CONCRETE CHLORIDE INGRESS: EFFECT OF FRP TYPE, LAYERS AND EPOXY

by

VINOD REDDY KAMAGANI KUNTLA

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Abstract

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Vinod Reddy Kamagani Kuntla, MS

The University of Texas at Arlington, 2015

Supervising professor: Nur Yazdani

The main objective of this research is to reduce the chloride ingress in concrete due to the effects of Fiber Reinforced Polymer (FRP) type, layers and Epoxy. It has been established from previous researches that FRP wrap used to retrofit concrete structures offer a high resistance to chemical solutions but in this case study different variables like FRP, layers of FRP and only epoxy are used to know the resistance of concrete structures 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 used in my research are Tyfo SCH-41 composite fabricated with carbon fibers and Tyfo WEB composites fabricated with glass fibers. The epoxy used in this study is Tyfo S, which is compromised in to two component (component A and component B). The Tyfo S epoxy matrix material is combined with the Tyfo fabrics to provide a wet-layup composite system for strengthening structural members. The wrapped FRP specimens, epoxy coated specimens and control specimens without FRP wrapping and epoxy coating were tested according to ASTM C1543 and ASTM C1152. The surfaces of samples wrapped with FRP, layers of FRP, epoxy coated samples and normal control specimens are exposed to sodium chloride solution (ponding process) for 16 weeks. At the end of ponding process, samples are made dry and powdered samples are collected at different depths (based on ACI and AASHTO minimum cover requirements) to determine the percentage of chloride in each specimen using the ASTM C1152 method.

Table of Contents

List of Illustrations

List of Tables

Chapter 1

Introduction

1.1 History and Introduction of Fiber Reinforced Polymers

Corrosion of steel in concrete leads to the failure of many structures exposed to harsh environments. This leads to crack and spall of concrete member, both of which can severely reduce the service life and strength of a member. Corrosion of steel in concrete structures is one of the major problems faced by civil engineers in the United States. Many bridges, parking garages, and other concrete structures have been damaged by corrosion, and repairs of those structures are required to ensure public safety (Jones 1996). As the structures approach the end of their service life, several methods for repair and rehabilitation of corroded members must be developed. To prevent and control corrosion activity at an early stage, accurate diagnosis techniques are necessary. Due to the increase in number of corrosion related problems in the field, many researches are taking place to control corrosion of steel in concrete.

Fiber Reinforced Polymer is a composite material made of polymer matrix reinforced with fibers. Fibers can be fabricated from natural or synthetic material (American Concrete Institute (ACI) 2007). Commonly used fibers are carbon, glass and aramid. Fiber reinforced polymers are first introduced in 1930's but in 1940's it was introduced in US for aerospace and naval applications. FRP are developed commercially after world war- II. FRP's are most commonly used in aerospace, marine, automotive and construction industries. There are many conventional materials and constructional techniques like external post tensioning, externally bonded steel plates, steel or concrete jackets for strengthening or retrofitting existing concrete structures. FRP became a valuable and best alternative to all the traditional methods for repair and rehabilitation.

Potential advantages in use of FRP composites:

- High strength and higher performance
- Corrosive resistance
- Resistance to effects of weather, moisture and salt
- Light weight
- Rehabilitating existing structures and increasing their life
- Resistance to ocean environments and seismic upgrades.

In 1942 the first fiberglass laminates are manufactured. The early applications of GFRP products were in the marine industry. Fiberglass boats were manufactured in the early 1940s to replace traditional wood or metal boats. The lightweight, strong fiberglass composites were not subject to rusting like their counterparts and they were easy to maintain. Fiberglass continues to be a major component of boats and ships today. In 1942, the U.S. Navy replaced all the electrical terminal boards on their ships with fiberglass composites. In 1943 Wright-Patterson air force base were launched to build structural aircraft parts from composite materials. This resulted in the first plane with GFRP composites. FRP technology spread rapidly in the 1950's. In France, a factory was opened in 1950 for the production of glass fibers. However, new demands emerged for the military space programs and new fibers which prompted the search for new high modulus fibers. In 1960's carbon fibers were manufactured and due to its superior processing capabilities and its lower cost, carbon fibers are used mostly than glass fibers. In 1971 aramid fibers were developed by Stephanie Kwolek. Aramids belong to the nylon family of polymers. According to the American Concrete Institute (ACI) 440R-07 report, the composite industry has grown in several markets including construction, corrosion-resistant equipment, marine, transportation, and other applications.

Now days, these materials are readily available in several forms, ranging from laminates to dry fiber sheets that can be wrapped to conform to the geometry of a structure before adding the resin. The relatively thin profiles of cured FRP systems are often desirable in applications where access is a concern (ACI 440.2R-08). FRP systems can also be used where there is limited access for traditional techniques. The type of material fibers used in the composite determines the physical properties, orientation, and modulus of elasticity.

Epoxy, is the material that is component of FRP composite. Epoxy adhesives are very well established in applications involving the bonding of structural materials and it is known that they are considered to be suitable for the bonding of FRP materials. Epoxy adhesives are also used for gap fillings and also it provides a long working time for application with no offensive odor. While using FRP composite for strengthening and retrofitting concrete structures, we also need to consider the properties of epoxy.

1.2 Strengthening or Retrofitting Concrete Structures

1.2.1 Methods for Strengthening or Retrofitting Concrete Structures

For reinforcing or retrofitting existing concrete structures, mainly used constructional techniques are external post tensioning, externally bonded steel plates, steel or concrete jackets. The reasons for the strengthening or retrofitting of concrete structures are typically to increase existing elements capacity to carry more loads or to resolve an existing problem. Figure 1 shows the external post tensioning method to strengthen concrete structures and Figure 2 shows the method to strengthen the concrete structures externally using steel plates but these methods have their own issues when exposed to prolonged chemical agents or due to continuous load. The method of externally post tensioning are prone to anchorage failures as the compressive forces are transferred at the beam ends and also fails due to snow over load(Figure 3). Whereas, the method of externally bonded steel plates have issues like transportation, handling, deterioration of the bond between steel and concrete, installation of heavy plates and corrosion of plates (when continuously exposed to chemical agents like salt, acids and alkaline).

Figure 1-1 External post tensioning for strengthening structure (www.cclint.com)

Figure 1-2 externally bonded steel plates (www.chemcosystems.com)

Figure 1-3 Failed post tensioned beam due to snow over load

1.2.2 Fiber Reinforced Polymer in Reinforcing Concrete Structures

FRP materials are applied for protection, seismic strengthening, load rating increases, repair corroded members, emergency repairs and construction error remediation. FRP can be applied to masonry, concrete, steel and timber substrates - among others .Rehabilitation of deteriorated civil engineering structures such as bridges, buildings beams, girders, parking structures, etc., are done using many constructional techniques like external post tensioning, externally bonded steel plates or concrete jackets and fiber reinforced polymer laminate. Among all these constructional techniques, FRP became a valuable alternative to traditional materials for repair and rehabilitation. These composite materials are different from traditional constructional methods because they are anisotropic and the properties of composites differ depending on the direction of fibers and these composite material gain their superior characteristics from the component materials(like epoxy) used. Unlike all the traditional methods, FRP composite will not corrode when exposed to prolonged chemical solutions like acids, salt or alkaline. FRP composite systems can be used in areas where the existing conventional methods may have limited access and are difficult to implement (ACI 2008). FRP composite systems have the resistance to corrosive agents. FRP systems should be determined whether it is suitable strengthening technique before selecting the type of FRP system. FRP fabrics or sheets can be wrapped around reinforced concrete columns thus increasing the confinement and axial strength. Moreover, it increases the flexural, shear and torsion strengths and also improves the ductility.

There are few projects were FRP wrap is used for strengthening and rehabilitation of structures. The projects were FRP wrap is used to strengthen are JFK Bridge over risley channel in Atlantic country New Jersey, Nashwaak River Bridge in Fredericton, New Brunswick Canada, Milwaukee South first street Bridge in Milwaukee, WI and FRP girder strengthening for Caltrans big oak side hill viaduct, Tuolumne County, CA. In these projects the FRP used mainly is Tyfo SCH-41 carbon FRP and Tyfo SEH-51A glass FRP.

Figure 1-4 JFK bridge over Risley Channel in Atlantic country, New Jersey

Figure 1-5 Nashwaak River Bridge in Frederiction, New Brunswick, Canada

Figure 1-6 New Brunswick, Canada, Milwaukee South first street Bridge

Figure 1-7 FRP girder strengthening for Caltrans big oak side hill viaduct

Chapter 2

Clear Cover Requirements

2.1 Clear Cover According to ACI 318

Concrete cover as a protection of reinforcement against weather and other effects is measured from the concrete surface to the outermost surface of the steel to which the cover requirement applies. Concrete cover for reinforcement is required to protect the rebar against corrosion and to provide resistance against fire. Thickness of cover depends on environmental conditions and type of structural member. The concrete cover shall be maintained by cement mortar cubes or other approved means. The use of pebbles or stones shall not be permitted. According to ACI 318-11, Chapter 7 "Details of reinforcement" provides the minimum clear cover requirements. According to ACI 318-11, minimum cover required for concrete cast against and permanently exposed to earth is 3 in (75 mm). According to ACI 318-11, minimum cover is provided for concrete exposed to earth or weather and concrete not exposed to weather or in contact with ground. ACI code also provides minimum cover for beams, columns, shells, folded plate members, slabs, walls etc. Concrete cover also depends on the size of reinforcement that is used in concrete. According to ACI 318, the minimum concrete cover ranges from 0.50 in (12.50 mm) to 3 in (75 mm). These clear cover distances apply to all reinforcements in concrete such as the top or bottom longitudinal mild reinforcement, stirrups, and pre-stressed 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. Table 2-1 shows the ACI minimum clear cover values of slabs, columns, beams and all concrete members.

Table 2-1 ACI minimum cover requirements

Situation	Concrete cover, in
Concrete cast against and permanently exposed to earth	3 in (75 mm)
Concrete exposed to earth or weather : No.6 through No.18 bars No.5 bar and lesser	2 in (50 mm) 1-1/2 in (37.5 mm)
Concrete not exposed to weather or in contact with ground : *Slabs, walls, joists* No.14 and No.18 bars No.11 bar and lesser	1-1/2 in (37.50 mm) 3/4 in (18.75 mm)
Beams, Columns : *Primary reinforcement, ties, stirrups, spirals*	1-1/2 in (37.50 mm)
Shells, Folded plate members: No.6 bar and larger No.5 bar and smaller	3/4 in (18.75 mm) 1/2 in (12.50 mm)

2.2 Clear Cover According To AASHTO LRFD Bridge Specifications

The AASHTO LRFD bridge design specification is a design guide which engineers follow when designing bridges. In the AASHTO LRFD bridge design specification, section 5 titled “Concrete structures” provides the minimum clear cover requirements. AASHTO provides concrete cover for cast against earth, bottom of cast in place slabs, precast reinforced piles, cast in piles, interior other than above etc. According to AASHTO, concrete cover depends on the size of reinforcement that is used in concrete. According to AASHTO, minimum cover is determined by multiplying concrete covers in Table 2-2 with modification factor. The modification factor of 0.8 is used for concrete, when the w/c ratio is less than or equal to 0.40 and modification factor of 1.2 is used for concrete, when w/c ratio is greater than or equal to 0.50. Modification factor is determined based on w/c ratio. In this case study the modification factor is 0.8 because the w/c ratio is equal to 0.40.

