.3	-16.8	0.8	1.1	2.1
Mix 2	-19.9	-17.0	-19.2	2.8	0.2	3.4
Mix 3	-21.2	-17.1	-20.4	4.2	2.2	4.3
Mix 4	-19.9	-16.9	-18.8	1.5	1.4	2.1
Mix 5	-19.3	-15.8	-18.1	1.5	1.8	2.3
Mix 6	-13.9	-13.6	-11.5	1.5	0.9	3.4

V.V.I.II Test Toughness for the 1” Thick FRC Specimen Exposed in the Barge Environment

From the force-displacement curve obtained by the modified indirect tensile test for each sample in the barge environment, the averaged values for the total area under the load displacement curve and the area up to a sample displacement of 0.4 mm were produced. These measurements accompanied by their corresponding standard deviations are shown in Table 16.

Table 16-Toughness Characteristics from the Modified Indirect Tensile Testing of 1 Inch Thick Specimen Exposed to Barge Conditioning.

Mix Name	Avg. Total Area (kN*mm)	Avg. Area at 0.4 mm (kN*mm)	Total Area Std	Area at 0.4 mm Std
Mix 1	-10.4	-6.5	2.4	0.8
Mix 2	-13.5	-7.2	4.6	0.8
Mix 3	-15.9	-7.2	3.2	1.2
Mix 4	-16.1	-7.7	3.0	2.0
Mix 5	-14.0	-7.0	1.6	0.8
Mix 6	-7.4	-5.1	1.8	0.6

V.V.II 2 Inch Thick Cylindrical Barge Samples

The barge environment was the only conditioning regime in this research to contain two inch thick cylindrical FRC samples. These two inch thick sample submerged at the barge consisted of four samples from each mix with the exception of Mix 5 which only had two representative samples. While testing these samples using the MIDT test, extensometers were fixed to both faces of the cylinder producing characteristic data for each side. This is true for all of the samples, except two specimens tested in Mix 3, where the extensometer readings from only the front face were recorded. The results from the modified indirect tensile test can be seen summarized in the tables below, or in Appendix C where each individual sample's performance results are provided.

V.V.II.I Barge Test Loads for the 2" Thick Cylindrical FRC Specimen

From the modified indirect tensile testing, the average maximum loads, loads to first crack, and loads at a displacement of 0.4 mm at both the front and back extensometers, and their corresponding standard deviations, for each mixture can be observed in Table 17.

Table 17-Load Characteristics from the Modified Indirect Tensile Testing of 2 Inch Thick Cylindrical Specimen Exposed to Barge Conditioning.

Mix Name	Avg. Max Load (kN)	Avg. First Crack Load (kN)	Front Avg. Load at 0.4 mm (kN)	Back Avg. Load at 0.4 mm (kN)	Max Load Std	First Crack Load Std	Front Load at 0.4 mm Std	Back Load at 0.4 mm Std
Mix 1	-29.6	-27.8	-27.8	-28.7	1.8	1.5	0.8	1.9
Mix 2	-27.8	-27.3	-23.7	-23.6	2.7	2.9	1.6	1.6
Mix 3	-28.5	-28.5	-23.7	-23.1	2.2	2.2	2.5	4.0
Mix 4	-26.7	-25.8	-22.4	-22.7	2.1	2.6	1.9	2.3
Mix 5	-28.6	-25.9	-25.2	-25.4	3.0	1.4	1.6	2.0

Mix 6	-28.2	-25.9	-25.2	-25.5	1.9	0.5	2.1	2.2

V.V.II.II Test Toughness for the 2" Thick Cylindrical FRC Specimen Exposed in the Barge Environment

For these two inch thick specimens, the average values for the total area under the load displacement curves and the average area up to a sample displacement of 0.4 mm are shown in Table 18. To formulate these toughness calculations, measurements from both the front and back extensometers were used to find the corresponding area. These measurements are accompanied by their respective standard deviations.

Table 18-Toughness Characteristics from the Modified Indirect Tensile Testing of 2 Inch Thick Cylindrical Specimen Exposed to Barge Conditioning.

Mix Name	Front Avg. Total Area	Back Avg. Total Area	Front Avg. Area at 0.4 mm	Back Avg. Area at 0.4 mm	Front Total Area Std	Back Total Area Std	Front Area at 0.4 mm Std	Back Area at 0.4 mm Std
*Note: Areas are given in (kN*mm)								
Mix 1	-26.5	-14.9	-10.7	-11.1	7.3	4.4	0.3	0.3
Mix 2	-20.9	-13.0	-9.7	-9.8	2.3	1.2	0.8	0.8
Mix 3	-19.0	-12.2	-11.0	-9.9	6.1	1.6	2.2	1.6
Mix 4	-17.4	-11.2	-8.8	-9.8	1.5	1.2	0.6	1.1
Mix 5	-23.7	-13.3	-9.9	-9.9	2.4	0.2	0.6	0.7
Mix 6	-19.3	-12.8	-9.9	-10.0	1.1	0.3	0.4	0.5

V.V.III 4 Inch Thick Cylindrical Barge Samples

The third geometry sample that was conditioned in the barge environment was the four inch thick cylindrical synthetic fiber reinforced concrete specimen. From this environment, four samples from each mix were tested, with the exception of mix 5, which had five samples. Each of these four inch samples were tested with extensometers on both faces of the cylinder and thus mechanical data has been developed for each side of the specimen. A summary of these testing results can be found in the succeeding sections, while the full results for each sample can be found in Appendix C of this report.

V.V.III.I Barge Test Loads for the 4" Thick Cylindrical FRC Specimen

By testing these barge conditioned four inch thick cylindrical concrete samples using the modified indirect tensile test, the values for the average maximum load, load to first crack, and load at a displacement of 0.4 mm (for both sides) of each sample could be grouped and averaged by mix. These averaged results, and their resultant standard deviations, can be seen in Table 19 below. It is important to note that for these cylindrical samples, extensometers were attached on both sides, thus the loads experienced when each respective side reached 0.4 mm were measured independently.

Table 19-Load Characteristics from the Modified Indirect Tensile Testing of 4 Inch Thick Cylindrical Specimen Exposed to Barge Conditioning.

Mix Name	Avg. Max Load (kN)	Avg. First Crack Load (kN)	Front Avg. Load at 0.4 mm (kN)	Back Avg. Load at 0.4 mm (kN)	Max Load Std	First Crack Load Std	Front Load at 0.4 mm Std	Back Load at 0.4 mm Std
Mix 1	-68.4	-57.5	-66.6	-62.7	3.2	3.7	2.4	4.3
Mix 2	-60.0	-50.8	-54.5	-53.8	4.5	4.7	4.0	2.8
Mix 3	-50.5	-48.1	-48.5	-48.4	2.3	3.0	1.6	1.4
Mix 4	-50.8	-48.4	-42.9	-43.0	2.3	2.7	2.9	3.1
Mix 5	-55.8	-50.4	-51.7	-50.1	3.7	2.1	5.8	4.9
Mix 6	-59.5	-50.0	-56.5	-55.9	3.0	5.6	2.5	2.8

V.V.III.II Test Toughness for the 4" Thick Cylindrical FRC Specimen Exposed in the Barge Environment

After the testing of each four inch thick cylindrical FRC sample had been complete, and the force-displacement graphs for each sample had been generated, the area under these curves could be analyzed to determine each sample's respective toughness. As shown summarized in Table 20, the average values of the total area under the load displacement curves, the average area up to a sample displacement of 0.4 mm, and the standard deviations for these measurements for each mix were determined. As depicted by the table, displacement measurements from both the front and back surface extensometers were used in computing the toughness of each sample.

Table 20-Toughness Characteristics from the Modified Indirect Tensile Testing of 4 Inch Thick Cylindrical Specimen Exposed to Barge Conditioning.

Mix Name	Front Avg. Total Area	Back Avg. Total Area	Front Avg. Area at 0.4 mm	Back Avg. Area at 0.4 mm	Front Total Area Std	Back Total Area Std	Front Area at 0.4 mm Std	Back Area at 0.4 mm Std
*Note: Areas are given in (kN*mm)								
Mix 1	-45.9	-32.0	-25.2	-23.4	9.8	6.5	0.9	1.4
Mix 2	-47.6	-25.9	-21.2	-20.4	1.3	1.7	1.0	1.4
Mix 3	-35.4	-20.9	-26.1	-17.9	6.7	3.8	11.9	1.8
Mix 4	-37.3	-24.1	-19.4	-19.9	2.5	1.5	1.6	3.4
Mix 5	-45.1	-24.1	-20.4	-19.2	3.9	5.0	1.2	1.6
Mix 6	-37.1	-28.8	-20.8	-21.1	11.7	1.8	1.1	1.4

V.VI Visual and Forensic Analysis of the Indirect Tensile Specimen Post Testing

As mentioned in the procedure and analysis sections of this thesis, photographic documentation of each specimen was recorded throughout each phase of modified indirect tensile testing procedure. Images of each sample were taken before testing, immediately after testing, and after removing the metal extensometer gauges and propagating the crack until failure. Additional photos of the samples cross-section were also taken after advancing the crack to failure. This procedure was completed for each sample that was tested. A depiction of how these images were presented for comparison is shown in Figure 13. This depiction shows the front and back surface of the two inch thick cylindrical samples from Mix 1 that were conditioned in the barge environment before and after testing using the MIDT test.

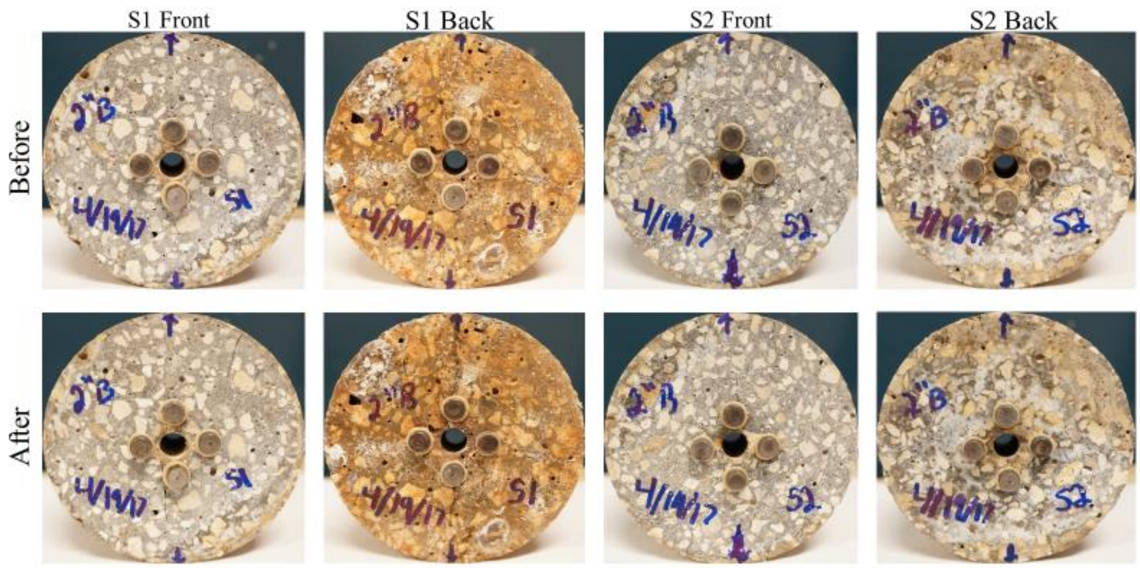


Figure 13-Visual Analysis of Mix 1, 2" Thick Cylindrical Samples 1 and 2 Before and After Testing.

Similarly to Figure 13, Figure 14 shows the same FRC samples after the crack had been advanced. This depiction (resembeling the same format and process followed for each sample that was tested) shows the front and back of the samples after crack propigation, and provides a view of the samples cross section.

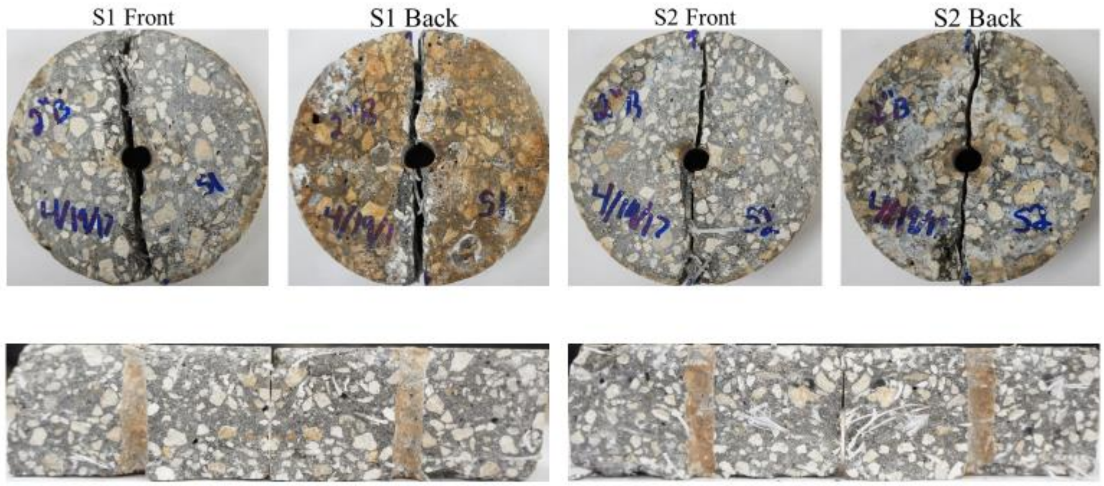


Figure 14-Visual Analysis of Mix 1, 2" Thick Cylindrical Samples 1 and 2 After Advancing the Crack

One of the main reasons that the crack is advanced after testing each sample is to gather insight as to the performance of the fibers that were acting at the specimen's cross section. Therefore, after opening the samples cross section, the fibers were counted, and their failures were classified as either a break or pull off as described in the analysis section of this Thesis. The type of failure, and over all quantity of fibers in each sample's cross section were averaged and tabulated. The full fiber count for each sample can be seen in Appendix E. Table 21, shown below, presents a summary of the average forensic analysis results of the one inch thick square samples grouped by mix in each environment.

Table 21-Average Fiber Count of Each 1" Thick Sample Mix Exposed in Each Environment.

Testing Condition	Mixture	Horizontal Avg.	Vertical Avg.	Avg. Total in Cross-Section

		Pull off	Break	Pull off	Break	
High Humidity	Mix 1	6.50	2.00	0.00	0.00	8.50
	Mix 2	3.50	9.00	0.25	0.50	13.25
	Mix 3	3.75	6.25	0.00	0.50	10.50
	Mix 4	6.50	3.00	0.25	0.00	9.75
	Mix 5	12.40	5.00	0.00	0.00	17.40
	Mix 6	12.80	0.00	0.00	0.00	12.80
Calcium Hydroxide	Mix 1	19.00	4.00	1.50	0.00	24.50
	Mix 2	5.50	6.00	0.00	0.00	11.50
	Mix 3	9.50	6.00	0.00	0.00	15.50
	Mix 4	11.00	5.00	1.00	0.00	17.00
	Mix 5	11.50	1.50	0.00	0.00	13.00
	Mix 6	5.50	0.00	0.00	0.00	5.50
Sea Water	Mix 1	3.33	1.00	0.33	0.00	4.67
	Mix 2	10.00	7.33	0.67	0.33	18.33
	Mix 3	10.67	5.67	0.67	0.33	17.33
	Mix 4	6.00	0.00	1.00	0.00	7.00
	Mix 5	16.33	3.67	0.00	0.00	20.00
	Mix 6	15.33	0.00	0.33	0.00	15.67
Low pH	Mix 1	11.00	3.67	0.00	0.00	14.67
	Mix 2	17.67	8.67	0.67	0.00	27.00
	Mix 3	13.00	4.33	0.33	0.00	17.67
	Mix 4	14.00	4.00	0.00	0.00	18.00
	Mix 5	5.00	3.50	1.50	0.50	10.50
	Mix 6	23.00	0.00	0.00	0.00	23.00
Barge	Mix 1	11.33	2.33	0.67	0.00	14.33
	Mix 2	13.00	9.00	0.33	0.00	22.33
	Mix 3	12.33	6.00	0.33	0.00	18.67
	Mix 4	6.00	0.67	0.00	0.00	6.67
	Mix 5	15.00	2.00	0.00	0.00	17.00
	Mix 6	16.00	0.00	0.67	0.00	16.67

Similar to the results presented in Table 21, Table 22 provides the summary fiber analysis of the two inch thick cylindrical specimen. As previously mentioned, this geometry sample was only immersed in the barge environment, therefore only one conditioning regime is represented.

Table 22-Average Fiber Count of Each 2" Thick Sample Mix Exposed in Each Environment.

Testing Condition	Mixture	Horizontal Avg.		Vertical Avg.		Avg. Total in Cross-Section
		Pull off	Break	Pull off	Break	
Barge	Mix 1	30.25	12.00	0.50	0.00	42.75
	Mix 2	20.00	21.50	0.75	0.00	42.25
	Mix 3	15.00	9.75	0.25	0.00	25.00
	Mix 4	14.50	8.75	0.50	0.00	23.75
	Mix 5	18.00	9.00	1.50	0.00	28.50
	Mix 6	44.50	0.00	0.50	0.00	45.00

Like the other two geometry samples tested in this research, the four inch thick cylindrical specimen were also subject to forensic analysis on the fibers in their cross section. By averaging the total fiber counts and the failure classifications, the results from this analysis are presented in Table 23.

Table 23-Average Fiber Count of Each 4" Thick Sample Mix Exposed in Each Environment.

Testing Condition	Mixture	Horizontal Avg.		Vertical Avg.		Avg. Total in Cross-Section
		Pull off	Break	Pull off	Break	
High Humidity	Mix 1	27.50	19.50	0.00	0.00	47.00
	Mix 2	31.00	37.50	2.50	0.00	71.00
	Mix 3	22.00	37.00	0.50	0.00	59.50
	Mix 4	25.00	22.50	0.00	0.00	47.50
	Mix 5	46.50	18.00	0.00	0.00	64.50
	Mix 6	76.50	0.50	0.00	0.00	77.00

Low pH	Mix 1	37.25	27.75	1.00	0.00	66.00
	Mix 2	59.75	34.75	2.00	0.75	97.25
	Mix 3	45.25	19.25	2.00	0.00	66.50
	Mix 4	17.50	0.00	0.00	31.00	48.50
	Mix 5	36.25	19.50	0.25	0.00	56.00
	Mix 6	87.00	0.00	0.25	0.00	87.25
Barge	Mix 1	45.25	21.50	1.50	0.00	68.25
	Mix 2	58.75	31.25	3.00	0.00	93.00
	Mix 3	35.25	24.75	2.50	0.75	63.25
	Mix 4	29.00	13.25	0.25	0.25	42.75
	Mix 5	42.80	15.80	0.20	0.00	58.80
	Mix 6	79.00	0.50	1.00	0.00	80.50

VI. DISCUSSION

Through the modified indirect tensile testing procedure that was performed on each sample prepared in this study, a variety of results on each sample's mechanical performance were generated. By organizing these samples based off their independent variables, each factor that influenced the samples performance to some degree could be looked at in greater detail to better understand what occurred throughout the duration of this test. In this section of the thesis report, the different factors such as the environment in which the samples were exposed, the samples geometry, and the type of fiber used in each mix will be looked at in order to compare what factors influenced the fiber reinforced concrete sample's toughness. These results will also be compared with studies that had similar testing techniques to see if there was any correlation between the findings.

