EFFECTS OF FIBER REINFORCED POLYMER (FRP) WRAP ON REDUCING CHLORIDE PENETRATION IN CONCRETE

by

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ABSTRACT

EFFECTS OF FIBER REINFORCED POLYMER (FRP) WRAP

ON REDUCING CHLORIDE PENETRATION

IN CONCRETE

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The University of Texas at Arlington, 2012

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The objective of this study was to investigate the effects of FRP wrap on reducing chloride penetration in concrete. It has been established that FRP wrap used to retrofit concrete structures offer a high resistance to chemical solutions. The ACI 318-11 Code allows for a reduction of clear cover depth if an equivalent clear cover depth can be establish. The FRP material used herein consisted of Tyfo SCH-41 and Tyfo SEH-51A composites fabricated from carbon and glass fibers, respectively. The wrapped FRP concrete specimens and control specimens without FRP wrap were tested according to ASTM C 1543 and ASTM C 1152 specifications. A sodium chloride solution was used to expose the surface of the concrete and FRP composite materials for a period of six weeks. At the end of chemical exposure, small powder samples were collected from various depths in order to determine the level of chloride in each specimen. Results obtained indicate that both FRP composite materials resulted in significant reduction of chloride in the concrete. The decrease in chloride content was maximum near the surface and reduced with depth. Equivalent clear cover depths for the FRP samples were determined that would result in similar chloride ingress and possible steel corrosion. The

cover reductions can range between 16% - 26% for beams and 44% - 50% for slabs, based on the FRP type. The reduced equivalent clear covers can lead to increased load capacity of the concrete members. Likewise, the FRP application may be used to satisfy existing unacceptable clear cover values in older structures compliant to current Code provisions.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 History of Fiber Reinforce Polymers

The introduction of fiber reinforce polymer (FRP) was first accomplished in the mid-1930s when a manufacturer produced a load carrying boat that was made of fiberglass and polyester resin (ACI 2007). In the 1940s, the U.S. Air Force and Navy had FRP composite materials that were used for aerospace and naval applications. One of the major advantages of FRP is its high strength-to-weight ratio. After it was introduced to the public sector, it became a valuable alternative to other conventional materials. One of the significant advantages of FRP is its high resistance to the effects of the weather, moisture, and salt. Composites have evolved since the 1950s due to their applications in retrofitting and strengthening of structures in civil engineering applications. In 1986 the first highway bridge was built using composite reinforcing tendons in Germany. In 1992 the first ever composite pedestrian bridge was built in Aberfeldy, Scotland. In the U.S., the first FRP reinforced concrete bridge deck was built in 1996 at McKinleyville, West Virginia. According to the American Concrete Institute (ACI) 440R-07 report, the composite industry has grown in several markets including construction, consumer products, corrosion-resistant equipment, marine, transportation, and other applications. In the coming years, FRP composite materials will continue to grow as new markets will to accept them with confidence (ACI 2007).

1.2 Fiber Reinforce Polymer

In general, a fiber reinforced polymer is a composite material that consists of a matrix resin and fibers (Uomoto 2001). The significance of the matrix resin in the composite material is to hold the fibers in the orientation, to protect the fibers from the environment, and to transfer the stresses between the fibers. The type of fiber in the composite material determines the mechanical properties such as the strength and the modulus of elasticity. Fibers can be fabricated from natural or synthetic material (ACI 2007). However, most commercially fabricated fiber reinforcements are synthetic. The most common principal types of fibers in commercial use for civil engineering applications are aramid, glass, and carbon. Another material that is a component of the FRP composite is the epoxy. The epoxy material can be engineered to achieve varying levels of performance (ACI 2007). Epoxy material is used to fabricate high performance for the composite, give superior mechanical properties to the composite, provide good performance at elevated temperature, and provide excellent adhesion when installing FRP composites. The properties of the epoxy material are essential when considering FRP composite material to externally reinforce and retrofit concrete structures (Uomoto 2001).

1.3 Reinforcing Structures

1.3.1 Current Methods for Reinforcing Concrete Structures

In reinforce concrete, mild steel bars shown in Figure 1.1 and prestressed strands shown in Figure 1.2 are the two common methods used as reinforcement (GangaTao et al. 2007). The issue with these two methods is that they are likely to corrode when the reinforcement is exposed to prolonged chemical agents such as salt, alkaline, and acids (ACI 2007). The possible continuous corrosion of the reinforcement in the concrete will lead to a lower design life which will tend to make the structure unsafe. Therefore, the need to externally reinforce deteriorating concrete structures must be considered.

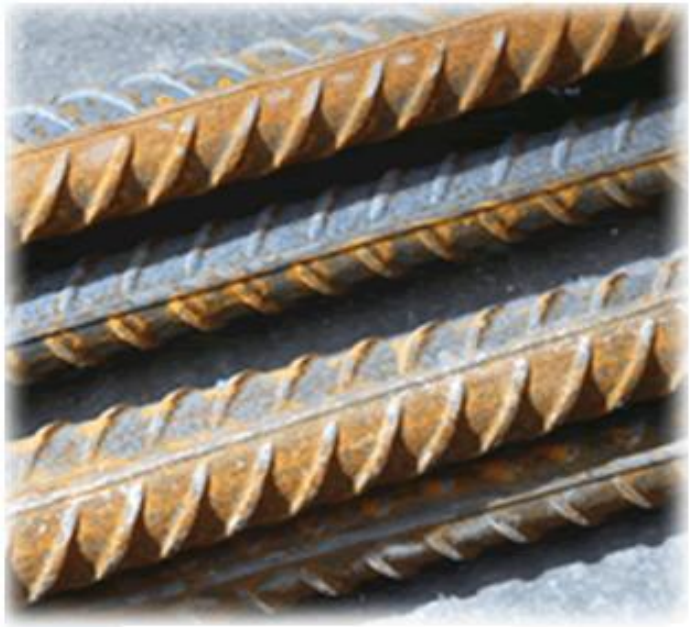

Figure 1.1 Mild reinforcement used to reinforce concrete (www.mace.manchestr.ac.uk).

Figure 1.2 Prestressed strand used to reinforce concrete (www.grin.com).

Figure 1.3 Corrosion of reinforcement in reinforced concrete (www.structuremag.org).

1.3.2 Fiber Reinforce Polymers in Reinforced Concrete Structures

Resistance to higher design loads, strength loss due to deterioration, or increasing the ductility of the structure are some of the reasons to reinforce structures using externally applied materials (ACI 2008). Current traditional available methods to externally reinforce structures include steel or concrete jackets, external post-tensioning and externally bonded steel plates. FRP rebar rods, and FRP sheets are the different alternative methods to externally reinforce concrete structures (Uomoto 2001). FRP composite rebar rods, shown in Figure 1.4, are used to reinforce concrete internally and are capable of producing the same strength as the mild reinforcement. Unlike the mild reinforcement and prestressed strands, FRP rods do not corrode when exposed to prolonged chemical solutions. FRP composite sheets are commonly used in order to externally reinforce concrete on existing deteriorating structures. Figure 1.5 shows FRP sheets reinforcing a concrete beam. Like the FRP composite rods, FRP composite sheets also offer a high resistance to the effects of weather and prolonged chemical exposure (Uomoto 2001). FRP composite systems can be used in areas where existing conventional methods may have limited access and are difficult to implement (ACI 2008). FRP composite sheets are also commonly used to retrofit concrete, which helps with the deterioration of the structure. Usually retrofitting reinforce concrete is preferred because it avoids a total reconstruction of the structure (Fyfe Co. LLC 2008). A concrete structure that is deteriorating will continue to lose structural capacity over time. FRP sheets can be used to provide additional capacity to help the structure stay in service. Figure 1.6 shows a group of girders being reinforced using carbon fiber reinforce polymers on the Bow River Bridge Project located in Calgary, Canada (Fyfe Co. LLC 2008). Steel fibers, shown in Figure 1.7, are also used to reinforce concrete by incorporating them when casting concrete. Unlike the other two types of FRP composites, steel fibers are not made up of a composite material (Uomoto 2001). Therefore, steel fibers are generally not classified as FRP composite material.

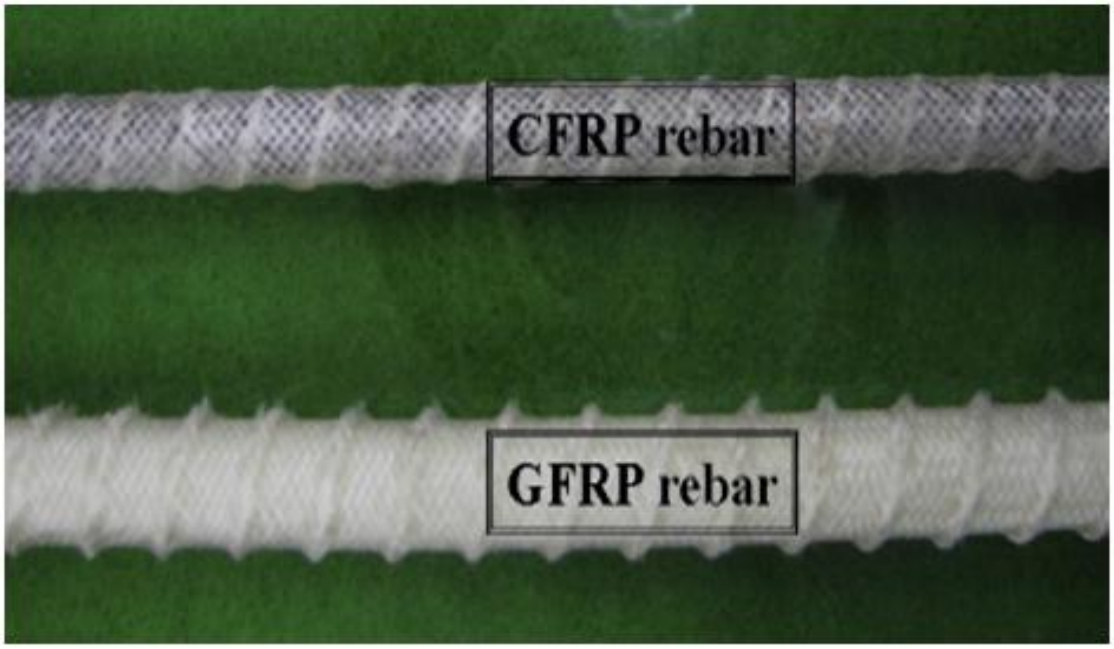

Figure 1.4 CFRP and GFRP composite rods (www.sciencedirect.com).