Table 2-2 AASHTO minimum cover values

Situation	**Concrete cover, in**
Direct exposure to salt water	4.0 in (100 mm)
Cast against earth	3.0 in (75 mm)
Coastal	3.0 in (75 mm)
Exposure to deicing salts	2.5 in (62.5 mm)
Deck surface subjected to tire stud	2.5 in (62.5 mm)
Exterior other than above	2.0 in (50 mm)
Interior other than above	-
Up to No.11bar	1.5 in (37.5 mm)
No. 14 and No. 18 bars	2.0 in (50 mm)
Bottom of cast in place slabs	-
Up to No. 11 bar	1.0 in (25 mm)
No. 14 and No. 18 bars	2.0 in (50 mm)
Precast soffit from panels	0.8 in (20 mm)
Precast reinforced piles	-
Non-corrosive environments	2.0 in (50 mm)
Corrosive environments	3.0 in (75 mm)
Precast Pre-stressed piles	2.0 in (50 mm)
Cast in Place piles	
Non-corrosive environments	2.0 in (50 mm)
Corrosive environments	-
General	3.0 in (75 mm)
Protected	3.0 in (75 mm)
Shells	2.0 in (50 mm)
Auger-cast, slurry construction	3.0 in (75 mm)

Chapter 3

Literature Review

3.1 Scope of Work

The study is intended here is to show possible reduction of chloride ingress and ACI concrete cover with FRP wrapping. The research design is based on possible chloride penetration in concrete based on ASTM specifications. The ACI required minimum covers are provided to reduce possible corrosion of steel rebar's 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.

The use of FRP composite sheets in this study is to know the effects of FRP wrap, layers of FRP and epoxy on reducing the chloride penetration in concrete. The FRP composite materials offer a high resistance to chemical solutions like acids, alkaline, salt solution etc. It is common that FRP composite sheets are used for retrofitting and strengthening existing deteriorating structures. The FRP composites installed here are carbon FRP and glass FRP. In this study, the concrete specimens are installed with the single layer FRP, multi-layer FRP and only epoxy.

For this study ASTM C 1543 and ASTM C 1152 methods are used to determine the resistance of FRP wraps, when the concrete is exposed to sodium chloride solution. ASTM C 1543 tests for the ingress of sodium chloride solution into the concrete by ponding. Ponding process 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. The depths at which the percentage of chloride specimens was determined are taken from the ACI and AASHTO minimum clear cover values. Beside ASTM method, we have tried to study the effects of FRP on reducing the chloride penetration in concrete using multi-layers and also with application of epoxy. According to ASTM method, the ponding process is done for 6 weeks but in this study the ponding process is done for 16 weeks.

In this case study, if the chloride ingress percentage values obtained from specimens installed with FRP (carbon and glass), layers of FRP and specimen with application of only epoxy are lower than the normal concrete specimens. Then we can conclude that chloride ingress has an effect with application of FRP, layers of FRP and epoxy. Moreover, due to the reduction of chloride percentage we can also reduce the minimum clear cover values as specified by ACI and AASHTO.

3.2 Literature Review

Literature review is necessary to know the different procedures and methods performed in this study and related to this study. The topic in this study is to determine the possible effects of FRP, layers of FRP and only epoxy. Different test methods were considered to determine the percentage of chloride in concrete specimen. At first, the test method considered ahead of ASTM methods is laser induced breakdown spectroscopy (LIBS). LIBS method is an important criterion for the evaluation of reinforced concrete structures in the measurement of the chloride content. These LIBS method is normally be done without any time consumption like other standard chemical methods. The application of a spectroscopic technique, LIBS process provides the advantages of a fast measurement and also has the possibility to investigate a wide range of different measuring points. This method can be performed directly on the sample surface and the results are available in real time. This method presents results measured on concrete cores and also on grinded powder, so that we can compare with the results of standard chemical methods. The LIBS set-up and the experimental conditions to detect and measure chlorine in building materials are reported. This LIBS method gives the accurate percentage of chloride content in concrete and very easy to perform than standard chemical methods. But due to unavailability of laser equipment in laboratory, we used standard ASTM method using chemicals to determine the chloride penetration.

Before the study of chloride penetration, we considered different corrosive agents. The corrosive agents are chlorides, acids, sulfates, concentration of these chemicals, availability of moisture and oxygen, thickness of concrete cover. Among all corrosive agents, sulfates and chlorides causes more corrosion than remaining corrosive agents. At first, the study was done on penetration of sulfates in to concrete. The procedure used to detect the sulfur in reinforced concrete structures using dual pulsed laser induced breakdown spectroscopy (LIBS). Sulfate attack can be external or internal. In concrete structures, an excessive amount of sulfate ions can cause severe damage to the strength and the stability of the building structures and hence a sensitive and reliable technique for sulfate ion detection in concrete is highly desirable. Laser induced breakdown spectroscopy (LIBS) is one of the most reliable and sensitive techniques to detect the presence of sulfur in the concrete structure. The atomic emission lines of sulfur are very weak. In order to enhance the sensitivity of the conventional LIBS system, dual pulsed LIBS system is used for detection of weak spectral line of sulfur in concrete. The Nd:YAG laser in conjunction with spectrograph/gated ICCD camera are the core factors in improvement of sensitivity and identifying the sulfur content. Moreover, the dual pulsed LIBS system is also helpful for improvement in the sensitivity and this LIBS signal gives the concentration of sulfur in the concrete sample. In order to know the percentage of sulfur content in concrete, a calibration curve will be drawn by recording the LIBS spectra of sample having sulfur in various concentrations. But the reason to study on chloride penetration beside sulfates penetration is sulfate ions causes less damage than chlorides. Chloride ingress is one of the major causes of reinforced concrete (RC) deterioration.

The literature review was necessary to investigate the possible effects of different types of FRP wrap can provide by reducing chloride penetration in concrete. The literature review is also done on effects of layers of FRP and epoxy. The review is done on epoxy to know whether the reduced chlorine percentage is from FRP composite or only from epoxy. Among the two ASTM methods considered, ASTM C 1543 method is used to determine the percentage of chloride in the concrete for different depth intervals (depths are known from ACI 318 and AASHTO LRFD bridge design specifications minimum clear cover values). 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. 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. 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. FRP composites and two component Epoxy are donated by FYFE Company.

Chapter 4

Properties Of FRP, Epoxy And Concrete

4.1 Properties of FRP

Fiber reinforced polymer is a composite material made of polymer matrix reinforced with fibers. Fibers can be fabricated from natural or synthetic material (ACI 2007). Commonly used fibers are carbon, glass and aramid. The properties of fiber reinforced polymer (FRP) depend on the properties of epoxy also. Now days, there is less usage of aramid fibers when compared to carbon and glass fibers. FYFE Company is supplying carbon and glass fibers only. The FRP used in my research are Tyfo SCH-41 and Tyfo WEB. While using FRP composite for strengthening and retrofitting concrete structures, we also need to consider the properties of epoxy. The epoxy used here is two components Tyfo S epoxy. The Tyfo SCH-41 and Tyfo WEB composite systems were the FRP composite materials used that were donated by FYFE Co. LLC. The Tyfo S epoxy material is a two-component epoxy resin was also donated by FYFE Co. LLC. Properties of Tyfo SCH-41, Tyfo WEB and Tyfo S epoxy material are listed below. The design strength of the composite is based on a combination of the raw carbon fiber and epoxy formulation. As a finished good, the end user does not have the ability to increase the strength beyond the design properties as published by the manufacturer. As the actual thickness of the composite changes (due to variability of epoxy used) the other material properties will correspondingly adjust. There are different thicknesses of composites because some applications require more strength than others.

In this research Tyfo SCH-41 (Carbon FRP) and Tyfo WEB (Glass FRP) are used. Whereas, Tyfo SCH-41 is a unidirectional laminate and Tyfo WEB is a bidirectional laminate. Unidirectional (0°) laminate are extremely strong and stiff in the 0° direction.

However, they are very weak in the 90° direction because the load must be carried by the much weaker polymeric matrix. In the case of bidirectional(0^0 / 90^o) laminate, laminate are strong and stiff in both directions. Laminate direction will not matter in knowing the chloride ingress percentage. Both uni and bidirectional direction laminate will give same results in penetration of chloride but differ when loads are applied.

Table 4-1 Tensile Strength Properties of CFRP and GFRP in unidirectional and bidirectional direction

Properties	CFRP	GFRP
Ultimate Tensile Strength in Primary Fiber Direction	121,000 psi (834 MPa)	35,840 Psi (247 MPa)
Ultimate tensile strength 90 degrees to primary fiber, psi	-	35,840 Psi (247 MPa)

The penetration of sodium chloride solution through FRP composite in to concrete is likely due to due to a combination of mechanisms involving chemical attack by alkalis on the fibers themselves, and the subsequent growth of hydration products on the surface of the fibers. The amount of absorption of moisture or solution penetration in a particular FRP depends on different factors:

- the type and concentration of liquid;
- the type of polymer resin, its chemical composition, and its degree of cure
- the fiber type; the fiber-resin interface characteristics
- the manufacturing methods used;
- the ambient temperature;
- the applied stress level;

- the extent of pre-existing damage (cracking of the polymer matrix); and
- the presence (or absence) of protective coatings.

FRPs may potentially be damaged by the alkaline environment within concrete through several interrelated mechanisms. Alkaline solutions that manage to penetrate the FRP and affect the fibers typically cause embrittlement of the individual fibers resulting in a reduction in tensile properties and contribute to damage at the fiber resin interface resulting in a reduction of both the longitudinal and transverse properties. In the specific case of glass FRP materials, moisture that penetrates to the fibers may extract ions from the fiber and result in etching and pitting of the fibers (Benmokrane et al., 2006). This can cause deterioration of tensile strength and elastic modulus. Certain chemicals such as sodium hydroxide and hydrochloric acid can cause severe hydrolysis of fibers, and these chemicals should thus be avoided. Carbon fibers do not show significant effect by exposure to moist environments. The effects of saline solutions have also been studied extensively to simulate exposure to both seawater and deicing salts. Tests on carbon and glass FRP composites has indicated that decreases in strength and increases in moisture uptake are greater when the exposure solution is salt water as opposed to fresh water. In most cases, however, the effects of salt solutions have not been separated from the effects of moisture, and it has been observed that FRPs introduced to non-saline solutions show only very slightly less degradation than those in saline solutions.