VI.I The Environmental Influence on Performance

Establishing the environmental conditions that each sample was prepared in; the High Humidity and Calcium Hydroxide environments were to serve as the control groups as the samples submerged in them would not be expected to suffer detrimental attack. The Sea Water, Low pH, and Barge environments, on the other hand, were implemented in order to observe the effects that degradation would have on the fiber-matrix interface, and how this would influence the toughness that was measured during the MIDT test. In order to look at the toughness characteristics measured in each of these respective environments, the toughness up to a displacement of 0.4 mm was calculated to provide a standard displacement at which each sample could be compared. Taking the findings generated in the results section, Table 24 shows the side by side average toughness measurements up to a displacement at 0.4 mm for each mix and environment of the 1 inch thick specimens. This sample geometry is looked at for drawing this comparison, as it is the only one with samples that were exposed in every environment.

Table 24-Average Mix Toughness's Up to a Displacement of 0.4 mm in Each Environment.

Sample Name	High Humidity	Calcium Hydroxide	Sea Water	Low pH	Barge	Average Per Mix
*Note: Areas are given in (kN*mm)						
Mix 1	-10.4	-8.5	-6.6	-8.0	-6.5	-8.0
Mix 2	-7.3	-9.0	-7.7	-7.4	-7.2	-7.7
Mix 3	-6.9	-6.7	-7.2	-6.5	-7.2	-6.9
Mix 4	-6.3	-6.2	-7.0	-7.9	-7.7	-7.0
Mix 5	-7.9	-6.0	-7.9	-7.2	-7.0	-7.2
Mix 6	-7.4	-6.6	-7.3	-6.7	-5.1	-6.6
Average	-7.7	-7.2	-7.3	-7.3	-6.8	

Since the displacement readings in this table always ranged from 0 to 0.4 mm displacement, a higher toughness would indicate that the sample was capable of withstanding a greater energy absorption and thus has suffered less degradation in the specified environment. From the table, it can be seen that the highest average toughness calculations came from the High Humidity environment while the lowest average readings were from the Barge conditioning regime. The maximum average toughness reading up to 0.4 mm displacement was from the samples of set High Humidity Mix 1 having a value of 10.4 kN*mm, while the lowest average toughness was found in Mix 6 of the Barge environment with a measurement of 5.1 kN*mm. In table 24, by including all of the mix groups, the overall average toughness up to a 0.4 mm displacement in the high humidity set was 7.7 kN*mm while samples exposed at the barge had an overall average toughness of 6.8 kN*mm. There was not much difference in the toughness at a sample displacement of 0.4 mm when comparing the samples exposed in the other environments as there averages across all mix groups only ranged between 7.2 and 7.3 kN*mm. This toughness ranking, however, varied by fiber type and amount. The overall toughness up to a displacement of 0.4 mm for samples of Mix 1 was 8 kN*mm (7.12 kg/m^3) while was 7 kN*mm for samples of Mix 4 (5.34 kg/m^3) of the same fiber type. A similar comparison can be seen between mixes 2 and 3 (7.12 and 5.34 kg/m^3) having average toughness up to 0.4 mm displacement of 7.7 and 6.9 kN*mm respectively.

In Figures 15 and 16, one force-displacement curve per mix is shown from each environment. These graphs differ from the results shown in Table 24, as they only focus on one sample per mix rather than the combined average values of each mix in the given environment, however, they can help provide insight as to how samples of similar makeup interact in varying environments. A vertical dotted line has been added to indicate that for the toughness values up to a displacement of 0.4 mm, the areas under each curve were taken to the left of that line.

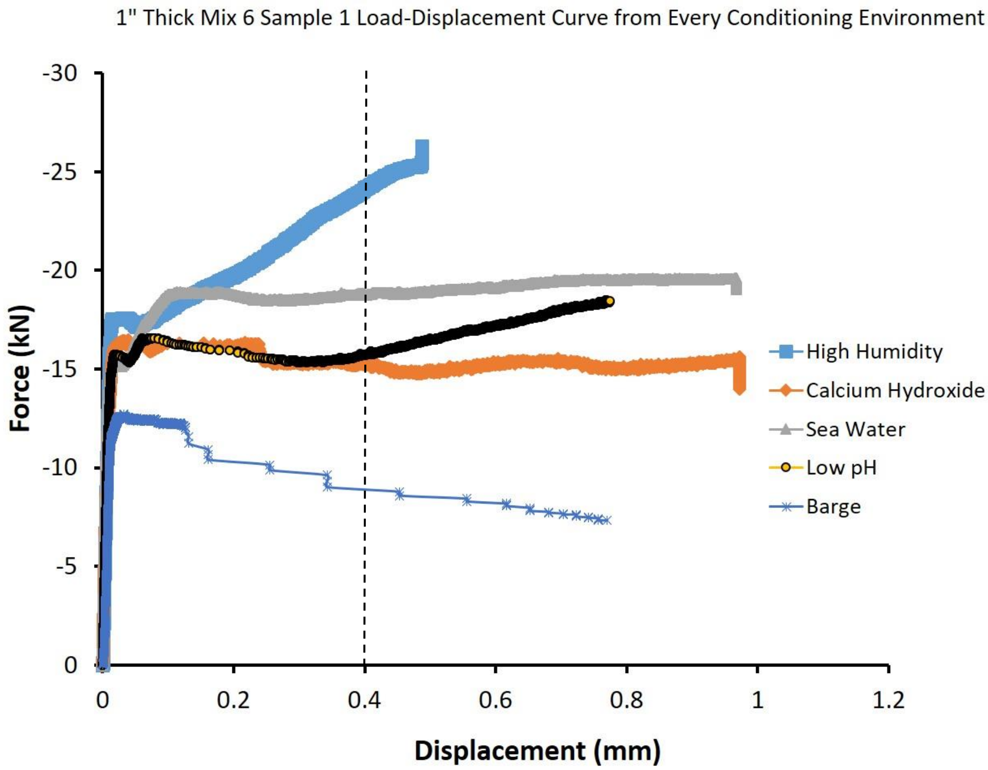


Figure 15-One Inch Thick Mix 6 Sample 1 Load Displacement Curve from Every Conditioning Environment.

In Figure 15, the load displacement curves from sample 1 of Mix 6 for each environment are graphed. Although the data plotted in the figures above are from one individual sample per environment, rather than the combined and averaged values within the mix (like the results shown in Table 24), they outline the fact that the barge conditioned specimen almost always seemed to have lower calculated toughness than the other environments.

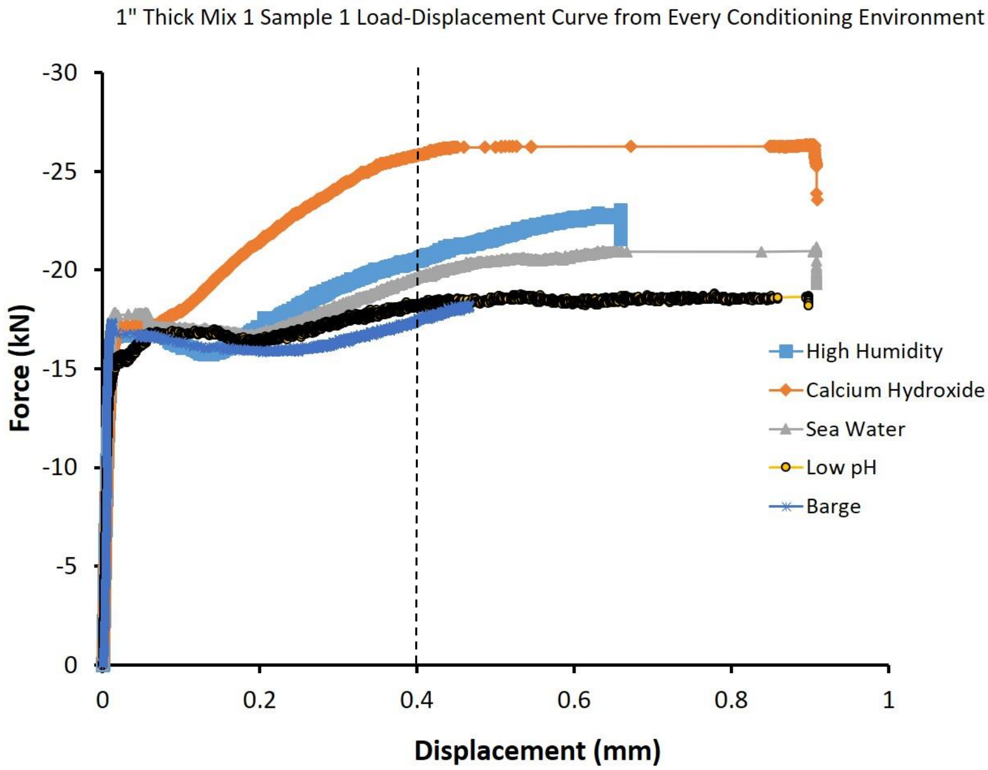


Figure 16-One Inch Thick Mix 1 Sample 1 Load Displacement Curve from Every Conditioning Environment.

Additionally, Figure 16 shows similar results, however this time the curves are generated from the load displacement data of Mix 1 Sample 1 for each environment. Despite the Calcium Hydroxide conditioned sample showing the highest toughness, this figure shows how the difference between the toughness of the sample exposed to High Humidity, and the toughness of the Barge environment conditioned sample is minor but still evident.

When looking at the influence that the environment in which samples were conditioned in had on their mechanical performance, the load up to 0.4 mm displacement is a good place to start. As this measurement compares each sample to a standard displacement, the toughness up to this point can be used to compare one sample to another. By doing this it was seen that relatively no definitive difference existed between the performance of 1” FRC samples. However, it seemed as though often times the High Humidity and Sea Water conditioned samples exhibited higher toughness to 0.4 mm displacement then their counterparts. On the other hand, the barge conditioned specimen seemed to have relatively lower toughness readings comparatively. For the barge conditioned samples, the instances at which they had somewhat higher toughness levels than the other environments occurred in samples of Mixes 3 and 4. It is important to note that these mixes had lower fiber contents than the other mixes (having only 5.34 kg/m^3 compared to other samples with 7.12 or 8.90 kg/m^3 volume in the cast). A possible speculation as to why this high toughness phenomenon was experienced by mixes 3 and 4 in the barge environment is that with lower fiber content within the specimen, there are fewer fiber-matrix interfaces, meaning that there are less chances for degradation to occur, thus these mixes might not have been subject to the degradation that the other mixes encountered. As a result, this assumption or other factors could have resulted in higher apparent toughness readings witnesses in mixes 3 and 4 in the barge environment as shown by Table 24.

Only looking at the force displacement-curve up to a displacement of 0.4 mm may give an incomplete depiction of what is occurring in the samples at larger displacements.

In table 25 provided below, the average total area (total toughness) for each mix in each environment was provided.

Table 25-Average Mix Total Toughness in Each Environment

Sample Name	High Humidity	Calcium Hydroxide	Sea Water	Low pH	Barge	Average Per Mix
*Note: Areas are given in (kN*mm)						
Mix 1	-15.1	-20.6	-16	-18.4	-10.4	-16.1
Mix 2	-10.1	-19.3	-17.1	-15.8	-13.5	-15.2
Mix 3	-8.8	-17.5	-17	-13.1	-15.9	-14.5
Mix 4	-8.1	-13.3	-17.7	-17.6	-16.1	-14.6
Mix 5	-10.4	-16.8	-18.8	-17.1	-14	-15.4
Mix 6	-9.6	-15.3	-20.5	-14.2	-7.4	-13.4
Average	-10.4	-17.1	-17.9	-16.0	-12.9	

Like the toughness measurements show in Table 24, the average total toughness for each environment support the claim that the barge environment exhibited a low toughness comparatively. Although the average total toughness in the barge environment is low ranging from 7.4 to 16.1 kN*mm, it is not always the lowest observed. Oddly enough, the lowest average total toughness samples came from the High Humidity conditioning regime. This would not be expected as this environment is home to the highest maximum load average per mix (with an average 23.65 kN across each mix which is acquired from Table 3), but due to the lower maximum displacements of these samples the area under the curve was smaller than all other environments. For the High Humidity environment, the force-displacement curves would be steep as they reached high applied loads but would be cut short by their low horizontal displacement readings. In this environment, the average total toughness per mix ranged from 8.1 to 15.1 kN*mm (only increasing 2 to 3 kN*mm from the toughness to 0.4 mm), while environments like

Sea Water ranged in average total toughness from 16 to 20.5 kN*mm. Generally, the other environments resembled the findings of the toughness shown up to 0.4 mm in the extended displacement results increasing in toughness's around 10 kN*mm. The samples exposed to environments, other than high humidity, with higher maximum applied loads generally resulted in higher toughness averages as expected.

VI.II The Influence of Fiber Type on Performance

For this investigation, there were three different fibers contents and four different fiber types that were used to produce the samples that were later conditioned and tested. With the goals of this research being to validate the application of fiber reinforced concretes, the mechanical characteristics that the specific fibers had within the samples plays an important role. Looking at the mechanical performance of the samples during the modified indirect tensile test, the results can be used to determine the fibers role in each sample. By looking at the values shown in Tables 24 and 25, and comparing the one inch thick samples on the basis of the average total toughness, and toughness's up to a displacement of 0.4 mm, the samples from Mix 1 displayed the highest average toughness while the samples from Mix 6 had resulted in the lowest. Despite the fiber content in samples of mix 6 being the largest, the low toughness results could be attributed due to the fact that these fibers had the shortest length being only 30 mm long, vs. ~50 mm long for the other fibers. As expected, samples of mix three and four were towards the lower end for resultant average toughness measurements as they only had 5.34 kg/m^3 of their respective fibers, while samples of mixes 1 and 2 had 7.12 kg/m^3. For both instances of fiber quantity, mixes 1 and 4 (the MasterFiber MAC Matrix) displayed higher toughness than the Mixes 2 and 3 (Tuff Strand SF) of similar fiber content.

However, these toughness results for mix 1 and 4 are only slightly above those of 2 and 3. This observation also holds true when looking at samples of mix 5, which had the same fiber content and comparable toughness readings as samples from mixes 1 and 2. The samples from mix 5 had an average total toughness between the values recorded for mixes 1 and 2, and an average toughness to a displacement of 0.4 mm that was slightly lower than those of mixes 1 and 2, yet still above the samples of lesser fiber content's (3 and 4) average toughness to 0.4 mm. Additionally, this difference in toughness due to fiber content is only evident in some of the environments and not in others but it is a large enough difference to be reflected in the overall average toughness readings from each mix across all environments. A depiction of the fibers influence on the measured toughness can be seen in Figures 17 and 18. In Figure 17, sample 1 from each one inch thick specimen mix that was conditioned in the High Humidity environment are plotted.

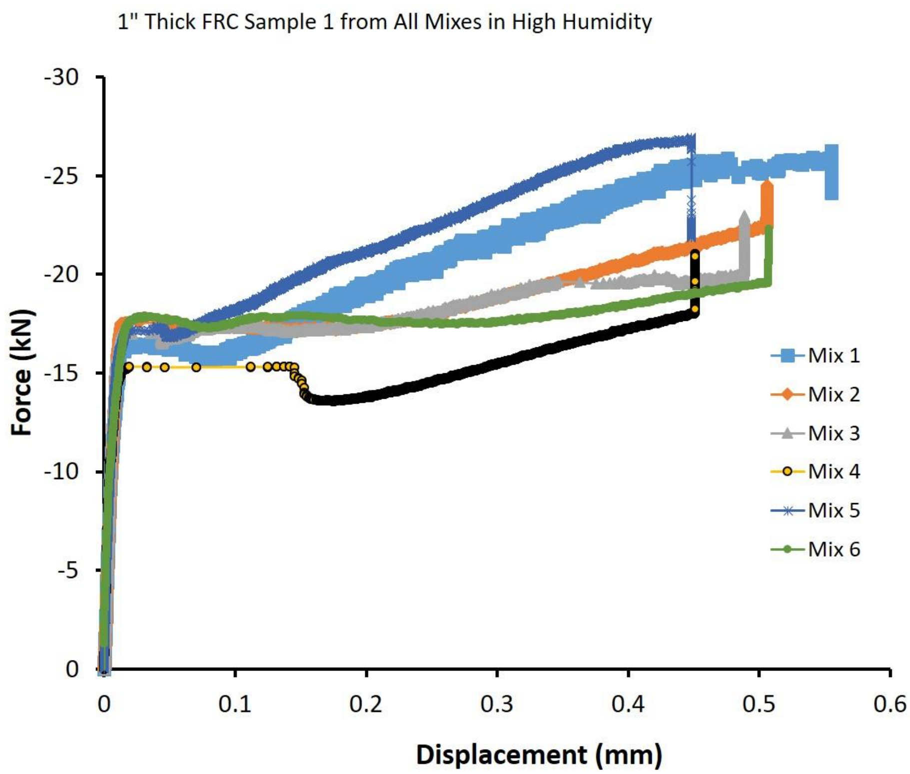


Figure 17-One Inch Thick FRC Sample 1 from All Mixes in High Humidity.

The force-displacement graphs shown in Figure 17 show how in the high humidity environment the fibers generally tended to resemble one another in shape and values. This depiction also shows how mixes 1 and 2 reach higher load values than mixes 3 and 4 at similar displacements due to the lower fiber quantities distributed in the samples. Here, the sample from mix 5 was observed to achieve the highest load up to the 0.4 mm displacement, while the mixture that experienced the lowest load was from mix 4. Mix 1 having the same fiber type but higher fiber content than mix 4 (the lowest performing mix in this sample) can be seen reaching the second highest maximum load with the longest recorded displacement, displaying a performance was above the sample with fewer fibers present. The relationship exhibited by mixes 2 and 3, which contained the same fiber type in different quantities show very similar characteristics, however as greater displacements are achieved the mixture with the lesser fiber content (mix 3) begins to flatten out and doesn't reach the high load its higher fiber content counterpart does. Although mix 6 has the largest fiber content it can be seen as reaching the second smallest load (and thus toughness) up to a displacement of 0.4 mm.

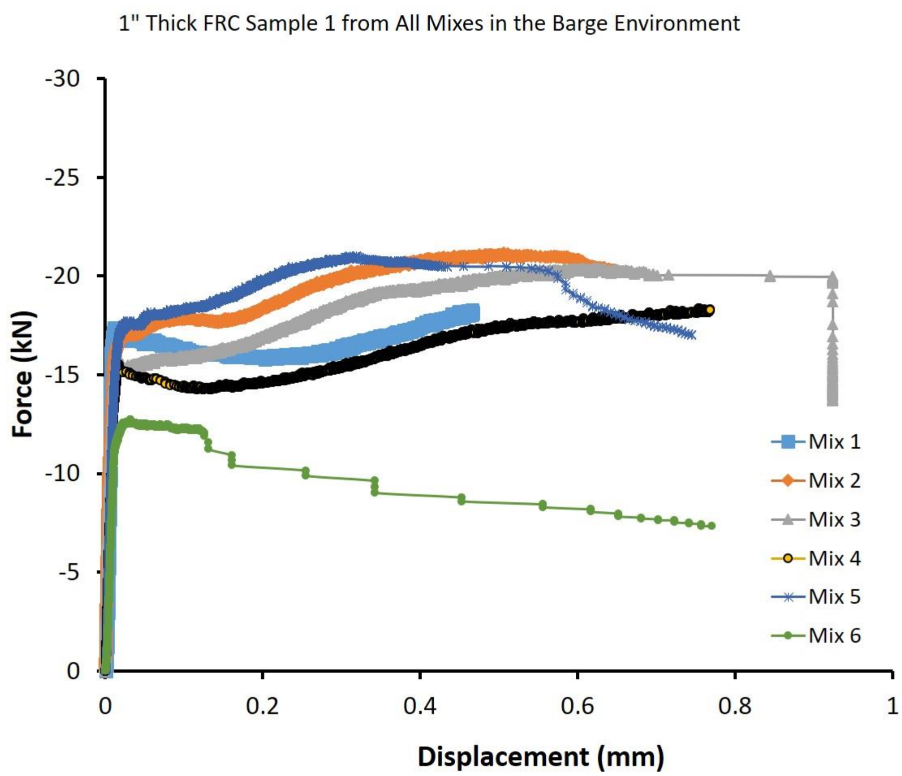


Figure 18-One Inch Thick FRC Sample 1 from All Mixes in the Barge Environment.

