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Evaluation of Protection of FRP Wrap on Bridge Piers from Corrosive Effects of Snow and Ice Chemicals

Honors Thesis

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Department: Civil and Environmental Engineering

Advisor: Elias Toubia, PhD, P.E.

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Abstract

Highway bridge components, such as decks and piers, are structures that are often exposed to chlorine-heavy chemicals. Corrosion of rebar, one of the main contributors to structural deficiencies in highway bridges, is largely caused by chloride contamination from exposure to deicing salts and chemicals. Current forms of external protection to highway bridge piers include paint coatings, shells, and wraps. This thesis will focus on the protective capabilities that Fiber Reinforced Polymer (FRP) wraps could provide to bridge piers. ASTM C666 was utilized to recreate environmental conditions, during which concrete samples were exposed to calcium chloride. ASTM C1760-12 was utilized to determine the bulk electrical conductivity of samples exposed and not exposed to calcium chloride, in order to overall evaluate the protection that the wraps provided to the concrete samples. Overall, tests showed that unexposed GFRP wrap provided a slight layer of protection to the concrete. However, exposed FRP wraps did not provide protection to the concrete, and in some cases, even caused a reduction in resistivity of the concrete.

Dedication or Acknowledgements

Special thanks to University of Dayton Honors Program for funding, as well as Dr. Elias Toubia and Sadra Emami for helping guide this project.

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Introduction

The need for protecting infrastructure is a growing concern in the United States. In 2012, the Federal Highway Administration (FWHA) estimated total replacement and rehabilitation costs for structurally deficient highway bridges to be approximately 87 billion dollars [Ohio]. One of the main contributors to these structural deficiencies, particularly in bridges, is the use of chlorine-induced chemical solutions. Often found in deicer solutions used to prevent snow, ice, or frost from accumulating, the chloride in the solutions can cause corrosion of reinforcing steel within bridge structures [Ohio]. In 2013, 15% of bridges in the US were found to be deficient after a life of only thirty years, with one of the main contributors to structural damage being corrosion [Dhakal]. Additionally, the accumulation of chloride ions from the deicing chemicals negatively affects the concrete itself, causing spalling and degradation. Overall, the strength and service life of the pier can be negatively affected, and potentially cause future structural issues [Pantazopoulou].

Many methods have been created, and are still being created, in order to protect concrete structures, like highway bridge piers, against the attack of these deicers. Internal protection methods include the use of epoxy-coated steel, catholic protection methods, or corrosion inhibitors [Kepler]. External protection methods, those used on the exterior surface of the concrete, include protective paint coatings, hard shells, and wraps [Kepler]. Each method varies in cost, application, life span, and reliability. This study specifically focused on the use of Fiber Reinforced Polymer (FRP) wraps.

Fiber Reinforced Polymer Wraps

Fiber Reinforced Polymers, referred to as FRPs, consist of fibers bound tightly together in a resin matrix. FRP wraps are used in a variety of applications, ranging from structural to chemical uses, and are found in anything from helicopters to civil infrastructure [Masuelli]. The FRP is composed of two distinct phases: the first phase is composed of fibers bound together, and the second consists of a resin, either thermoset or thermoplastic. The fiber phase is commonly made from carbon, glass, aramid, or another type of synthetic material. The fibers can be manipulated in a variety of ways: cut short, elongated, chopped, or woven. The function of the second phase resin is to bind these

fibers together, allowing the transfer of stress. Additionally, the resin protects the fibers against any environmental or mechanical damage. Thermoset resins are liquid at room temperature, but then cure into a hardened, insoluble polymer form that cannot be reversed. These resins are mainly composed of polyester, vinyl ester, polyurethane, or epoxy materials. Thermoplastic resins start solid at room temperature, are heated to a liquid state, and then cooled and hardened under pressure [McDaniel].

FRPs can be manufactured in the form of plates, laminates, bars, cables, and wraps. They are traditionally used for strengthening of civil structures' strength, stiffness, ductility, or durability [McDaniel]. FRPs utilized as an external protection method is a comparatively new field of research.

Deicing Chemicals

Deicing chemicals are those that are used to melt existing snow and ice. Currently, the most common deicing chemicals utilized by Departments of Transportation throughout the country are sodium chloride, magnesium chloride, calcium chloride, and some new, more natural and organic solutions. All solutions containing chloride have been found to be harmful to concrete, both degrading the concrete physically and chemically [Shi]. The exposure that concrete bridge piers have to these chemical solutions varies drastically, dependent on location, local weather conditions, and traffic patterns.

In a study done by University of Kansas, it was found that while at low concentrations, calcium chloride can have a small impact on concrete properties; at higher concentrations, calcium chloride can greatly alter the properties of concrete, reducing the overall strength and stiffness of the material [Darwin]. Similarly, wetting of the concrete with the de-icer in a cyclic manner can cause deterioration of the concrete to increase [Darwin].

The study done by the University of Kansas, as well as several other research studies, often measured the moduli of elasticity of concrete samples. Samples exposed to calcium chloride experienced a significant drop in the modulus over time, resulting in a reduction of stiffness and strength [Darwin].

The physical effect of deicers on concrete surfaces can easily be seen, and has been analyzed in various studies. The chemical effect of deicers is an area that is being researched more, trying to understand the interaction of deicer fluids with the cement paste and aggregates of the concrete mix. Researchers believe that this chemical interaction is what causes a loss of stiffness and strength [Shi].

Concrete mixes for bridge piers are designed with this potential negative effect in mind. Ground granulated blast-furnace slag (GGBFS) is commonly utilized in order to protect against chloride intrusion, overall increasing the structural life of the bridge pier and reducing the need for stainless steel reinforcing. Air entrainment is added to the concrete in order to create small bubbles, allowing a place for water to expand when freezing, and limiting internal additional stresses on the concrete. Air entrainment is usually in the 4% to 7% range [Air-entrained].

Reinforcing steel is also negatively affected by chloride ions. A protective oxide layer that is developed when cement hydration starts is destroyed when chloride ions are present. The corrosion of steel has two negative consequences: first, the increase in volume of the steel causes cracking of the concrete that can lead to spalling; second, the decrease of the cross-sectional area of the steel causes its capacity to be reduced, weakening the structure [Neville].

Electrical Resistivity and Concrete Durability

Durability is the ability for concrete to maintain its strength and primary properties under differing conditions over time. Chloride ion intrusion is an example of what would reduce the durability of concrete. Durability is affected by the microstructure of the concrete, specifically the pore network, size, and channel structure [Electrical]. Smaller pores that are not connected have a lower permeability, and stronger durability.

Measuring the resistance of concrete to the transfer of ions can reveal the resistivity of a concrete sample, and can reveal the inner structure and permeability of the concrete. The resistivity of concrete can be affected by the connectedness of the internal concrete microstructure, the porosity and conductivity of the pore solution, moisture content, temperature, geometry of the specimen, and electrical signal frequency

[Electrical]. Using established relationships, the resistivity of the concrete can be utilized to determine the Chlorine Ion Penetrability for the purpose of this study.

Two different ASTM test methods were examined for this purpose. ASTM C1202-12, “Standard Test Method for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration” determines the electrical conductance of a concrete sample. The concrete sample is put in a test cell in between a 3% NaCl solution and a 0.3 M NaOH solution, and hooked to a 60 V power supply. Every 30 minutes, a current passing through the concrete is recorded, the duration of the test being six hours [ASTM C12012-12]. Similar in setup, ASTM C1760-12, “Bulk Electrical Conductivity of Hardened Concrete”, measures the bulk conductivity of a concrete sample. This current is measured in one minute, and can be mathematically manipulated to correlate to an equivalent charge value from the six hour test [ASTM C1760-12]. Because of time limitations, ASTM C1760-12 was chosen to utilize in this study.

Purpose of Study

The purpose of this study was to determine if FRP could be a suitable external cover to protect concrete bridge piers against the detrimental effects of deicers. Within the study, samples with and without FRP are evaluated throughout testing and compared to one another. Similarly, samples with CFRP and GFRP as covers are compared to one another to determine if one FRP type provides a better protective layer to the concrete.

Materials

Concrete

The concrete mix chosen to use for testing was representation of the mix utilized by Ohio Department of Transportation for highway bridge piers in Ohio and surrounding Midwestern states. The compressive strength of highway concrete bridge piers is usually specified to be above 6000 psi. It is very common to add 1037 admixture to the concrete mix, reducing the water needed, while producing a flowing, workable concrete with sufficient strength. The mix composition chosen can be seen below in Table 1. While normally highway bridge piers utilize aggregates larger than pea gravel, the size was decreased due to the small size of the cylinders being utilized in testing.

Table 1: Concrete Mix Specifications

Date
Cylinders with rebar (Batch 1) made 9/20/2016
Cylinders without rebar (Batch 2) made 9/29/2016
**Same batch specifications used for both batches*

CONCRETE MIX SPECIFICATIONS			
Mixture		**Results**	
Material	***Amount***	Volume	1.1 ft^3
#57 Gravel	0.00 lb	Slump	7.5 in
#8 Peagravel	71.90 lb	Air	6 %
Sand	49.80 lb	Unit Weight$_1$	142.9 pcf
Cement	16.10 lb	Unit Weight$_2$	35.85 pcf
GGBFS100	10.70 lb		
Water	7.80 lb		
Moisture			
#57 Stone Moisutre	0.00 %		
#8 Peagravel Moisture	1.50 %		
Sand Moisture	5.00 %		
Admixtures			
Air	6.34 mL		
1037	79.19 mL		

After mixed, it was found that the concrete had the correct air entrainment of 6%, a slump of 7.5 inches, and a unit weight of 142.9 pcf, all acceptable measures compared to concrete bridge piers.

GFRP Wrap

The GFRP Wrap chosen for this study was a unidirectional glass fabric, intended to be utilized with an epoxy matrix. The glass fibers were oriented in the 0° direction, with additional yellow glass cross fibers at 90°. The material was characterized as being suitable for use in both high and low temperature profiles. The density of the material was 0.092 lbs/in^3.

CFRP Wrap

Similar to composition as the GFRP Wrap, the CFRP wrap chosen was a unidirectional fabric oriented in the 0° direction. However, unlike the GFRP, there were no additional cross fibers perpendicular to the main fibers. The material was suitable for use in both high and low temperature profiles. The density of the material was 0.063 lbs/in^3.