Figure 1.5 FRP composite sheets used to reinforce a concrete beam (www.fyfeco.com).

Figure 1.6 Girders being reinforced with Tyfo SCH-41 FRP sheets (www.fyfeco.com).

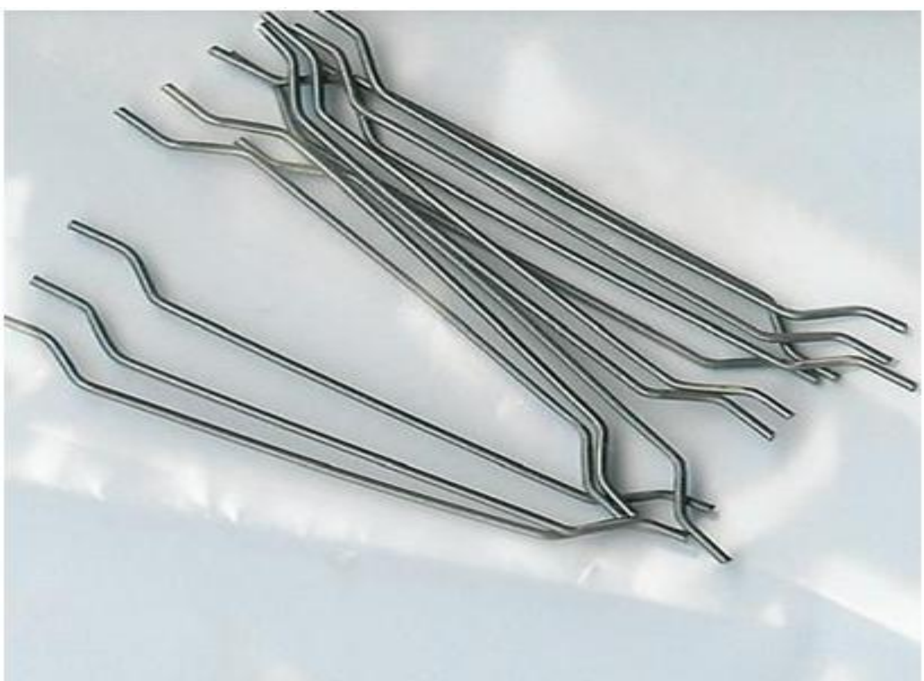

Figure 1.7 Steel fibers that can be used to reinforce concrete (www.diytrade.com).

1.4 Clear Cover in the ACI 318

The ACI 318-11 “Building Code Requirements for Structural Concrete and Commentary Building Code Requirements” is used by engineers to design various concrete members in a structure. The ACI 318-11 design guide helps engineers with determining the various aspects of reinforce concrete such as spacing of the reinforcement, serviceability, prestress concrete etc. In the ACI 318-11, Chapter 7, “Details of Reinforcement” the details of reinforcement for concrete is provided which includes a section for minimum clear cover requirements for reinforcing steel. According to the ACI 318-11 clear cover is measured from the edge or surface of the concrete to the face of the outer most surface of the steel as illustrated in Figure 1.8. The clear cover distance is intended to protect the reinforcement from the weather (ACI 318 2011). The required minimum clear cover in the ACI 318-11 depends on whether the reinforced concrete is exposed to the earth, not exposed to the earth, and concrete cast against and permanently exposed to the earth. The minimum clear cover also depends on the size of the reinforcement that is used in the concrete. These required clear cover requirements vary from 18.75 mm (¾ inch) up to 75 mm (3 inch) (ACI 318 2011). These clear cover distances apply to all reinforcements in concrete such as the top or bottom longitudinal mild reinforcement, stirrups, and prestressed strands. It should be noted that the ACI 318-11 also allows for the reduction of clear cover as long as an equivalent clear cover can be established.

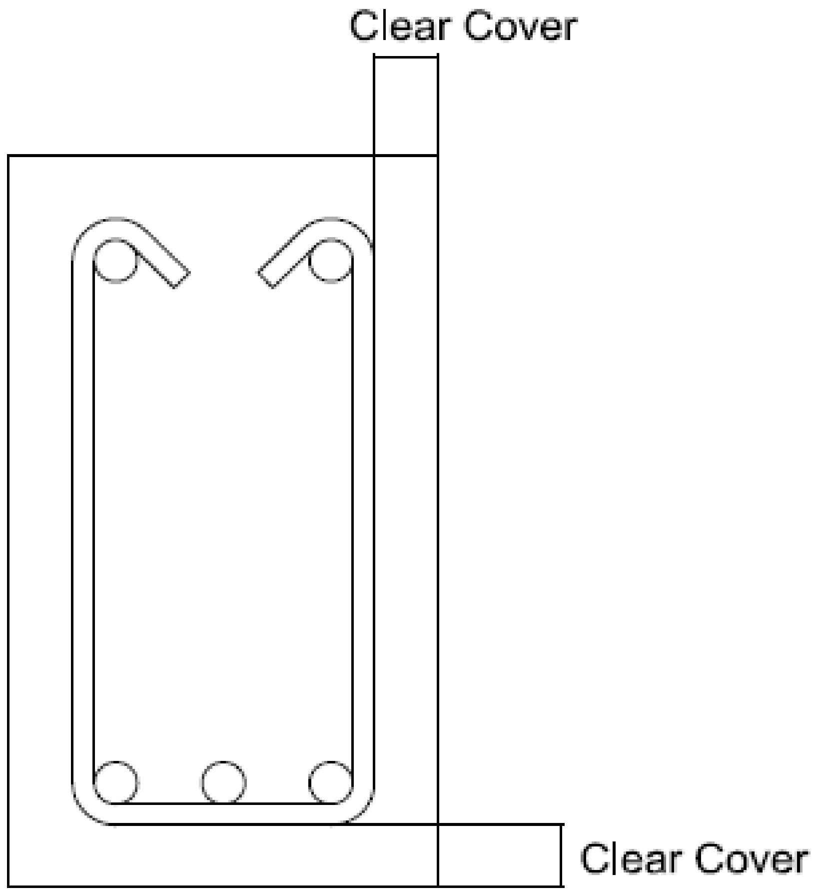

Figure 1.8 Clear cover at various locations in a reinforced concrete beam.

1.5 Clear Cover in the AASHTO LRFD Bridge Specifications

The American Association of State Highway and Transportation Official (AASHTO) represent the highway and transportation departments of the 50 states, Puerto Rico, and the District of Colombia (AASHTO 2007). AASHTO has set technical standards for design, construction of highways and bridges, and other areas in the highway system development. The AASHTO LRFD Bridge Design Specifications is a design guide which engineers follow when designing bridges. In the AASHTO LRFD Bridge Design Specification, section 5 titled “Concrete Structures” covers the different aspects to consider when designing a concrete bridge. The aspects to consider in a concrete bridge vary but are not limited to the limit states, design considerations, and material properties. Like ACI 318, AASHTO provides a provision for concrete clear cover. According to AASHTO, the minimum clear cover is determined by multiplying the clear cover value from Table 1.1 with a modification factor. The modification factor is determined by the water-cement (w/c) ratio from concrete (AASHTO 2007). A modification factor of 0.8 is used for concrete with w/c ratio less than or equal to 0.40 and a 1.2 factor is used for W/C ratios greater than or equal to 0.50. AASHTO's modification factor of 0.8 is used because of the decrease in permeability in concrete which is a result of lower w/c ratio (AASHTO 2007). Unlike ACI 318, AASHTO does not provide a provision to use equivalent clear covers. AASHTO does consider the use of protective coatings by using epoxy coating or galvanizing of reinforcing steel, post-tensioning duct, and by epoxy coating of prestressing strands. If epoxy coating is used in reinforcing steel then the clear cover for "interior exposure" from Table 1.1 may be used. However, this reduction of cover must still be multiplied by the modification factor for the w/c ratio. Therefore, a concrete exposed to deicing salts with protective coating on No. 5 bars and a w/c less than 0.40 may have a minimum clear cover of 30 mm (1.2 in.). However, the absolute minimum cover in concrete for rebar with protective coating must not be less than 1.0 in.

Table 1.1 AASHTO minimum clear cover values.

Situation	**Cover mm (in.)**
Direct exposure to salt water	100 (4.0)
Cast against earth	75 (3.0)
Coastal	75 (3.0)
Exposure to deicing salts	62.5 (2.5)
Deck surface subject to tire stud or chain wear	62.5 (2.5)
Exterior other than above	50 (2.0)
Interior other than above	-
Up to No. 11 bar	37.5 (1.5)
No. 14 and No. 18 bars	50 (2.0)
Bottom of cast-in-place slabs	-
Up to No. 11 bar	25 (1.0)
No. 14 and No. 18 bars	50 (2.0)
Precast soffit form panels	20 (0.8)
Precast reinforced piles	-
Noncorrosive environments	50 (2.0)
Corrosive environments	75 (3.0)
Precast prestressed piles	50 (2.0)
Cast-in-place piles	-
Noncorrosive environments	50 (2.0)
Corrosive environments	-
General	75 (3.0)
Protected	75 (3.0)
Shells	50 (2.0)
Auger-cast, tremie concrete, or slurry construction	75 (3.0)

1.6 Scope of Work

The purpose of using FRP composite sheets in this study is to investigate the effects of FRP wrap on reducing the chloride penetration in concrete. The characteristic that FRP composite materials offer a high resistance to chemical solutions has already been established. It is common that FRP composite sheets are used for retrofitting and strengthening existing deteriorating structures. The FRP composites considered here are taken as if the concrete had been installed with FRP material from the initial design of the structure.