In this graph, the difference between Mix 6 compared to the other fiber mixes, as mentioned above, is evident. This figure depicts in stark contrast the difference in magnitude of forces experienced between mix 6 and the other sample mixtures when analyzed at similar displacements. Furthermore, while the majority of the graphs resemble the same force-displacement shape and mechanical property measurements, mixes 5 and 6 show a slightly different trend. It can be seen from these aforementioned force displacement curves that there is a gradual decrease after a certain displacement has occurred. Within the barge conditioned environment, the results for a variety of fiber performances resemble the ones found above indicating that degradation may have occurred on those sample's fibers.

By comparing these force displacement curves (Figures 17 and 18) generated in the high humidity and barge regions, the overall difference in the applied loads and displacements support the claims made in section VI.I above. It can be seen that greater loads were achieved at a displacement of 0.4 mm and beyond by each mix in the high humidity samples than those that were conditioned in the barge environment.

To ensure that these fibers were distributed uniformly throughout the sample, and to verify that the findings in the load displacement curves were associated with the fiber-matrix interactions, the fibers in the cross section were counted and tabulated as shown in Tables 21-23. From these tables, the difference in fiber quantity between mixes 1,2, and 5 with 7.12 kg/m^3 can be seen as being greater than those of mixes 3 and 4. By looking at the results in tables 21 and 25, a comparison between the average fiber content per mix in a specific environment, and the average total toughness results per mix in that environment, can be made. It can be seen that, in general, the samples with more fibers in the cross section resulted in higher toughness measures, while the samples with lower fiber count had lower toughness readings. For this reason, the overall lower total toughness measurement in the High Humidity environment can be explained. The samples that were conditioned in the High Humidity regime, often had lower average total fibers in their cross section compared to samples in other environments. This phenomenon can also explain the reasoning for the barge conditioned samples having relatively higher performance in some mixes such as mix 3 where it had, on average, the highest quantity of fibers in its cross section. Although it was assumed that there would be a homogeneous distribution of fibers through the entire sample, this was not always the case at the center of the sample and along the vertical axis, as there were some samples that had a lower amount of fibers in their cross section which possibly could have explained their lower mechanical performance characteristics.

Commenting on the fibers tendency to break or pull out of the concrete matrix, it is important to note that majority of the failures occurred upon propagating the crack after MIDT testing had occurred. Taking this into account, a majority of the fibers in this study preferentially pulled out. Even though most fibers experienced a pull-out failure, there was a substantial amount of fibers that broke as well. This generalization is not necessarily true for the Tuff Strand SF fibers, however, as these fibers usually experienced similar quantities of breaking and pull out failure mechanisms. On the opposite side of the spectrum, the PVA fibers in Mix 6 rarely experienced a break and almost always witnessed the pull out of the fibers. This observation on the rarity of experiencing breaks could have been because the failure of the concrete could have caused little splitting on the fibers, or because of the shorter length of the PVA macro fibers. Unfortunately for this study, there were no samples prepared with 5 cm PVA macro fiber so a direct comparison with the other fiber type's failure tendencies was not warranted. Regardless, if you wanted to predict the failure of a concrete specimens fibers from the lattice to be a pull out failure, the PVA fibers used in mix 6 would be the fiber of choice, while if more of a breaking type of failure was sought the Tuff Strand SF

(Polypropylene/Polyethylene blend) fibers of mixes 2 and 3 would be better utilized. Using fibers such as those in mixes 1, 4, or 5 would result in mostly pull out failures, in addition to a significant amount of breaking still occurring.

VI.III The Influence of Geometry on Performance

While this study primarily prepared and conditioned square specimen in every environment, a number of different geometry and thickness samples were prepared to determine to what degree these factors affected the modified indirect tensile test results. Since the barge environment was the only conditioning regime where all different geometries were immerged, the results from testing these samples will be looked at in this section. In the table below, Table 26, all three geometries are presented for comparison. This table presents the average values for the loads to first crack, total areas, areas up to a displacement of 0.4 mm, and the total fiber count in the cross section for each mix in each geometry that was submerged in the barge environment. It is important to note that for this comparison, only the front side of the cylindrical samples are presented, as this side saw the largest displacement for most of the tests.

Table 26-Different Barge Conditioned Geometries' Performance Analytics.

Geometry	Sample Name	Avg. First Crack Load (kN)	Avg. Total Area (kN*mm)	Avg. Area at 0.4 mm (kN*mm)	Total Fibers in the Cross Section
1" Thick Squares	Mix 1	-17.3	-10.4	-6.5	14.3
	Mix 2	-17.0	-13.5	-7.2	22.3
	Mix 3	-17.1	-15.9	-7.2	18.7
	Mix 4	-16.9	-16.1	-7.7	6.7
	Mix 5	-15.8	-14.0	-7.0	17.0
	Mix 6	-13.6	-7.4	-5.1	16.7
	Average	-16.3	-12.9	-6.8	16.0
2" Thick Squares	Mix 1	-27.8	-26.5	-10.7	42.8
	Mix 2	-27.3	-20.9	-9.7	42.3

	Mix 3	-28.5	-19.0	-11.0	25.0
	Mix 4	-25.8	-17.4	-8.8	23.8
	Mix 5	-25.9	-23.7	-9.9	28.5
	Mix 6	-25.9	-19.3	-9.9	45.0
	Average	-26.9	-21.1	-10.0	34.6
4" Thick Squares	Mix 1	-57.5	-45.9	-25.2	68.2
	Mix 2	-50.8	-47.6	-21.2	93.0
	Mix 3	-48.1	-35.4	-26.1	63.2
	Mix 4	-48.4	-37.3	-19.4	42.7
	Mix 5	-50.4	-45.1	-20.4	58.8
	Mix 6	-50.0	-37.1	-20.8	80.5
	Average	-50.9	-41.4	-22.2	67.7

From this table the difference between the different thicknesses of the samples can clearly be seen. The most obvious difference between the different samples, which is inherent in their preparation, is the amount of fibers in each sample's cross section. As expected, increasing the samples thickness resulted in an increase in the quantity of fibers in the cross section as the 2" thick specimen had on average 6.3 to 28.5 more fibers than the 1" thick square samples, while the 4" specimen averaged 36 to 63.8 more fibers. Due to this increase in fiber count and sample thickness, the samples average load to first crack, average total toughness, and average toughness up to a displacement of 0.4 mm increased as well. It was seen that increase in the load required to crack the sample from the 1" sample to the 2" sample was in the order of 8.9 to 12.3 kN, while the difference between the 1" and 4" sample was 31.0 to 40.2 kN. This increase in load required indicates a near linear increase in the load required, with every extra inch requiring approximately another 10 kN of force to crack. This assumption is shown by the fact that on average the 2" thick samples required 10.6 kN to initially crack compared to the 1" samples, while the 4" samples required an average additional load of 34.6 kN comparatively. It is important to note that as the sample gets larger, the 10 kN increase in load to first crack per inch of thickness added is below what was observed, as the results tend to stray from this linear increase. Additionally, the difference in total toughness measured up to 0.4 mm experienced increases between 1.1 to 4.8 kN*mm going from the 1" sample to the 2" sample and increased in magnitude ranging from 11.7 to 18.9 kN*mm when the thickness increased from 1" to 4". This average toughness up to 0.4 mm follows a similar trend as the average load to first crack as the increase is linear increasing on average 3.2 kN*mm from the 1" sample to the 2" but then beginning to stray the larger sample gets as the average increase was 15.4 kN*mm going from 1" samples to 4" samples. For the toughness (total area measurement), the range of toughness values observed for the 2" sample are 1.3 to 16.1 kN*mm higher than the 1" specimen, while the 4" thick samples showed an increase in the average values between 19.5 and 35.5 kN*mm. The average increase in toughness from the 1" thick samples was 8.3 kN*mm for the 2" thick specimen, and 28.5 kN*mm for the 4" thick FRC samples. This depicts a clear increase in the total toughness as the sample thickness increases however, the range of increase is rather large making it hard to accurately depict the order of improvement said increased thickness would provide. An explanation offered to explain why the mechanical properties measured using the modified indirect tensile test began to stray from a linear increase with an increase in thickness is because as the specimen became thicker, less ingress of detrimental materials could penetrate the sample, thus resulting in higher toughness and load to first crack readings.

VI.IV Strain Softening and Differences Between Similar Research Findings

Looking at the force displacement graphs of the various geometry, fiber content, and exposure environment samples in Appendix D, a handful of the results provide evidence showing that strain softening of the synthetic fibers occurred. The specific mixtures and environments that depict moderate strain softening in their force displacement curves include: 1” thick samples of mixes 4 and 6 in the Barge environment, 2” thick samples of mixes 2, 3 and 4 in the Barge environment, 4” thick samples of Barge conditioned mix 4, and 4” thick samples of mixes 1, 2, and 3 from the low pH environment to name a few. While these plots contained several samples that potentially experienced moderate strain softening, the round two-inch-thick 3 barge condition FRC specimen shown in Figure 19 presents a clear depiction of the strain softening across all the samples in the mix.

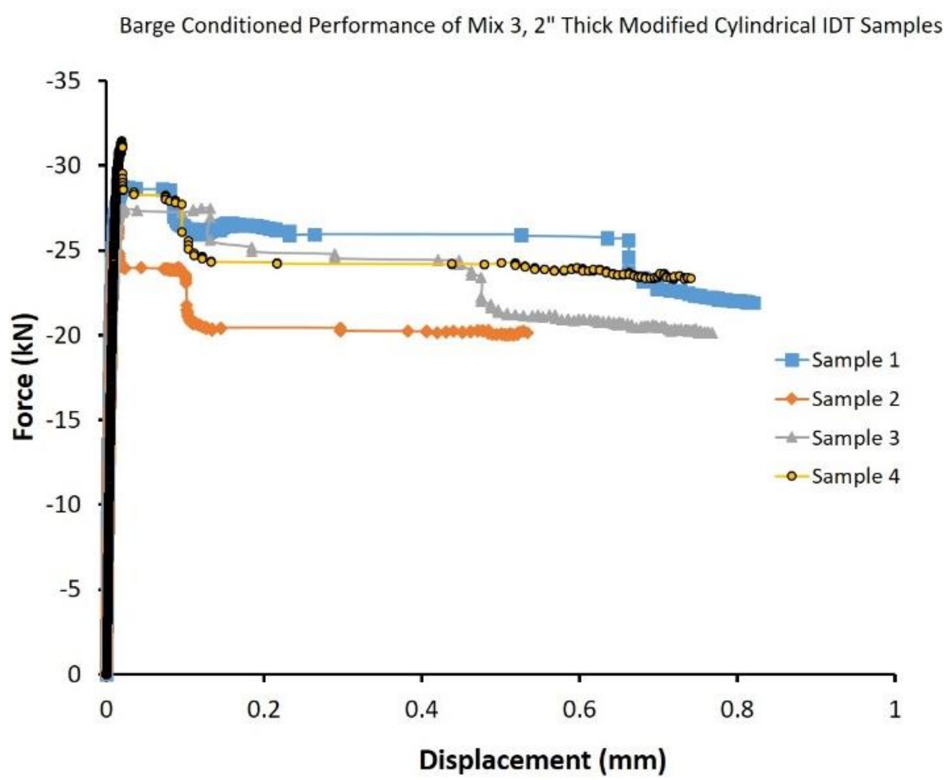


Figure 19-Barge Conditioned Performance of Mix 3 from the 2-Inch-Thick Modified Cylindrical IDT Samples.

This strain softening phenomenon is identified by the tiered decrease in the samples force as the displacement increases. When strain softening after first cracking is evident, it can potentially indicate the deterioration of the fiber reinforcement within the concrete lattice itself. This phenomenon is detrimental to the fiber reinforced concretes mechanical properties as it results in lower toughness characteristics, being capable of withstanding less loading. Similar strain softening characteristics could be identified in the results generated by [4]. However, there are a number of factors that may have been the reasoning behind why this strain softening wasn't identified as often in the modified indirect tensile testing procedure performed and outlined by this thesis compared to that of [4]. The main difference between the findings in these two research projects could be explained by differences in the fiber reinforced concrete's preparation and exposure regimes. Due to the fact that the samples prepared and tested for this thesis contained 23% fly ash and began their exposure after 56 day, the samples underwent more aging and thus the pore size was considerably smaller than those produced for Ryan Flaherty research (using similar fly ash content). Additionally, while both studies had barge specimen that were fully immersed, this thesis implemented cyclic wetting and drying exposure to both the low pH and sea water specimens while only the low pH samples in the Flaherty paper underwent wetting and drying as the sea water specimens were continuously exposed. These alterations in the preparation and conditioning phase of the FRC testing procedure could potentially indicate the differences in the data that was observed.

Similar to the aforementioned difference between the results obtained in this study and those obtained by another researcher, the preparation and conditioning of the

FRC samples from test to test utilizing the indirect tensile testing method could also explain the moderate differences that were observed from one researcher to the next using MIDT testing. As the samples that were prepared for this research contained a high quantity of fly ash, the time after pouring the concrete to its time of immersion is crucial in order to obtain consistent results. These high fly ash samples were immersed in their conditioning environments anywhere ranging from 137-179 days after being poured and molded. This timeframe is important to note since when fly ash is initially introduced to concrete, the porosity of the sample is relatively high, however, as the pozzolanic reaction takes place, the pore size and exposure decreases which as a result decreases the penetration of solution into the concrete. Because of this, the highest diffusivity of high fly ash concrete samples would occur when emerging the samples around 28 days after pouring the concrete. Other factors that could influence the results observed from researcher to researcher on the basis of sample preparation could have been the water to cement ratio used, sample geometry, or even the total immersion time over which the sample is undergoing conditioning. For instance, even within this thesis, the conditioning times varied between the different environments, as each environment was tested in groups. In this thesis exposure durations lasted 20-24 months, while similar studies had immersion times of only 8 months to a year.

VI.V Future Improvements

Upon fully testing and analyzing the results from each fiber reinforced concrete sample, there are a few improvements that could have been made to further enhance the findings of this research. The main factor that should be improved upon in further studies involving the testing of fiber reinforced concrete is the number of samples available to analyze the effect each independent variable. Throughout this research there were four independent variables which were: the environment in which each sample was conditioned, the duration that each sample was exposed, fiber content within each sample, and the sample's geometry. Upon applying these independent variables, the sample size for each group is relatively small. For example, there were five environments, that had three geometries of samples, consisting of six different fiber type mixtures, that were exposed for different lengths of time between the different research projects. As a result, some sample groups only had two or three samples that were prepared and conditioned exactly the same making it hard to compile all the different data points and formulate one decisive conclusion on what influenced the FRC's mechanical performance. Moving forward, future research projects regarding fiber reinforced concrete should try to limit the independent variables and maximize the quantity of samples prepared and conditioned in the same manor to help formulate a more accurate depiction of what affected the samples performance.

Additionally, other changes that could have been made throughout the duration of this research could have been to implement the auto dosing pumps into the Low pH environment earlier in the process. Initially, the Low pH solution was manually dosed daily to ensure an adequate pH was reached, however after about two years an automatic dosing pump was introduced and was able to keep the solution at a more consistent pH. Had this automatic dosing procedure been followed from the beginning of the experiment, the solution would've maintained more stable pH reading and could have influenced (degraded) the samples more.

VII. CONCLUSIONS

This study was conducted on synthetic fiber reinforced concrete samples of varying geometries, fiber content, and conditioning environment. The modified indirect tensile test was used to determine a number of important mechanical properties. By gathering and recording the load and displacement data throughout the MIDT testing procedure, each samples toughness could be looked at to provide insight as to whether or not degradation of the fiber-matrix interface occurred.

Looking at the toughness of each sample up to a horizontal sample displacement of 0.4 mm, the samples could be compared based on similar criteria. The results observed by the modified indirect tensile test of the 1" thick specimen indicate that out of all of the environmental conditions in which samples were immerged, samples exposed to the high humidity environment showed the highest average toughness while samples from the barge environment displayed the lowest average toughness. Similarly, from the one inch thick samples, the environment and mix that showed the highest toughness readings (an average reading of -10.4 kN*mm) up to a displacement of 0.4 mm was Mix 1 from the High Humidity conditioning regime, while the lowest average toughness readings (-5.1 kN*mm) to this same displacement was from Mix 6 in the Barge conditioned group. For a couple of mixes, however, the samples exposed at the barge did exhibit toughness's slightly higher than other environments, but upon the cross-sectional forensic analysis, the samples of these mixes had a larger number of fibers distributed in the samples cross section exposed at the barge than the fiber count found on the cross section of the samples exposed to the other environments for the same mixture group.

Looking at the performance of the fibers themselves, as expected, the samples with the lower volume of fibers per mix (5.34 kg/m^3 compared to corresponding mixes with 7.12 kg/m^3) exhibited lower observed toughness results. It was also observed that the 1” samples from mix 6 has the lowest average toughness to a displacement 0.4 mm across all of the environments, despite having the largest fiber volume per cast of 8.90 kg/m^3. This result was due to the fibers being substantially shorter than the other synthetic fibers used in sample preparation. Despite being unable to determine when exactly the failure mechanisms took place on each fiber analyzed throughout this thesis (whether it was during the MIDT test or during the post-test crack propagation), it was witnessed that the PVA fibers of mix 6 tended to experience pull out failure rather than break as this was almost always the case. This pull out of fibers was fairly common among the other mixes as well as it was observed as the predominant failure mode the majority of the time. The exception to this observation was from samples reinforced with the Tuff Strand SF fibers which saw very similar quantities of failures by breaking and pull out. Therefore, when developing future concrete samples, if the desired failure method is by pull out, then the PVA fibers should be used, while if the desired failure is to break the Tuff Strand fibers have a greater chance at breaking.

By observing the modified indirect tensile testing results from samples of different geometries, the influence that sample thickness had was clear. It was seen that an increase in sample thickness increased the sample's average load to first crack, maximum load, toughness at a sample displacement of 0.4 mm, and total toughness. The increase in these mechanical performance characteristics, however, do not necessarily increase linearly with the increase in sample thickness. It was seen, when looking at the load to first crack across all mixes in the barge environment, that an additional 10.6 kN would be required to crack a 2" thick specimen, while an additional load of 34.6 kN would be needed to crack the 4" thick specimen (instead of the load of approximately 31.8 kN that would be needed to indicate a linear increase).This trend is also followed for the total toughness across all samples in the barge environment, with the additional toughness gained by increasing the sample geometry from 1" thick to 2" thick being 8.3 kN*mm, and increasing 28.5 kN*mm going from 1" to 4" thick specimens. Although there is clearly a correlation between the increase in the size of the samples and the increase in mechanical properties, the degree to the improvement is hard to pinpoint as it tends to vary from sample to sample and may be influenced by the ability of detrimental materials to penetrate the concrete specimen.

Analyzing the results generated by performing the modified indirect tensile test on various geometry, and fiber content, FRC samples that were conditioned in different environments for periods ranging from 20 to 24 months, it was observed that degradation appeared to occur on the samples immersed in the intercoastal Barge condition.