Epoxy

Both the CFRP and GFRP composites were customized to be combined with a particular epoxy, per the manufacturer's specifications. The epoxy recommended by the manufacturer was utilized. The epoxy was applied to the FRP using a brush, saturating and fully covering the fabric.

Deicing Fluid

A 32% solution of calcium chloride was chosen to use as the deicing agent during testing. This particular solution was chosen, as it was one of the more harmful and more common solutions currently used by Ohio Department of Transportation.

Testing

Test Preparation

The test samples observed during this study were eight inch long by four inch diameter cylinders. Nineteen cylinders were filled with the above specified concrete mix. Within fourteen of the nineteen cylinders, a six inch long ½' diameter piece of reinforcing steel was placed, in order to increase the potential for chloride ions to penetrate the concrete. The steel was longitudinally centered, leaving approximately one inch of concrete cover above and below the steel, as seen Figure 1 below. The steel was also laterally centered in the cylinder, leaving about 1.75" of cover on either side.

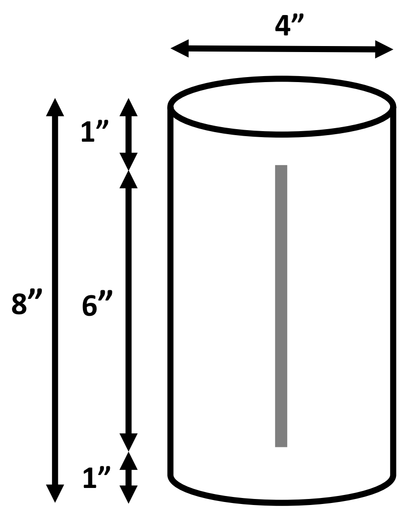


Figure 1: Reinforced Cylinder Setup

All cylinders were cured according to ASTM standards for at least 18 days inside of a Forney concrete curing chamber. After curing, ten samples with steel reinforcing were chosen to be covered with FRP, five of which would be CFRP, five of which would be GFRP. Each FRP cover was cut to match the surface area of the cylinder. Plastic cylinders were left surrounding the concrete, however, the cap was removed. This exposed area was then covered with the circle-cut FRP. After application, the samples were cured according to the manufacturer's recommendations, before being tested. All observations for individual cylinders before testing can be seen in the Appendix in Table A.3.

Tests Performed

In order to determine if the FRPs provided protection to the concrete cylinders, two distinct tests were performed during this study, ASTM C666 and ASTM C1760-12. Each will be described separately due to the distinct nature of the tests. However, quantitative and qualitative results from both tests were utilized in order to make concluding statements in this study.

ASTM C666

ASTM C666 exposes concrete specimens to freezing and thawing temperature cycles. No quantitative results were expected from this test; rather, the test was performed to observe the effects of exposure to calcium chloride in a temperature-changing chamber on the samples. The traditional test method, as explained by the ASTM standards, was altered slightly in order to modify the test for this study's purpose.

The ten FRP covered samples, as well as two uncovered and reinforced samples, were placed in a temperature-controlled chamber. The chamber fluctuated from -40° C to 40° C, each cycle lasting six hours. Overall, the cylinders were exposed to 228 cycles total, remaining in the temperature chamber for eight weeks.

During the first two weeks, as well as the last two weeks, all of the cylinders were exposed to a 32% solution of calcium chloride. The cylinders were sprayed with 10 mL of this solution once a day during these four weeks. Therefore, overall, the cylinders were exposed for approximately 114 cycles to the calcium chloride solution.

ASTM C1760-12

ASTM C1760-12 was utilized to determine the bulk electrical conductivity of both exposed and unexposed, covered and uncovered samples. Samples either one or two inches in length were put in the Perma2, the device used to run ASTM C1760-12. Surrounded on one side by 0.3 M NaOH and the other by 3% NaCl, the test cell was connected to a 60 V power source, and a current was forced through the concrete specimen. At the end of the one minute test period, a current was determined, which was then related to a chloride ion penetration rating. Those specimens that were covered by

GFRP and CFRP were put in the test cell so the current would run through the wall of the covered side of concrete first.

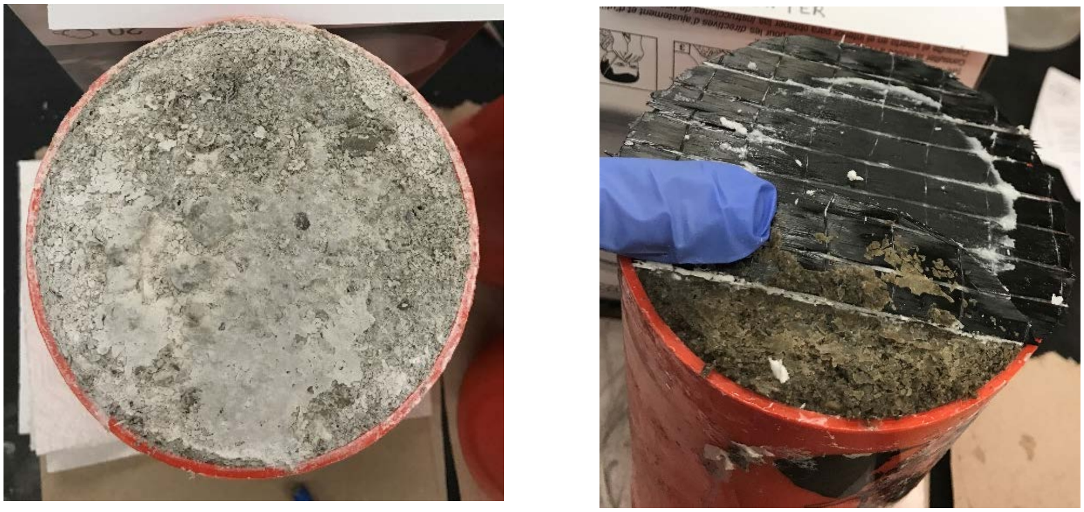
Results

ASTM C666

Results from the first test executed, ASTM C666, were qualitative in nature. Main areas of pertinent concern included any degradation of the concrete at surface level and any debonding or delamination of the FRP. After removing the concrete cylinders from their plastic molds, the level of chloride ion intrusion into the concrete was also examined. These aspects will all be discussed individually.

Degradation of Surface Concrete

Overall, all surfaces of the concrete cylinders degraded throughout the test cycles, regardless of whether they had a FRP covering or not. However, the location of disintegration of concrete did vary from covered to uncovered sample. As seen in Image 1a below, almost the entire surface area of the cylinder was affected. Contrastingly, only the edges of those samples covered in CFRP were affected. However, the concrete on the edges that was affected for covered samples was much more degraded than the concrete of the uncovered samples. As seen below in Image 1b, the edges were often chipped away, or fell away after light handling. Those samples with GFRP had degradation of the concrete on the edge of the cylinders, similar to that of the CFRP cylinders, however, degradation was much less drastic; the degradation was similar to that of uncovered samples, if not much less. Observations for all cylinders after ASTM C666 can be seen in Table A.3 in the Appendix.



(a) *(b)*

Image 1: (a) Degradation of Uncovered Exposed Concrete Sample, (b) Degradation of CFRP Covered Exposed Concrete Sample

Delamination and Debonding of FRP with Concrete

Delamination is used to refer to the separation of layers within the FRP itself, while debonding is used to refer to the separation of the FRP from the concrete. Delamination occurred throughout samples, however, only in very small locations on the edges of FRP. There were not significant enough differences to differentiate.

However, debonding occurred for a large amount of samples, sometimes over the majority of the surface area of the sample. Those samples covered with CFRP experienced significantly more debonding as opposed to those samples covered with GFRP. All CFRP-covered samples showed signs of debonding, with three of them having significant amounts of separation. Conversely, those samples covered with GFRP showed far less signs of debonding after testing. Only significant amounts of debonding occurred in one of the GFRP samples, while the rest of the samples had signs of separation similar to that shown in Image 2b below. Observations for all cylinders after ASTM C666 can be seen in Table A.3 in the Appendix.

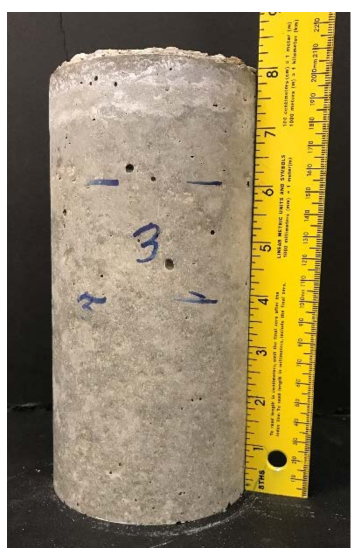
(a) (b)

Image 2: (a) Debonding of CFRP; (b) Debonding of GFRP

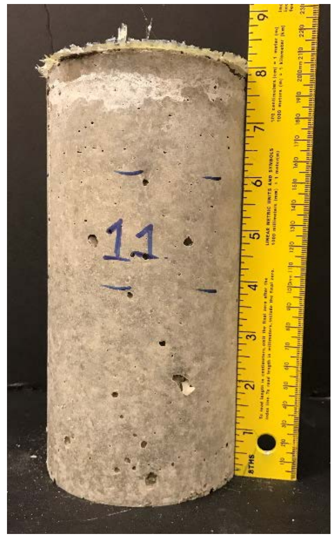
Depth of Calcium Chloride Intrusion

After removing the outer mold from the concrete cylinder, the depth of intrusion was measured on all samples. Additionally, each concrete cylinder was given a rating pertaining to the concentration of chloride visible. Below are listed the characteristics of each rating, along with a correlating example image:

- Rating 1: Chloride concentration evenly spread throughout; not overly concentrated in one area; "pale"



- Rating 2: Chloride concentration seen in dark patches scattered throughout affected zone



- Rating 3: Large, dark, chlorine-heavy areas clearly seen; heavy bands of chloride around entire perimeter of cylinder

Table A.7 in the Appendix shows the chloride intrusion length and rating given to each individual concrete cylinder. Table 2 below gives the average values.