The American Society for Testing and Materials (ASTM) has published different volumes of manuals that can be used to determine different variables in concrete. For this study ASTM C 1542 and ASTM C 1152 was used in order determine the resistance that the FRP sheets can provide when the concrete is exposed to a chemical reagent. ASTM C 1543 tests for the ingress of sodium chloride solution into the concrete by ponding. Ponding is referred to as leaving the sodium chloride solution on the surface of the concrete for a period of time. Afterwards, ASTM C 1152 provided the sodium chloride profiling for each concrete specimen. From the sodium chloride profiling the percentage of chloride in the concrete specimens was determined at various depths.

If the percentage of chloride values obtained for the FRP concrete specimens produce lower values than the control specimens at the same depth. One can conclude that the FRP application helped reduce the percentage of chloride. Therefore, the minimum clear cover of the concrete could be reduced with the incorporation of FRP composite material in new structures. Also, for existing structures, previously unacceptable clear covers would be acceptable with the FRP application.

1.7 Literature Review

Literature review was necessary in order to understand the methods and procedures performed in this study. The topic of this study was to investigate the possible effects FRP wrap can provide by reducing chloride penetration in concrete. Different ASTM tests were considered before choosing ASTM C 1543 and ASTM 1152. Afterwards, a thorough understating of ASTM C 1543 and ASTM C 1152 was necessary. ASTM C 1543 was investigated and it was found that this test could be used to determine the percentage of chloride in the concrete for different depth intervals. As per ASTM C 1543, ASTM C 1152 was used to determine the percentage of chloride present in the concrete. Afterwards, the materials and equipment needed for both ASTM tests were investigated. All ASTM tests provide sections were the required equipments and materials are listed. It was found that all of the equipment needed was available. It was also necessary to find suppliers for the materials needed for the ASTM tests. Time was spent to locate suppliers which could provide with the materials for the ASTM tests. Materials needed for this study include but are not limited to FRP material, chemical reagents, concrete material, and other materials noted in Chapter 2. The materials were estimated based on the number of specimens that were going to be considered for this study. After conservative estimates, the materials were quantified for the amount needed per specimen. According to Fyfe Co, LLC, when the Texas Department of Transportation (TxDoT) considers FRP application, Fyfe Co. LLC is usually the supplier. The ACI 318 and AASHTO LRFD Bridge Design Specifications consider clear cover for concrete buildings and concrete bridges, respectively. As noted before, clear cover values from the ACI 318 may be lower as long as equivalent clear cover values can be established. AASHTO LRFD Bridge Design Specifications does not provide a provision for possible reduction of equivalent clear cover values. The only possible reduction in the cover of the concrete comes from having w/c ratio less than 0.40 or providing protective coating around the rebar reinforcement.

A recent study conducted by Medeiros investigated the effects of different surface treatments to determine the chloride resistance of concrete in marine environments. The corrosion of steel is the process of chloride ions contacting the surface of the steel eroding the passive layer of the steel. The surface treatments were conducted according to ASTM C 1202 test standard, a rapid chloride penetration test (RCPT). RCPT test standards are usually known for their short duration and rapid results to determine the chloride ingress in concrete. According to Yoon, these types of surface treatments are use to reduce the corrosion process by reducing the chloride in the concrete. These types of surface treatments are categorized as coatings, pore blockers, and pore liners (Yoon et al. 2012). The coatings are used because it provides a continuous film on the surface of the concrete preventing the ingress of chloride (Medeiros et al. 2012). Pore blockers are materials that can react with certain concrete constituents which form an insoluble product. Pore liners are used to make the concrete water repellent. In Medeiros' study, the surface treatments used are shown in Table 1.2. Medeiros concluded that the Double A+C and B+C showed the significant reduction of chloride with the exception of the polyurethane coating. The polyurethane coating is regarded as a high efficiency material (Medeiros et al. 2009). In this study the use of FRP with an epoxy resin was used to investigate the effects of chloride ingress by ASTM C 1543. Unlike ASTM C 1202, ASTM C 1543 is not a RCPT.

Table 1.2 The different surface treatments used in Medeiros study.

System	**Product**
Single A	Silane/siloxane dispersed in water (A)
Single B	Silane/siloxane dispersed in solvent (B)
Single C	Acrylic dispersed in solvent (C)
Single D	Polyurethane (D)
Double A+C	(A+C)
Double B+C	(B+C)

Byung H. Oh and Seung Y. Jang developed a model that predicts the chloride penetration into concrete which include parameters such as the age of concrete, temperature, relative humidity, chloride binding and chloride convection by moisture transport are taken into account. In this study a simple model, ASTM C 1543, was used to determine the chloride penetration in concrete. ASTM C 1543 only takes into account the parameters such as constant temperature, constant age of the concrete, and constant relative humidity. Although Oh and Jang's model takes into account additional parameters that were not considered in ASTM C 1543. This study was conducted to determine the possible effects FRP wrap can provide for reducing the chloride penetration in concrete. Therefore, the exact chloride percentage was not the main focus of this study. This study does not consider proposing a model that could predict the chloride percent in the concrete. Oh and Jang's study concluded that in order to predict the chloride penetration into concrete accurately, the chloride convention should be consider. This parameter has shown that the chloride ingress into concrete accumulates near the surface of the concrete (Oh and Jang 2007). Therefore, the percent of chloride in the concrete from ASTM C 1152 will yield lower chloride percentage results. From Oh and Jang's study it was also concluded that the presence of fly ash in the concrete reduces the penetration of chloride into concrete. This type of admixture was not considered in this study. Oh also concluded that the chloride present in the concrete produce higher values with high elevated temperatures and higher relative humidity.

CHAPTER 2

PROCEDURE

2.1 FRP, Epoxy, and Concrete Properties

The Tyfo SCH-41 and the Tyfo SEH-51A FRP composite systems were the two FRP composite materials used that were donated by Fyfe Co. LLC. The Tyfo SCH-41 is composed of carbon fibers orientated in the 0^o direction. Table 2.1 shows the physical properties for the Tyfo SCH-41 composite material. The Tyfo SEH-51A material is composed of glass fibers orientated in the 0^o and 90^0 directions. Table 2.2 shows the physical properties for the Tyfo SEH-51A composite material. Both FRP composite materials need the application of the Tyfo Saturant (S) Epoxy. Both FRP composite systems are used to strengthened and add ductility to buildings, bridges, and other structures. The Tyfo S Epoxy material is a two component epoxy resin material with properties shown in Table 2.3. A total of eight concrete specimens were casted for this study. Table 2.4 represents the concrete properties used for casting the concrete. Three concrete specimens were installed with Tyfo SCH-41 and another three concrete specimens were installed with Tyfo SEH-51A. The remaining two specimens were used as the control specimens with no FRP application. Table 2.5 represents the eight concrete specimens that were considered for this study.

Table 2.1 Physical properties of the Tyfo SCH-41 composite material (Fyfe Co. LLC).

Typical Dry Fiber Properties			
Tensile Strength		550,000 psi (3.79 GPa)	
Tensile Modulus		33.4×10^6 psi (230 GPa)	
Ultimate Elongation		1.7%	
Density		0.063 lbs./in.^{3} (1.74 g/cm^3)	
Minimum weight per sq. yd.		19 oz. (644 g/m^2)	
Composite Gross Laminate Properties			
PROPERTY	**ASTM METHOD**	**TYPICAL TEST VALUE**	**DESIGN VALUE***
Ultimate tensile strength in primary fiber direction	D3039	143,000 psi (986 MPa) (5.7 kip/in. width)	121,000 psi (834 MPa) (4.8 kip/in. width)
Elongation at break	D3039	1.0%	0.85%
Tensile Modulus	D3039	13.9×10^6 psi (95.8 GPa)	11.9×10^6 psi (82 GPa)
Flexural Strength	D790	17,900 psi (123.4 MPa)	15,200 psi (104.8 MPa)
Flexural Modulus	D790	452,000 psi (3.12 GPa)	384,200 psi (2.65 GPa)
Longitudinal Compressive Strength	D3410	50,000 psi (344.8 MPa)	42,500 psi (293 MPa)
Longitudinal Compressive Modulus	D3410	11.2×10^6 psi (77.2 GPa)	9.5×10^6 psi (65.5 GPa)
Longitudinal Coefficient of Thermal Expansion	D696	3.6 ppm./°F	
Transverse Coefficient of Thermal Expansion	D696	20.3 ppm./°F	
Nominal Laminate Thickness		0.04 in. (1.0mm)	0.04 in. (1.0mm)
* Gross laminate design properties based on ACI 440 suggested guidelines will vary slightly. Contacted Fyfe Co. LLC engineers to confirm project specifications values and design methodology			

Table 2.2 Physical properties of the Tyfo SEH-51A composite material (Fyfe Co. LLC).