Comparing the barge conditioned 1" thick samples to similar samples exposed to different environments, the barge samples had lower average total toughness and toughness up to a sample displacement of 0.4 mm across all mixes comparatively. From these, the 1" thick samples immersed in the barge condition, mix 6 samples exhibited the lowest average toughness to a displacement of 0.4 mm seen throughout this whole study as it was from the lowest average toughness environment, and the poorest performing fiber type. Similarly, when looking at the average total toughness's across all mixes of the 4" thick cylindrical samples, the Barge had the lowest toughness values. Furthermore, looking at the force displacement curves generated for a handful of specimens tested from the barge condition, there is evidence of strain softening, as they resemble the findings of a studies that was performed using this similar technique. This strain softening phenomenon can help explain the lower physical properties observed for some of the Barge conditioned specimens and can provide evidence of potential degradation within these samples. There are some indications that degradation occurred on a few samples exposed in the low pH conditioning environment, including having moderate strain softening witnessed in the force displacement curves. However, the MIDT testing results from the 1" thick Low pH conditioned samples provide evidence contradicting that this degradation took place. The modified indirect tensile test of the 1" thick low pH conditioned samples indicate that their load and toughness calculations (for both the average total toughness and the average toughness at a displacement of 0.4 mm) are comparable with the other conditioning environments (including the two control groups that were prepared) that did not indicate any signs of degradation.

As a qualitative look at the potential degradation of the synthetic fiber reinforced concrete, and the influence that the environment played on these samples, a clear difference in durability could be seen when propagating the cracks formed during testing. In the process of hammering each sample with a metal chisel along the pre-cracked face to open up the samples post testing (in order to view their cross-sectional area) the ease of opening some samples compared to others was noticed. When opening the 4” thick cylindrical samples that were exposed to a high humidity environment, it was noticed that approximately 40-60 strikes (of a hammer and chisel) were necessary to fully separate the two halves of the specimen along the vertical axis. The 4” thick cylindrical samples that were conditioned in the Barge environment, on the other hand, behaved rather differently. When attempting to open the barge conditioned samples after testing, the samples opened with comparative ease as they only required around 10 strikes from the hammer and chisel to fully separate. Similarly, when propagating the crack that were formed on the 4” thick cylindrical samples exposed in the Low pH solution, a decrease in the quantity of hammer and chisel strikes needed to open the samples compared to the High Humidity conditioned samples was observed. These low pH conditioned samples, however, did not open as easily as the Barge conditioned fibers, as they required upwards of 20 hammer and chisel strikes to observe the specimens’ internal cross section. Although the opening of the samples was done to merely observe the fiber interaction (as the force of each hammer strike was not recorded), the ease of opening each sample provided valuable qualitative insight into the possible degree of degradation that took place.

VIII. APPENDIX

Appendix A. Abbreviations

Symbol	Definition
AVG	Average
cm	Centimeter
COD	Crack Opening Displacement
FL	Florida
FRC	Fiber Reinforced Concrete
IDT	Indirect Tensile Test
ITZ	Interfacial Transition Zone
kN	Kilonewton
kg	Kilogram
m	Meters
MIDT	Modified Indirect Tensile Test
mL	Milliliter
mm	Millimeter
ms	Millisecond
pH	Potential Hydrogen
PVA	Polyvinyl Alcohol
STD	Standard Deviation
SF	Structural Fibers
µM	Micrometer

Appendix B. Typical Concrete Mix Composition

Material	Classification	Quantity
Aggregate	Mixed Diameter Aggregates	949.2 kg/m^3
Sand	Quikrete Natural Play Sand	872.1 kg/m^3
Cement	Portland Cement (Types I and II)	296.6 kg/m^3
Fly Ash	23% Type F	68.2 kg/m^3
Synthetic Fiber	Various Types of Synthetic Fibers	5 to 9 kg/m^3
Water/Cement Ratio	City of Gainesville Tap Water	0.41
Admixture	MasterGlenium 7920	1335.41 mL

Appendix C. Modified Indirect Tensile Test Performance Results for Each Sample

Appendix C.1 Individual Sample Performance from the 1” Thick Square Specimen Exposed to High Humidity

Mixture	Sample	Unit	Max Load	First Peak	Total Area	Load at 0.4 mm	Area at 0.4 mm
Mix 1	1	kN	-23.037	-16.885	-12.758	-20.450	-7.052
		mm	0.659	0.065			
	2	kN	-26.264	-16.633	-22.826	-24.082	-16.714
		mm	0.555	0.053			
	3	kN	-25.783	-17.523	-12.944	-24.981	-8.435
		mm	0.577	0.025			
	4	kN	-28.966	-18.532	-11.748	-28.290	-9.230
		mm	0.488	0.045			
Mix 2	1	kN	-24.281	-15.525	-10.099	-20.189	-6.848
		mm	0.551	0.037			
	2	kN	-24.480	-17.630	-9.534	-20.597	-7.161
		mm	0.506	0.050			
	3	kN	-22.682	-11.502	-9.002	-20.717	-6.920
		mm	0.498	0.027			
	4	kN	-26.492	-17.181	-11.868	-25.029	-8.135
		mm	0.544	0.040			
Mix 3	1	kN	-20.348	-15.514	-8.679	-16.810	-6.390
		mm	0.527	0.037			
	2	kN	-22.969	-17.188	-8.948	-19.522	-7.127
		mm	0.489	0.043			
	3	kN	-19.084	-17.018	-8.050	-15.396	-6.541
		mm	0.498	0.051			
	4	kN	-24.635	-16.891	-9.722	-21.939	-7.472

		mm	0.496	0.037			
Mix 4	1	kN	-22.110	-16.912	-8.950	-19.245	-6.690
		mm	0.511	0.054			
	2	kN	-21.035	-15.319	-6.937	-17.236	-6.023
		mm	0.451	0.137			
	3	kN	-22.502	-16.118	-9.276	-16.864	-6.364
		mm	0.564	0.028			
	4	kN	-18.112	-15.981	-7.049	-14.277	-6.072
		mm	0.465	0.232			
Mix 5	1	kN	-24.552	-16.981	-9.783	-21.635	-7.455
		mm	0.502	0.045			
	2	kN	-26.941	-17.326	-9.801	-26.376	-8.515
		mm	0.448	0.045			
	3	kN	-23.551	-16.593	-11.445	-22.570	-7.627
		mm	0.564	0.054			
	4	kN	-27.504	-18.493	-10.302	-26.555	-8.702
		mm	0.457	0.019			
	5	kN	-22.774	-17.761	-10.479	-19.461	-7.016
		mm	0.565	0.179			
Mix 6	1	kN	-26.286	-17.557	-10.182	-24.137	-7.955
		mm	0.487	0.014			
	2	kN	-22.316	-17.883	-9.079	-18.475	-6.999
		mm	0.507	0.031			
	3	kN	-23.811	-17.589	-9.908	-22.404	-7.515
		mm	0.504	0.061			
	4	kN	-19.483	-17.847	-9.139	-17.679	-6.835
		mm	0.526	0.114			
	5	kN	-25.923	-17.482	-9.840	-22.454	-7.511
		mm	0.499	0.033			

Appendix C.2 Individual Sample Performance from the 1" Thick Square Specimen Exposed in the Calcium Hydroxide Solution

Mixture	Sample	Unit	Max Load	First Peak	Total Area	Load At 0.4	Area at 0.4
Mix 1	1	kN	-26.342	-17.299	-21.907	-25.821	-8.4046
		mm	0.89941	0.0447			
	2	kN	-28.214	-18.939	- 19.3659	-24.8690	-8.6679
		mm	0.95174	0.04674			
Mix 2	1	kN	-25.439	-16.38		-23.3096	-7.5149

		mm	0.89205	0.04089	-19.8083		
	2	kN	-24.709	-16.651	-18.847	-24.46	-10.528
		mm	0.65532	0.02413			
Mix 3	1	kN	-22.807	-17.466	-17.238	-17.541	-6.6618
		mm	0.93624	0.05944			
	2	kN	-24.628	-17.171	-17.682	-18.85	-6.7758
		mm	0.89967	0.09093			
Mix 4	1	kN	-21.544	-16.173	NA	-17.651	NA
		mm*	0.02032	0.02362			
	2	kN	-19.814	-15.839	-13.335	-17.277	-6.1746
		mm	0.68682	0.1176			
Mix 5	1	kN	-19.813	-16.004	-17.755	-19.649	-6.6926
		mm	0.93294	0.05182			
	2	kN	-20.813	-12.662	-15.86	-16.019	-5.3126
		mm	0.94488	0.06121			
Mix 6	1	kN	-16.498	-16.471	-15.002	-15.218	-6.2535
		mm	0.03886	0.03886			
	2	kN	-21.371	-15.698	-15.551	-19.934	-6.9124
		mm	0.81509	0.04293			

Appendix C.3 Individual Sample Performance from the 1" Thick Square Specimen Exposed in the Low pH Environment

Mixture	Sample	Unit	Max Load	First Peak	Total Area	Load at 0.4 mm	Area at 0.4 mm
Mix 1	1	kN	-21.148	-17.850	-17.505	-19.588	-7.003
		mm	0.908	0.016			
	2	kN	-19.240	-17.154	-15.684	-17.539	-6.709
		mm	0.836	0.041			
	3	kN	-18.676	-16.137	-14.712	-15.353	-5.985
		mm	0.904	0.099			
Mix 2	1	kN	-26.419	-20.150	-15.475	-25.156	-8.701
		mm	0.620	0.052			
	2	kN	-19.183	-16.807	-17.087	-18.621	-6.971
		mm	0.592	0.054			
	3	kN	-21.929	-17.899	-18.836	-20.842	-7.395
		mm	0.606	0.080			
Mix 3	1	kN	-18.733	-18.673	-13.297	-17.644	-7.008

		mm	0.762	0.070			
	2	kN	-22.643	-17.635	-19.207	-21.766	-7.390
		mm	0.530	0.069			
	3	kN	-21.660	-17.092	-18.358	-20.526	-7.164
		mm	0.926	0.068			
Mix 4	1	kN	-19.448	-16.089	-17.790	-18.711	-6.486
		mm	0.987	0.085			
	2	kN	-21.095	-16.553	-17.776	-21.021	-7.458
		mm	0.533	0.041			
	3	kN	-22.333	-17.331	-17.552	-18.731	-7.038
		mm	0.950	0.059			
Mix 5	1	kN	-25.634	-19.149	-23.144	-24.866	-9.173
		mm	0.872	0.017			
	2	kN	-24.354	-18.097	-20.423	-24.243	-9.007
		mm	0.506	0.025			
	3	kN	15.405	-15.401	-12.784	-12.924	-5.607
		mm	0.015	0.059			
Mix 6	1	kN	-19.615	-15.260	-18.187	-18.785	-7.215
		mm	0.967	0.023			
	2	kN	-20.549	-17.535	-24.130	-18.689	-6.809
		mm	0.943	0.040			
	3	kN	-23.616	-19.715	-19.157	-21.690	-7.769
		mm	0.809	0.046			

Appendix C.4 Individual Sample Performance from the 1" Thick Square Specimen Exposed in the Sea Water Environment

Mixture	Sample	Unit	Max Load	First Peak	Total Area	Load At 0.4 mm	Area at 0.4 mm
Mix 1	1	kN	-18.817	-15.724	-17.433	-18.271	-7.6366
		mm	0.778	0.03124			
	2	kN	-18.896	-17.557	-20.427	-16.5365	-8.8106
		mm	0.61138	0.01905			
	3	kN	-24.052	-17.046	-17.289	-22.4248	-7.6991
		mm	0.69063	0.01981			
Mix 2	1	kN	-19.756	-17.863	-13.910	-18.3675	-6.7057
		mm	0.72619	0.01524			
	2	kN	-22.798	-16.422	-15.369		-7.1809

		mm	0.60554	0.01829		-20.9298	
	3	kN	-25.237	-17.207	-18.067	-24.1752	-8.1881
		mm	0.54915	0.02134			
Mix 3	1	kN	-17.12	-16.963	-12.204	-16.2572	-6.3525
		mm	0.54661	0.01524			
	2	kN	-19.747	-19.408	-14.749	-17.4946	-7.2191
		mm	0.79807	0.01676			
	3	kN	-18.934	-17.485	-12.486	-15.8340	-6.0446
		mm	0.7686	0.01524			
Mix 4	1	kN	-23.946	-17.235	-15.783	-22.1939	-7.6084
		mm	0.73279	0.01575			
	2	kN	-24.578	-17.385	-17.786	-22.4850	-7.8991
		mm	0.77572	0.0188			
	3	kN	-27.476	-18.489	-19.114	-23.3611	-8.1199
		mm	0.63297	0.01422			
Mix 5	1	kN	-23.1	-16.602	-19.003	-20.4311	-7.1582
		mm	0.6665	0.01651			
	2	kN	-17.621	-16.622	-14.243	-16.7022	-6.1071
		mm	0.74447	0.016			
	3	kN	-23.146	-18.031	-18.177	-20.9703	-8.333
		mm	0.66142	0.01626			
Mix 6	1	kN	-18.505	-15.742	-12.623	-15.7151	-6.2335
		mm	0.7681	0.01829			
	2	kN	-20.787	-16.984	-15.038	-20.1536	-6.9595
		mm	0.47447	0.01676			
	3	kN	-23.289	-16.736	-15.059	-20.8414	-7.0568
		mm	0.76098	0.02083			

Appendix C.5 Individual Sample Performance from the 1" Thick Square Specimen Exposed in the Barge Environment

Mixture	Sample	Unit	Max Load	First Peak	Total Area	Load At 0.4 mm	Area at 0.4 mm
Mix 1	1*	kN	-18.285	-17.339	-7.967	-17.372	-6.6412
		mm	0.46601	0.012116			
	2	kN	-19.004	-18.3718	-10.327	-18.5479	-7.2352
		mm	0.31852	0.019812			

	3	kN	-17.352	-16.1416	-12.787	-14.5112	-5.742
		mm	0.84303	0.020066			
Mix 2	1	kN	-21.151	-17.0686	-12.641	-20.7840	-7.4136
		mm	0.50546	0.0254			
	2	kN	-16.753	-16.7347	-9.344	-15.3740	-6.2743
		mm	0.05563	0.055118			
	3	kN	-21.891	-17.0681	-18.441	-21.5062	-7.8007
		mm	0.33045	0.021844			
Mix 3	1	kN	-20.415	-15.7971	-17.432	-19.2376	-6.8895
		mm	0.62103	0.013462			
	2	kN	-17.435	-15.9683	-12.271	-16.7663	-6.2009
		mm	0.68428	0.03556			
	3	kN	-25.811	-19.6436	-18.031	-25.1853	-8.5484
		mm	0.53848	0.017272			
Mix 4	1	kN	-18.376	-15.5374	-12.553	-16.5329	-5.9763
		mm	0.75413	0.01651			
	2	kN	-21.279	-16.8939	-17.947	-20.7059	-7.1642
		mm	0.4511	0.02667			
	3	kN	-20.011	-18.4010	-17.712	-19.2513	-9.9264
		mm	0.3523	0.07620			
Mix 5	1	kN	-21.019	-17.7285	-14.31	-20.6303	-7.67
		mm	0.31039	0.027686			
	2	kN	-18.529	-15.6883	-12.247	-16.1543	-6.123
		mm	0.72796	0.01676			
	3	kN	-18.225	-14.08486	-15.379	-17.6536	-7.1473
		mm	0.4638	0.04191			
Mix 6	1	kN	-12.734	-12.7202	-7.220	-9.0198	-4.6618
		mm	0.03226	0.032258			
	2	kN	-15.523	-14.5707	-5.777	-15.4051	-5.7768
		mm	0.38557	0.02794			
	3	kN	-13.427	-13.4273	-9.323	-10.0250	-4.8495
		mm	0.04064	0.04064			

Appendix C.6.1 Individual Sample Performance from the Front Side of the 2" Thick Cylindrical Specimen Exposed in the Barge Environment.

Mixture	Sample	Unit	Max Load	First Peak	Total Area	Load at 0.4 mm	Area at 0.4 mm
Mix 1	1	kN	-31.412	-29.689	-37.308	-28.061	-10.956
		mm	0.71603	0.02972			
	2	kN	-28.613	-27.132	-21.174	-27.158	-10.455
		mm	0.52959	0.13538			
	3	kN	-27.618	-26.229	-23.252	-27.164	-10.406
		mm	0.34442	0.02083			
	4	kN	-30.806	-28.047	-24.194	-28.824	-10.888
		mm	0.64922	0.06121			
Mix 2	1	kN	-30.287	-30.287	-21.605	-24.423	-10.036
		mm	0.016	0.016			
	2	kN	-29.125	-29.04	-22.556	-24.571	-10.544
		mm	0.02591	0.08433			
	3	kN	-27.692	-25.881	-22.039	-24.579	-9.682
		mm	0.8697	0.02235			
	4	kN	-24.071	-24.052	-17.473	-21.311	-8.670
		mm	0.00508	0.00508			
Mix 3	1	kN	-28.768	-28.755	-20.931	-25.959	-13.867
		mm	0.01981	0.01981			
	2	kN	-26.396	-26.396	-11.147	-20.233	-8.567
		mm	0.01524	0.01524			
	3	kN	-27.483	-27.481	-25.765	-24.524	-10.636
		mm	0.01778	0.11989			
	4	kN	-31.44	-31.426	-18.116	-24.209	-10.900
		mm	0.0188	0.0188			
Mix 4	1	kN	-25.334	-23.726	-17.841	-23.142	-8.874
		mm	0.67081	0.07137			
	2	kN	-29.639	-29.618	-17.795	-22.285	-9.295
		mm	0.02134	0.02134			
	3	kN	-26.642	-24.572	-18.776	-24.411	-9.166
		mm	0.77267	0.04775			
	4	kN	-25.225	-25.183	-15.183	-19.794	-8.017
		mm	0.01422	0.01448			
MIX 5	1	kN	-26.439	-24.943	-22.061	-24.102	-9.455
		mm	0.8956	0.00965			
	2	kN	-30.696	-26.908	-25.43	-26.356	-10.335
		mm	0.84811	0.01651			
Mix 6	1	kN	-29.604	-26.049	-20.141	-25.962	-9.862
		mm	0.75895	0.01549			

	2	kN	-30.076	-25.216	-20.147	-27.136	-10.524
		mm	0.72923	0.04902			
	3	kN	-26.478	-26.478	-17.756	-22.163	-9.511
		mm	0.01219	0.01219			
	4	kN	-26.701	-25.871	-19.139	-25.704	-9.758
		mm	0.73609	0.01473			

Appendix C.6.2 Individual Sample Performance from the Back Side of the 2" Thick Cylindrical Specimen Exposed in the Barge Environment.