Table 2: ASTM C666 Chloride Intrusion Observations

Cylinder Type	Avg. Chloride Intrusion Length	Standard Deviation	Rating	Standard Deviation
No FRP	1.375	0.177	2	0
CFRP	1.2	0.326	1.8	0.837
GFRP	1.25	0.306	2.4	0.548

All images of concrete samples before and after exposure to calcium chloride can be seen in Appendix 2.

ASTM C1760-12

Direct results from each test included an electrical current after one minute of potential difference maintained across a 60 V difference. Per sample, four tests were run. For all tests, the temperature was held constant at 22° C. The average of all currents was used for further calculations.

This average current was first utilized to calculate a bulk electrical conductivity for samples, using Eq. 1 as defined by ASTM C1760-12:

$$\sigma = K \frac{I_1}{V} \frac{L}{D^2}$$

where

σ = bulk electrical conductivity, mS/m
I_1 = current at 1 min, mA
V = applied voltage, V
L = average length of specimen, mm
D = average diameter of specimen, mm
K = conversion factor = 1273.3

The inverse of the bulk electrical conductivity is resistivity, given by the equation

$$\rho = 1/\sigma$$

Finally, utilizing simple electrical engineering principles, this resistivity or conductivity was utilized to find an equivalent charge passed over a 6 hour time period.

$$I = \frac{V}{R} \quad \text{and} \quad I = \frac{Q}{t}$$

$$\text{therefore} \quad Q = \frac{Vt}{R} = \frac{Vt}{\rho\frac{L}{A}} = \left(\frac{VAt}{L}\right)\sigma$$

The charge of each cylinder was then adjusted to an equivalent charge value for a specimen of two inches in width, allowing comparison to be made between values of different specimens.

With this final equivalent charge value, a Chloride Ion Penetrability Rating could be assigned to each concrete sample, based on Table X1.1 from ASTM C1202, shown below.

Table 3: ASTM Table X1.1: Chloride Ion Penetrability, Based on Charge Passed

TABLE X1.1 Chloride Ion Penetrability Based on Charge Passed (1)

Charge Passed (coulombs)	Chloride Ion Penetrability
>4,000	High
2,000–4,000	Moderate
1,000–2,000	Low
100–1,000	Very Low
<100	Negligible

In order to find an “average” rating for groups of samples, equivalent 6-hr charges passed for each sample were averaged, and then this was correlated to a corresponding Chlorine Ion Penetrability. Table 4 shows these results:

Table 4: Chlorine Ion Penetrability Results

Group	Equivalent Charge Passed	Chlorine Ion Penetrability
No Exposure, No Cover	170.90	Very Low
No Exposure, GFRP Cover	35.37	Negligible
No Exposure, CFRP Cover	257.94	Very Low
Exposure, No Cover	1005.47	Low
Exposure, GFRP Cover	1723.05	Low
Exposure, CFRP Cover	-	-

As seen, no results are listed for those specimens that were exposed to ASTM C666 with CFRP Cover. Due to how degraded the samples were, tests were too variant to report. However, it is estimated that the Chlorine Ion Penetrability would be in the range "Moderate" to "High", with an average Equivalent Charge Passed value higher than all other values.

All relationships between current, resistivity, conductivity, and equivalent charge passed can be seen in Charts A.1 through A.4 in Appendix 1.

Analysis of Results

ASTM C666

Overall, in comparing covered concrete samples to uncovered concrete samples, it was observed that FRP did not provide a cover that eliminated the effects of calcium chloride; rather those cylinders with FRP only performed slightly better than those without, some even performing worse.

The chloride did intrude those concrete specimens that did not have a FRP cover more than those that did have a cover, as shown by the first column in Table 2. This being said, there was only a slight difference in chloride intrusion length between those with and without the cover.

The surface layer of those with the CFRP cover were degraded far more than those with a GFRP cover or those even without a cover. CFRP was also debonded in far more instances than the GFRP. This could be due to the lack of perpendicular strands holding the 0° strands together, as seen in the GFRP. Without this perpendicular strand, there were more opportunities for the calcium chlorine to get through to the concrete specimen. However, this reasoning does not necessarily explain why the CFRP would, in some cases, provide a *worse* result than those cylinders that were not covered. Further investigation may have to be done to determine any chemical interactions occurring in between the calcium chloride and CFRP.

Overall, in comparing the GFRP and CFRP, one could say that GFRP did provide a slight layer of protection to the concrete against calcium chloride, while the CFRP did not. Because there was a small amount of debonding in samples, it would be suggested further research be performed to help mitigate this problem.

ASTM C1760-12

From the results of ASTM C1760-12, one could conclude that when samples had not been exposed to calcium chloride, GFRP provided the best protection against chloride ion penetration, raising the rating of the concrete from “Very Low” to “Negligible”. It should also be noted that although CFRP-covered and not covered unexposed samples had the same Chlorine Ion Penetrability Rating, and the CFRP equivalent charge passed was slightly higher, there did seem to be an outlier data point raising this value. Without this

data point, the CFRP would have performed better than the uncovered sample, however, not as well as the GFRP.

Because results on samples that were exposed to calcium chloride and covered with CFRP were inconclusive, only analysis of exposed samples uncovered and covered with GFRP could be done. GFRP did not protect against chloride ion penetration after exposure to calcium chloride, seen when comparing the average charge passed for covered and uncovered samples (2103.52 C vs. 1720.65 C).

Several reasons could exist for the results that were obtained at the end of testing. Overall, the FRP performed far worse than expected. This could, firstly, be due to the nature of degradation of the covered samples. While the uncovered exposed samples degraded on the entire surface area of the sample in an even fashion, those covered samples experienced the most degradation on the edges of the concrete around the perimeter. Because calcium chloride was pushed to these areas during testing, large pieces of concrete fell off from the sides of the cut cylinders. This "chipping" of concrete around the edges could have contributed to a lower durability of the concrete, thus raising the equivalent charge passed, and making the Chloride Ion Penetrability Rating decrease. Secondly, the FRP could have itself conducted a charge that altered results. If this was true, than results would appear falsely high. While this could be the case, the physical appearance of the concrete leads to believe that the first reason may be more accurate.

Improvements and Further Research

Overall, while concluding statements like those above can be made, this study would need several large modifications in order to be more accurate. First, the quantity of the samples should be increased. Within this study, nineteen cylinders were used for testing – only 5 of which were covered with CFRP and 5 of which were covered with GFRP. While this size served this small study well, utilizing a larger number of samples would reduce the large standard deviations calculated. Great variability in results occurred when testing different samples, especially those samples that had been previously exposed to calcium chloride. Utilizing more samples would hopefully mitigate this variability.

Secondly, testing may expand to either include ASTM C1202-12 or replace ASTM C1760-12 with ASTM C1202-12. ASTM C1760-12 was used in this study to indirectly calculate an equivalent charge passed in 6 hours, which could be directly calculated with ASTM C1202-12. Results, again, may be more accurate and show a decreased variability, with use of this recommendation.

Thirdly, the length of samples during ASTM C1202 or ASTM C1760 should be increased to two inches (50mm). Samples were cut to one inch during testing because of the inclusion of rebar. However, because the samples were so thin, testing was difficult, and some samples had to be omitted because of lack of results. Creating two inch samples would ensure that results would be obtained.

Finally, this study focused on a very small FRP type selected out of hundreds of products. A more comprehensive study could focus on the protection that FRPs with difference strand arrangements, matrices, or thicknesses/layers provide to concrete.

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Appendix 1

Table A.1: Tabulation of Concrete Cylinder Masses

Cylinder #	Type	A	B	C	D	E	F
		Initial Cylinder (kg)	Initial Cylinder w/clay (kg)	Cylinder after ASTM C666 w/clay (kg)	Cylinder after ASTM C666 w/out clay (kg)	D - A (kg) (gain in mass)	E/A * 100 (percent gain in mass)
1	No FRP (Not Exposed)	4.034	-	-	-	-	-
2	CFRP	4.034	4.112	4.118	4.050	0.016	0.397
3	No FRP	4.086	-	4.096	4.094	0.008	0.196
4	CFRP	4.046	4.145	4.160	4.072	0.026	0.643
5	CFRP	4.052	4.161	4.154	4.062	0.010	0.247
6	CFRP	4.033	4.134	4.134	4.068	0.035	0.868
7	CFRP	4.074	4.172	4.164	4.082	0.008	0.196
8	No FRP (Not Exposed)	3.982	-	-	-	-	-
9	No FRP	4.046	-	4.056	4.050	0.004	0.099
10	GFRP	4.067	4.168	4.162	4.070	0.003	0.074
11	GFRP	4.066	4.154	4.150	4.076	0.010	0.246
12	GFRP	4.062	4.168	4.162	4.072	0.010	0.246
13	GFRP	4.076	4.176	4.172	4.086	0.010	0.245
14	GFRP	4.074	4.160	4.150	4.080	0.006	0.147

Table A.2: Concrete Mix Specifications

Date
Cylinders with rebar (Batch 1) made 9/20/2016
Cylinders without rebar (Batch 2) made 9/29/2016
**Same batch specifications used for both batches*

CONCRETE MIX SPECIFICATIONS					
Mixture			**Results**		
Material	***Amount***		Volume	1.1	ft^3
#57 Gravel	0.00	lb	Slump	7.5	in
#8 Peagravel	71.90	lb	Air	6	%
Sand	49.80	lb	Unit $Weight_1$	142.9	pcf
Cement	16.10	lb	Unit $Weight_2$	35.85	pcf
GGBFS100	10.70	lb			
Water	7.80	lb			
Moisture					
#57 Stone Moisture	0.00	%			
#8 Peagravel Moisture	1.50	%			
Sand Moisture	5.00	%			
Admixtures					
Air	6.34	mL			
1037	79.19	mL			

Table A.3: Observations of Concrete Cylinders Before and After ASTM C666

(gray)	No FRP, Not Exposed
(green)	No FRP, Exposed
(blue)	CFRP, Exposed
(orange)	GFRP, Exposed

Observations 11/2/2016	Cylinders taken out of Forney curing chamber
Observations 11/27/2016	Cylinders after FRP Placement
Observations 2/6/2017	Cylinders after ASTM C666
Observations 2/6/2017	Cylinders after ASTM C666