Typical Dry Fiber Properties			
Tensile Strength		470,000 psi (3.24 GPa)	
Tensile Modulus		10.5×10^6 psi (72.4 GPa)	
Ultimate Elongation		4.5%	
Density		0.092 lbs./in.^{3} (2.55 g/cm^3)	
Minimum weight per sq. yd.		27 oz. (915 g/m^2)	
Composite Gross Laminate Properties			
PROPERTY	**ASTM METHOD**	**TYPICAL TEST VALUE**	**DESIGN VALUE***
Ultimate tensile strength in primary fiber direction	D3039	83,400 psi (575 MPa) (4.17 kip/in. width)	66,720 psi (460 MPa) (3.3 kip/in. width)
Elongation at break	D3039	2.2%	1.76%
Tensile Modulus	D3039	3.79×10^6 psi (26.1 GPa)	3.03×10^6 psi (20.9 GPa)
Ultimate tensile strength in 90 degrees to primary fiber	D3039	3,750 psi (25.8 MPa)	3,000 psi (20.7 MPa)
Nominal Laminate Thickness		0.05 in. (1.3mm)	0.05 in. (1.3mm)
* Gross laminate design properties based on ACI 440 suggested guidelines will vary slightly. Contacted Fyfe Co. LLC engineers to confirm project specifications values and design methodology			

Table 2.3 Properties of the Tyfo Saturant (S) Epoxy material (Fyfe Co. LLC).

Epoxy Material Properties		
Curing Schedule 72 hours post cure at 140° F (60° C).		
PROPERTY	**ASTM METHOD**	**TYPICAL TEST VALUE***
T_g	D4065	180° F (82° C)
Tensile Strength[1]	D638 Type 1	10,500 psi (72.4 MPa)
Tensile Modulus	D638 Type 1	461,000 psi (3.18 GPa)
Elongation Percent	D638 Type 1	5.0%
Compressive Strength	D695	12,500 psi (86.2 MPa)
Compressive Modulus	D695	0.465 x 10^6 psi (3.2 GPa)
Flexural Strength	D790	17,900 psi (123.4 MPa)
Flexural Modulus	D790	452,000 (3.12 GPa)
[1] Testing temperature: 70° F (21° C). Crosshead speed: 0.5 in. (13mm)/min. Grips Instron 2716-0055 - 30 kips.		
* Specifications values can be provided upon request.		

Table 2.4 Concrete compressive strength properties (Quikrete).

Compressive Strength, ASTM C 39	
Age	Typical Values
7 days	17.2 MPa (2500 psi)
28 days	27.6 MPa (4000 psi)
Slum Range	51-76 mm (2" - 3")

Table 2.5 Concrete specimens labeled according to FRP and non-FRP application.

Specimens	Tyfo SCH (CFRP)	Tyfo SEH (GFRP)	Control
1	x	-	-
2	x	-	-
3	x	-	-
1	-	x	-
2	-	x	-
3	-	x	-
1	-	-	x
2	-	-	x

2.2 Specimen Preparation

The molds were created by a sheet of plywood with a thickness of 19 mm (0.75 inch). The molds that were created for this study had a shape of a cube with an open top surface as shown Figure 2.1. The plywood was cut into three different sizes which would be used to hold the concrete from the bottom and the four sides. Eight plywood sides were cut to have a surface of 175 mm by 175 mm (7 inch by 7 inch). These eight sides were going to be used as the foundation of the mold. Sixteen plywood sides were cut to dimensions of 200 mm by 150 mm (8 inch by 6 inch). These sixteen plywood sides were going to be used to hold two sides of the cube. The other two sides were cut into dimensions of 175 mm by 150 mm (7 inch by 6 inch) in order to complete the cubic mold. Each cubic mold was created to hold a 175 mm by 175 mm by 100 mm (7 inch by 7 inch by 4 inch) deep concrete specimen. The concrete samples were casted from two 80 lb premixed concrete bags which were mixed in the Civil Engineering Laboratory Building. The concrete was cured for a period of 28 days at a temperature of 28 ℃ (83℉). After the 28 day of curing the concrete was ready to have the FRP composite material installed to the surface of the concrete as shown in Figure 2.2. The plywood dimensions mentioned here complied with the required dimensions of the concrete specimen per ASTM C 1543.

Figure 2.1 Cubic mold used to cast a concrete specimen.

Figure 2.2 Concrete specimens before FRP installation.

2.3 Fiber Reinforce Polymer Installation

The epoxy material was mixed with 500 mL of Tyfo S Component A to 210 mL of Tyfo S Component B. A small mixing machine was used to properly mix both components of the epoxy. About 7% of silica powder was used for this mixing procedure as recommended by a Fyfe technician. Silica powder was added during the mixing process in order to thicken the epoxy. After the epoxy was properly mixed the FRP composite fabric was ready to be bonded to the concrete. The procedure was initiated by evenly distributing the epoxy on the surface of the exposed concrete. Meanwhile, the FRP composite fabric was also saturated with epoxy on both sides of the fabric. Once this was completed the FRP composite fabric was placed on the concrete surface and even pressure was applied. The pressure was applied in order to make sure the FRP bonded with the concrete and to squeeze out any entrapped air. Figure 2.3 shows a Tyfo SCH-41 composite material ready to be installed. Pressure was applied with the use of the hands for a period of 10 minutes. Lastly, the FRP fabric with epoxy was allowed to cure, shown in figure 2.4, for a period of 72 hours.

Figure 2.3 Tyfo SCH-41 composite material ready to be installed.

Figure 2.4 FRP installed on the concrete specimens.

2.4 Procedures for ASTM C 1543

Following the completion of the FRP and epoxy application ASTM C 1543 was performed. This test called for using a saline solution that would cover the top surface of the concrete specimens up to a height that ranged between 12.5 mm (0.5 inch) to 25 mm (1.0 inch). It was decided that 12.5 mm of solution would be kept constant throughout the course of the ponding procedure. A 5% sodium chloride solution was used in order to perform the ponding procedure. Next, all of the specimens were covered with a 2 μm polyethylene thick sheet around the perimeter of the molds as shown in Figure 2.5. Durable tape was used in order to enclose the polyethylene sheet around the molds in order to prevent any evaporation of water from the 5% sodium chloride solution. The specimens were stored in the mixing room of the civil engineering laboratory facility of the University of Texas at Arlington with a room temperature of 28 ℃ (83℉) and having a relative humidity of 40 %. Each specimen was inspected and, if needed, fresh solution was added in order to keep the surfaces exposed to the solution. Figure 2.6 shows all of the specimens completely taped and covered with the polyethylene sheet. All of the specimens were checked and inspected twice a week for a period of 6 weeks.

Figure 2.5 Concrete specimen being taped with polyethylene sheet.

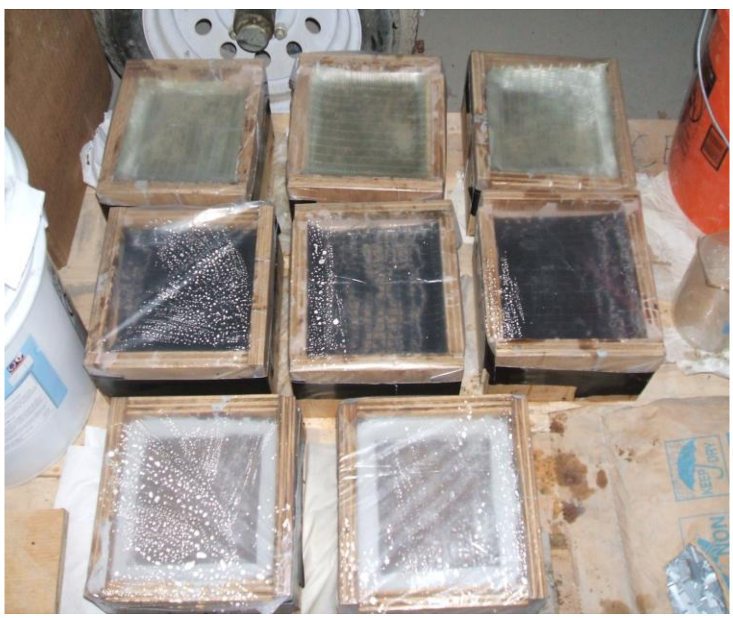

Figure 2.6 Concrete specimens completely taped and covered with polyethylene sheet.

2.4.1 Collecting the Samples

After the 6th week of ponding, the solution of each specimen was removed and the specimens were left to dry completely. Powder concrete samples were collected from each specimen at three different depth intervals of 10 mm (0.4 inch), 25 mm (1.0 inch), and 40 mm (1.6 inch). Two samples weighing about 10 g were taken at each different depth by using a rotary-impact hammer as shown in Figure 2.7. The samples were collected with a plastic spoon, stored in a re-sealable bag, and then labeled accordingly. Each sample location was taken about 25 mm away from the previous sample locations.

Figure 2.7 Collecting the samples by using a rotary-impact hammer.

2.5 Procedures for ASTM C 1152

The samples collected were taken to the Nedderman Hall Building Environmental Lab of the University of Texas at Arlington where they were each weighted. Each weighted sample was then transferred to a 250 mL beaker as shown in Figure 2.8. Next, the sample beakers were diluted with 75 mL of reagent water and mixed well as shown in Figure 2.9. Then, 25 mL of nitric acid having a normality of 8 mol/L, shown in Figure 2.10, was poured into the sample beaker. The sample beaker was stirred with a glass rod in order to break any lumps that could be found inside. Approximately 3 drops of methyl orange indicator was added to the sample beaker and stirred with a glass rod. The sample beaker was then covered with a watch-glass and observed for a period of 2 minutes. This observation was conducted in order to make sure that a pink to red color was present. Otherwise, an additional 10 mL of nitric acid was added to the sample beaker, followed by 3 drops of methyl orange indicator until a constant pink to red color was observed. The beaker was than heated on a hot plate for 10 seconds and then allowed to cool to room temperature before proceeding to the next step. Using a standardized NaCl solution having a normality of 0.025 mol/L, 2.0 mL was transferred into the beaker. The beaker was then placed on a magnetic stirrer and a magnetic stir bar was placed inside. Subsequently, a silver/sulfide electrode was submerged inside the sample beaker while making sure the stir bar did not strike the electrode in any way, as shown in Figure 2.11. A 25 mL burette filled to the zero mark with $AgNO_3$, silver nitrate, solution having a normality of 0.05 mol/L was used. The sample beaker was gradually titrated with the $AgNO_3$ solution until the silver/sulfide electrode reached the equivalence point. Once this was achieved the amount of silver nitrate solution was also recorded from the 25 mL burette. The percent of chloride by mass of concrete was than calculated based on the equation that was provided by ASTM C 1152.