Migration of highly alkaline solutions and alkali salts through the resin is always possible and however, the potential for alkali migration is enhanced by the presence of stress, which causes the development of micro-cracks in the matrix and elevated temperature, which increases sorption rates.

4.1.1 Tyfo SCH-41

The Tyfo SCH-41 composite is comprised of Tyfo S epoxy and Tyfo SCH-41 reinforcing fabric. Tyfo SCH-41 is a custom, uni-directional carbon fabric orientated in the 0^o direction. Tyfo SCH-41 fabric is combined with Tyfo S epoxy to add strength to bridges, buildings, and other structures. Table 4-2 shows the properties of Tyfo SCH-41 carbon FRP. This is the typical carbon fiber product used to strengthen buildings and civil structures, including bridges. This system has a higher modulus but a lower ultimate strain.

Table 4-2 Properties of Tyfo SCH-41 carbon FRP composite

Typical Dry Fiber Properties			
Tensile Strength			550,000 psi (3.79 GPa)
Tensile Modulus			33.4 x 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 x 10^6 psi (95.8 GPa)	11.9 x 10^6 psi (82 GPa)
Flexural Strength	D790	17,900 psi (123.4 MPa)	15,200 psi (104.8 MPa)

Table 4-2—*Continued*

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)

4.1.2 Tyfo WEB

The Tyfo WEB composite material comprised of Tyfo S epoxy and Tyfo WEB reinforcing fabric. Tyfo WEB is a custom $0^o/90^o$ bi-directional weave glass fabric used in the Tyfo fibrwrap system. The glass material is orientated in both the 0^o and 90^o direction in optimum configuration. The Tyfo S epoxy is a two-component epoxy matrix material. Tyfo WEB fabric is combined with Tyfo epoxy material for lightweight reinforcement for masonry, as a reinforced coating, and finish fabric application for bridges, buildings, and other structures. The detail properties of Tyfo WEB glass FRP is shown in Table 4-3.

Table 4-3 Properties of Tyfo WEB Glass FRP composite

<table>
<tr><th colspan="4">Typical Dry Fiber Properties</th></tr>
<tr><td colspan="2">Tensile Strength</td><td colspan="2">470,000 psi (3.24 GPa)</td></tr>
<tr><td colspan="2">Tensile Modulus</td><td colspan="2">10.5×10^6 psi (72.4 GPa)</td></tr>
<tr><td colspan="2">Ultimate Elongation</td><td colspan="2">4.5%</td></tr>
<tr><td colspan="2">Density</td><td colspan="2">0.092 lbs./in.^{3} (2.55 g/cm^3)</td></tr>
<tr><td colspan="2">Minimum weight per sq. yd.</td><td colspan="2">27 oz. (915 g/m^2)</td></tr>
<tr><th colspan="4">Composite Gross Laminate Properties</th></tr>
<tr><th>PROPERTY</th><th>ASTM METHOD</th><th>TYPICAL TEST VALUE</th><th>DESIGN VALUE*</th></tr>
<tr><td>Ultimate tensile strength in primary fiber direction</td><td>D3039</td><td>44,800 psi (309 Mpa)</td><td>35,840 psi (247 Mpa)</td></tr>
<tr><td>Elongation at break</td><td>D3039</td><td>1.6%</td><td>1.30%</td></tr>
<tr><td>Tensile Modulus</td><td>D3039</td><td>2.8×10^6 psi (19.3 Gpa)</td><td>2.24×10^6 psi (15.4 Gpa)</td></tr>
<tr><td>Ultimate tensile strength in 90 degrees to primary fiber</td><td>D3039</td><td>44,800 psi (309 Mpa)</td><td>35,840 psi (247 Mpa)</td></tr>
<tr><td>Nominal Laminate Thickness</td><td></td><td>0.01 in. (0.25 mm)</td><td>0.01 in. (0.25 mm)</td></tr>
<tr><td colspan="4">* 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</td></tr>
</table>

4.1.3 Durability of FRP on Concrete

FRP materials are potentially influenced to different environmental factors that may influence their long term durability of FRP composites. This is very important, when inspecting the use of FRP materials in an application. Although the strength and stiffness of FRP material or component are governed predominantly by the fibers, the overall properties and durability depend also on the properties of the resin, the fiber volume fraction, the fiber cross- sectional area, and the process of preparing FRP. The interaction between the fibers and the epoxy that gives FRPs their superior mechanical and durability characteristics. The effects of harsh environment conditions on the long term performance of FRP wraps and FRP-concrete bonds were studied in previous researches. Results so far indicate outstanding resistance of both CFRP and GFRP wraps to the exposed conditions. GFRP and CFRP to concrete bonds performed well in resisting the effects of low alkaline environments. However, the bond strength was adversely affected by high alkalinity and freeze-thaw and temperature cycles in both materials.

Clearly, it is important to recognize that FRP materials, while potentially susceptible to various forms of environmental degradation, are highly durable in comparison with conventional materials such as concrete, timber, or steel. All engineering materials have weaknesses and the task of engineers is to account for these weaknesses in ways that best take advantage of the materials properties. FRP materials appear to be very well suited to infrastructure applications.

4.2 Properties of Epoxy

There are different types of epoxies available in market. Whereas the epoxies available in Fyfe.co are Tyfo S and Tyfo SW1. In this research study, Tyfo S epoxy was used because Tyfo S is stronger than Tyfo SW1. SW1 is an underwater system and is used primarily in the waterfront projects, such as piers. In SW1 we can expect 20% drop in properties when using the underwater resin because it is not as strong as the Tyfo S epoxy and is susceptible to damage from anything present in the water at the time of application.

4.2.1 Tyfo S

The Tyfo S epoxy is a two-component epoxy matrix material for bonding applications. The Tyfo S epoxy combined with Tyfo SEH and Tyfo SCH fabrics is a NSF/ANSI standard 61 listed product for drinking water systems. It is a high elongation material which gives optimum properties as a matrix for the Tyfo fibrwrap system. It provides a long working time for application with no offensive odor. Tyfo S epoxy may be thickened with fumed silica (such as Cab-O-Sil TS-720) to produce Tyfo WS epoxy and used as a prime or finish coat depending upon the project requirements. The Tyfo S epoxy matrix material is combined with the Tyfo fabrics to provide a wet-layup composite system for strengthening structural members. Table 4-4 shows the properties of Tyfo S epoxy.

Table 4-4 Properties of Tyfo S epoxy Material

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.		

4.3 Properties of Concrete

A total of 12 concrete specimens were casted for this study. Four concrete specimens installed with carbon FRP and layers of carbon FRP, four more concrete specimens are installed with glass FRP and layers of glass FRP, another two more specimens installed with only epoxy and remaining two more specimens are used as control specimens with no application of FRP. The mix design used for making concrete molds is ACI mix design with w/c ratio of 0.40 and aggregate size of 3/4 in (18.75 mm).

Three cylindrical samples are casted using ACI mix design for knowing the strength at 7 days and 28 days. Samples are tested for 7 days to know the compressive strength. The test results are shown in Table 4-4. According to ACI, minimum compressive strength for 7 days is 3500 psi (24,131 KPa). Table 4-5 gives the detailed properties of concrete.

Table 4-5 Properties of Concrete (ACI mix design)

COMPRESSIVE STRENGTH		
Samples	**Age**	**Typical values**
Sample - 1	7 days	3984 psi (27,468 KPa)
Sample - 2	7 days	4429 psi (30,536 KPa)
Sample - 3	7 days	4680 psi (32,267 KPa)

Figure 4-1 Cylindrical Specimens ready for compressive strength Test

Figure 4-2 Specimens after strength test

Chapter 5

Procedure

5.1 Specimen Preparation

A total of 12 concrete specimens were casted for this study. Among these twelve specimens, two concrete specimens installed with single layer carbon FRP (Tyfo SCH-41), two with single layer glass FRP (Tyfo WEB), two with only epoxy, two with double layer carbon FRP, two more with double layer glass FRP and remaining two are normal concrete specimens without any application of FRP. For making these concrete specimens, molds are created by a plywood sheet with a thickness of 0.75 in (18.75 mm). The molds that were created to make concrete specimens should be in shape of cube with top surface exposed to earth. Twelve plywood sides were cut to have a bottom surface as foundation of the mold of 7 in by 7 in (175 mm by 175 mm). Twenty four sides were cut in to dimensions of 8 in by 6 in (200 mm by 150 mm). These twenty four sides were used to support the mold from two sides. The remaining two sides were cut to dimensions of 7 in by 6 in (175 mm by 150 mm), so that these two sides fix into make a mold and holds the concrete. Make sure with the mold made using plywood, so that it tightly holds the concrete casted in it without any leakage. Each cubic mold is created to hold a 7 in by 7 in by 4 in (175 mm by 175 mm by 100 mm) deep concrete specimen. The concrete samples were casted using ACI mix design. Using ACI mix design calculations, the amount required for casting concrete are calculated. While casting concrete using ACI mix design the material properties considered are w/c ratio of 0.40, aggregate size of 3/4 in (18.75 mm) and slump range between 1 - 4 in (25-100 mm). The concrete samples were cured for a period of 28days at a temperature of 28^{o}c. Before casting the concrete specimens, 3 cylindrical concrete molds made using ACI mix design are tested for 7 days to know the strength. The test results are shown in Table 6-1 and table 6-2. After the 28 day of curing, the concrete was ready to have the FRP composite material installed to the surface of the concrete. The plywood dimensions mentioned here complied with the required dimensions of the concrete specimen per ASTM C 1543.