		Observations 11/2/2016	**Observations 11/27/2016**	**Observations 2/6/2017**
Cylinder #	**Type**	**Cured**	**Cylinders**	**Cylinders after ASTM C666**
1	No FRP	minor bumps	(will not be exposed)	-
2	CFRP	smooth	slight spaces where main fibers are separated more than normal	large amount of debonding
3	No FRP	very bumpy, not level - worst out of all samples	(will be exposed)	entire top crumbling, disintegrated
4	CFRP	smooth	minor separations	large amount of debonding around edges, especially parallel to strand axis
5	CFRP	smooth, minor bumps around edge	minor separations, overall good	can see concrete cracking in between cracks of CFRP; debonding, splitting on edges
6	CFRP	smooth, minor bumps around edge	large separations in multiple places	small amount of debonding, small piece removed from edge when removing CFRP
7	CFRP	minor bumps, with larger divot near center	separations that do not have resin, frayed CFRP in areas	slight amount of debonding around exterior
8	No FRP	medium bumps, larger aggregate piled in center, about 1/2 cm short of filing cylinder	(will not be exposed)	-
9	No FRP	bumps near center of cylinder	(will be exposed)	entire top crumbling, disintegrated
10	GFRP	minor bumps	minor crystallization occurring	slight debonding around edges
11	GFRP	smooth, two minor bump areas	slight separations near edges	large amount of debonding around exterior, under this concrete is affected, frayed edges of CFRP from removal of clay
12	GFRP	smooth	good condition	slight debonding of large area (1/3A)
13	GFRP	smooth		very little debonding
14	GFRP	smooth	minor crystallization occurring, very small crack	very little debonding

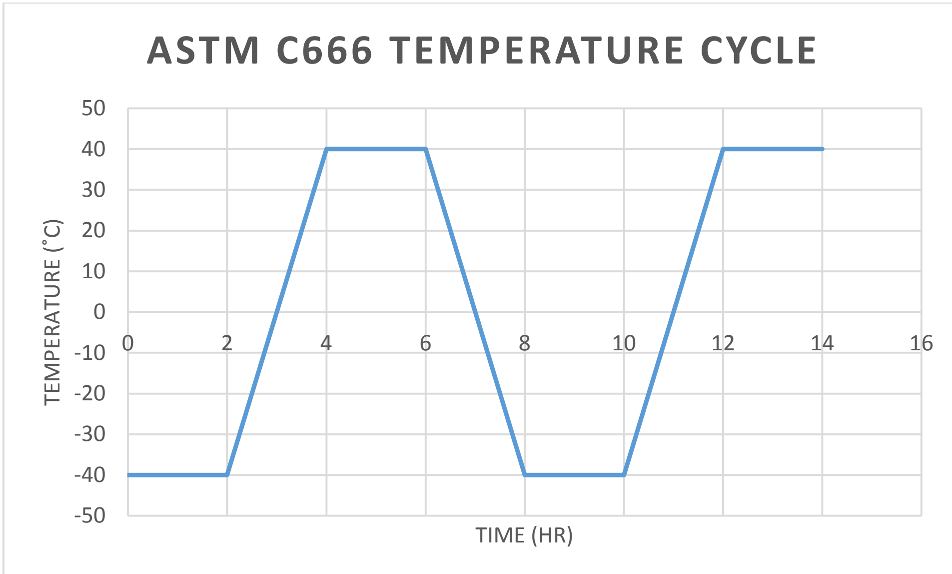
Table A.4: Results of ASTM C1760-12

Legend	
I	Current
L	Length
V	Voltage
D	Diameter, 101 mm
SA	Surface Area, 8011.85 mm
T	Time, 6 hr = 21600 sec
ρ	Resistivty
σ	Conductivity

Sample Description			Weight After Covering (kg)	Length (mm)	Measured Current at 1 minute (mA)				SD	Average (mA)	Bulk Electrical Conductivity (mS/m)	Bulk Electrical Resistivity (Ohm-m)	Estimated Charge Passed in 6 hr	Chloride Ion Penetrability
											1273.3*I*L/(V*D^2)	1/σ*1000	V*SA*T/L*ρ/1000000	
A-4	no exposure	NONE	1.925	50.80	11.7	12	12	12.3	0.24	11.70	1.26	792.98	257.76	Very Low
B-1	no exposure	NONE	0.874	46.04	6.7	4.8	4.7	6	0.97	5.55	0.54	1844.62	122.27	Very Low
Summary of No Exposure, No Cover				**48.42**						**8.63**	**0.89**	**1128.60**	**190.01**	**Very Low**
B-4	no exposure	GFRP	0.756	42.86	3.9	1.3	1.2	1.1	1.35	1.88	0.17	5864.54	41.31	Negligible
B-3	no exposure	GFRP	0.97	50.80	1.3	1.5	2.1	2.1	0.41	1.75	0.19	5301.65	38.55	Negligible
B-2	no exposure	GFRP	0.858	33.34	1.6	1.5	2.3	2.6	0.54	2.00	0.14	7068.86	44.06	Negligible
Summary of No Exposure, GFRP Cove				**42.33**						**1.88**	**0.17**	**5937.85**	**41.31**	**Negligible**
A-1	no exposure	CFRP	0.85	44.45	6.9	3.2	2.6	4.4	1.90	4.28	0.40	2480.30	94.18	Negligible
A-2	no exposure	CFRP	0.818	39.69	37.4	35.3	33.6	33.9	1.73	35.05	2.95	338.82	772.17	Very Low
A-3	no exposure	CFRP	0.928	47.63	1.7	0.8	0.4	0.3	0.64	0.80	0.08	12370.51	17.62	Negligible
Summary of No Exposure, CFRP Cove				**43.92**						**13.38**	**1.25**	**802.32**	**294.66**	**Very Low**
3-1	exposure	NONE	1.375	33.34	144.6	144.1	1429	140.7	642.94	464.60	32.86	30.43	10235.39	High
9-1	exposure	NONE	1.345	33.34	42.6	47.5	56.1	62.1	8.71	52.08	3.68	271.49	1147.24	Low
Summary of Exposure, No Cover				**33.34**						**258.34**	**18.27**	**54.73**	**5691.31**	**High**
10-1	exposure	GFRP	1.22	33.34	1.9	1	1	1	0.45	1.23	0.09	11541.00	26.99	Negligible
12-1	exposure	GFRP	1.265	33.34	12.4	15.2	7.7	5.2	4.51	10.13	0.72	1396.32	223.06	Very Low
14-1	exposure	GFRP	1.46	47.63	265.70	262.40	253.10	245.30	9.24	256.63	25.93	38.56	5653.59	High
Summary of Exposure, GFRP Cover				**38.10**						**89.33**	**7.22**	**138.49**	**1967.88**	**Low**

Sample	Original Length (mm)	Original RCPT	New Length (mm)	Eq. Charge Passed (°C)	Chloride Ion Penetrability
A-4	50.8	257.76	50	261.88137	Very Low
B-1	46.0375	122.26947	50	132.79334	Very Low
Summary of No Exposure, No Cover				**197.337**	**Very Low**
B-4	42.8625	41.307252	50	48.185771	Negligible
B-3	50.8	38.553436	50	37.946295	Negligible
B-2	33.3375	44.061069	50	66.083343	Negligible
Summary of No Exposure, GFRP Cover				**50.7385**	**Negligible**
A-1	44.45	94.180536	50	105.93986	Negligible
A-2	39.6875	772.17024	50	972.8129	Very Low
A-3	47.625	17.624428	50	18.503336	Negligible
Summary of No Exposure, CFRP Cover				**365.752**	**Very Low**
3-1	33.3375	10235.386	50	15351.161	High
9-1	33.3375	1147.2401	50	1720.6451	Low
Summary of Exposure, No Cover				**1720.65**	**Low**
10-1	33.3375	26.987405	50	40.476048	Very Low
12-1	33.3375	223.05916	50	334.54693	Low
14-1	47.625	5653.5859	50	5935.5233	High
Summary of Exposure, GFRP Cover				**2103.52**	**Low**

Table A.5: **ASTM C666 Cycle Description**



Cycle Length = 6hr

Cycle Timeline = 57 days, 228 cycles

Cycle #	Time (hrs)	Temp (°C)
1	0	-40
2	2	-40
3	4	40
4	6	40
continue for 228 cycles…		

Table A.6: Concrete Property Relationships for Sample Length of 50mm (2”)

L (mm)	I (mA)	ρ (mS/m)	σ (Ohm-m)	Equivalent Q in 6 hr ('C)	Chloride Ion Penetrability
50	0	0.00	-	0.00	Negligible
	10	1.06	942.63	220.31	Very Low
	20	2.12	471.32	440.61	Very Low
	30	3.18	314.21	660.92	Very Low
	40	4.24	235.66	881.22	Very Low
	50	5.30	188.53	1101.53	Low
	60	6.37	157.11	1321.83	Low
	70	7.43	134.66	1542.14	Low
	80	8.49	117.83	1762.44	Low
	90	9.55	104.74	1982.75	Low
	100	10.61	94.26	2203.05	Moderate
	110	11.67	85.69	2423.36	Moderate
	120	12.73	78.55	2643.66	Moderate
	130	13.79	72.51	2863.97	Moderate
	140	14.85	67.33	3084.27	Moderate
	150	15.91	62.84	3304.58	Moderate
	160	16.97	58.91	3524.89	Moderate
	170	18.03	55.45	3745.19	Moderate
	180	19.10	52.37	3965.50	Moderate
	190	20.16	49.61	4185.80	High
	200	21.22	47.13	4406.11	High
	210	22.28	44.89	4626.41	High
	220	23.34	42.85	4846.72	High
	230	24.40	40.98	5067.02	High
	240	25.46	39.28	5287.33	High
	250	26.52	37.71	5507.63	High

Legend	
L	Length of Sample
I	Measured Current
ρ	Bulk Electrical Conductivity
σ	Bulk Electrical Resistivity
Q	Equivalent Charge Passed in 6 hr

Chart A.1: Relationship between Measured Current and Bulk Electrical Conductivity for 50mm (2") Sample Length