Figure 2.8 Powder sample transferred to a beaker.

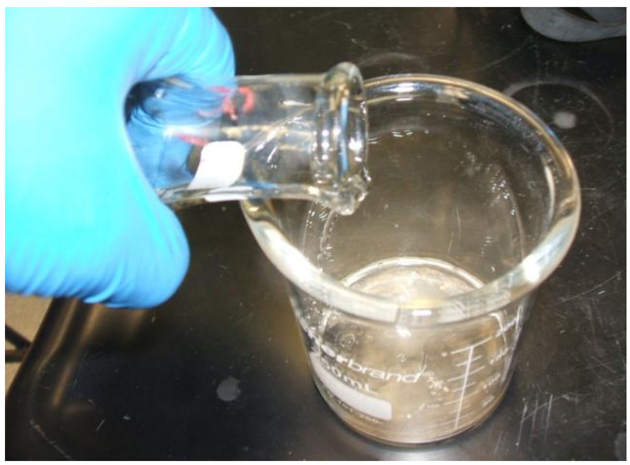

Figure 2.9 Water poured into the beaker.

Figure 2.10 Nitric acid being added to the beaker.

Figure 2.11 Silver/sulfide electrode being submerged into the beaker.

2.5.1 Chloride Profiling Determination

In order to determine the chloride profiling for each of the specimens the equation, shown in Equation 1, was used. This equation determines the acid-soluble chloride that is found in most hydraulic-cement systems that is equal to the total amount of chloride in the system (ASTM 1152). It is know that sulfides can interfere with determining the chloride of the sample. These sulfides can be found in blast-furnace slag aggregates and cements which could potentially produce erroneous test results. In order to avoid such interferences with the results the use of hydrogen peroxide was introduced. The blank sample is used when the results obtained were from concrete samples that were introduced to blast-furnace slag aggregates and cements, which could contain sulfides, during the casting of the concrete (ASTM C1152 2008). In the process of casting the concrete for this study the premixed bags did not contain such aggregates or cement.

$$\mathrm{CL, \%} = 3.545 \frac{[(V_1 - V_2)N]}{W} \quad (1)$$

where:

V_1 = mL of 0.05 N $AgNO_3$ solution used for sample titration (equivalance point).

V_2 = mL of 0.05 N $AgNO_3$ solution used for blank titration (equivalance point).

N = normality of the 0.05 N $AgNO_3$ solution

W = mass of sample, g.

2.5.2 Equivalence Point

The equivalence point was determined by first immersing the silver/sulfide electrode into a 250 mL beaker filled with water only. The beaker was titrated with the $AgNO_3$ until the pH meter gave a potential mV reading below 60 mV from the standard mV reading. The mV readings were taken at every 0.2 mL increment in the burette. The change in mV was then calculated as shown in column 3. The equivalence point is the maximum change in mV value from column 3 as shown in column 4. The equation following the recorded values in Table 2.6 was used to determine the equivalence point.

Table 2.6 Method to determine the equivalence point from ASTM C 114.

Equivalence Point Determination ASTM C 114			
$AgNO_3$ (mL) (Column 1)	Potential (mV) (Column 2)	ΔmV[A] (Column 3)	Δ^2mV[B] (Column 4)
1.6	125.3		
		5.8	
1.8	119.5		1.4
		7.2	
2	112.3		1.3
		8.5	
2.2	103.8		1.3
		9.8	
2.4	94		0.6
		9.2	
2.6	84.8		2.3
		6.9	
2.8	77.9		0.8
		6.1	
3	71.8		1.3
		4.8	
3.2	67		

The equivalence point is in the maximum Δ mV interval (Column 3) and thus between 2.20 and 2.40 mL. The exact equivalence point in this 0.20 mL increment is calculated from the Δ mV (Column 4) data as follow:

$$E = 2.20 + \left(\frac{1.3}{(1.3 + 0.6)}\right) * 0.20 = 2.337 \text{ mL} \rightarrow \text{Round to } 2.34 \text{ mL}$$

A Differences between successive readings in Column 2

B Differences between successive Δ readings in Column 3

CHAPTER 3

RESULTS

3.1 Introduction

This chapter contains the results that were obtained after performing ASTM C 1152 test. The results that were obtained from the Tyfo SCH-41 (CFRP), Tyfo SEH-51A (GFRP), and control specimens are shown in Table 3.1. Appendix A has a sample calculation on the average chloride percentages found in the concrete.

3.2 FRP and Control Specimen Results

The results shown on Table 3.1 indicate that the chloride percentage from the FRP specimens were lower than those from the control specimens. This reduction in percentage of chloride can be seen at every depth. However, at the 40 mm depth the reduction of chloride percentage is seen to be the least among the FRP composites and control specimens. The percent of chloride reduction for the 40 mm depth was less than 0.01%. One of the possible reasons for such low differences could be due to the time period that the specimens were exposed to the sodium chloride solution. In this study, only six weeks were used to determine the percentage of chloride for the concrete specimens. If a longer period of ponding was used than the results would have indicated different values for all of the depths. The chloride percentage at 10 mm had the highest rate of chloride reduction between the FRP composites and controlled specimens. This percent of chloride reduction was about 0.05% for both FRP composite materials.

Table 3.1 Results obtained from each sample at each depth.

Specimen	Depth (mm)	Chloride (%)
CFRP	10	0.232
GFRP	10	0.239
Control	10	0.297
-	-	-
CFRP	25	0.188
GFRP	25	0.181
Control	25	0.224
-	-	-
CFRP	40	0.163
GFRP	40	0.161
Control	40	0.170

3.3 Effects of FRP on Concrete Specimens

3.3.1 CFRP vs. Control Specimens

The points plotted on Figure 3.1 are from the chloride percentage values obtained from the CFRP and Control specimens at the three different depths. Figure 3.1 plots a cast-in-place reinforced, nonprestressed, concrete beam (green) that is exposed to the weather with a minimum clear cover depth of 38 mm. The green horizontal line drawn in Figure 3.1 from the red control specimen line to the blue CFRP specimen line shows an equivalent chloride percentage of 0.177%. Therefore, an equivalent clear cover can be established as it is shown with the green vertical line drawn to the depth axis. The equivalent clear cover value from the nonprestressed beam is 31.8 mm (1.3 inch). The established clear cover provides a reduction of 6.2 mm (0.25 inch) from the 38 mm required by the ACI 318-11. Figure 3.1 also shows a plot of a cast-in-place reinforced, prestressed, concrete slab (orange) that is exposed to the weather with a minimum clear cover depth of 25 mm. The orange horizontal line drawn from the control to the CFRP plotted line shows the equivalent chloride percentage of 0.224%. The equivalent clear cover value for the prestressed concrete slab is determined in the similar fashion as described for the beam. The equivalent clear cover of the prestressed slab is 13.0 mm (0.52 inch). This established clear cover provides a reduction of 12 mm (0.48 inch). Table 3.2 represents the equivalent clear cover values and clear cover reduction for the nonprestressed beam and prestressed slab.

Table 3.2 Equivalent clear cover from the CFRP application.

Concrete Member	ACI Minimum Clear Cover (mm)	Equivalent Clear Cover (mm)	Clear Cover Reduction (mm)	Clear Cover Reduction (%)
Beam	38.0	31.8	6.2	16.0
Slab	25.0	13.0	12.0	50.0

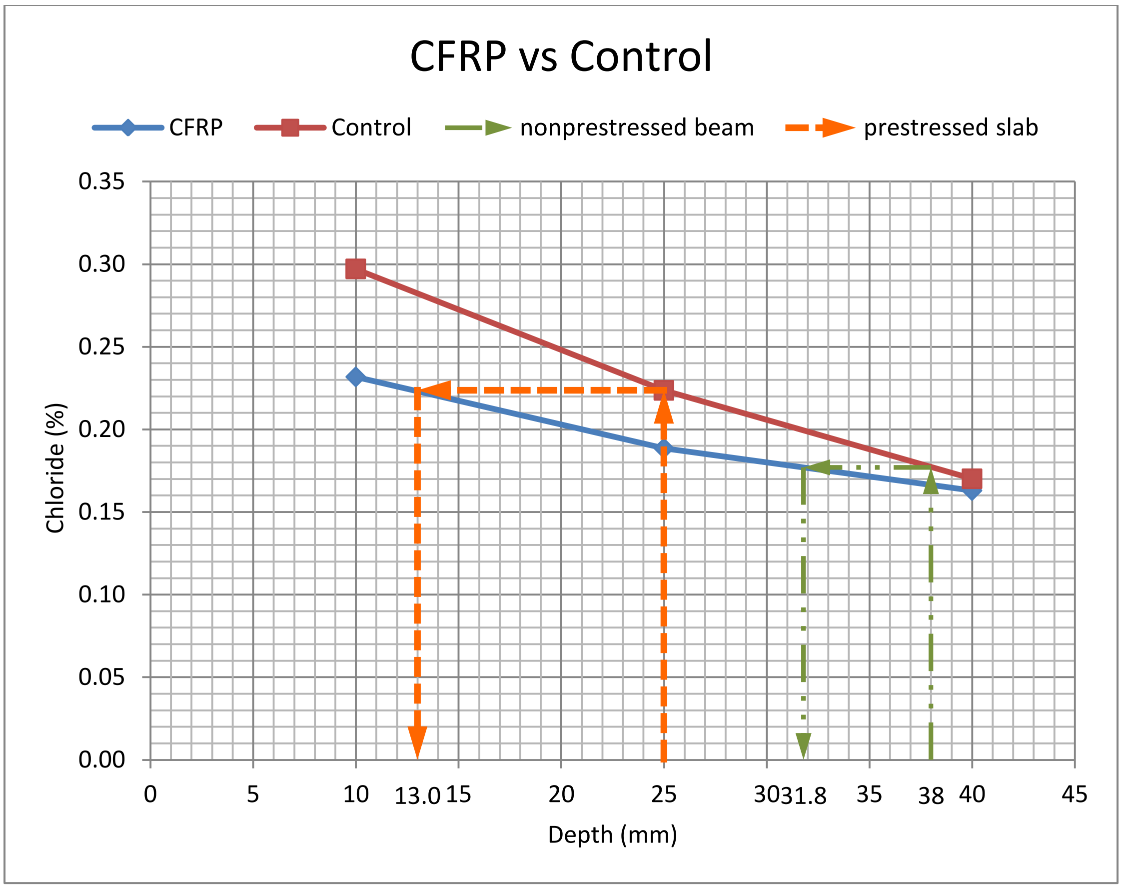

Figure 3.1 Graphical chloride percent plot at each depth between the CFRP and Control specimens