Mixture	Sample	Unit	Max Load	First Peak	Total Area	Load at 0.4 mm	Area at 0.4 mm
Mix 1	1	kN	-31.412	-29.689	-21.472	-29.582	-11.180
		mm	0.49479	0.00254			
	2	kN	-28.613	-27.132	-13.129	-28.282	-10.908
		mm	0.35357	0.03353			
	3	kN	-27.618	-26.229	-13.577	-26.333	-10.891
		mm	0.01981	0.00483			
	4	kN	-30.806	-28.047	-11.607	-30.666	-11.607
		mm	0.19482	-0.0028			
Mix 2	1	kN	-30.287	-30.287	-12.047	-24.228	-10.072
		mm	0.01702	0.01702			
	2	kN	-29.125	-29.04	-14.419	-24.486	-10.582
		mm	0.01067	0.08001			
	3	kN	-27.692	-25.881	-11.849	-24.518	-9.734
		mm	0.48514	0.00787			
	4	kN	-24.071	-24.052	-13.556	-21.281	-8.719
		mm	0.03175	0.04064			
Mix 3	1	kN	-28.768	-28.755	-13.319	-25.940	-11.035
		mm	0.00864	0.00864			
	2	kN	-26.396	-26.396	-11.086	-20.233	-8.782
		mm	0.01245	0.01245			
Mix 4	1	kN	-25.334	-23.726	-11.816	-23.510	-9.245
		mm	0.5047	0.03556			
	2	kN	-29.639	-29.618	-11.417	-22.261	-11.417
		mm	0.016	0.016			
	3	kN	-26.642	-24.572	-12.126	-25.212	-9.564
		mm	0.49962	0.00381			

	4	kN	-25.225	-25.183	-9.469	-19.805	-8.956
		mm	0.02667	0.02794			
Mix 5	1	kN	-26.439	-24.943	-13.421	-23.949	-9.409
		mm	0.56286	0.01753			
	2	kN	-30.696	-26.908	-13.159	-26.813	-10.448
		mm	0.49632	0.00356			
Mix 6	1	kN	-29.604	-26.049	-13.253	-26.452	-9.932
		mm	0.51994	0.03861			
	2	kN	-30.076	-25.216	-12.703	-27.549	-10.575
		mm	0.47549	0.00432			
	3	kN	-26.478	-26.478	-12.851	-22.397	-9.440
		mm	0.01778	0.01778			
	4	kN	-26.701	-25.871	-12.573	-25.594	-9.889
		mm	0.50292	0.02743			

Appendix C.7.1 Individual Sample Performance from the Front Side of the 4" Thick Cylindrical Specimen Exposed to High Humidity

Mixture	Sample	Unit	Max Load	First Peak	Total Area	Load at 0.4 mm	Area at 0.4 mm
Mix 1	1	kN	-53.335	-50.579	-36.892	-50.492	-17.700
		mm	0.77721	0.40998			
	2	kN	-69.242	-51.036	-45.856	-60.452	-22.357
		mm	0.74905	0.00559			
Mix 2	1*	kN	-41.397	-41.337	-38.988	-40.964	-18.856
		mm	0.80256	0.81598			
	2	kN	-67.406	-50.183	-48.006	-61.220	-23.869
		mm	0.76911	0.00508			
Mix 3	1	kN	-50.448	-48.447	-42.822	-44.382	-18.872
		mm	0.93312	0.04265			
	2	kN	-51.682	-51.618	-45.277	-47.450	-21.231
		mm	0.2924	0.32154			
Mix 4	1	kN	-52.295	-45.612	-39.133	-45.544	-19.295
		mm	0.79847	0.00264			
	2	kN	-47.58	-47.575	-37.097	-40.978	-17.313
		mm	0.01295	0.01295			
Mix 5	1	kN	-65.254	-51.737	-48.407	-58.181	-22.342
		mm	0.81432	0.00813			

	2*	kN	-53.944	-50.737	-11.288	-46.705	-11.288
		mm	0.09881	0.00965			
Mix 6	1	kN	-60.414	-53.695	-51.044	-54.496	-21.860
		mm	0.89499	0.19517			
	2	kN	-58.545	-53.715	-54.439	-58.218	-22.008
		mm	0.40919	0.04597			

Appendix C.7.2 Individual Sample Performance from the Back Side of the 4" Thick Cylindrical Specimen Exposed to High Humidity

Mixture	Sample	Unit	Max Load	First Peak	Total Area	Load at 0.4	Area at 0.4 mm
Mix 1	1	kN	-53.335	-50.579	-30.046	-49.854	-24.336
		mm	0.51064	0.25037			
	2	kN	-69.242	-51.036	-28.923	-54.740	-20.524
		mm	0.54153	0.03454			
Mix 2	1*	kN	-41.397	-41.337	-18.398	-40.959	-15.314
		mm	0.51171	0.51171			
	2	kN	-67.406	-50.183	-29.686	-58.146	-21.836
		mm	0.53162	0.05359			
Mix 3	1	kN	-50.448	-48.447	-24.050	-44.318	-18.485
		mm	0.52423	0.15431			
	2	kN	-51.682	-51.618	-26.702	-51.618	-20.374
		mm	0.42575	0.45715			
Mix 4	1	kN	-52.295	-45.612	-24.015	-47.811	-18.411
		mm	0.51836	0.10018			
	2	kN	-47.58	-47.575	-19.693	-41.308	-17.382
		mm	0.0254	0.0254			
Mix 5	1	kN	-65.254	-51.737	-26.817	-56.973	-21.367
		mm	0.48336	0.03073			
	2*	kN	-53.944	-50.737	-21.362	-46.658	-18.961
		mm	0.45034	0.03073			
Mix 6	1	kN	-60.414	-53.695	-25.699	-52.436	-20.194
		mm	0.50137	0.35314			
	2	kN	-58.545	-53.715	-27.185	-58.445	-21.984
		mm	0.37592	0.01016			

Appendix C.8.1 Individual Sample Performance from the Front Side of the 4" Thick Cylindrical Specimen Exposed in the Low pH Environment

Mixture	Sample	Unit	Max Load	First Peak	Total Area	Load at 0.4 mm	Area at 0.4 mm
Mix 1	1	kN	-68.334	-60.856	-53.403	-59.953	-24.756
		mm	0.72898	0.00508			
	2	kN	-59.011	-57.048	-45.603	-51.958	-21.633
		mm	0.83922	0.03505			
	3	kN	-80.515	-60.203	-57.605	-66.175	-23.819
		mm	0.84811	0.03099			
	4	kN	-71.559	-58.14	-51.954	-60.722	-22.611
		mm	0.83871	0.01905			
Mix 2	1	kN	-80.004	-56.81	-61.484	-69.288	-24.050
		mm	0.85065	0.07493			
	2	kN	-53.536	-53.485	-43.838	-47.639	-20.536
		mm	0.0188	0.07493			
	3	kN	-49.994	-49.938	-41.571	-45.820	-19.747
		mm	0.00914	0.01016			
	4	kN	-51.223	-50.448	-44.296	-47.777	-20.221
		mm	0.08179	0			
Mix 3	1	kN	-52.719	-50.647	-44.816	-49.415	-22.432
		mm	0.83947	-0.0196			
	2	kN	-59.027	-59.027	-46.374	-49.217	-29.467
		mm	0.02413	0.02413			
	3	kN	-55.578	-55.567	-47.470	-50.782	-21.856
		mm	0.00889	0.00889			
	4	kN	-53.412	-51.269	-46.813	-51.438	-20.474
		mm	0.24079	0.02921			
Mix 4	1	kN	-57.953	-53.445	-52.263	-53.793	-21.308
		mm	0.79883	0.01905			
	2	kN	-44.646	-41.62	-38.326	-43.305	-16.738
		mm	0.90348	0.03835			
	3	kN	-55.908	-47.542	-48.062	-49.316	-19.402
		mm	0.93726	0.0094			
	4	kN	-59.226	-50.117	-51.418	-52.921	-19.660
		mm	0.8255	0.03531			
Mix 5	1	kN	-58.84	-56.68	-58.787	-52.955	-22.398
		mm	0.94056	0.01194			
	2	kN	-63.067	-51.964	-49.533	-52.835	-21.031
		mm	0.89027	0.00686			
	3	kN	-52.573	-48.638	-44.789	-46.161	-18.761
		mm	0.92278	0.00305			

	4	kN	-71.9	-56.009	-53.768	-56.559	-22.129
		mm	0.89306	0.04115			
Mix 6	1	kN	-58.896	-48.275	-48.310	-53.275	-19.604
		mm	0.67132	0.06477			
	2	kN	-59.211	-52.957	-43.432	-55.526	-21.825
		mm	0.52857	0.10211			
	3	kN	-58.667	-55.211	-41.569	-53.082	-21.548
		mm	0.72898	0.04089			
	4	kN	-72.969	-56.561	-50.053	-62.653	-23.140
		mm	0.78689	0.01803			

Appendix C.8.2 Individual Sample Performance from the Back Side of the 4" Thick Cylindrical Specimen Exposed in the Low pH Environment

Mixture	Sample	Unit	Max Load	First Peak	Total Area	Load at 0.4 mm	Area at 0.4 mm
Mix 1	1	kN	-68.334	-60.856	-30.950	-59.452	-24.900
		mm	0.49962	0.06096			
	2	kN	-59.011	-57.048	-26.896	-51.879	-21.860
		mm	0.49555	0.01092			
	3	kN	-80.515	-60.203	-33.634	-66.706	-24.236
		mm	0.52197	0.01245			
	4	kN	-71.559	-58.14	-32.797	-66.329	-23.903
		mm	0.52883	0.01346			
Mix 2	1	kN	-80.004	-56.81	-27.856	-63.247	-22.698
		mm	0.47701	0.13995			
	2	kN	-53.536	-53.485	-31.396	-47.417	-20.379
		mm	0.03429	0.06579			
	3	kN	-49.994	-49.938	-25.710	-45.847	-19.682
		mm	0.03353	0.0221			
	4	kN	-51.223	-50.448	-24.628	-49.162	-19.776
		mm	0.2347	0.09703			
Mix 3	1	kN	-52.719	-50.647	-24.459	-50.637	-18.647
		mm	0.5141	0.43993			
	2	kN	-59.027	-59.027	-23.974	-49.512	-23.974
		mm	0.02235	0.02235			
	3	kN	-55.578	-55.567	-28.883	-52.794	-23.227
		mm	0.03277	0.03277			

	4	kN	-53.412	-51.269	-28.203	-51.166	-21.202
		mm	0.10312	0.00635			
Mix 4	1	kN	-57.953	-53.445	-26.278	-51.356	-20.289
		mm	0.51638	0.25425			
	2	kN	-44.646	-41.62	-21.674	-42.375	-18.015
		mm	0.48362	0.00533			
	3	kN	-55.908	-47.542	-23.832	-47.330	-18.984
		mm	0.49759	0.03861			
	4	kN	-59.226	-50.117	-28.215	-54.420	-21.381
		mm	0.52095	0.01118			
Mix 5	1	kN	-58.84	-56.68	-34.343	-52.684	-24.038
		mm	0.56693	0.02235			
	2	kN	-63.067	-51.964	-24.297	-51.074	-20.383
		mm	0.47371	0.02921			
	3	kN	-52.573	-48.638	-23.009	-45.333	-18.556
		mm	0.49632	0.11633			
	4	kN	-71.9	-56.009	-28.232	-58.819	-22.432
		mm	0.48463	0.01422			
Mix 6	1	kN	-58.896	-48.275	-37.946	-57.072	-21.756
		mm	0.56134	0.0061			
	2	kN	-59.211	-52.957	-26.831	-55.617	-21.835
		mm	0.48565	0.00457			
	3	kN	-58.667	-55.211	-25.837	-52.234	-20.498
		mm	0.50038	0.19228			
	4	kN	-72.969	-56.561	-29.307	-60.165	-22.379
		mm	0.50876	0.05766			

Appendix C.9.1 Individual Sample Performance from the Front Side of the 4" Thick Cylindrical Specimen Exposed in the Barge Environment

Mixture	Sample	Unit	Max Load	First Peak	Total Area	Load at 0.4 mm	Area at 0.4 mm
Mix 1	1	kN	-70.773	-59.508	-36.896	-70.231	-26.409
		mm	0.4539	0.00787			
	2	kN	-65.793	-54.082	-38.015	-65.628	-24.379
		mm	0.40462	-0.0013			
	3	kN	-65.544	-54.58	-53.119	-65.267	-25.131

		mm	0.4887	0.0033			
	4	kN	-71.623	-61.668	-55.381	-65.352	-24.995
		mm	0.59588	0.01168			
Mix 2	1	kN	-61.924	-52.347	-46.693	-60.349	-22.557
		mm	0.50394	0.00406			
	2	kN	-57.105	-51.053	-46.960	-53.490	-20.352
		mm	0.86512	0.0442			
	3	kN	-55.53	-44.411	-47.261	-52.751	-20.948
		mm	0.54966	-0.0003			
	4	kN	-65.311	-55.517	-49.539	-51.467	-20.827
		mm	0.88494	0.13157			
Mix 3	1	kN	-51.58	-51.58	-29.482	-50.126	-19.571
		mm	0.01092	0.01092			
	2	kN	-51.058	-49.149	-37.750	-49.288	-18.827
		mm	0.53391	0.02311			
	3	kN	-47.163	-47.163	-43.852	-46.460	-43.852
		mm	0.00533	0.00533			
	4	kN	-52.238	-44.509	-30.478	-48.174	-22.281
		mm	0.28727	0.00457			
Mix 4	1	kN	-51.122	-51.061	-36.920	-38.943	-21.626
		mm	0.00991	0.00965			
	2	kN	-48.945	-48.945	-35.138	-42.575	-18.198
		mm	0.03429	0.03429			
	3	kN	-49.281	-49.06	-36.151	-45.035	-18.532
		mm	0.77038	0.01016			
	4	kN	-53.941	-44.72	-40.828	-44.926	-19.124
		mm	0.81864	0.09652			
Mix 5	1	kN	-52.081	-48.456	-41.030	-47.525	-19.336
		mm	0.06528	0.00533			
	2	kN	-58.87	-48.569	-45.085	-58.259	-22.102
		mm	0.44983	0.00584			
	3	kN	-54.211	-49.955	-44.899	-48.871	-19.652
		mm	0.86538	0.00889			
	4	kN	-60.552	-51.977	-51.500	-57.682	-21.222
		mm	0.91034	0.06071			
	5	kN	-53.171	-53.154	-42.969	-46.068	-19.700
		mm	0.01549	0.01549			
Mix 6	1	kN	-57.42	-51.168	-41.374	-54.091	-20.927
		mm	0.70485	0.03353			

	2	kN	-63.383	-46.598	-41.781	-56.549	-20.213
		mm	0.75692	0.08153			
	3	kN	-60.241	-57.378	-45.323	-59.980	-22.392
		mm	0.4506	0.01651			
	4	kN	-56.832	-44.82	-19.779	-55.331	-19.779
		mm	0.03708	-0.0005			

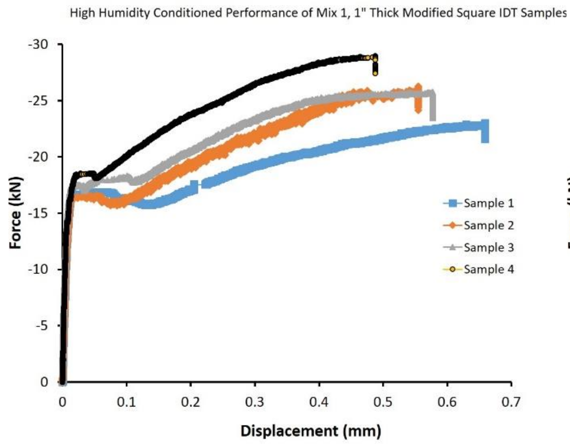
Appendix C.9.2 Individual Sample Performance from the Back Side of the 4" Thick Cylindrical Specimen Exposed in the Barge Environment

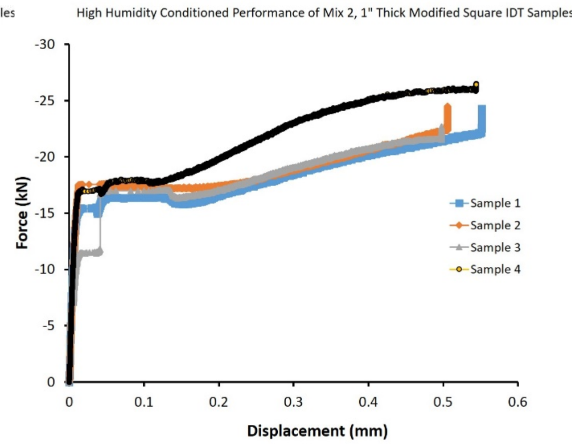
Mixture	Sample	Unit	Max Load	First Peak	Total Area	Load at 0.4 mm	Area at 0.4 mm
Mix 1	1	kN	-70.773	-59.508	-41.280	-66.012	-24.617
		mm	0.64465	0.02286			
	2	kN	-65.793	-54.082	-26.390	-57.817	-21.878
		mm	0.47574	0.0828			
	3	kN	-65.544	-54.58	-29.005	-60.463	-22.523
		mm	0.50343	0.02007			
	4	kN	-71.623	-61.668	-31.390	-66.655	-24.674
		mm	0.49581	0.01702			
Mix 2	1	kN	-61.924	-52.347	-26.858	-55.209	-20.735
		mm	0.50394	0.06426			
	2	kN	-57.105	-51.053	-26.927	-55.165	-21.543
		mm	0.49378	0.00229			
	3	kN	-55.53	-44.411	-23.376	-49.513	-18.408
		mm	0.4986	0.03683			
	4	kN	-65.311	-55.517	-26.629	-55.210	-21.008
		mm	0.49581	0.04039			
Mix 3	1	kN	-51.58	-51.58	-22.849	-47.845	-18.975
		mm	0.02642	0.02642			
	2	kN	-51.058	-49.149	-15.242	-49.098	-15.242
		mm	0.00432	0.00762			
	3	kN	-47.163	-47.163	-22.987	-46.782	-18.588
		mm	0.03226	0.03226			
	4	kN	-52.238	-44.509	-22.433	-49.847	-18.888
		mm	0.47193	0.03912			
Mix 4	1	kN	-51.122	-51.061	-24.999	-38.855	-24.999

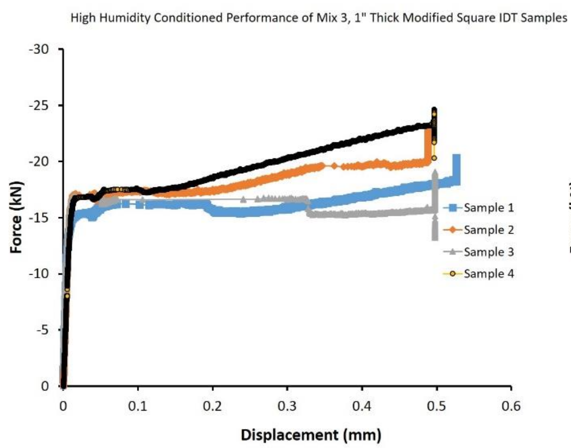
		mm	0.04623	0.04928			
	2	kN	-48.945	-48.945	-22.622	-42.613	-18.470
		mm	0.01575	0.01575			
	3	kN	-49.281	-49.06	-25.654	-44.439	-18.092
		mm	0.56439	0.03073			
	4	kN	-53.941	-44.72	-23.131	-46.060	-18.126
		mm	0.5047	-0.0015			
Mix 5	1	kN	-52.081	-48.456	-23.629	-48.445	-19.970
		mm	0.24638	0.0447			
	2	kN	-58.87	-48.569	-17.967	-46.770	-17.967
		mm	0.36474	0.03988			
	3	kN	-54.211	-49.955	-26.131	-50.059	-19.339
		mm	0.53162	0.02438			
	4	kN	-60.552	-51.977	-31.158	-58.525	-22.387
		mm	0.53873	0.0762			
	5	kN	-53.171	-53.154	-21.482	-46.784	-19.712
		mm	0.02692	0.02642			
Mix 6	1	kN	-57.42	-51.168	-30.056	-53.892	-22.055
		mm	0.54254	0.00864			
	2	kN	-63.383	-46.598	-30.501	-59.972	-22.156
		mm	0.53416	0.00076			
	3	kN	-60.241	-57.378	-27.832	-55.589	-21.732
		mm	0.49835	0.03632			
	4	kN	-56.832	-44.82	-26.748	-54.315	-19.184
		mm	0.53442	0.08661			