Table 5-1 Concrete specimens labeled according to application of FRP, layers of FRP, epoxy and control specimens

Specimens	Single layer CFRP	Double layer CFRP	Single layer GFRP	Double layer GFRP	Epoxy	Control specimens
1	X	–	–	–	–	–
2	X	–	–	–	–	–
1	–	X	–	–	–	–
2	–	X	–	–	–	–
1	–	–	X	–	–	–
2	–	–	X	–	–	–
1	–	–	–	X	–	–
2	–	–	–	X	–	–
1	–	–	–	–	X	–
2	–	–	–	–	X	–
1	–	–	–	–	–	X
2	–	–	–	–	–	X

Figure 5-1 Plywood molds for casting concrete

Figure 5-2 Concrete specimens before FRP and epoxy installation

5.2 Concrete surface preparation before FRP installation

Surface preparation should be done before installing FRP because installation of FRP composites is specialized operation, only trained and certified contractors should be used but in this case the application of FRP composites is only on top of concrete mold. Each FRP system manufacturers has developed their own application procedures that may differ slightly in some cases. The following is a general outline of the steps in a typical externally-bonded FRP strengthening application on a reinforced concrete member. Manufacturer specifications should be followed when using any specific FRP system. Once the concrete specimen is ready for FRP installation, the bonding surface must be prepared to receive the adhesive. The end goal of the surface preparation activities is typically to provide a freshly-exposed, clean, sound, open, dry, and roughened texture. The surface of the concrete should be leveled using mortar or epoxy putty to ensure that any surface irregularities are smoothed. In cases where FRP systems are applied around corners, the corners must be rounded to a minimum radius as specified by manufacturer. This is done to avoid stress concentrations at sharp edges. Corners need not be rounded in cases where the fiber direction runs parallel to the sharp edge. This is typically achieved by using sand or water blasting, or a hand grinder, to expose the fine and coarse aggregate surfaces.

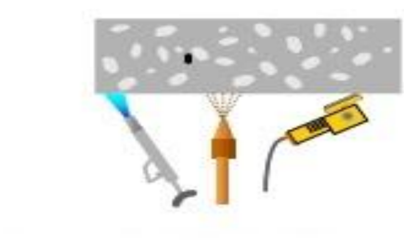

Figure 5-3 Concrete surface preparation by water blasting, sandblasting, or grinding

5.3 Application of Fiber Reinforced Polymer and Epoxy

The epoxy material was mixed with 0.1320 US gal (500 ml) of Tyfo S component A to 0.0555 US gal (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 in order to thicken epoxy. After the epoxy was properly mixed the FRP composite fabric was ready to be bonded to the concrete. For specimens installed with only epoxy, the procedure is evenly distributing epoxy on the surface of the concrete. For specimens installed with single layer FRP, 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. Below figures shows Tyfo SCH-41, Tyfo WEB composite material and epoxy ready to be installed. Pressure was applied with the use of the hands for a period of 10 minutes. For specimens installed with two layers of FRP, the procedure was initiated by evenly distributing the epoxy on the surface of the exposed concrete. Meanwhile, the two layers of FRP composite fabric cut in to require size was also saturated with epoxy on both sides of the fabric. Place the first layer on concrete specimen and then apply even pressure in order to make sure the FRP bonded with the concrete. After applying the first layer, place the second layer on the top of first layer which should also be saturated with epoxy on both sides and apply even pressure. The FRP fabric with epoxy and specimens with only epoxy was allowed to cure for a period of 72 hours.

Figure 5-4 Tyfo SCH-41 composite installed on concrete specimen

Figure 5-5 Tyfo WEB composite installed on concrete specimen

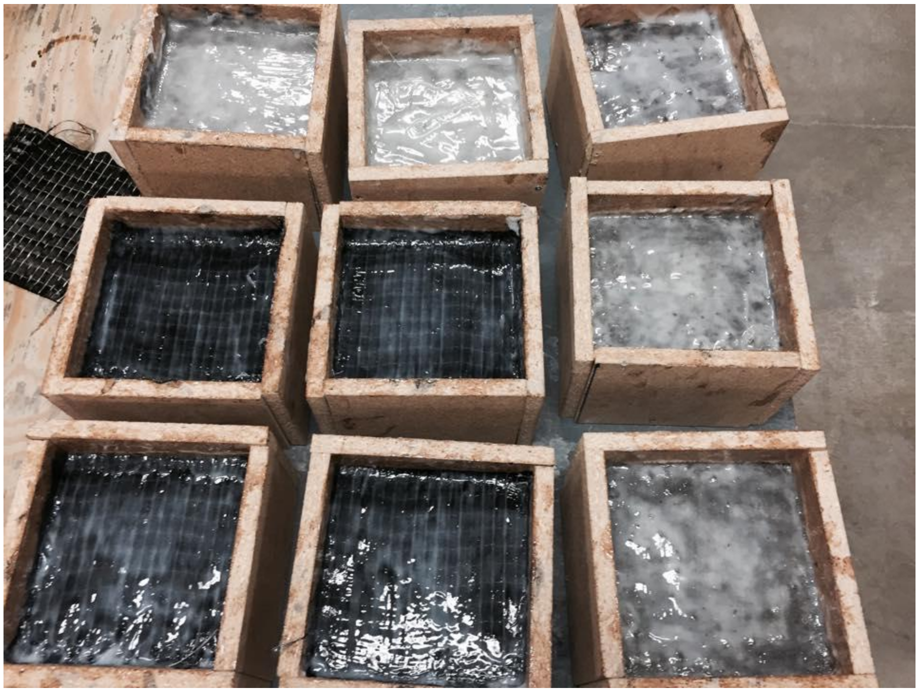

Figure 5-6 FRP and EPOXY installed on concrete specimens

5.4 Ponding Process

After the completion of the FRP and epoxy application, ponding process was performed. In this process, a saline solution will be placed on the top surface of the concrete specimens up to a height that ranged between 0.5 inch (12.5 mm) to 1.0 inch (25 mm). A 3% - 5% sodium chloride solution was used in order to perform the ponding procedure. Next, all of the specimens were covered with a polyethylene thick sheet (approximately of 2 μm) around the perimeter of the molds. Durable tape was used in order to enclose the polyethylene sheet around the molds in order to prevent any evaporation of water from the 3% - 5% sodium chloride solution. The specimens were stored in the small specimen testing room of the civil engineering laboratory facility of the University of Texas at Arlington with a room temperature of 83℉ (28 ℃). Each specimen was inspected for every two days. If there is decrease in the amount of saline solution on the specimen add fresh solution to it. In this case study the ponding process is for 16 weeks, so the solution should be changed for every two months with fresh solution. Figure 15 shows all of the specimens completely taped and covered with the polyethylene sheet. All of the specimens were checked and inspected for every two days for a period of 16 weeks.

Figure 5-7 Concrete specimen being taped with polythene sheet

5.5 ASTM C1543 Procedure

5.4.1 Collecting the Samples

Prior to sampling, remove the ponded solution and allow the specimen surface to dry. After drying is completed, remove the salt crystals from the surface by brushing with a wire brush. Using rotary impact hammer, powdered sample is collected as described in ASTM C1152. Space the sampling point at least 1 in (25 mm) away from the inside edge of the dike or the edge of any previous sampling point. Samples shall be obtained from depths like 0.4-0.8 in (10-20 mm), 1-1.4 in (25-35 mm), 1.6-2 in (40-50 mm), and 2.2-2.6

in (55-65 mm) to provide a profile of the chloride penetration. In this case study, rotary impact hammer is used to collect the powdered sample. Using 3/8 in (9.375 mm) and half inch (12.5 mm) rock carbide bit, specimens are drilled to certain depths. According to ACI minimum clear cover and AASHTO LRFD bridge specifications concrete cover, four depths i.e., 0.75 in, 1.5 in, 2 in, 3 in (18.75 mm, 37.5 mm, 50 mm, and 75 mm) are specified. In this case study, it is difficult to collect all the samples from top of the surface. so for depths 075 in (18.75 mm) and 1.5 in (37.5 mm) the powdered samples are collected from top, whereas for depths 2 in (50 mm) and 3 in (75 mm) the powdered samples are collected from bottom of the mold. The powdered samples collected form concrete specimen should be weighed approximate to 10 g (0.022046 lbs) and these powdered samples should be collected in a re-sealable bag using measuring spoons and then labeled accordingly.

Figure 5-8 Collecting powdered samples using rotary hammer

5.6 ASTM C1152 Procedure

5.6.1 Determination of Chloride Content

After collecting the powdered samples from concrete specimen at certain depths (according to ACI minimum clear cover and AASHTO concrete cover). Using ASTM C1152, we can determine the percentage of chloride in the powdered samples collected at certain depths. The samples collected at certain depths were taken to the environmental lab of the University of Texas at Arlington where they were each weighted. Each weighted sample was then transferred to a 0.0660 US gal (250 mL) beaker as shown in Figure 17. Next, the sample beakers were diluted with 0.0198 US gal (75 ml) of reagent water and mixed well as shown in is Figure 18. Then 0.0660 US gal (25 ml) of nitric acid having a normality of 30.283 mol/US gal (8 mol/L), shown in Figure 19, 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 0.00264 US gal (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 0.0946 mol/US gal (0.025 mol/L), 0.00028 US gal (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 17. A 0.0660 US gal (25 mL) burette filled to the zero mark with AgNO3, silver nitrate, solution having a normality of 0.1893 mol/US gal (0.05 mol/L) was used. The sample beaker was gradually titrated with the AgNO3 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 0.0660 US gal (25 mL) burette. Using the amount of silver nitrate required for reaching equivalence point and weight of the sample, we can determine the percentage of chloride in powdered sample at certain depth. In order to determine the chloride profiling for each of the specimens the equation, shown in below equation 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).

$$\mathrm{CL\%} = \frac{3.545[(\mathrm{V1} - \mathrm{V2})\mathrm{N}]}{\mathrm{W}}$$

Where:

V_1 = ml of 0.05 N AgNO3 solution used for sample titration (equivalence point).

V_2 = ml of 0.05 N AgNO3 solution used for blank titration (equivalence point).

N = normality of the 0.05 N $AgNO_3$ solution

W = mass of sample in grams.

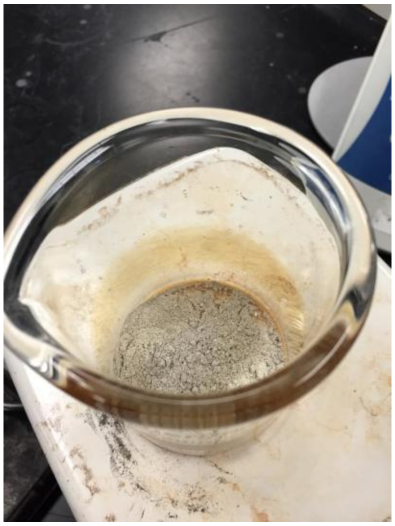

Figure 5-9 Powdered samples transferred in to beaker

Figure 5-10 Reagent water poured in to beaker

Figure 5-11 Nitric acid being added in to beaker

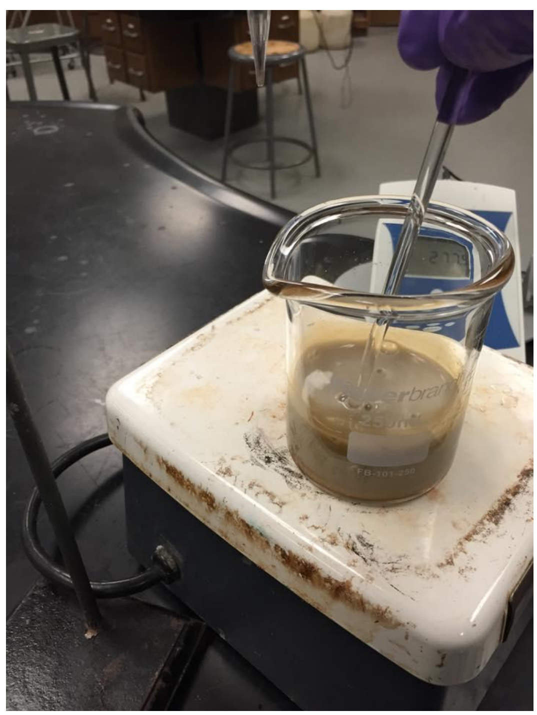

Figure 5-12 Mixing Samples Using Glass Stirrer

Figure 5-13 Silver/Sulfur Electrode being submerged in to beaker

5.6.2 Equivalence Point

The equivalence point was determined by first immersing the silver/sulfide electrode into a 0.0660 US gal (250 ml) beaker filled with water only. The beaker was titrated with the AgNO3 until the pH meter gave a potential mV reading below 60 mV from the standard mV reading. The mV readings were taken at every 0.00005283 US gal (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 below Table was used to determine the equivalence point. (ASTM C114-15 Appendix XI).