3.3.2 GFRP vs. Control Specimens

In Figure 3.2 the percentage of chloride vs. depth is plotted for the GFRP and control specimens. Additional plots have been plotted on Figure 3.2 in order to establish an equivalent clear cover value for a nonprestressed beam and prestressed slab. The same clear cover values of 25 mm and 38 mm are used in Figure 3.2 for the prestressed slab and nonprestressed beam, respectively. From Figure 3.2 an equivalent clear cover value of 28 mm (1.1 inch) is obtained for the nonprestressed beam. This established clear cover value provides a reduction of 10.0 mm (0.4 inch) and is slightly higher than the 6.2 mm value obtained from the CFRP. The established equivalent clear cover value for the prestressed slab is 14 mm (0.6 inch). The GFRP provided a clear cover reduction of 11.0 mm (0.4 inch) which is slightly lower when compared to the CFRP value of 12 mm. Table 3.3 represents the equivalent clear cover values for the nonprestressed beam and prestressed slab.

Table 3.3 Equivalent clear cover from the GFRP application.

Concrete Member	ACI Minimum Clear Cover (mm)	Equivalent Clear Cover (mm)	Clear Cover Reduction (mm)	Clear Cover Reduction (%)
Beam	38.0	28.0	10.0	26.0
Slab	25.0	14.0	11.0	44.0

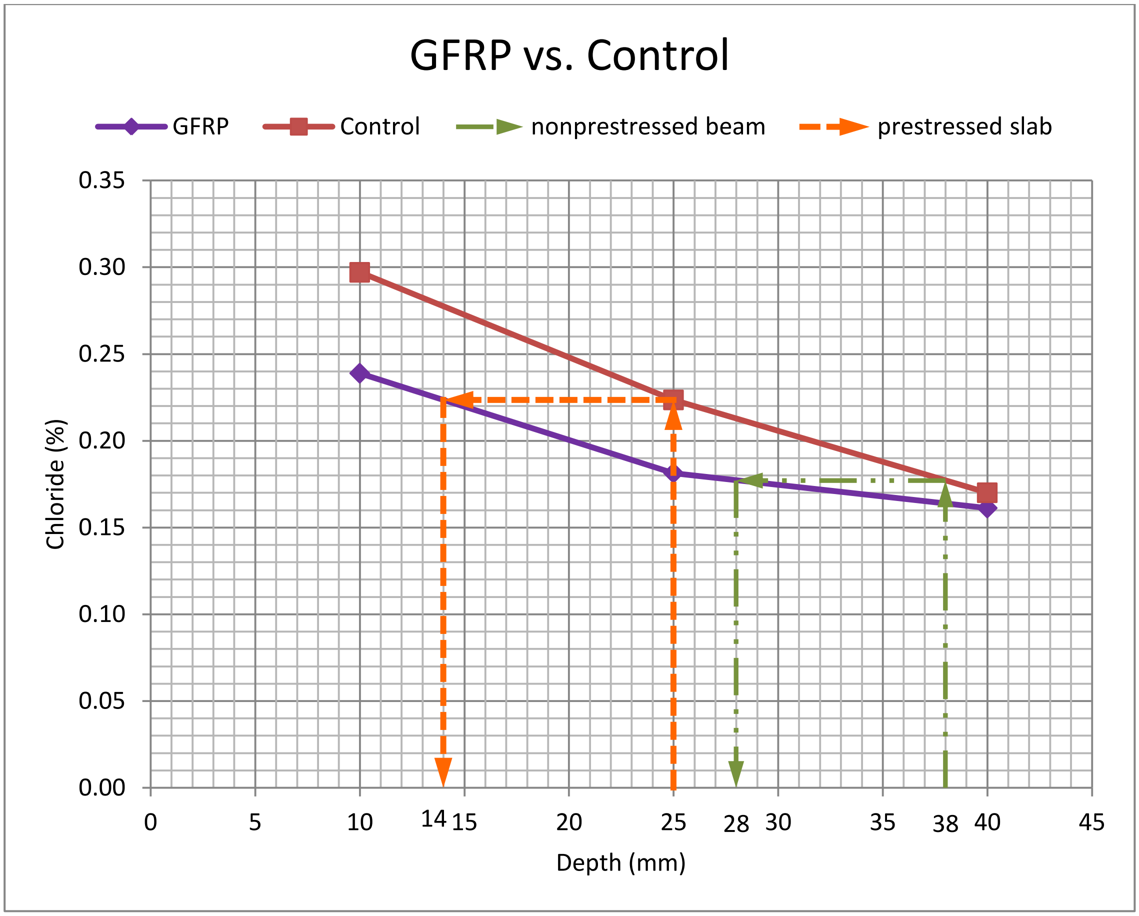

Figure 3.2 Graphical chloride percent plot at each depth between the GFRP and Control specimens.

3.3.3 CFRP vs. GFRP Specimens

Figure 3.3 plots the chloride percentage vs. depth for the CFRP and GFRP specimens. This figure is used to determine any significant differences that could be shown between the two FRP composite materials. Both FRP composites yielded similar results at the 40 mm depth. On the contrary, the chloride percentage values at the 25 mm and 10 mm depths were found to be different. From Table 3.1 the chloride percentage difference between the CFRP and the GFRP did not vary by more than 0.01% for any of the depths. This could indicate that the epoxy resin used in the FRP composite materials is one of the determining outcomes that produce these results and not the fibers themselves. Another possible factor that may lead to these results is the properties of the epoxy resin. If a different epoxy resin with different physical properties would have been used then this could have yielded different results. The epoxy resin is the component that provides the adhesion between the FRP composite material and the concrete surface. Therefore, if the FRP composite material was not installed correctly an exposed surface area of concrete could have resulted. This would have left the sodium chloride solution to penetrate the concrete during the ponding period leading to different chloride percentage values.

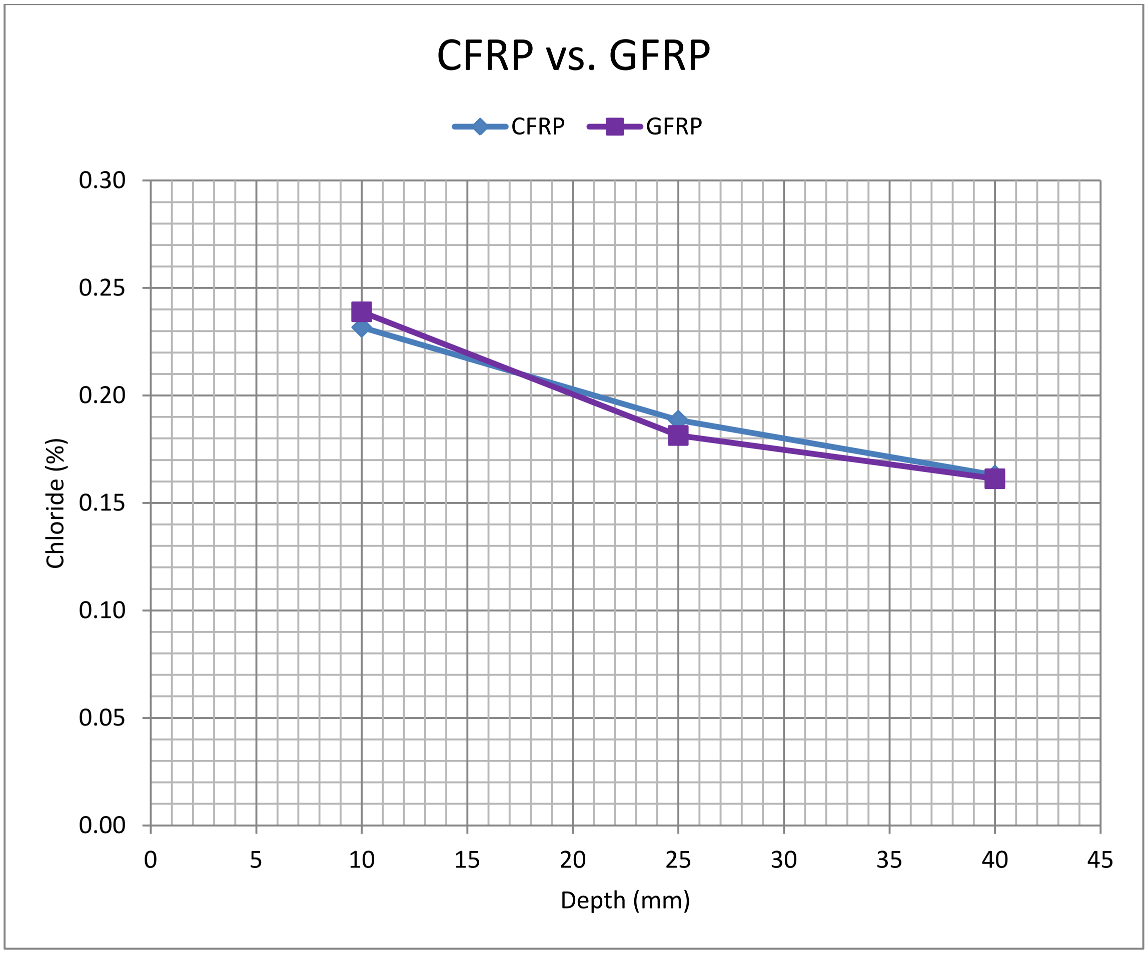

Figure 3.3 Graphical chloride percent plot at each depth between the CFRP and GFRP specimens.