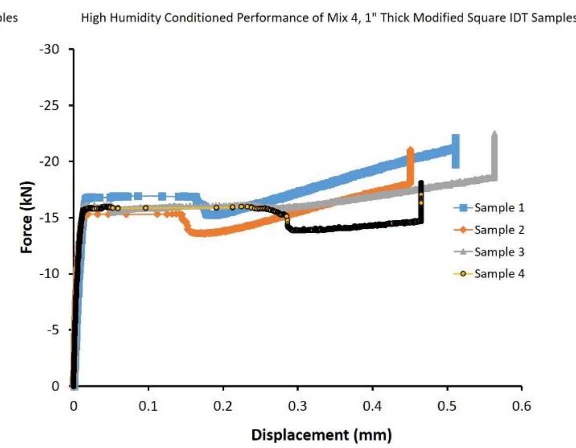
Appendix D. Combined Force-Displacement Graphs for Each Mix in Each Environment

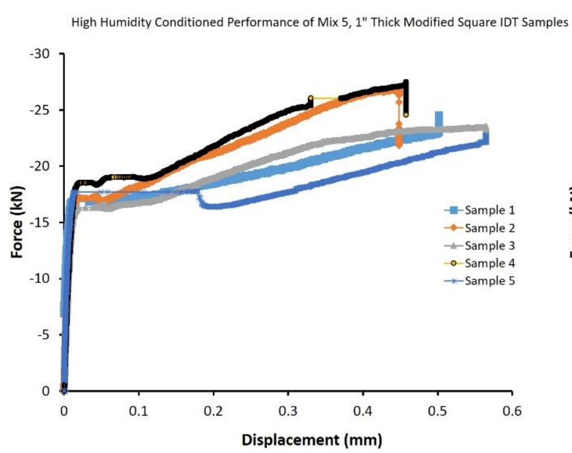
Appendix D.1 Force Displacement Graphs for Each 1" Thick Sample in Each Mix Exposed to High Humidity

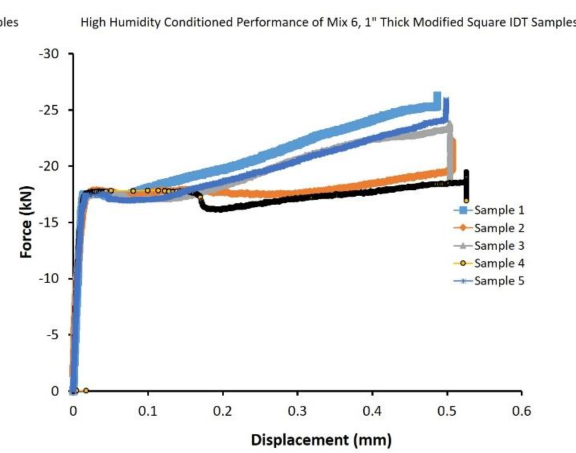




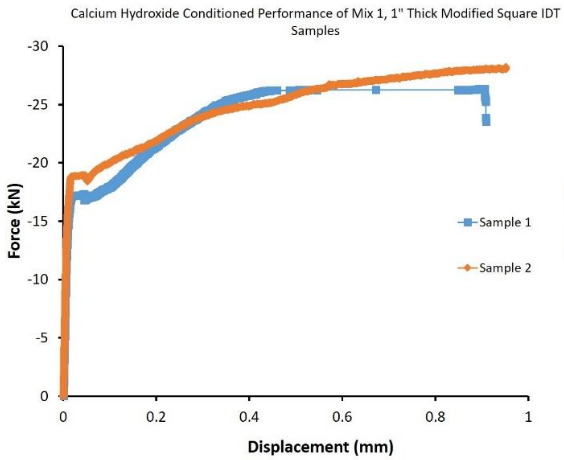


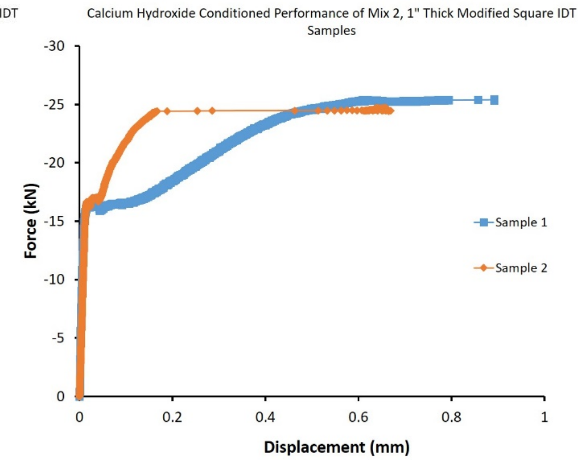


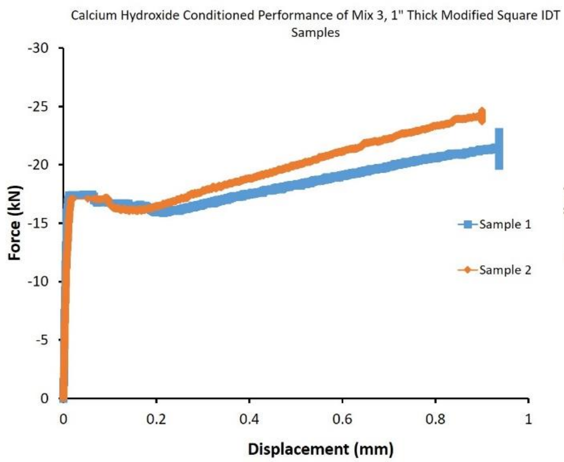


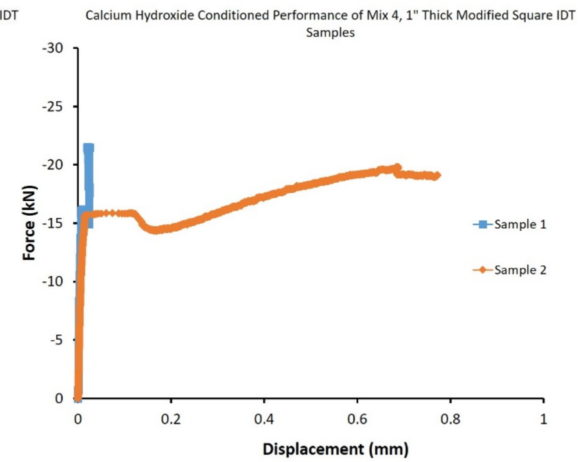


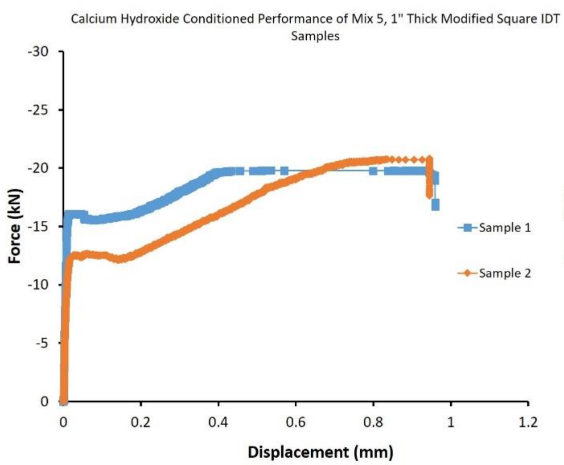
Appendix D.2 Force Displacement Graphs for Each 1" Thick Sample in Each Mix Exposed to the Calcium Hydroxide Solution

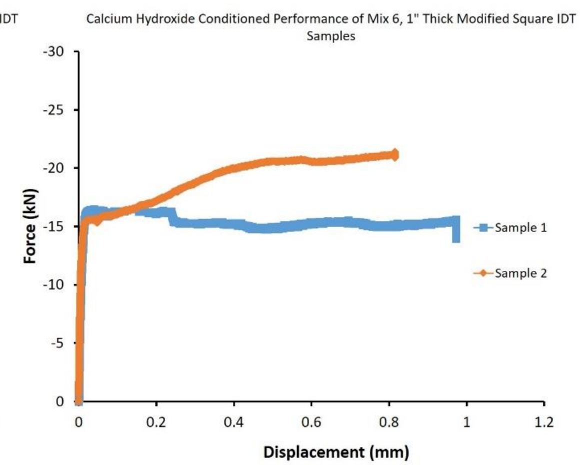




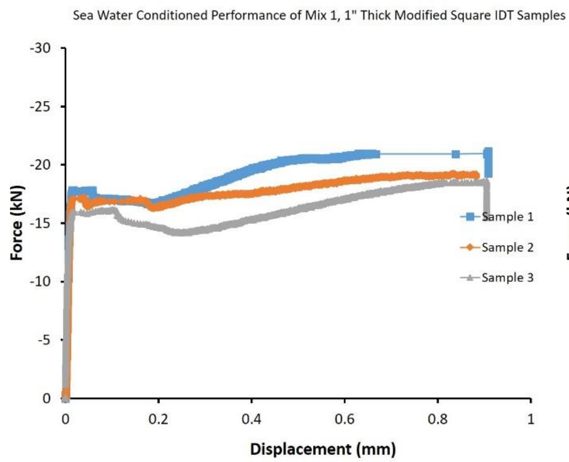


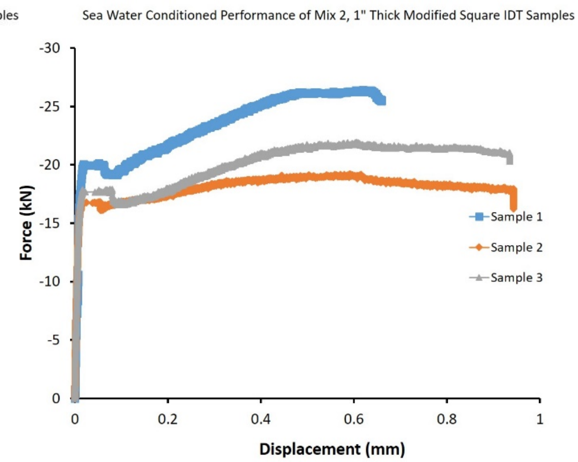


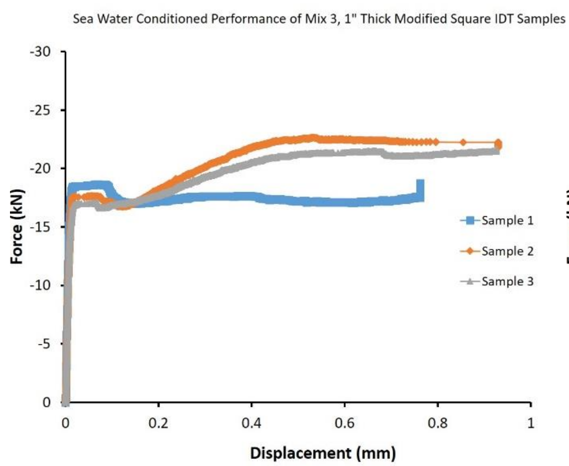


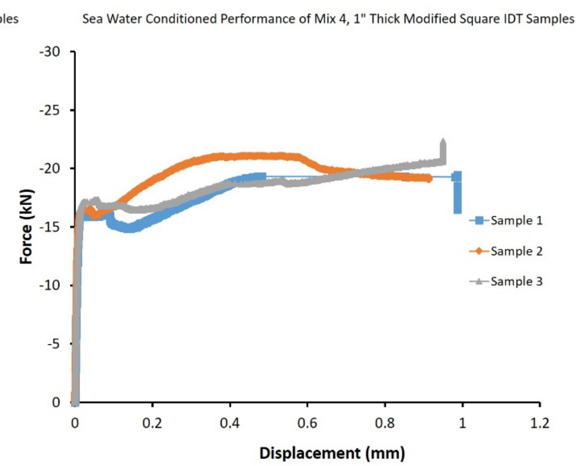


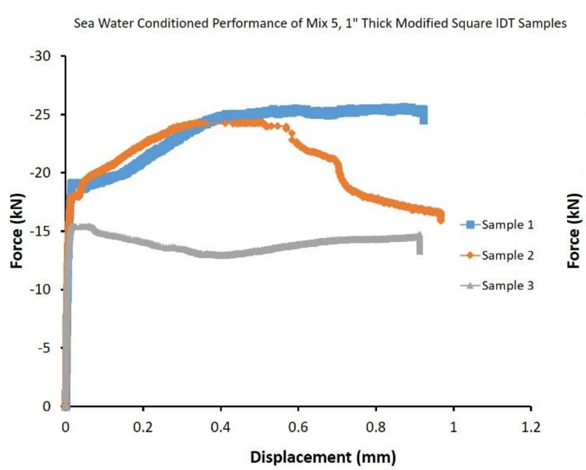
Appendix D.3 Force Displacement Graphs for Each 1" Thick Sample in Each Mix Exposed to the Sea Water Environment

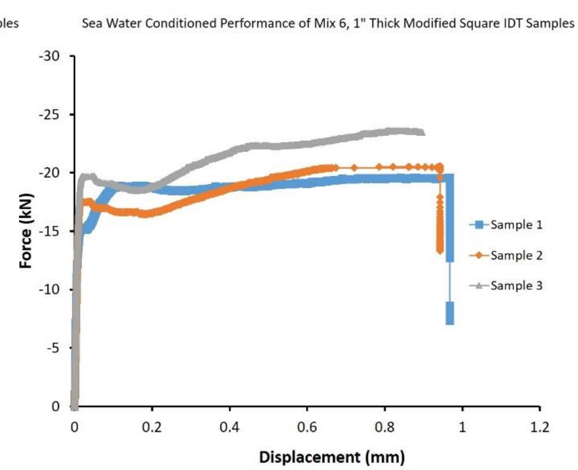




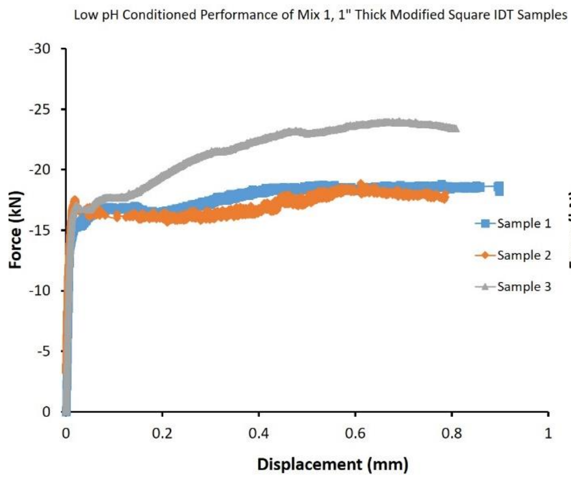


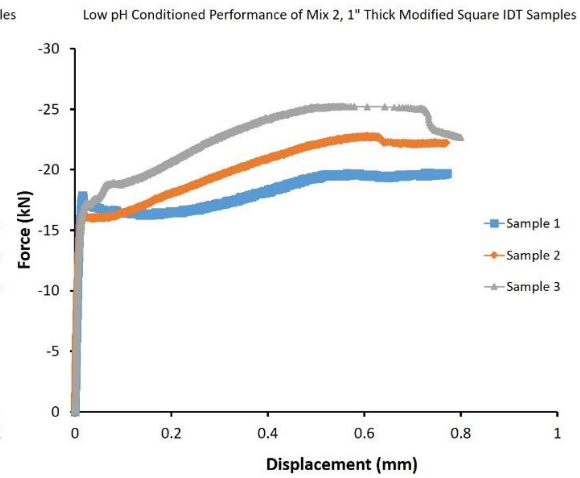


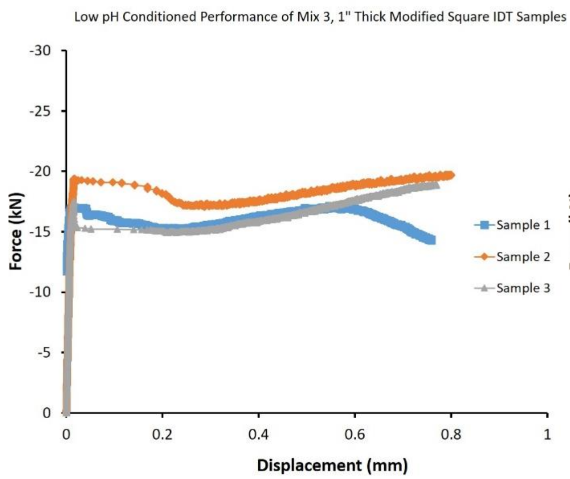


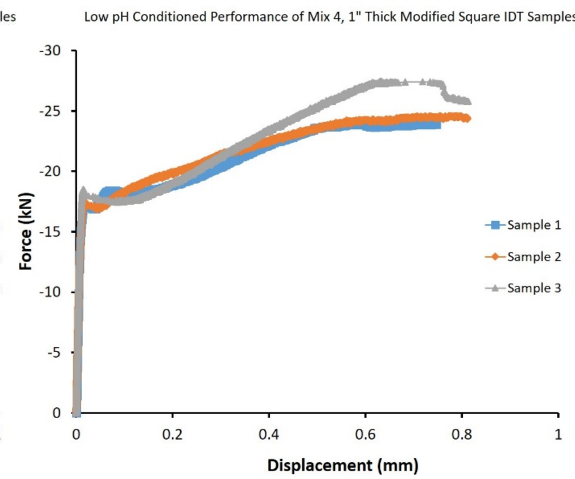


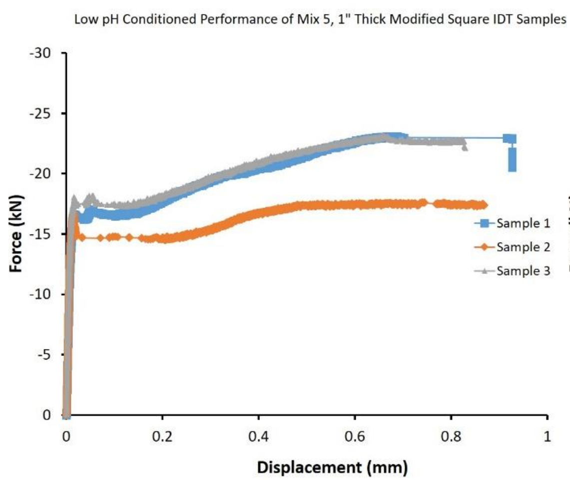
Appendix D.4 Force Displacement Graphs for Each 1" Thick Sample in Each Mix Exposed to the Low pH Environment