Table 5-2 Determination of equivalence point

$AgNo_3$, ml	Potential, mV	ΔmV^A	ΔmV^B
1.60	125.3		
		5.8	
1.80	119.5		14
		7.2	
2.00	112.3		1.3
		8.5	
2.20	103.8		1.3
		9.8	
2.40	94		0.6
		9.2	
2.60	84.8		2.3
		6.9	
2.80	77.9		0.8
		6.1	
3.00	71.8		1.3
		4.8	
3.20	67.0		

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 0.00005282 US gal (0.20 ml) increment is calculated from the ΔmV (Column 4) data as follow:

$\mathrm{E} = 2.20 + \left(\frac{1.3}{1.3+0.6}\right) * 0.20$ = 2.337 ml => Round to 2.34 ml (0.000618 US gal)

Chapter 6

Results

6.1 FRP, Epoxy and Control Specimen Results

The results shown in the below Table indicate that the chloride ingress percentage is lower in concrete specimens installed with FRP and only epoxy than normal concrete specimens. From the below results, we can observe that chloride ingress is less in concrete specimens installed with double layer FRP than single layer FRP in both carbon FRP and glass FRP. We can also observe that concrete specimen installed with only epoxy shows better results than normal concrete specimen but the percentage of chloride penetration is more when compared to specimen installed with FRP. The reduction in percentage of chloride can be seen at every depth. However, at the 3 in (75 mm) depth the reduction of chloride percentage is seen to be the least among the FRP composites, epoxy and control specimens. Due to the reduction in chloride ingress, we can observe the reduction of clear cover for new structures. For existing structures the unacceptable clear cover can be accepted by installing FRP.

Table 6-1 Results obtained from each sample at different depths for specimens 1

Specimen	Depth (in)	Chloride (%)
S-CFRP(1)	0.75 in (18.75 mm)	0.3212
S-CFRP(1)	1.5 in (37.5 mm)	0.2639
S-CFRP(1)	2 in (50 mm)	0.2570
S-CFRP(1)	3 in (75 mm)	0.2087
S-WEB(1)	0.75 in (18.75 mm)	0.3269
S-WEB(1)	1.5 in (37.5 mm)	0.3100
S-WEB(1)	2 in (50 mm)	0.3019
S-WEB(1)	3 in (75 mm)	0.2850
EPOXY(1)	0.75 in (18.75 mm)	0.3643
EPOXY(1)	1.5 in (37.5 mm)	0.3545
EPOXY(1)	2 in (50 mm)	0.3440
EPOXY(1)	3 in (75 mm)	0.3357
D-CFRP(1)	0.75 in (18.75 mm)	0.2760
D-CFRP(1)	1.5 in (37.5 mm)	0.2446
D-CFRP(1)	2 in (50 mm)	0.2407
D-CFRP(1)	3 in (75 mm)	0.2053
D-WEB(1)	0.75 in (18.75 mm)	0.2885
D-WEB(1)	1.5 in (37.5 mm)	0.2654
D-WEB(1)	2 in (50 mm)	0.2514
D-WEB(1)	3 in (75 mm)	0.2062

Table 6-2 Results Obtained from each sample at different depths for specimens 2

Specimen	Depth (in)	Chloride (%)
S-CFRP(2)	0.75 in (18.75 mm)	0.3194
S-CFRP(2)	1.5 in (37.5 mm)	0.2717
S-CFRP(2)	2 in (50 mm)	0.2731
S-CFRP(2)	3 in (75 mm)	0.2180
S-WEB(2)	0.75 in (18.75 mm)	0.3230
S-WEB(2)	1.5 in (37.5 mm)	0.2942
S-WEB(2)	2 in (50 mm)	0.2875
S-WEB(2)	3 in (75 mm)	0.2790
EPOXY(2)	0.75 in (18.75 mm)	0.3650
EPOXY(2)	1.5 in (37.5 mm)	0.3566
EPOXY(2)	2 in (50 mm)	0.3232
EPOXY(2)	3 in (75 mm)	0.3172
D-CFRP(2)	0.75 in (18.75 mm)	0.2883
D-CFRP(2)	1.5 in (37.5 mm)	0.2640
D-CFRP(2)	2 in (50 mm)	0.2330
D-CFRP(2)	3 in (75 mm)	0.2080
D-WEB(2)	0.75 in (18.75 mm)	0.2919
D-WEB(2)	1.5 in (37.5 mm)	0.2685
D-WEB(2)	2 in (50 mm)	0.2600
D-WEB(2)	3 in (75 mm)	0.2150

Table 6-3 Results obtained from Normal Concrete Specimens

SPECIMEN	DEPTH (in)	CHLORIDE (%)
CONTROL SPECIMEN	0.75 in (18.75 mm)	0.4050
CONTROL SPECIMEN	1.5 in (37.50 mm)	0.3603
CONTROL SPECIMEN	2 in (50 mm)	0.3594
CONTROL SPECIMEN	3 in (75 mm)	0.3482

6.1.1 Tyfo SCH-41 Results

The results obtained from the chemical tests indicate that both single layer carbon FRP and double layer carbon FRP has less percentage of chloride ingress than normal concrete specimens. Among single layer and multi-layer carbon FRP, single layer FRP has more chloride ingress than double layer FRP. The results shows that at 0.75 in (18.75 mm) depth the chloride ingress is more in both cases when compared to 3 in (75 mm) depth. Penetration of chloride of glass FRP has highest rate than carbon FRP. Moreover, chloride ingress in concrete specimen installed with epoxy only also has highest rate than concrete specimens installed with carbon FRP. The results for specimen 1 and specimen 2 are almost same, so the below results are the average results of both specimen 1 and specimen 2.

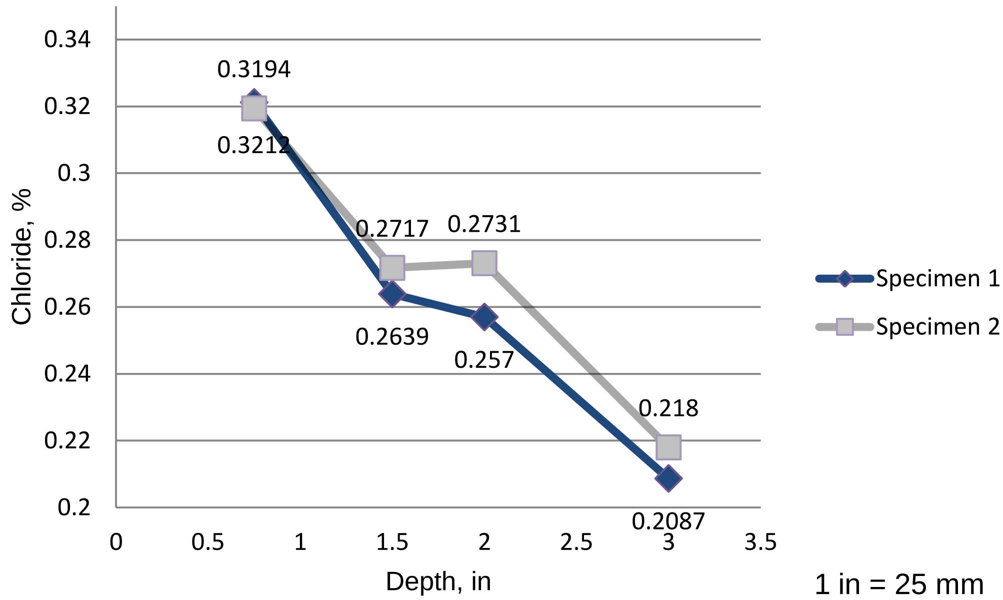

Figure 6-1 Graphical chloride percent plot of single layer carbon FRP Specimens

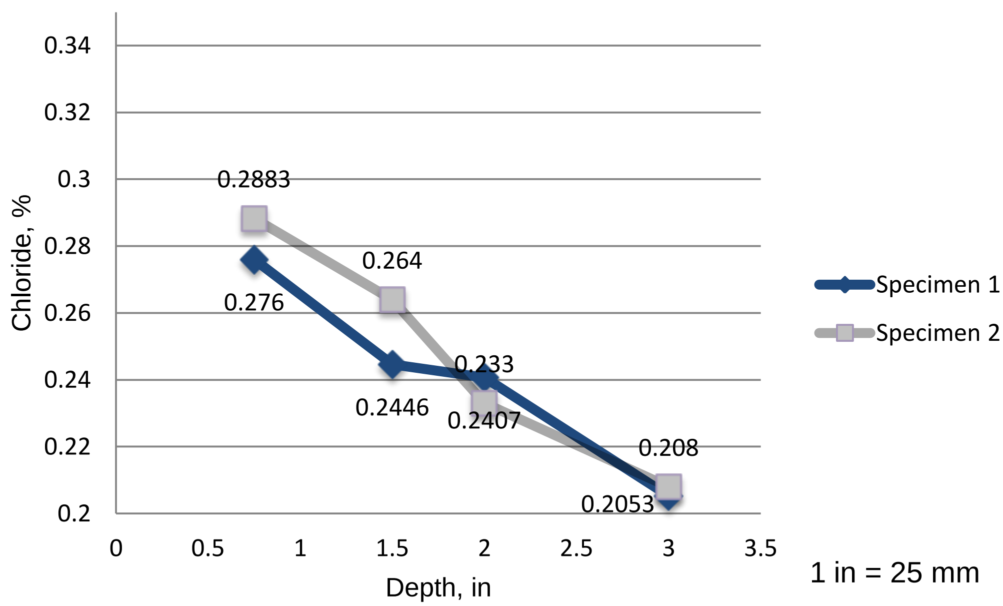

Figure 6-2 Graphical chloride percent plot of double layer carbon FRP specimens

Table 6-4 Average values obtained from specimens 1 & 2 installed with Tyfo SCH-41

SPECIMEN	DEPTH (in)	CHLORIDE (%)
S-CFRP	0.75 in (18.75 mm)	0.3203
S-CFRP	1.5 in (37.50 mm)	0.2678
S-CFRP	2 in (50 mm)	0.2650
S-CFRP	3 in (75 mm)	0.2133
D-CFRP	0.75 in(18.75 mm)	0.2821
D-CFRP	1.5 in (37.50 mm)	0.2543
D-CFRP	2 in (50 mm)	0.2368
D-CFRP	3 in (75 mm)	0.2066

6.1.3 Tyfo WEB Results

The results shown in the below Table indicates that the chloride percentage from the specimens installed with glass FRP (Tyfo WEB) were lower than the normal concrete specimens. The reduction in percentage of chloride is shown at each depth. Moreover, the chloride percentage in double layer glass FRP is lower than single layer glass FRP but the percentage change of chloride between double layer glass FRP and single layer carbon FRP is only of 0.01% at 3 inch (75 mm) depth. From the results it indicates that chloride ingress from specimens with glass FRP application has higher rate than concrete specimens installed with carbon FRP. However, the percentage of chloride ingress from glass FRP is lower than concrete specimens installed with only epoxy and also normal concrete specimens. The below results are the average results obtained from specimen 1 and specimen 2.