Equation of the Line: $\rho = \left(\frac{1273.03L}{VD^2}\right) I$ where $\left(\frac{1273.03L}{VD^2}\right) = 0.1061$

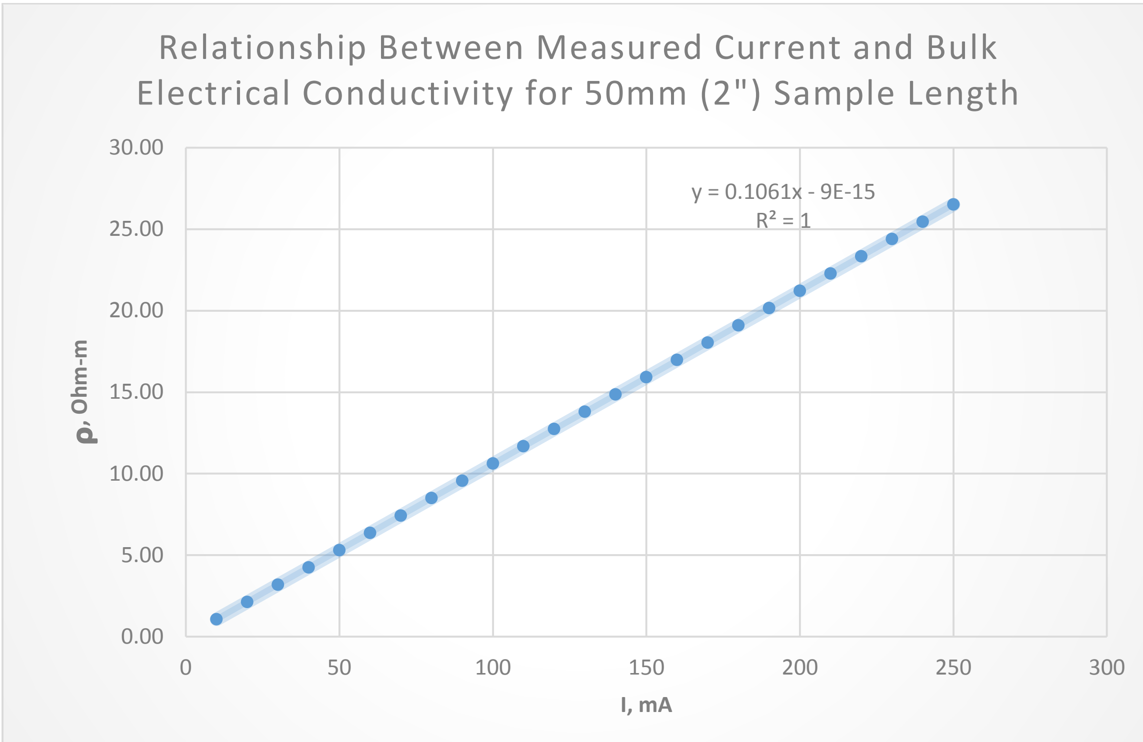


Chart A.2: Relationship between Measured Current and Bulk Electrical Resistivity for 50mm (2”) Sample Length

Equation of the Line: $\sigma = \left(\frac{VD^2}{1273.03L}\right) I^{-1}$ where $\left(\frac{VD^2}{1273.03L}\right) = 9426.3$

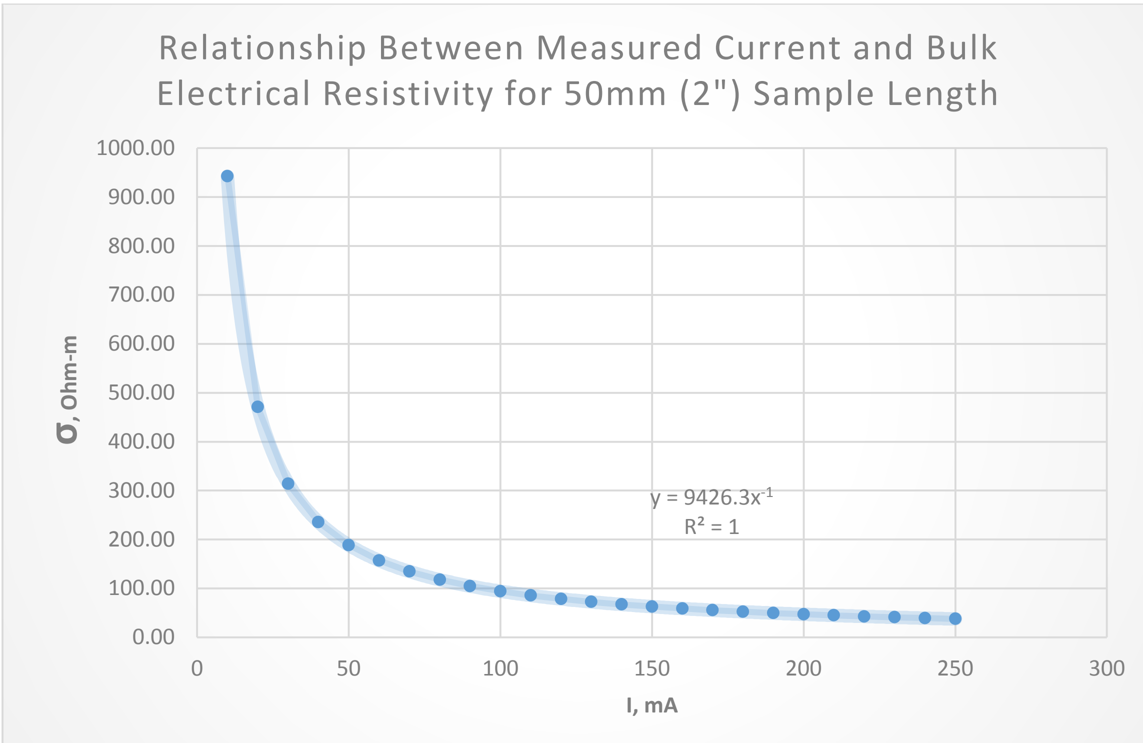


Chart A.3: Relationship between Measured Current and Equivalent Charge Passed Over 6 hr for 50mm (2”) Sample Length

Equation of the Line: $Q = \left(\frac{1273.03\pi T}{4*10^6}\right) I$ where $\left(\frac{1273.03\pi T}{4*10^6}\right) = 22.031$

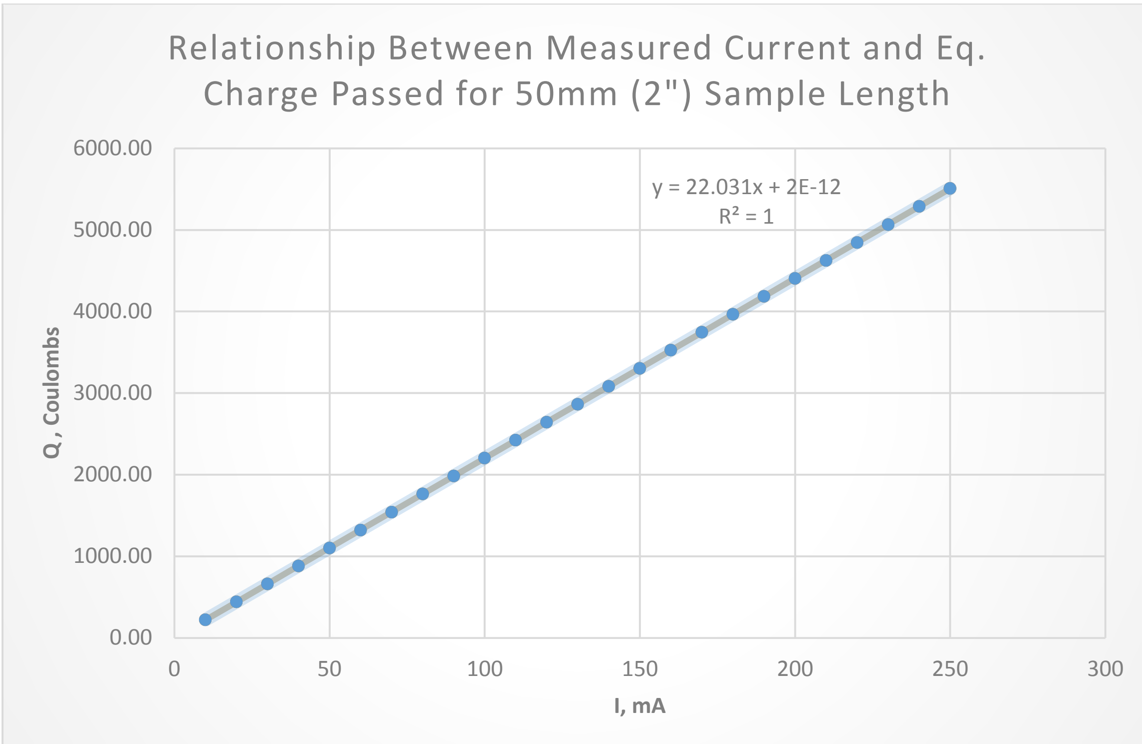


Chart A.4: Relationship between Measured Current and Equivalent Charge Passed Over 6 hr for 50mm (2”) Sample Length

Equation of the Line: $Q = \left(\frac{V*SA*T}{L*10^3}\right)\sigma^{-1}$ where $\left(\frac{V*SA*T}{L*10^3}\right) = 207667$