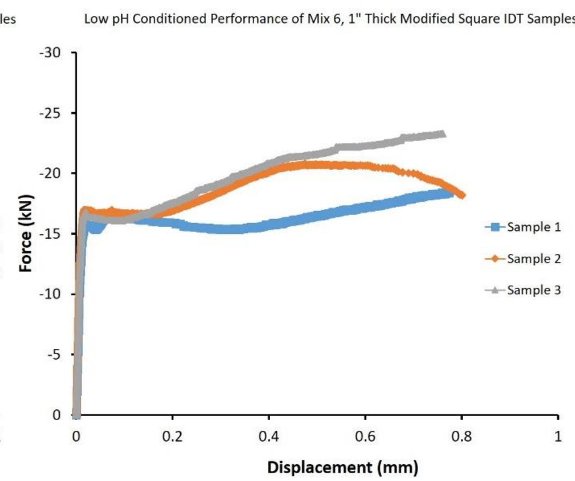




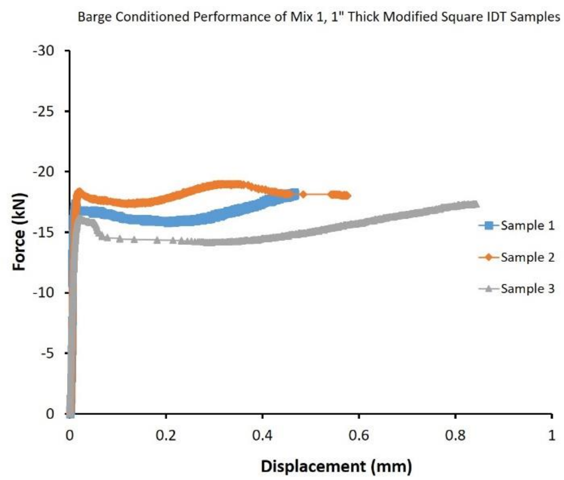


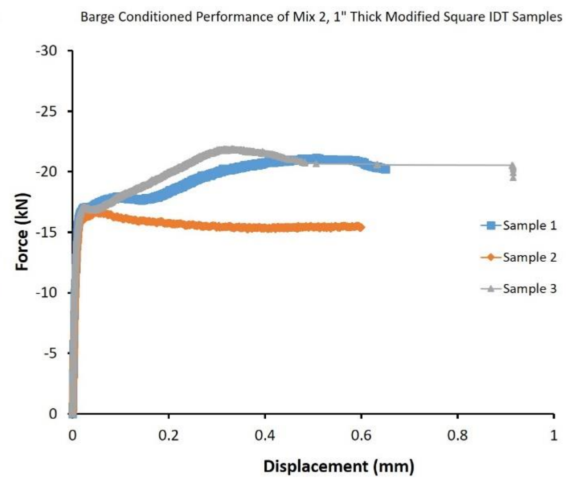


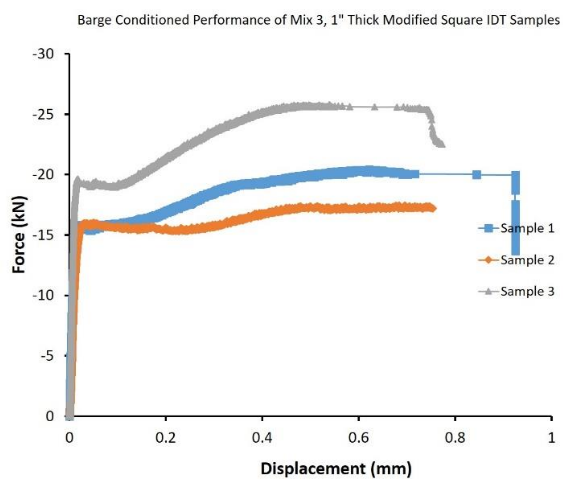


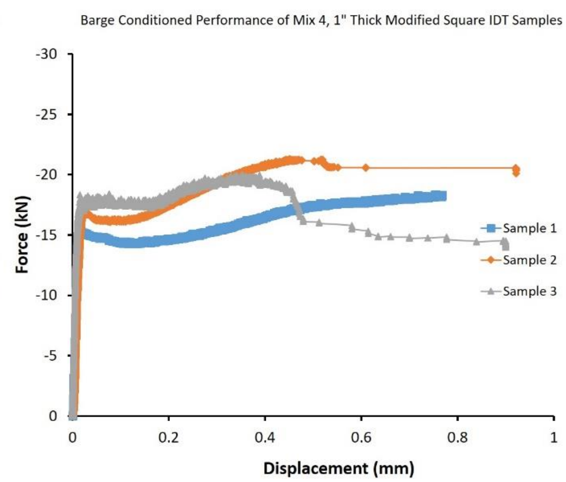


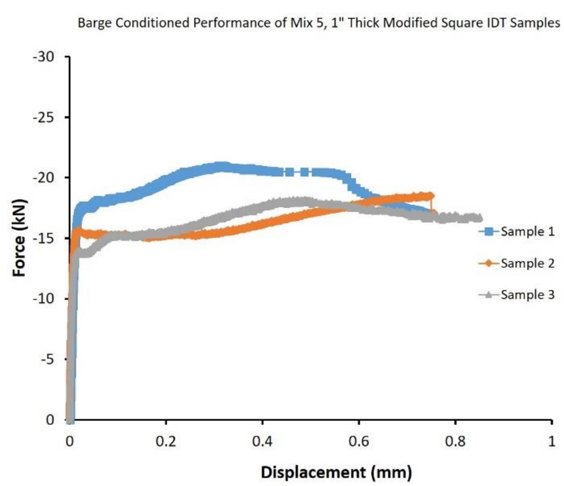
Appendix D.5 Force Displacement Graphs for Each 1" Thick Sample in Each Mix Exposed to the Barge Environment

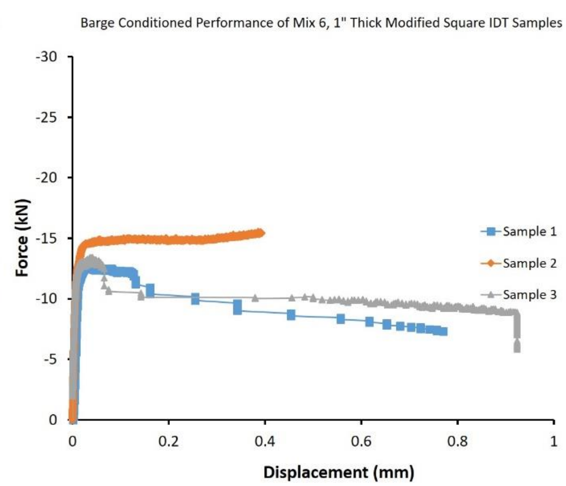




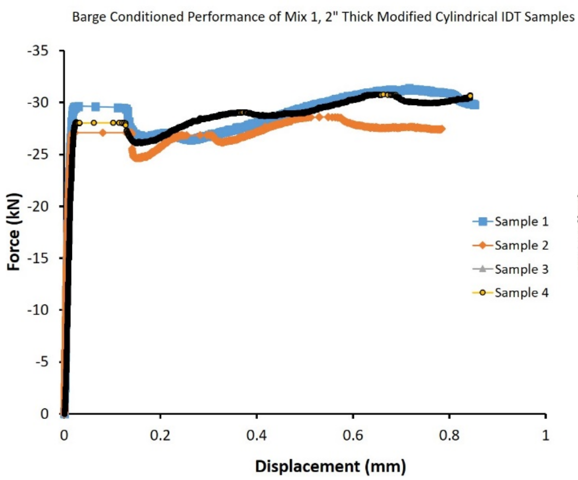


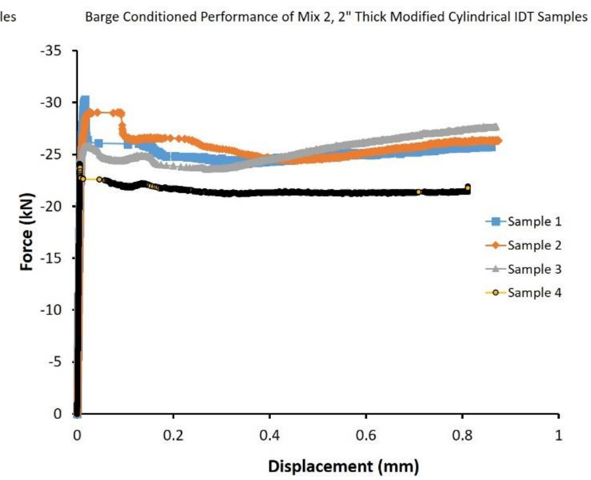


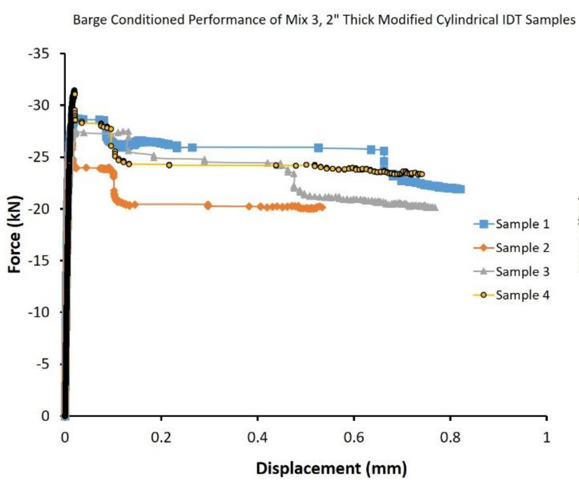


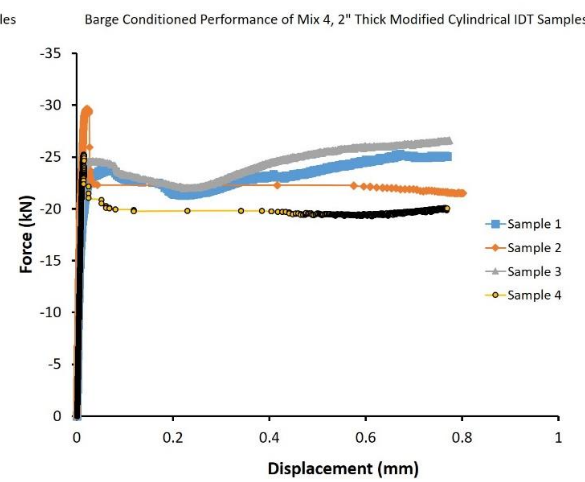


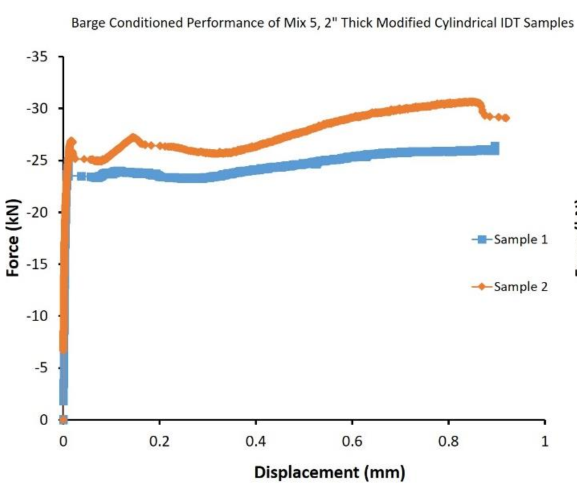
Appendix D.6 Force Displacement Graphs for Each 2" Thick Sample in Each Mix Exposed to the Barge Environment

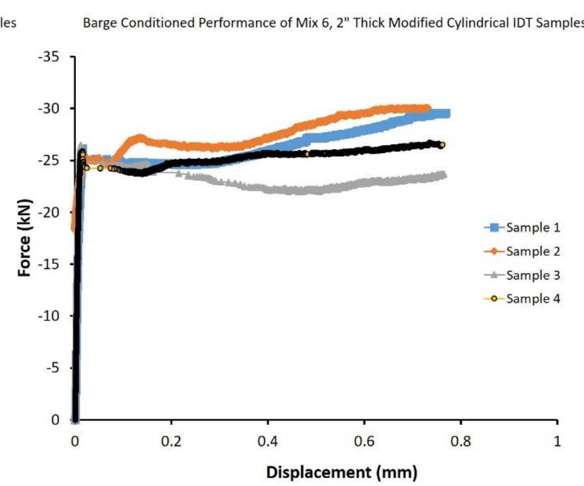




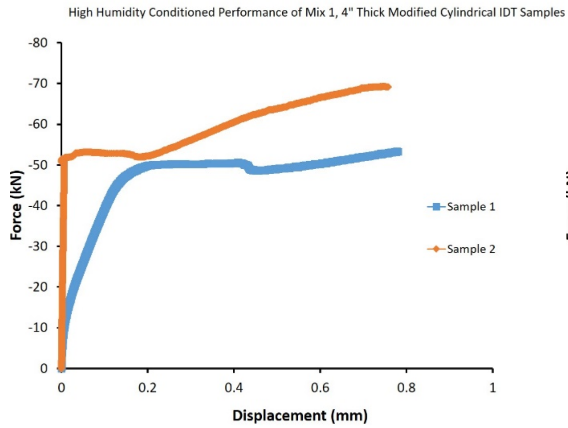


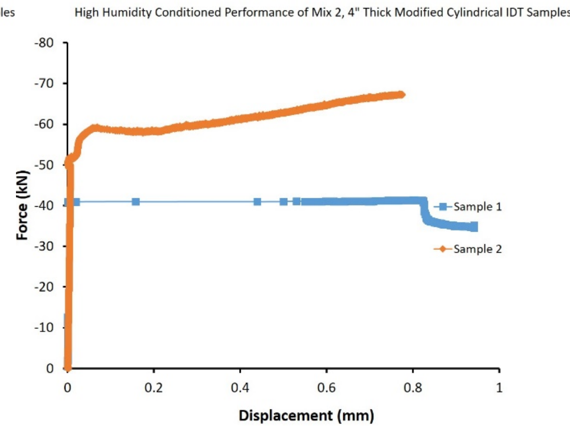


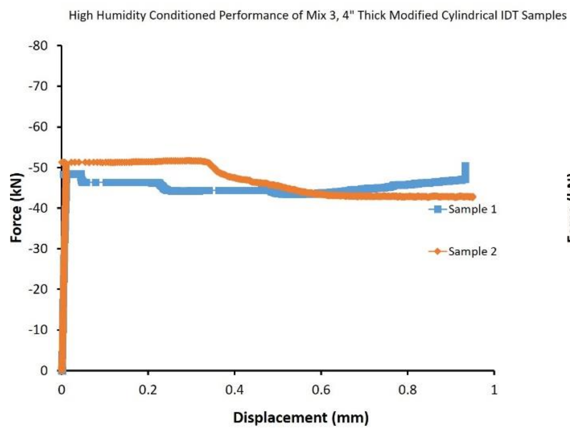


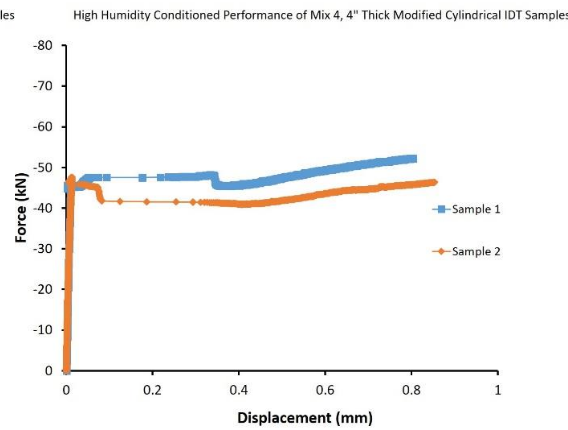


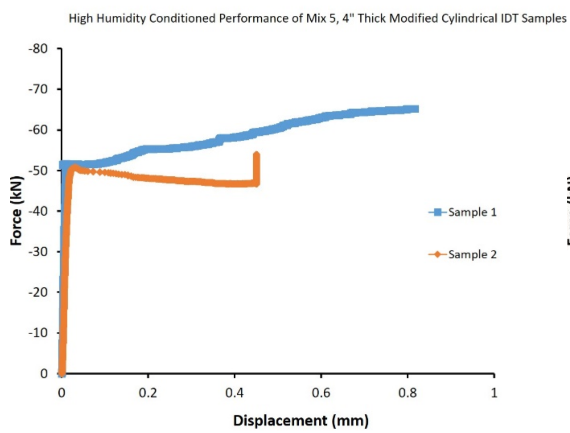
Appendix D.7 Force Displacement Graphs for Each 4" Thick Sample in Each Mix Exposed to High Humidity

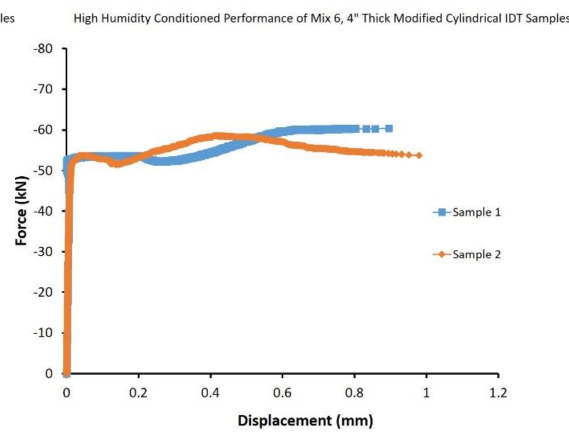




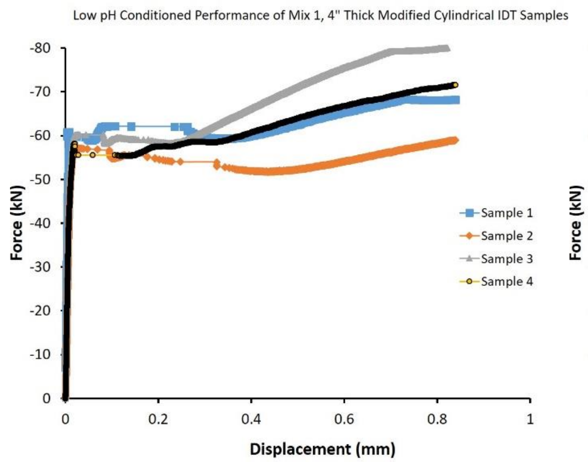


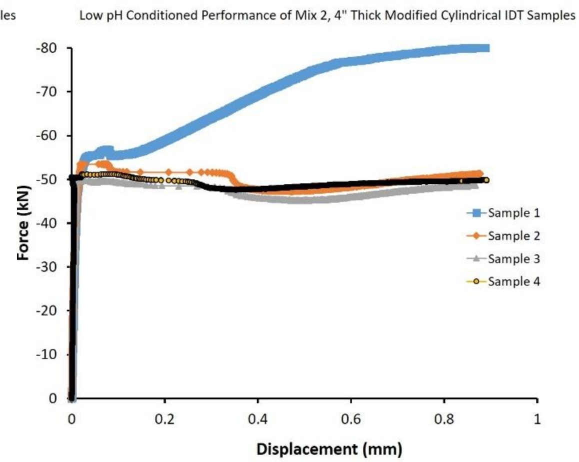


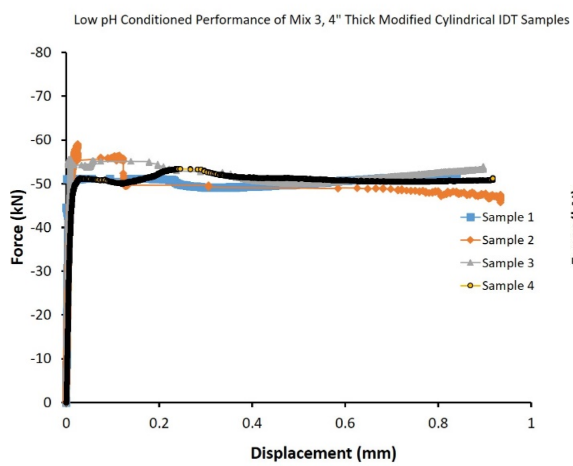


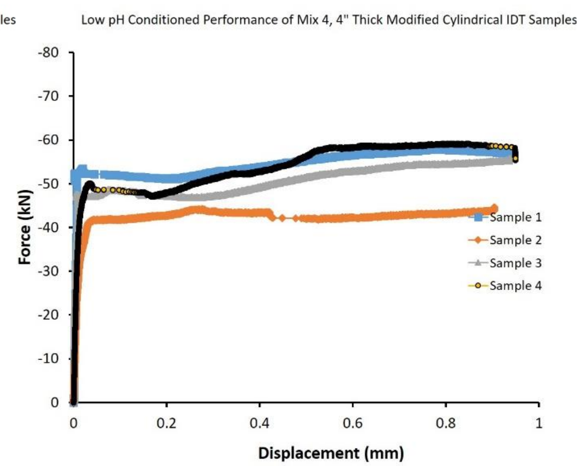


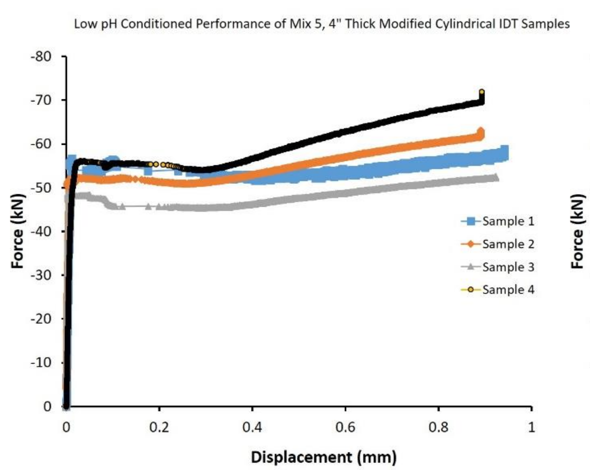
Appendix D.8 Force Displacement Graphs for Each 4" Thick Sample in Each Mix Exposed to the Low pH Environment