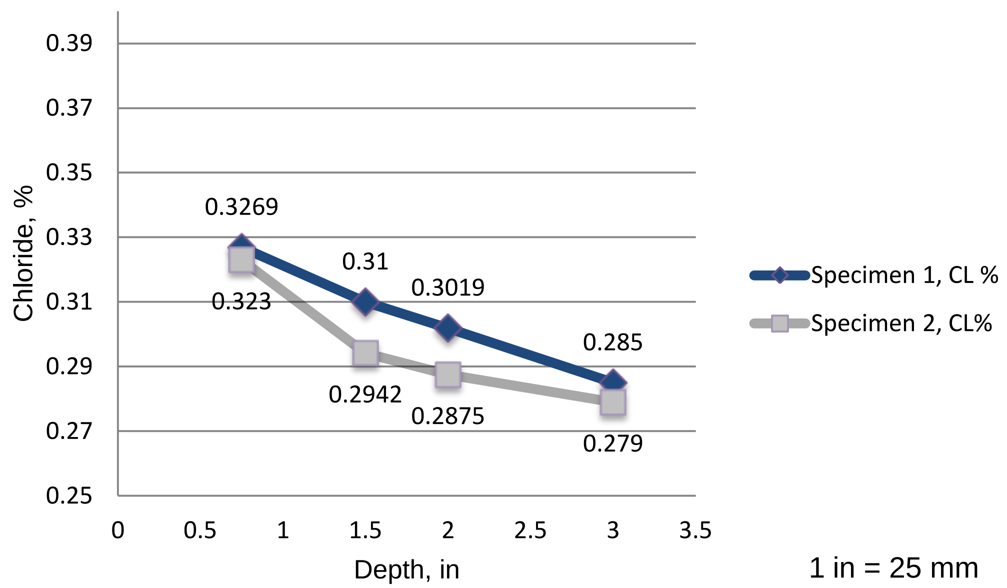

Figure 6-3 Graphical chloride percent plot of single layer glass FRP specimens

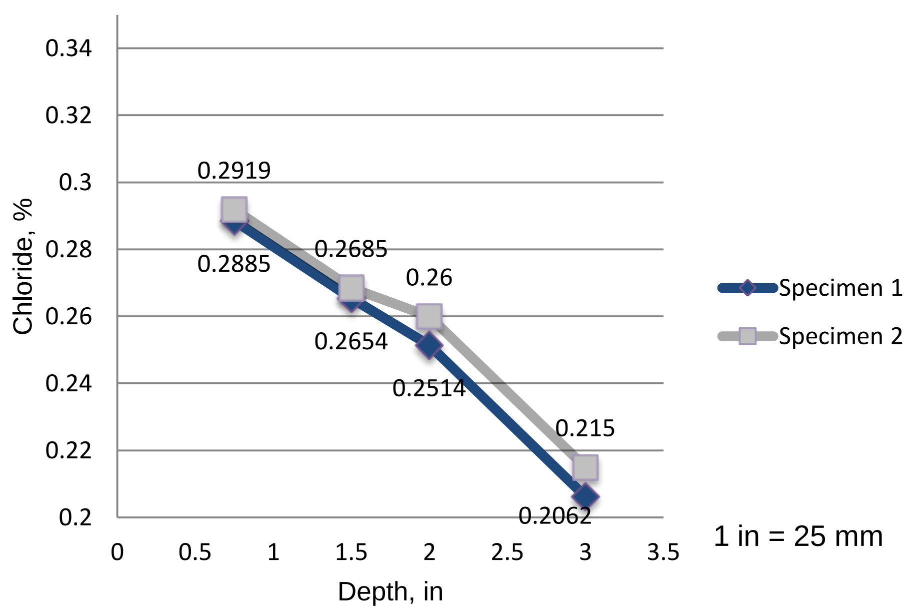

Figure 6-4 Graphical chloride percent plot of double layer glass FRP specimens

Table 6-5 Average Results obtained from specimens 1 & 2 installed with Glass FRP

SPECIMEN	DEPTH (IN)	CHLORIDE (%)
S - WEB	0.75 in (18.75 mm)	0.3249
S - WEB	1.5 in (37.50 mm)	0.3021
S - WEB	2 in (50 mm)	0.2947
S - WEB	3 in (75 mm)	0.2820
D - WEB	0.75 in (18.75 mm)	0.2902
D - WEB	1.5 in (37.50 mm)	0.2669
D - WEB	2 in (50 mm)	0.2557
D - WEB	3 in (75 mm)	0.2106

6.1.4 Tyfo S Epoxy Results

The chloride percentages obtained from the specimen test results shows that chloride ingress from concrete specimen applied with only epoxy is less than normal concrete specimens. However, the chloride percentage from epoxy coated specimen has higher rate than all specimens installed with FRP composites.

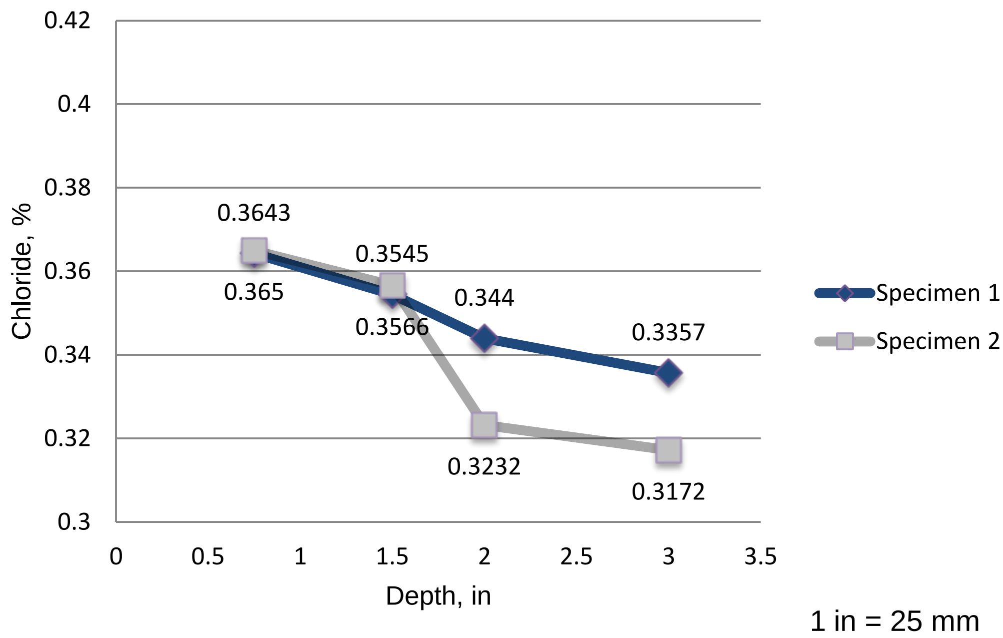

Figure 6-5 Graphical Chloride Percent Plot of Specimen installed with only epoxy

Table 6-6 Results obtained from specimens installed with only epoxy

SPECIMEN	DEPTH (IN)	CHLORIDE (%)
EPOXY	0.75 in (18.75 mm)	0.3646
EPOXY	1.5 in (37.50 mm)	0.3555
EPOXY	2 in (50 mm)	0.3336
EPOXY	3 in (75 mm)	0.3264

6.1.5 Control Specimen Results

The below Table shows the Normal Concrete Specimen results:

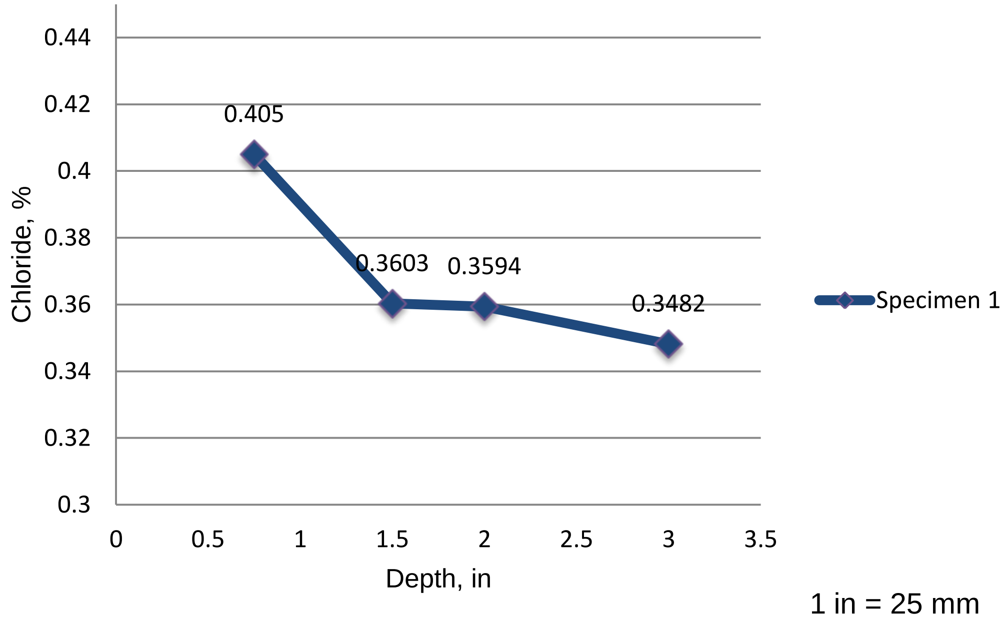

Figure 6-6 Graphical chloride percent plot of control specimen

Table 6-7 Results obtained from normal concrete specimens

SPECIMEN	DEPTH (in)	CHLORIDE (%)
CONTROL SPECIMEN	0.75 in (18.75 mm)	0.4050
CONTROL SPECIMEN	1.5 in (37.50 mm)	0.3603
CONTROL SPECIMEN	2 in (50 mm)	0.3594
CONTROL SPECIMEN	3 in (75 mm)	0.3482