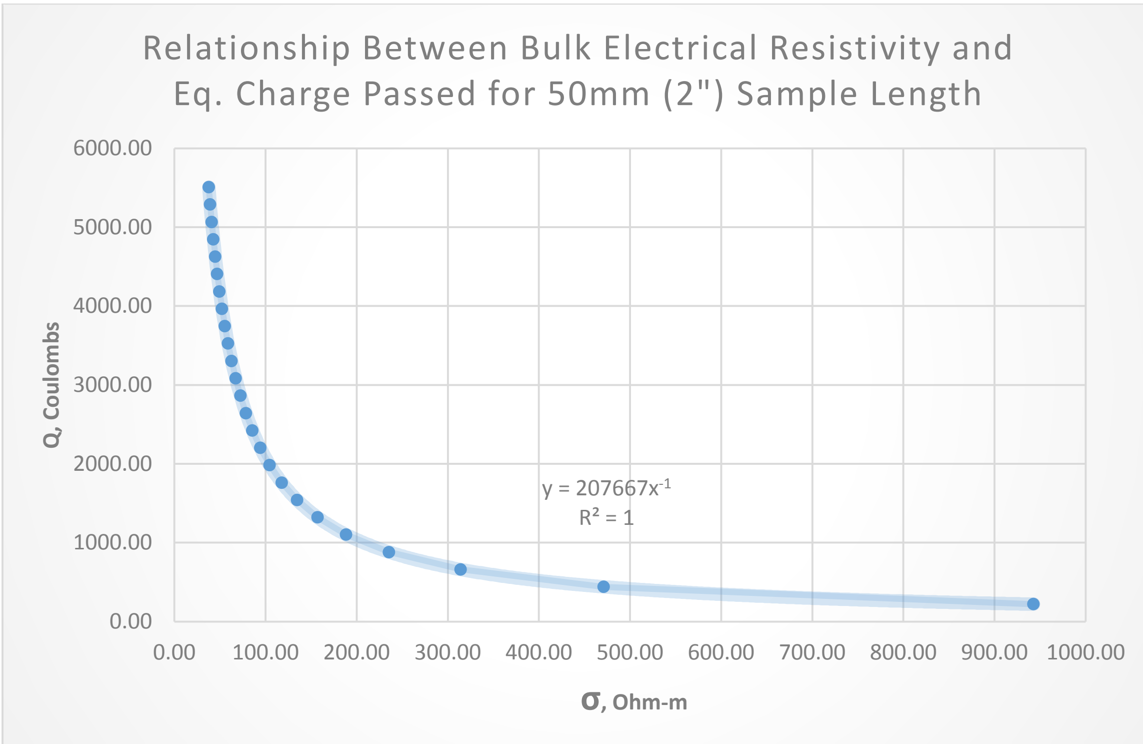


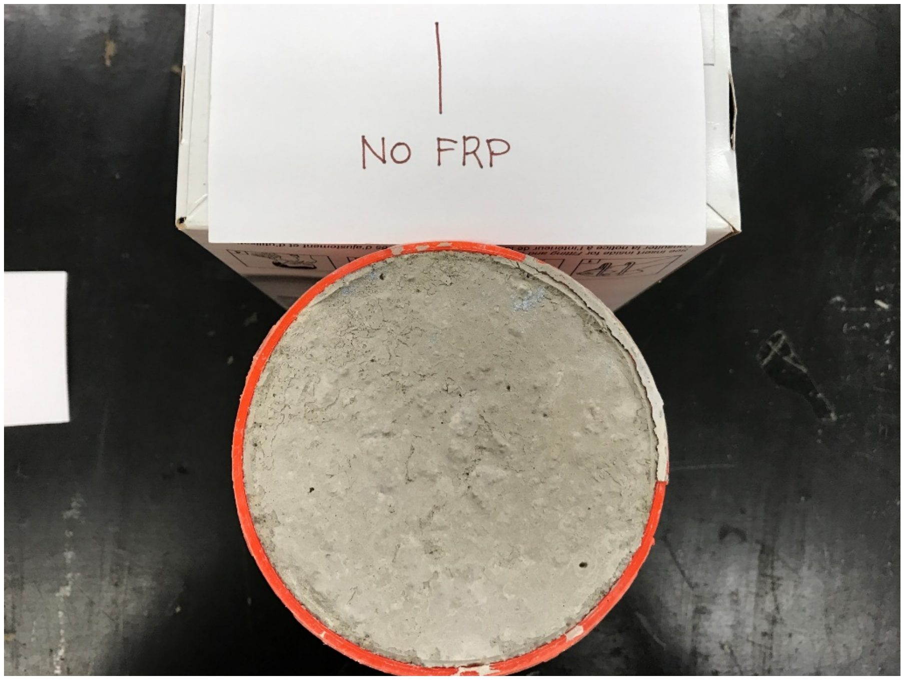
Table A.7 – Results of ASTM C666, Chloride Intrusion Length and Chlorine Concentration Rating

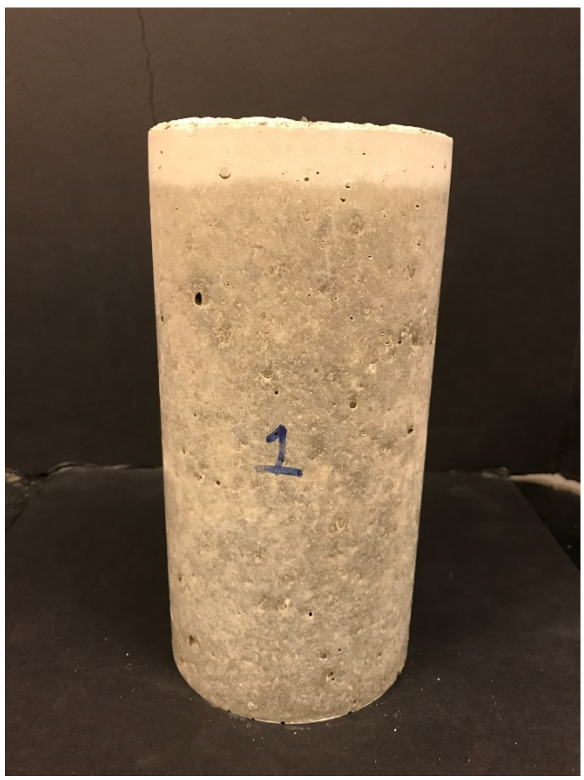
Cylinder #	Type	Chloride Intrusion Length	Chloride Concentration Rating
1	No FRP	*not exposed to ASTM C666*	*not exposed to ASTM C666*
3	No FRP	1.25	2
8	No FRP	*not exposed to ASTM C666*	*not exposed to ASTM C666*
9	No FRP	1.5	2
Average		**1.375**	**2**
4	CFRP	1	2
5	CFRP	0.75	1
6	CFRP	1.5	3
7	CFRP	1.25	2
2	CFRP	1.5	1
Average		**1.2**	**1.8**
10	GFRP	1.25	3
11	GFRP	1	2
12	GFRP	1	2
13	GFRP	1.25	2
14	GFRP	1.75	3
Average		**1.25**	**2.4**