3.4 Flexural Capacity Increase Due to Equivalent Clear Cover

3.4.1 MBrace Design Guide

The different modes of failure with the incorporation of FRP in concrete design are critical towards a safe structure. The MBrace design guide is mentioned here to give a representation on the flexure capacity increase using equivalent clear cover values. The modes of failure consider in the MBrace guide are concrete crushing before steel yielding and FRP rupture before steel yielding. The failure mode of concrete crushing before steel yielding represents the actual design that the ACI 318-11 uses to approximate the rectangular stress block in the compression side of the concrete. According to the MBrace design guide this approximation is permitted since it can be assumed that the concrete has reached is maximum usable strain value. Failure mode due to FRP rupture is considered when the FRP yields before the concrete reaches its ultimate assumed strain value of 0.003. Therefore, the approximation that the ACI 318-11 uses cannot be used and a different approach is considered in the MBrace design guide. This approach consists of using a rectangular stress block that is suitable to the strain level present in the concrete when FRP ruptures. The mode of failure is essential when calculating the nominal capacity of the concrete. Equation 2 is used in the MBrace design guide to design reinforce concrete with the incorporation of FRP sheets at ultimate strength.

In Equation 2, the nominal moment capacity of the concrete is proportional to the reinforcement from the prestressed strands, top and bottom rebar, and FRP composite sheets. Figure 3.5 illustrates typical reinforcements used in reinforce concrete. From Equation 2, increasing the FRP reinforcement will produce a higher moment capacity for the structure. However, keeping the moment constant and increasing the FRP reinforcement can lead to a reduction on some of the other terms when designing a reinforced concrete structure. Therefore, increasing the FRP reinforcement can lead to changing the area of the mild reinforcement in the tension or compression side. This reduction of area of the mild reinforcement could lead to a reduction of concrete clear cover. For example, a cast-in-place nonprestressed concrete member exposed to the weather has a minimum ACI clear cover requirement of 50 mm (2 inch) for a No 6. rebar reinforcement or higher (ACI 318-11). Incorporating FRP in the design could change the rebar size needed below a No 6. This will lead to a different clear cover minimum of 38.0 mm (1.5 inch). This change of size in the rebar will result in a reduction of 12.0 mm (0.5 inch) in clear cover depth. However, the changing of the rebar size for clear cover reduction is not the main focus of this study but it can be looked at by future studies. The MBrace design guide uses the following assumptions to correctly use Equation 2.

- Perfect bond is considered between the FRP and the surface of the concrete.
- The plane section of the concrete remains plane after bending of the concrete (Bernoulli's principle).
- The factored loads in the concrete are within the structure's elastic range during the FRP application.
- Completely evaluating the structural condition of the structure.
    - For example: steel areas and properties, concrete strength, effective prestress forces, etc.

This study has established equivalent clear cover depths which can be used to replace the required minimum clear cover depths found in the ACI 318-11. Therefore, the nominal moment capacity would increase because of an increase in the distance of the centroid from the reinforcement to the top of the concrete surface.

$$M_n = A_p f_{ps}\left(d_p - \frac{\beta_1 c}{2}\right) + A_s f_s\left(d - \frac{\beta_1 c}{2}\right) + A_s' f_s'\left(\frac{\beta_1 c}{2} - d'\right) + 0.85 A_f f_f\left(h - \frac{\beta_1 c}{2}\right) \quad (2)$$

where:

A_f = Total area of the FRP composite material.

A_p = Area of prestressing steel.

A_s = Area of tension steel.

A_s' = Area of compression steel.

β_1 = Constant which determines the depth of an equivalent rectangular stress distribution for concrete.

c = Depth to the neutral axis.

d = Depth to the tension steel reinforcement centroid.

d' = Depth to the compression steel centroid.

d_p = Depth to the prestressing steel centroid.

f_f = Stress in the FRP.

f_{ps} = Stress in the prestressing tendons.

f_s = Stress in the tension steel.

f_s' = Stress in the compression steel.

h = Depth of the FRP flexural reinforcement.

M_n = Nominal capacity of a section.

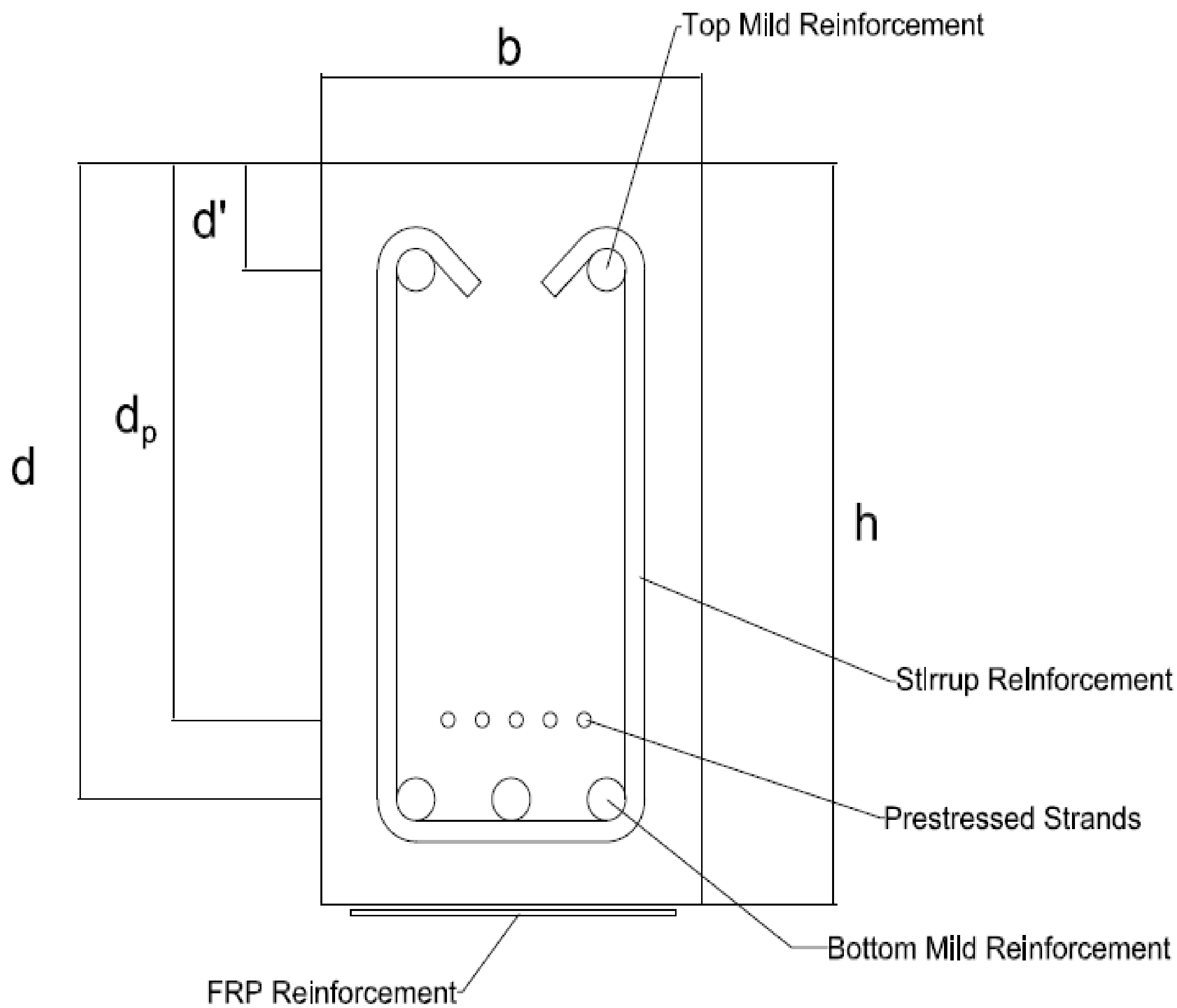

Figure 3.4 Typical reinforced concrete cross-section with FRP reinforcement

3.5 Limitations of the Study

Several limitations in the study reported herein are listed in the following:

1. The study is intended to show possible reduction of ACI 318 Code concrete clear cover with FRP wrapping. The research design is based on possible chloride penetration in concrete based on ASTM specifications. The ACI clear covers are provided to reduce possible corrosion of steel rebars in concrete due to moisture ingress, chloride and chemical ingress and elevated temperatures. An assumption is made herein that the chloride ingress is the major component responsible for steel corrosion.
2. The study is based on chloride ingress data from six weeks duration. Longer ponding periods would have resulted in greater chloride penetration inside the concrete, especially in the control samples without FRP applied. This would result in more drastic differences in the results from the control and the FRP samples, leading to larger reductions in the minimum clear covers.
3. The chloride ponding test used herein is based on the static ponding of a chloride solution on the concrete surface. This situation simulates concrete structures subjected to coastal structures in contact (constant) with saline sea water, such as bridge piers. In this study, it is assumed that this class of structures are covered under the ACI Code specified “concrete exposed to earth or weather” category (Section 7.7 ACI 318). Other structures defined in the ACI 318 Code, such as “concrete permanently exposed to earth” and “concrete not exposed to weather or earth” are not addressed in this study.
4. FRP wrapping is typically used currently for the strengthening of existing concrete structures that have been damaged due to corrosion, fire, collision or cracking. The clear covers provided in such existing structures are already in place and cannot be changed in the repaired structure. If the clear covers in the

original structure did not satisfy the minimum ACI specified values (which is quite common), the FRP strengthened structures could be made code compliant with the reduced cover requirements. In addition, as discussed previously, the reduced covers and increased moment arms could lead to greater moment capacities that would be beneficial to the structure in meeting new load requirements.