6.2 Graphical Chloride Percentage Plot of Specimens at Each Depths

6.2.1 Graphical Plot of Chloride Ingress Percent at 0.75 in (18.75 mm) Depth

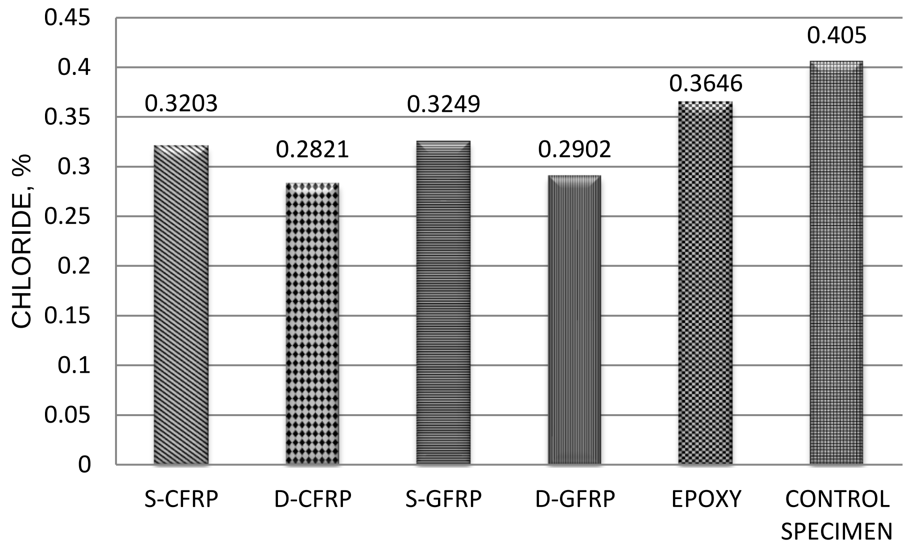

Figure 6-7 Graphical chloride percent plot of specimens at 0.75 in (18.75 mm) depth

6.2.2 Graphical Plot of Chloride Ingress Percent at 1.5 in (37.5 mm) Depth

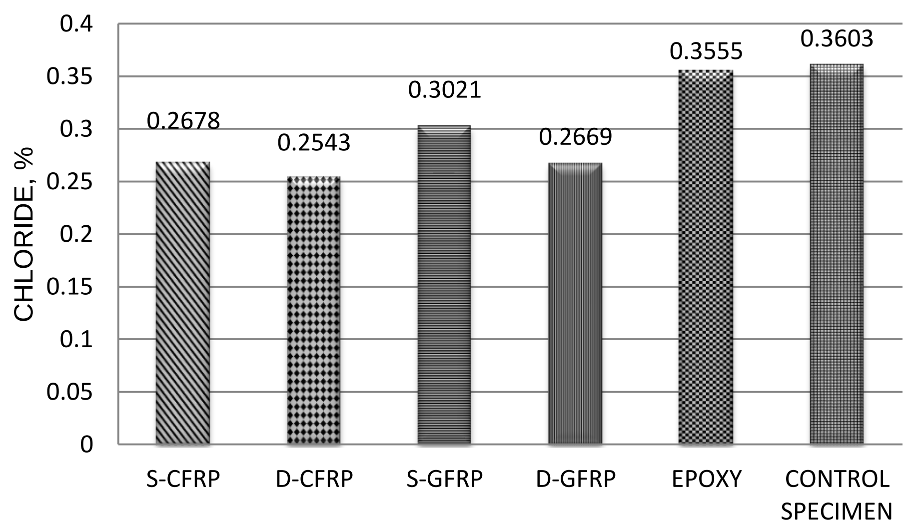

Figure 6-8 Graphical chloride percent plot of specimens at 1.5 in (37.5 mm) depth

6.2.3 Graphical Plot of Chloride Ingress Percent at 2 in (50 mm) Depth

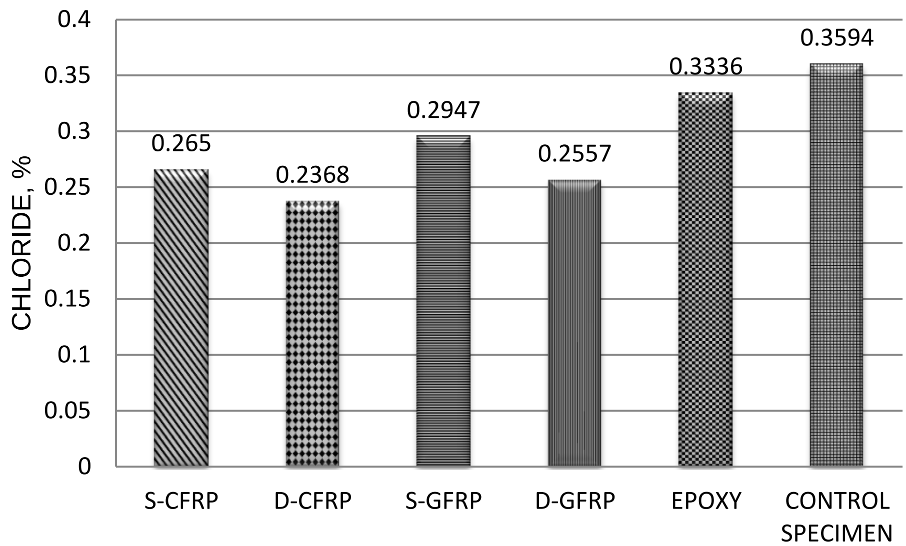

Figure 6-9 Graphical chloride percent plot of specimens at 2 in (50 mm) depth

6.2.4 Graphical Plot of Chloride Ingress Percent at 3 in (75 mm) Depth

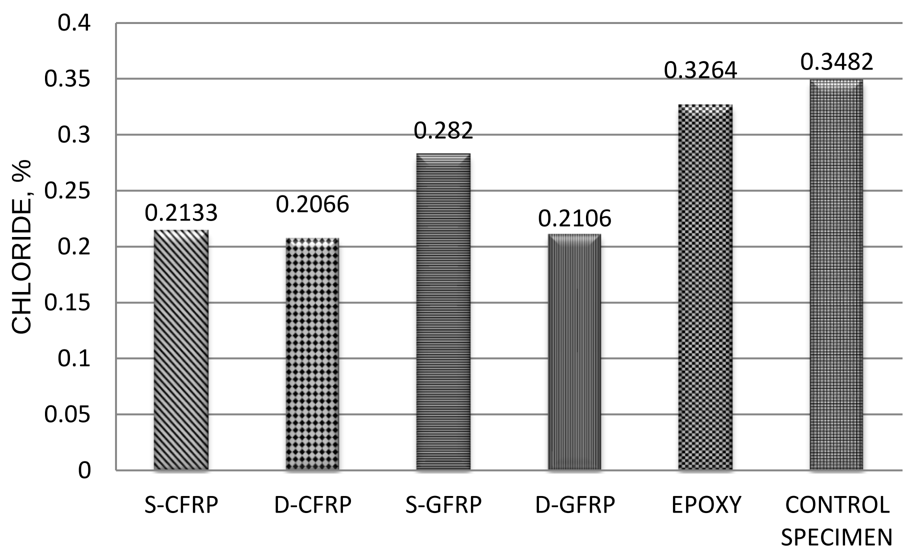

Figure 6-10 Graphical chloride percent plot of specimens at 3 in (75 mm) depth

6.3 Effects of FRP and Epoxy on Concrete Specimens

6.3.1 S-CFRP vs. Control Specimen

The points plotted on Figure 28 are from the chloride percentage values obtained from the single layer CFRP and control specimens at depths obtained from ACI and AASHTO minimum clear cover. According to ACI minimum clear cover, equivalent clear cover value for beams, columns, slabs (No. 14 and No. 18 bars) can be established. In the same way, we can also establish reduction in clear covers for members cast against earth, concrete exposed to weather and more with application of FRP.

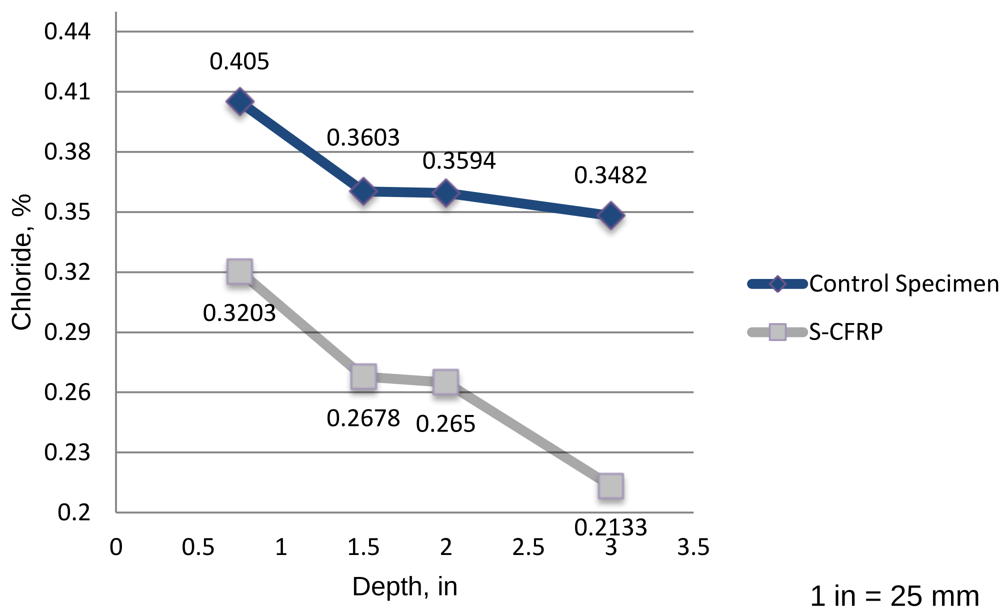

Figure 6-11 Graphical chloride percent plot between single layered CFRP and control specimen at each depth

6.3.2 D-CFRP vs. Control Specimen

The points plotted on Figure 29 are from the chloride percentage values obtained from the double layer CFRP and control specimens at depths obtained from ACI and AASHTO minimum clear cover. According to ACI minimum clear cover, equivalent clear cover value for beams, columns, slabs (No. 14 and No. 18 bars) can be established. Among all the specimens installed with different types of FRP, layers of FRP and Epoxy, the specimen installed with double layer CFRP is most effective. Using the results of D-CFRP, we can establish reduced clear cover value more than other specimens installed with FRP and epoxy.