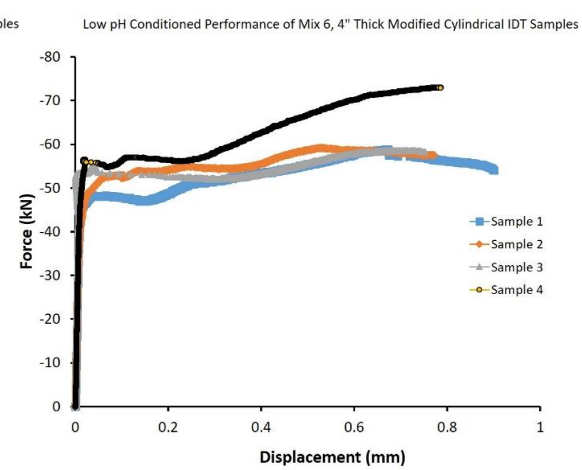




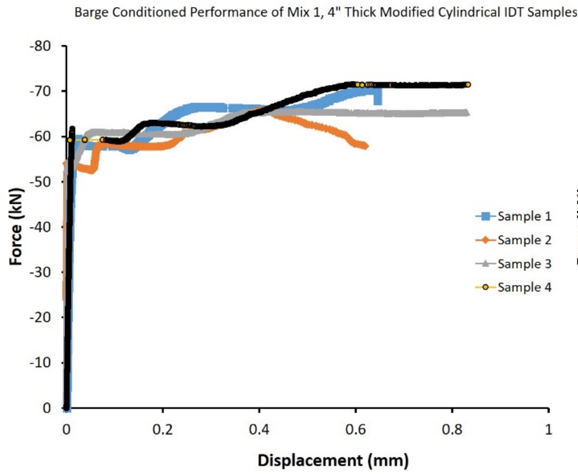


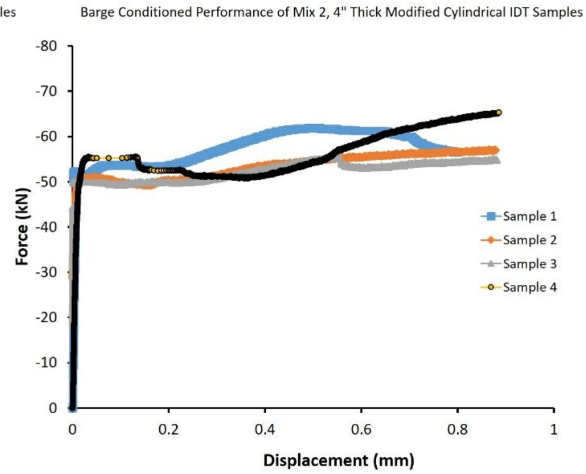


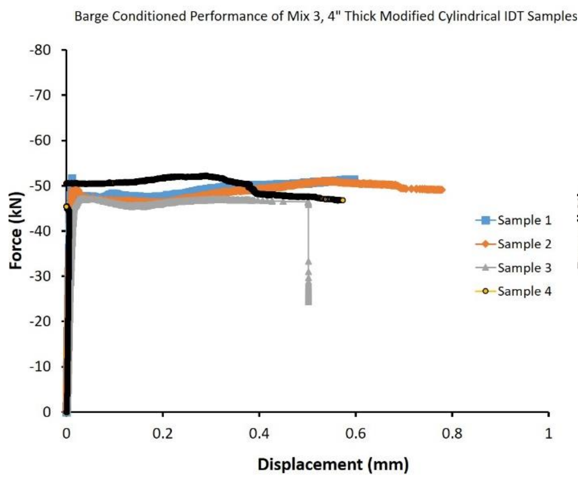


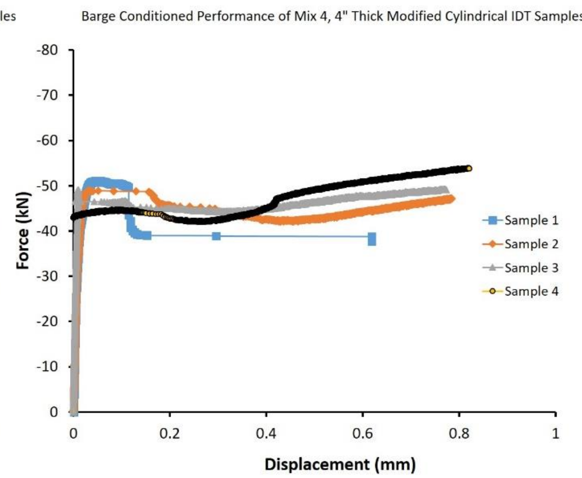


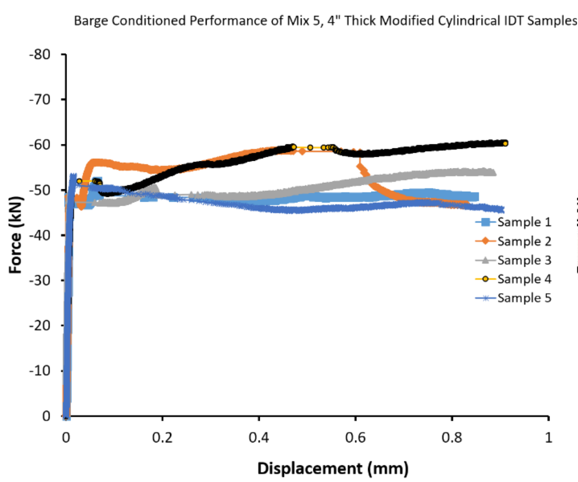
Appendix D.9 Force Displacement Graphs for Each 4" Thick Sample in Each Mix Exposed to the Barge Environment

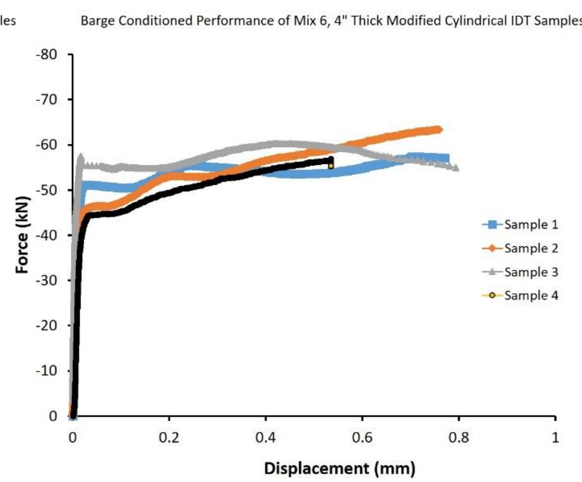












Appendix E. Cross-Sectional Fiber Count for Each Sample in Each Environment

Appendix E.1 Fiber Count of Each 1" Thick Sample's Cross Section in Each Environment.

Testing Condition	Date	Sample	Horizontal		Vertical		Total	
			Pull off	Break	Pull off	Break	Pull off	Break
High Humidity	4/19/2017	1	3	0	0	0	3	0
High Humidity	4/19/2017	2	5	2	0	0	5	2
High Humidity	4/19/2017	3	9	2	0	0	9	2
High Humidity	4/19/2017	4	9	4	0	0	9	4
High Humidity	4/26/2017	1	0	2	0	2	0	4
High Humidity	4/26/2017	2	3	4	1	0	4	4
High Humidity	4/26/2017	3	5	6	0	0	5	6
High Humidity	4/26/2017	4	6	24	0	0	6	24
High Humidity	5/10/2017	1	6	4	0	0	6	4
High Humidity	5/10/2017	2	3	12	0	0	3	12
High Humidity	5/10/2017	3	3	4	0	1	3	5
High Humidity	5/10/2017	4	3	5	0	1	3	6
High Humidity	5/17/2017	1	6	5	0	0	6	5
High Humidity	5/17/2017	2	7	2	0	0	7	2
High Humidity	5/17/2017	3	9	5	0	0	9	5
High Humidity	5/17/2017	4	4	0	1	0	5	0
High Humidity	5/24/2017	1	12	4	0	0	12	4
High Humidity	5/24/2017	2	12	7	0	0	12	7
High Humidity	5/24/2017	3	17	6	0	0	17	6
High Humidity	5/24/2017	4	12	3	0	0	12	3
High Humidity	5/24/2017	5	9	5	0	0	9	5
High Humidity	5/31/2017	1	16	0	0	0	16	0
High Humidity	5/31/2017	2	12	0	0	0	12	0
High Humidity	5/31/2017	3	16	0	0	0	16	0
High Humidity	5/31/2017	4	5	0	0	0	5	0
High Humidity	5/31/2017	5	15	0	0	0	15	0
Sea Water	4/19/2017	1	2	1	0	0	2	1
Sea Water	4/19/2017	2	5	0	1	0	6	0
Sea Water	4/19/2017	3	3	2	0	0	3	2
Sea Water	4/26/2017	1	10	8	0	0	10	8
Sea Water	4/26/2017	2	7	5	2	1	9	6
Sea Water	4/26/2017	3	13	9	0	0	13	9
Sea Water	5/10/2017	1	8	6	0	0	8	6
Sea Water	5/10/2017	2	10	3	2	1	12	4
Sea Water	5/10/2017	3	14	8	0	0	14	8

Sea Water	5/17/2017	1	3	0	1	0	4	0
Sea Water	5/17/2017	2	12	0	0	0	12	0
Sea Water	5/17/2017	3	3	0	2	0	5	0
Sea Water	5/24/2017	1	14	3	0	0	14	3
Sea Water	5/24/2017	2	21	4	0	0	21	4
Sea Water	5/24/2017	3	14	4	0	0	14	4
Sea Water	5/31/2017	1	11	0	1	0	12	0
Sea Water	5/31/2017	2	18	0	0	0	18	0
Sea Water	5/31/2017	3	17	0	0	0	17	0
Barge	4/19/2017	1	6	0	2	0	8	0
Barge	4/19/2017	2	21	5	0	0	21	5
Barge	4/19/2017	3	7	2	0	0	7	2
Barge	4/26/2017	1	12	5	0	0	12	5
Barge	4/26/2017	2	7	4	1	0	8	4
Barge	4/26/2017	3	20	18	0	0	20	18
Barge	5/10/2017	1	10	2	1	0	11	2
Barge	5/10/2017	2	14	6	0	0	14	6
Barge	5/10/2017	3	13	10	0	0	13	10
Barge	5/17/2017	1	3	1	0	0	3	1
Barge	5/17/2017	2	5	0	0	0	5	0
Barge	5/17/2017	3	10	1	0	0	10	1
Barge	5/24/2017	1	18	2	0	0	18	2
Barge	5/24/2017	2	20	4	0	0	20	4
Barge	5/24/2017	3	7	0	0	0	7	0
Barge	5/31/2017	1	13	0	2	0	15	0
Barge	5/31/2017	2	21	0	0	0	21	0
Barge	5/31/2017	3	14	0	0	0	14	0
Low Ph	4/19/2017	1	14	0	1	0	15	0
Low Ph	4/19/2017	2	3	1	0	0	3	1
Low Ph	4/19/2017	3	15	6	0	0	15	6
Low Ph	4/26/2017	1	16	10	0	0	16	10
Low Ph	4/26/2017	2	28	11	0	0	28	11
Low Ph	4/26/2017	3	9	5	2	0	11	5
Low Ph	5/10/2017	1	12	4	1	0	13	4
Low Ph	5/10/2017	2	12	2	0	0	12	2
Low Ph	5/10/2017	3	15	7	0	0	15	7
Low Ph	5/17/2017	1	11	0	0	0	11	0
Low Ph	5/17/2017	2	15	7	0	0	15	7
Low Ph	5/17/2017	3	16	5	0	0	16	5
Low Ph	5/24/2017	1	5	1	3	1	8	2
Low Ph	5/24/2017	2	5	6	0	0	5	6
Low Ph	5/24/2017	3	15	4	0	0	15	4

Low Ph	5/31/2017	1	21	0	0	0	21	0
Low Ph	5/31/2017	2	20	0	0	0	20	0
Low Ph	5/31/2017	3	28	0	0	0	28	0
Calcium Hydroxide	4/19/2017	1	18	4	3	0	21	4
Calcium Hydroxide	4/19/2017	2	20	4	0	0	20	4
Calcium Hydroxide	4/26/2017	1	8	7	0	0	8	7
Calcium Hydroxide	4/26/2017	2	3	5	0	0	3	5
Calcium Hydroxide	5/10/2017	1	13	6	0	0	13	6
Calcium Hydroxide	5/10/2017	2	6	6	0	0	6	6
Calcium Hydroxide	5/17/2017	1	3	0	1	0	4	0
Calcium Hydroxide	5/17/2017	2	8	5	0	0	8	5
Calcium Hydroxide	5/24/2017	1	7	2	0	0	7	2
Calcium Hydroxide	5/24/2017	2	16	1	0	0	16	1
Calcium Hydroxide	5/31/2017	1	5	0	0	0	5	0
Calcium Hydroxide	5/31/2017	2	6	0	0	0	6	0
Total			986	328	28	7	1014	335

Appendix E.2 Fiber Count of Each 2" Thick Sample's Cross Section in Each Environment.

Testing Condition	Date	Sample	Horizontal		Vertical		Total	
			Pull off	Break	Pull off	Break	Pull off	Break
Barge	4/19/2017	1	26	9	0	0	26	9
Barge	4/19/2017	2	25	16	1	0	26	16
Barge	4/19/2017	3	34	10	0	0	34	10
Barge	4/19/2017	4	36	13	1	0	37	13
Barge	4/26/2017	1	25	27	1	0	26	27
Barge	4/26/2017	2	18	24	0	0	18	24
Barge	4/26/2017	3	25	13	2	0	27	13
Barge	4/26/2017	4	12	22	0	0	12	22
Barge	5/10/2017	1	18	7	0	0	18	7

Barge	5/10/2017	2	18	8	1	0	19	8
Barge	5/10/2017	3	15	14	0	0	15	14
Barge	5/10/2017	4	9	10	0	0	9	10
Barge	5/17/2017	1	11	7	0	0	11	7
Barge	5/17/2017	2	10	7	2	0	12	7
Barge	5/17/2017	3	17	11	0	0	17	11
Barge	5/17/2017	4	20	10	0	0	20	10
Barge	5/24/2017	1	12	11	3	0	15	11
Barge	5/24/2017	2	24	7	0	0	24	7
Barge	5/31/2017	1	51	0	0	0	51	0
Barge	5/31/2017	2	58	0	0	0	58	0
Barge	5/31/2017	3	35	0	2	0	37	0
Barge	5/31/2017	4	34	0	0	0	34	0
Total			533	226	13	0	546	226

Appendix E.3 Fiber Count of Each 4" Thick Sample's Cross Section in Each Environment.

Testing Condition	Date	Sample	Horizontal		Vertical		Total	
			Pull off	Break	Pull off	Break	Pull off	Break
High Humidity	4/19/2017	1	27	14	0	0	27	14
High Humidity	4/19/2017	2	28	25	0	0	28	25
High Humidity	4/26/2017	1	20	31	0	0	20	31
High Humidity	4/26/2017	2	42	44	5	0	47	44
High Humidity	5/10/2017	1	25	46	1	0	26	46
High Humidity	5/10/2017	2	19	28	0	0	19	28
High Humidity	5/17/2017	1	28	20	0	0	28	20
High Humidity	5/17/2017	2	22	25	0	0	22	25
High Humidity	5/24/2017	1	54	18	0	0	54	18
High Humidity	5/24/2017	2	39	18	0	0	39	18
High Humidity	5/31/2017	1	68	1	0	0	68	1
High Humidity	5/31/2017	2	85	0	0	0	85	0
Barge	4/19/2017	1	57	16	0	0	57	16
Barge	4/19/2017	2	38	23	3	0	41	23
Barge	4/19/2017	3	48	19	1	0	49	19
Barge	4/19/2017	4	38	28	2	0	40	28
Barge	4/26/2017	1	50	46	4	0	54	46
Barge	4/26/2017	2	63	27	5	0	68	27
Barge	4/26/2017	3	54	20	2	0	56	20
Barge	4/26/2017	4	68	32	1	0	69	32
Barge	5/10/2017	1	42	32	0	1	42	33

Barge	5/10/2017	2	48	29	6	2	54	31
Barge	5/10/2017	3	20	8	3	0	23	8
Barge	5/10/2017	4	31	30	1	0	32	30
Barge	5/17/2017	1	28	11	0	0	28	11
Barge	5/17/2017	2	28	7	0	1	28	8
Barge	5/17/2017	3	27	20	1	0	28	20
Barge	5/17/2017	4	33	15	0	0	33	15
Barge	5/24/2017	1	41	17	0	0	41	17
Barge	5/24/2017	2	53	17	0	0	53	17
Barge	5/24/2017	3	34	18	0	0	34	18
Barge	5/24/2017	4	56	12	1	0	57	12
Barge	5/24/2017	5	30	15	0	0	30	15
Barge	5/31/2017	1	74	0	3	0	77	0
Barge	5/31/2017	2	83	0	0	0	83	0
Barge	5/31/2017	3	83	1	0	0	83	1
Barge	5/31/2017	4	76	1	1	0	77	1
Low Ph	4/19/2017	1	42	23	0	0	42	23
Low Ph	4/19/2017	2	28	25	0	0	28	25
Low Ph	4/19/2017	3	39	38	0	0	39	38
Low Ph	4/19/2017	4	40	25	4	0	44	25
Low Ph	4/26/2017	1	112	54	6	3	118	57
Low Ph	4/26/2017	2	45	32	0	0	45	32
Low Ph	4/26/2017	3	38	24	1	0	39	24
Low Ph	4/26/2017	4	44	29	1	0	45	29
Low Ph	5/10/2017	1	48	24	2	0	50	24
Low Ph	5/10/2017	2	40	15	1	0	41	15
Low Ph	5/10/2017	3	57	22	2	0	59	22
Low Ph	5/10/2017	4	36	16	3	0	39	16
Low Ph	5/17/2017	1	26	19	0	0	26	19
Low Ph	5/17/2017	2	26	12	0	0	26	12
Low Ph	5/17/2017	3	38	21	0	0	38	21
Low Ph	5/17/2017	4	34	18	0	0	34	18
Low Ph	5/24/2017	1	33	18	1	0	34	18
Low Ph	5/24/2017	2	45	18	0	0	45	18
Low Ph	5/24/2017	3	26	13	0	0	26	13
Low Ph	5/24/2017	4	41	29	0	0	41	29
Low Ph	5/31/2017	1	76	0	1	0	77	0
Low Ph	5/31/2017	2	89	0	0	0	89	0
Low Ph	5/31/2017	3	90	0	0	0	90	0
Low Ph	5/31/2017	4	93	0	0	0	93	0
Total			2846	1189	62	7	2908	1196

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