5. Only one layer of FRP was utilized in this study. Multiple layers of FRP and epoxy application could result in more dramatic reduction in chloride ingress, durability increase and clear cover requirements.

CHAPTER 4

CONCLUSIONS AND FUTURE RESEARCH

The significance of this study was to investigate the effects of FRP application in increasing concrete durability and possible reduction in minimum concrete clear cover. The result obtain in section 3.3.1 indicate that the FRP application helped with the ingress of the sodium chloride. The following conclusions may be made based on the findings from this study.

- Application of FRP wrapping on concrete surfaces decreases the ingress of chloride inside the concrete and increases the concrete durability. The reduction of chloride ingress for FRP applications varied between 0.05% and 0.01%, based on the depth of penetration. The reduction was most noticeable near the surface, and decreased at increasing depths. Therefore, it may be inferred that decreased chloride ingress should reduce the potential for rebar corrosion, concrete deterioration, loss of load capacity and service life. FRP application can be used to extend the design life of a concrete structure.
- Simple interpolations based on the plotted chloride ingress results at various depths showed that the required clear cover for rebars (based on equivalency of chloride ingress between unprotected concrete and FRP protected concrete) can be conveniently reduced for concrete with FRP application. The reductions can range between 16% – 26% for beams and 44% – 50% for slabs, based on the FRP type. The CFRP and the GFRP wraps yielded mixed results, with the CFRP showing slightly more benefits for slab clear covers and the GFRP showing more benefits for the beam clear covers.
- The study is based on chloride ingress data from six weeks duration. Longer ponding periods would have resulted in greater chloride penetration inside the

concrete, especially in the control samples without FRP applied. This would result in more drastic differences in the results from the control and the FRP samples, leading to larger reductions in the minimum clear covers.

- The chloride ponding test used herein is based on the static ponding of a chloride solution on the concrete surface. This situation simulates concrete structures subjected to coastal structures in contact (constant) with saline sea water, such as bridge piers. In this study, it is assumed that these classes of structures are covered under the ACI Code specified "concrete exposed to earth or weather" category (Section 7.7 ACI 318). Other structures defined in the ACI 318 Code, such as "concrete permanently exposed to earth" and "concrete not exposed to weather or earth" are not addressed in this study.
- Typically FRP wrapping is currently used for strengthening of existing concrete structures that have been damaged due to corrosion, fire, collision or cracking. The clear covers provided in such existing structures are already in place and cannot be changed in the repaired structure. If the clear covers in the original structures did not satisfy the minimum ACI specified values (which is quite common), the FRP strengthened structures could be made code compliant with the reduced cover requirements. In addition, as discussed previously, the reduced covers and increased moment arms could lead to greater moment capacities that would be beneficial to the structure in meeting new load requirements.
- Only one layer of FRP was utilized in this study. Multiple layers of FRP and epoxy application could result in more dramatic reduction in chloride ingress, durability increase and clear cover requirements.

The recommend future research based on the study findings are listed below.

- Use multiple layers of wrapped FRP composites on concrete in order to obtain the equivalent clear cover depths for a longer period of sodium chloride exposure. It is recommended that the concrete be exposed to the chemical reagent for a period of at least 12 months.
- Using different epoxy materials in combination with different FRP composites to find any differences when establishing the clear cover depths.
- Examine concrete with FRP wrapping exposed to other possible corrosion causing agents besides chloride, such as water, other chemicals and elevated temperatures.
- Design and test beams/slabs using FRP wrapped concrete with varying equivalent clear cover depths and required clear cover depths. Evaluate different aspects such as the type of failure and structural capacity.

APPENDIX A

SAMPLE CALCULATION ON CHLORIDE PERCENT DETERMINATION

The following equation was used in order to determine the percent of chloride in the concrete. The following figure is shown in order to define the eight concrete specimens.

$$CL,\% = 3.545\frac{[(V_1 - V_2)N]}{W}$$

$where$:

$V_1 = mL\ of\ 0.05\ N\ AgNO_3\ solution\ used\ for\ sample\ titration\ (equivalance\ point).$

$V_2 = mL\ of\ 0.05\ N\ AgNO_3\ solution\ used\ for\ blank\ titration\ (equivalance\ point).$

$N = normality\ of\ the\ 0.05\ N\ AgNO_3\ solution$

$W = mass\ of\ sample, g.$

Figure A.1 Defines the eight concrete specimens.

The following table represents the recorded values obtained for the GFRP-1, GFRP-2, and GFRP-3 specimen at the 10 mm depth.

Table A.1 Represents the values recorded for the GFRP-1, GFRP-2, and GFRP-3 specimen at the 10 mm depth.

Specimen	Depth (mm)	Weight, W (g)	Silver Nitrate ($AgNo_3$) used (mL)	Cl (%)
GFRP-1	10	9.8	12.8	0.232
GFRP-1	10	9.4	13.1	0.247
GFRP-2	10	9.4	13.2	0.249
GFRP-2	10	9.9	12.9	0.231
GFRP-3	10	10.4	13.3	0.227
GFRP-3	10	9.7	13.6	0.249
Average	-	-	-	0.239

The following calculation is shown in order to determine the percentage of chloride for the samples collected from ASTM C 1152 for the GFRP specimens at the 10 mm depth only. The normality of the silver nitrate solution was 0.05 mol/L. The blank titration value, V_2, was not considered in this study as noted from section 2.5.1. The 3.545 is a constant given in the equation from the ASTM C 1152. The average value was calculated from the Cl, chloride percentage, values obtained for each sample taken at the 10 mm depth. The CFRP and Control average values were calculated in a similar manner as described here for the GFRP specimens.

$$Using\ Equation\ from\ ASTM\ C\ 1152\ (above)$$

$$\boldsymbol{GFRP-1}$$

$$1st\ 10\ mm\ depth\ sample\ collected$$

$$CL,\% = \left[3.545\frac{[(V_1 - V_2)N]}{W}\right]$$

$$CL,\% = \left[3.545\frac{[(12.8\ mL - 0\ mL)0.05\ mol/L]}{9.8\ g}\right]$$

$$then,$$

$$\boldsymbol{CL},\% = \mathbf{0.232}\ \%$$

$$2nd\ 10\ mm\ depth\ sample\ collected$$

$$CL,\% = \left[3.545\frac{[(V_1 - V_2)N]}{W}\right]$$

$$CL,\% = \left[3.545\frac{[(13.1\ mL - 0\ mL)0.05\ mol/L]}{9.4\ g}\right]$$

$$then,$$

$$\boldsymbol{CL},\% = \mathbf{0.247}\ \%$$

$$\boldsymbol{GFRP-2}$$

$$1st\ 10\ mm\ depth\ sample\ collected$$

$$CL,\% = \left[3.545\frac{[(V_1 - V_2)N]}{W}\right]$$

$$CL,\% = \left[3.545\frac{[(13.2\ mL - 0\ mL)0.05\ mol/L]}{9.4\ g}\right]$$

$$then,$$

$$\boldsymbol{CL},\% = \mathbf{0.249}\ \%$$

$$2nd\ 10\ mm\ depth\ sample\ collected$$

$$CL,\% = \left[3.545\frac{[(V_1 - V_2)N]}{W}\right]$$

$$CL, \% = \left[3.545 \frac{[(12.9\ mL - 0\ mL)0.05\ mol/L]}{9.9\ g}\right]$$

$$then,$$

$$\boldsymbol{CL}, \% = \mathbf{0.231}\ \%$$

$$\boldsymbol{GFRP - 3}$$

$$1st\ 10\ mm\ depth\ sample\ collected$$

$$CL, \% = \left[3.545 \frac{[(13.3\ mL - 0\ mL)0.05\ mol/L]}{10.4\ g}\right]$$

$$then,$$

$$\boldsymbol{CL}, \% = \mathbf{0.227}\ \%$$

$$2nd\ 10\ mm\ depth\ sample\ collected$$

$$CL, \% = \left[3.545 \frac{[(13.6\ mL - 0\ mL)0.05\ mol/L]}{9.7\ g}\right]$$

$$then,$$

$$\boldsymbol{CL}, \% = \mathbf{0.249}\ \%$$

$$\boldsymbol{AVERAGE\ VALUE\ OF\ THE\ GFRP\ SPECIMENS}$$

$$Avereage = \frac{(0.232 + 0.247 + 0.249 + 0.231 + 0.227 + 0.249)\%}{6}$$

$$\boldsymbol{Average} = \mathbf{0.239}\%$$

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BIOGRAPHICAL INFORMATION

Gunther Geovany Garcia graduated from The University of Texas at Arlington earning a Bachelors of Science in Civil Engineering with an area of concentration in structures on May 14, 2011. During the fall of 2009 he applied for the Fast-Track program in the structural engineering area. His was approved for the Fast-Track engineering program after successfully completing the required courses. This opened a window for Gunther to continue his education at the University of Texas at Arlington. On May 2013 he graduated and obtained his Master of Science in Civil Engineering degree with structural engineering emphasis. Gunther Garcia's future plans are to first start working in order to obtain a professional license. Gunther will then consider coming back to school to obtain a Doctor of Philosophy degree or start a business.