Appendix 2

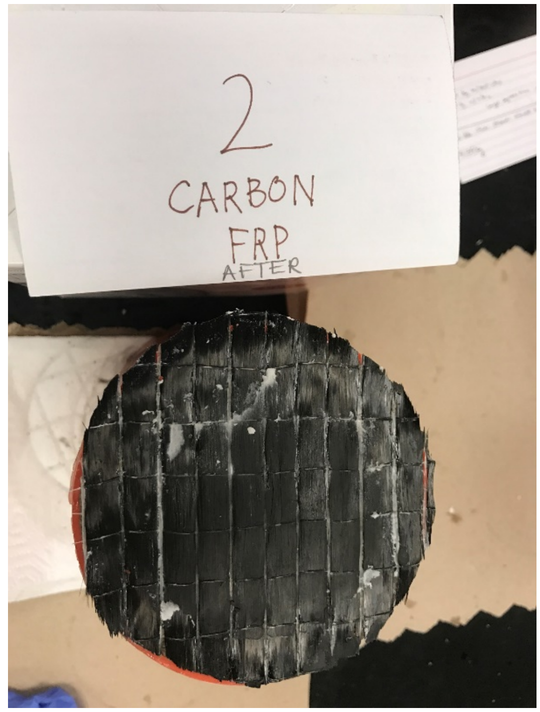
Cylinders Before and After Exposure

Cylinder #1

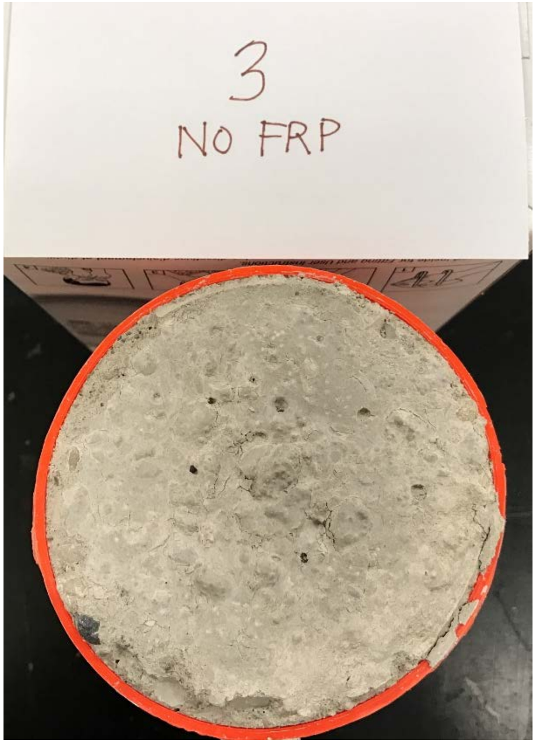


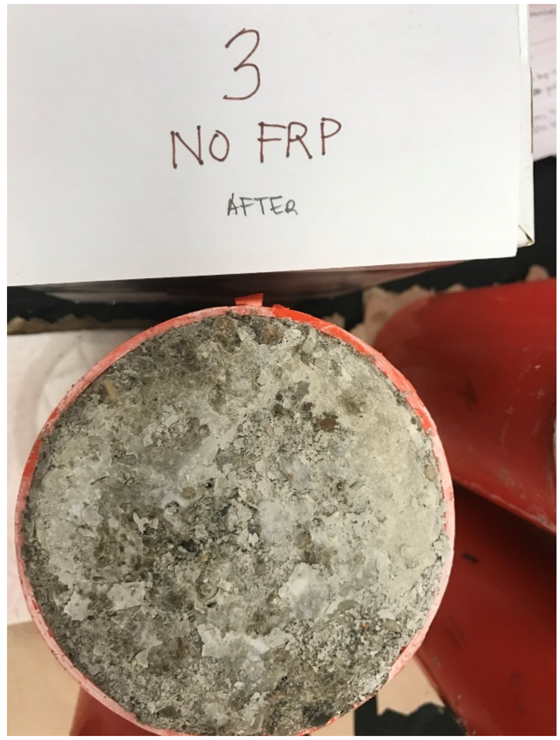


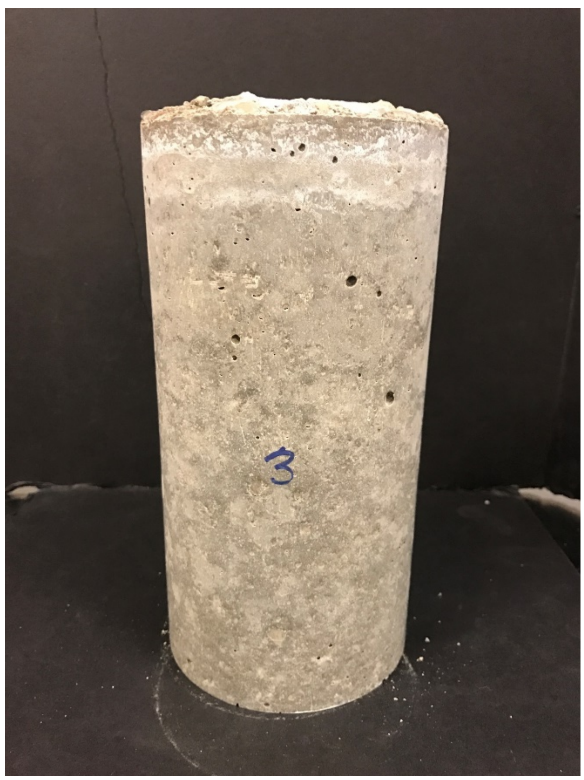
Cylinder #2



Cylinder #3







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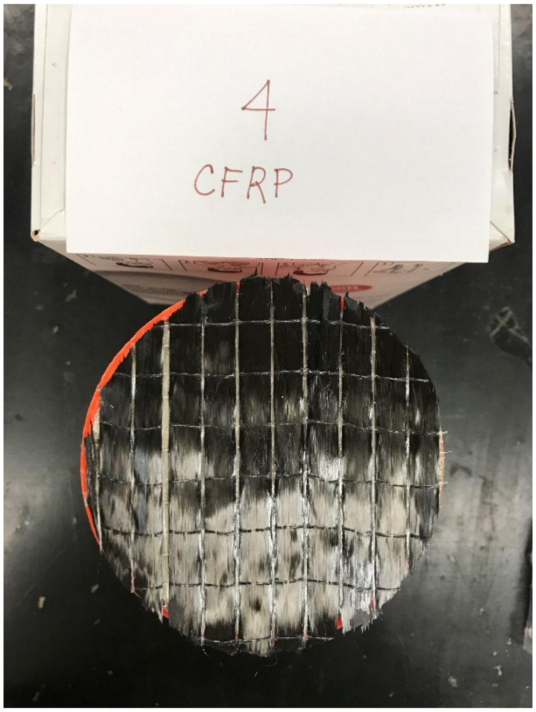
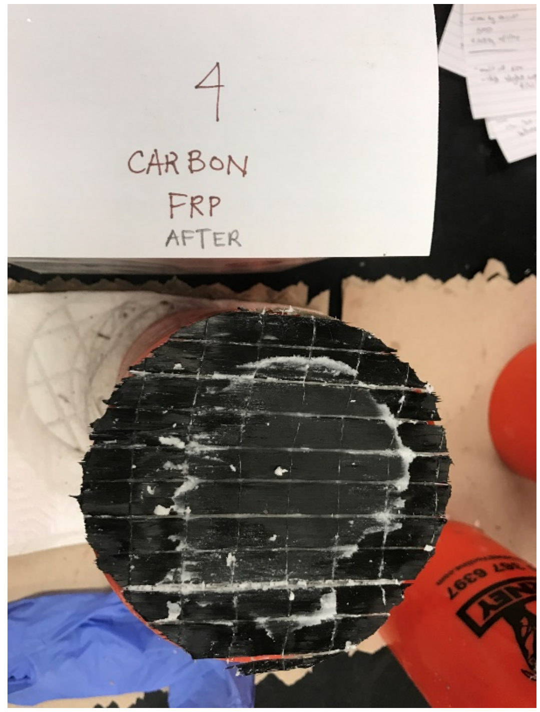
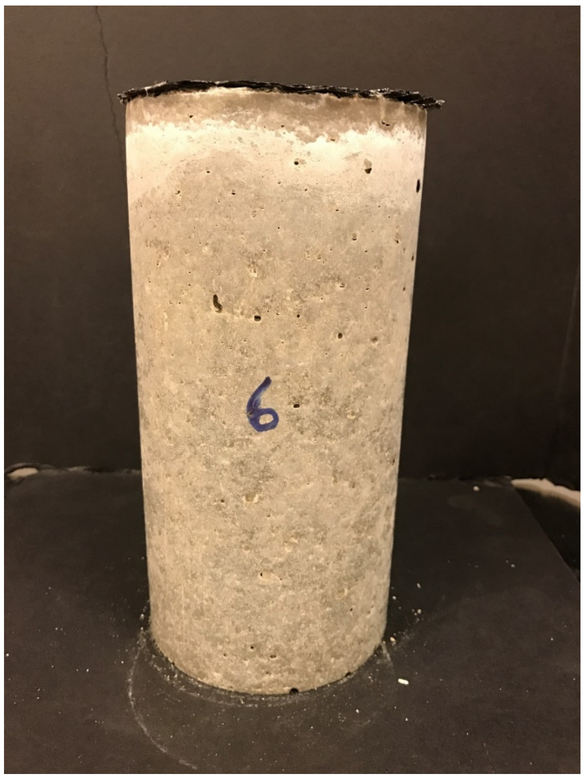


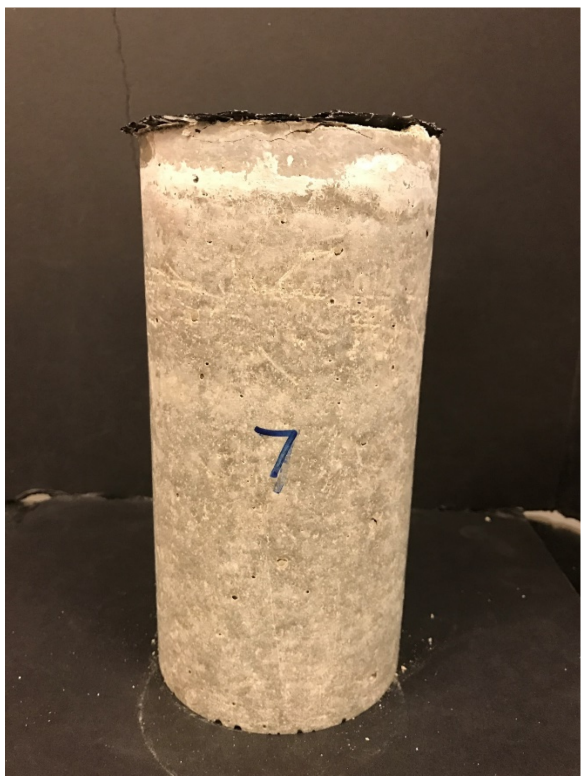


Cylinder #5

Cylinder #6

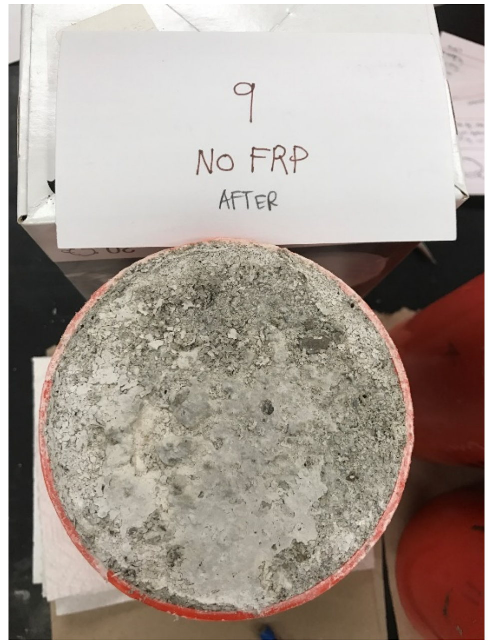


Cylinder #7

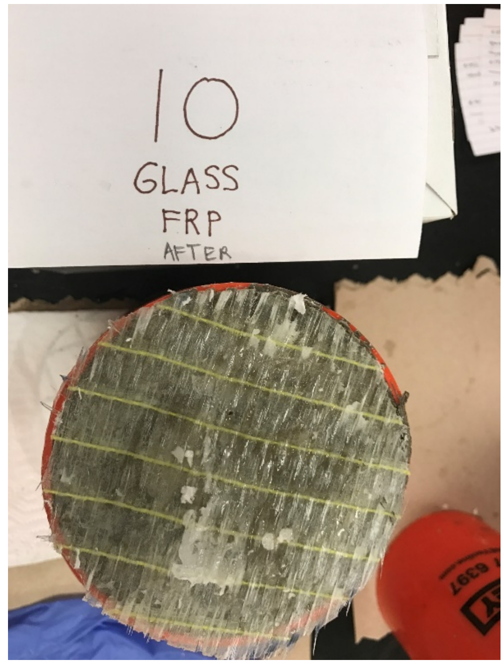


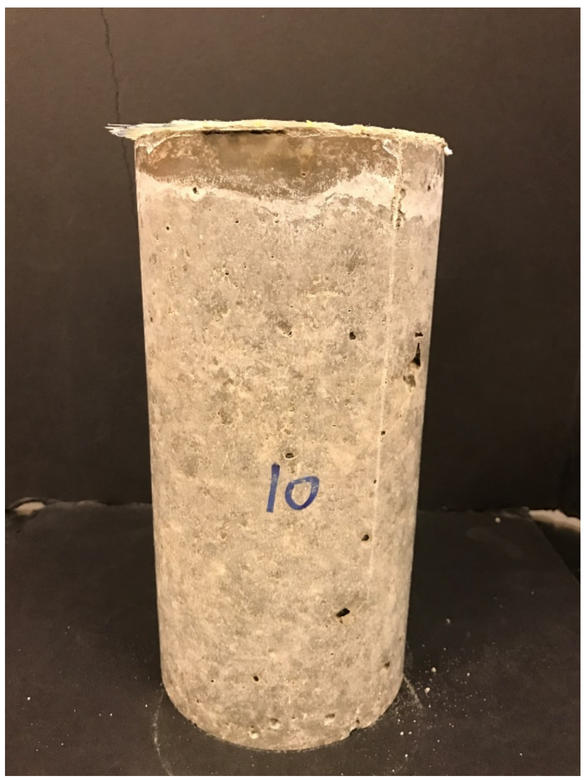
Cylinder #8

Cylinder #9

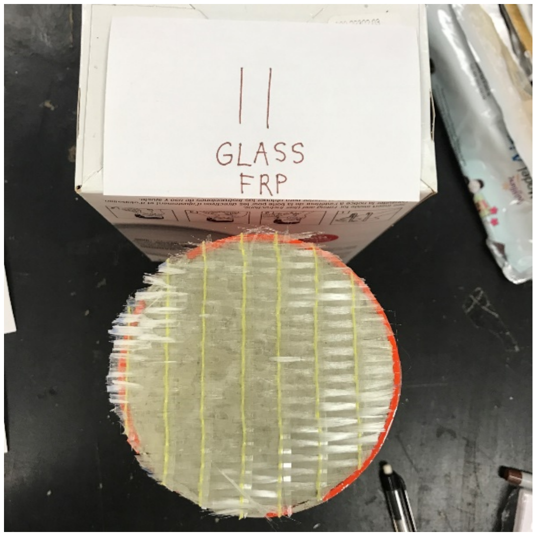


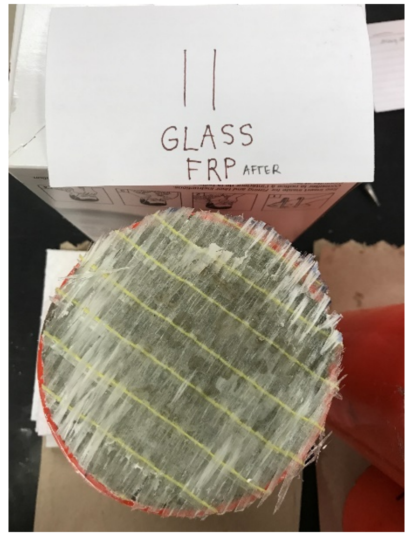
Cylinder #10

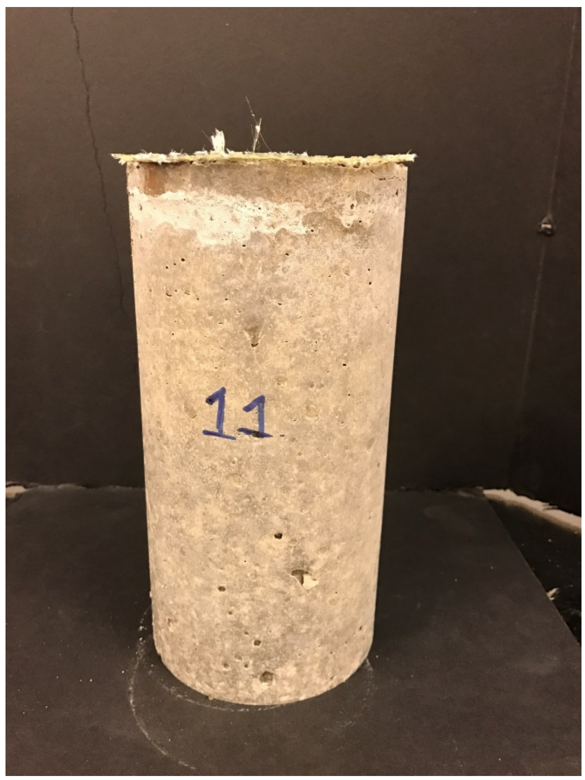




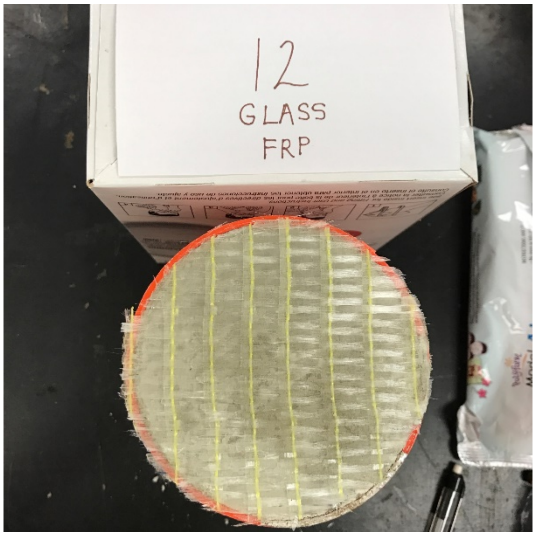
Cylinder #11

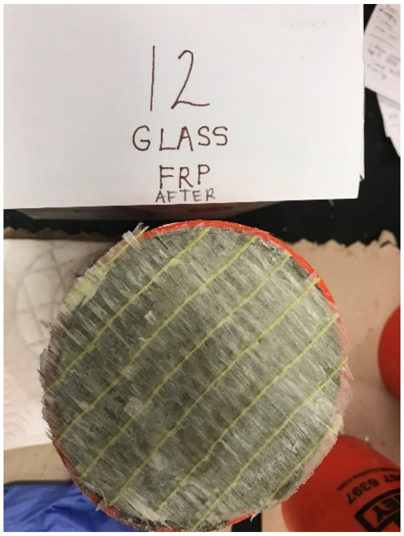


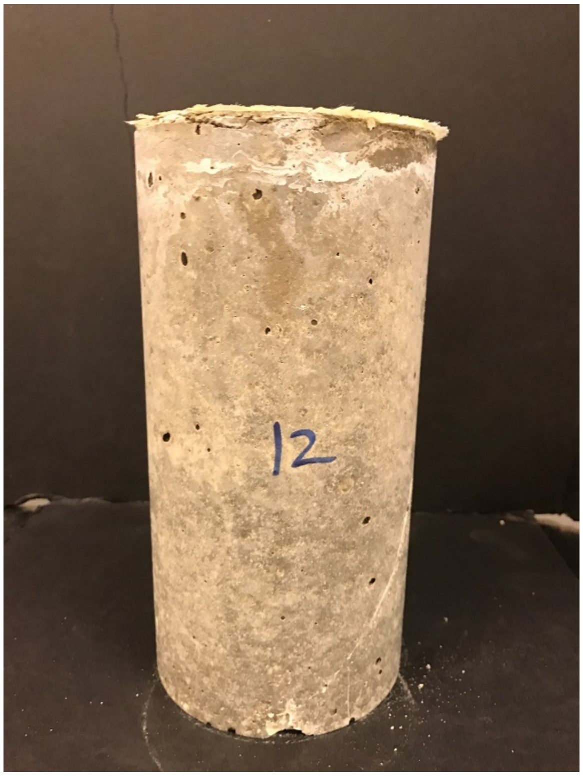




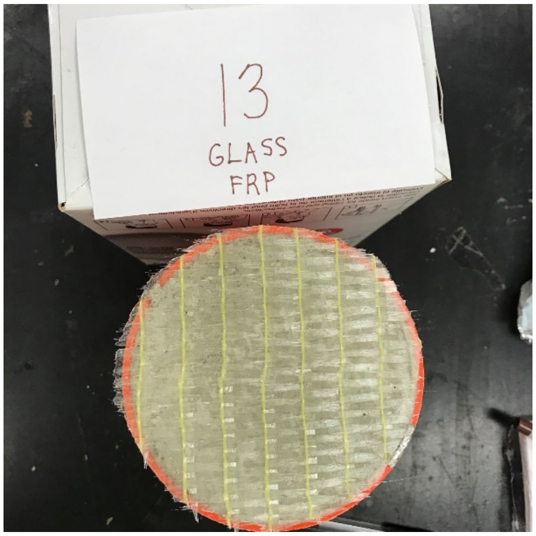
Cylinder #12

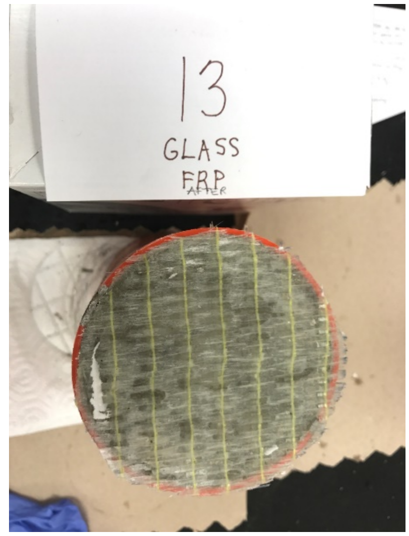


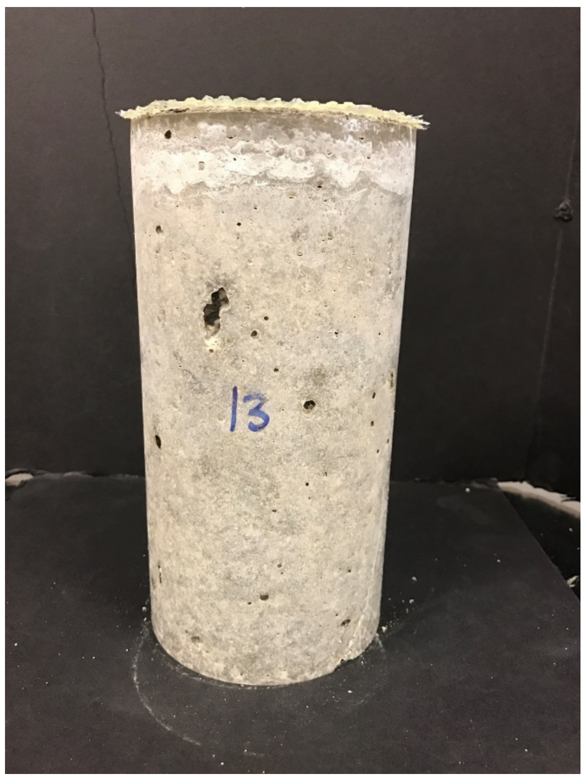




Cylinder #13







Cylinder #14