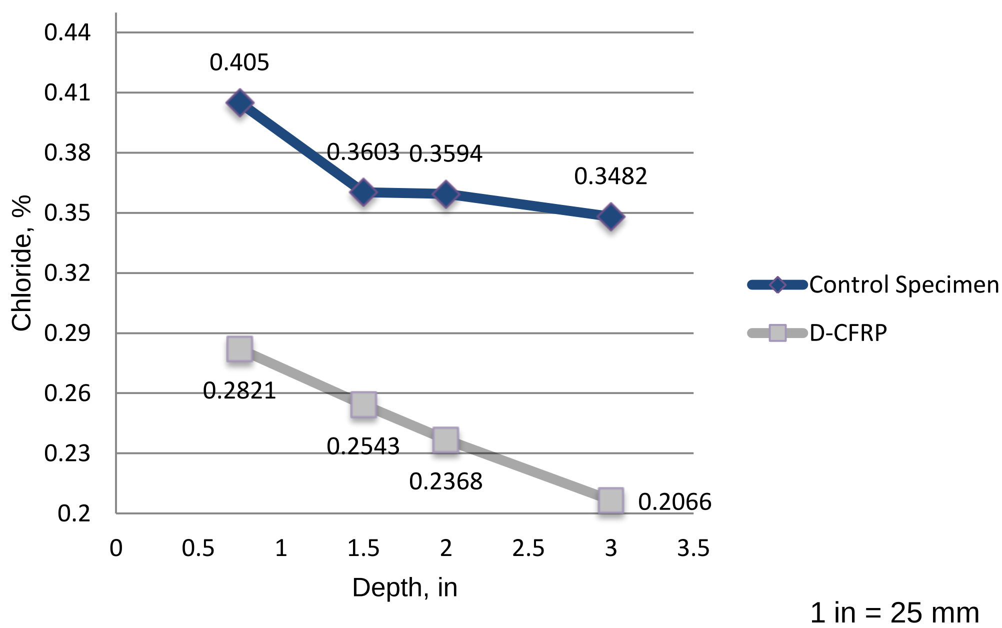

Figure 6-12 Graphical chloride percent plots between double layered CFRP and control specimen at each depths

6.3.3 S-GFRP vs. Control Specimen

The points plotted on Figure 30 are from the chloride percentage values obtained from the single layer GFRP and control specimens at depths obtained from ACI and AASHTO minimum clear cover. According to ACI minimum clear cover, equivalent clear cover value for beams, columns, slabs (No. 14 and No. 18 bars) can be established. The equivalent clear cover of the slabs (No. 11 bar and smaller) is 0.75 in (18.75 mm) but with the application of single layer GFRP we can establish reduced clear cover.

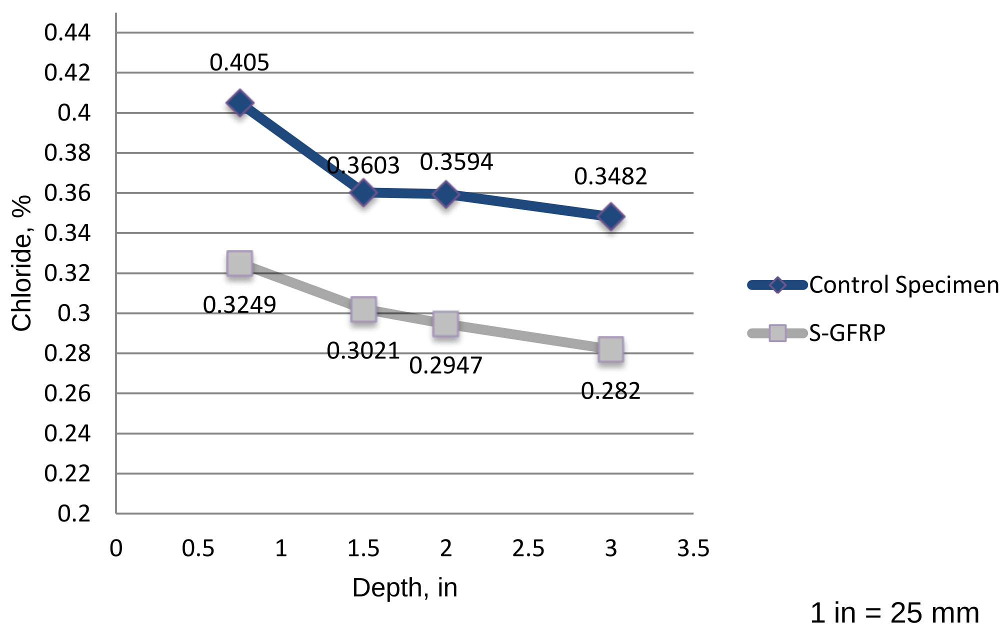

Figure 6-13 Graphical chloride percent plot between single layered GFRP and control specimen at each depths

6.3.4 D-GFRP vs. Control Specimen

The points plotted on Figure 31 are from the chloride percentage values obtained from the double layer GFRP and control specimens at depths obtained from ACI and AASHTO minimum clear cover. The equivalent clear cover of the slabs (No. 11 bar and smaller) is 0.75 in (18.75 mm) but with the application of double layer GFRP we can establish reduced clear cover.

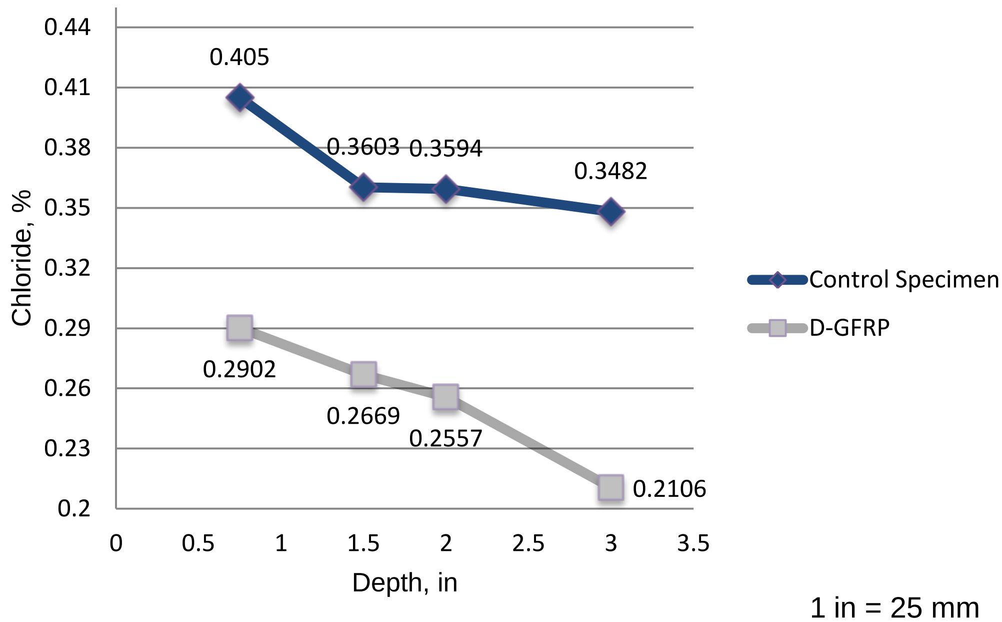

Figure 6-14 Graphical chloride percent plots between double layered GFRP and control specimen at each depth

6.3.5 EPOXY vs. Control Specimen

The points plotted on Figure 32 are from the chloride percentage values obtained from the Epoxy specimens and control specimens at depths obtained from ACI and AASHTO minimum clear cover. The equivalent clear cover of the slabs (No. 11 bar and smaller) is 0.75 in (18.75 mm) but with the application of epoxy can establish reduced clear cover values. In the below graph we can see that the difference between the specimens installed with Epoxy and control specimens is almost equal. So, we can conclude that we can establish only less reduction of clear cover values

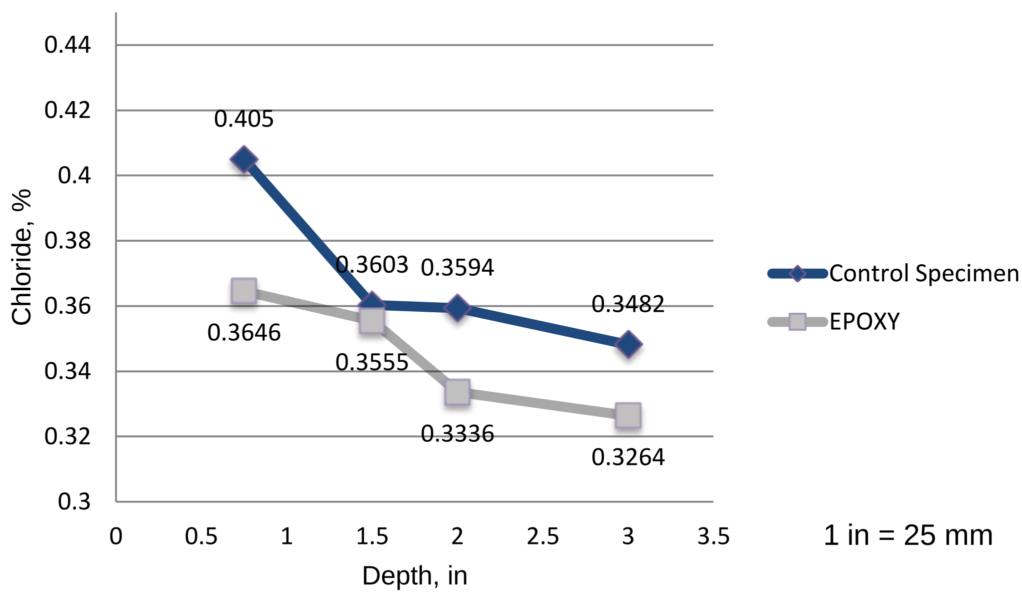

Figure 6-15 Graphical chloride percent plot between epoxy and control specimen at each depth

6.4 CFRP vs. GFRP at Each Depths

As we considered Tyfo SCH41(Carbon FRP) and Tyfo web (Glass FRP), the performance of CFRP is better than GFRP because the thickness and strength of CFRP is more than GFRP in this case. Normally in cases of prolonged exposure to harsh environments CFRP is preferable than GFRP. From the results it can be observed that chloride ingress in GFRP specimens has higher rate than CFRP.

Table 6-8 Properties of CFRP and GFRP laminates

Properties	CFRP	GFRP
Nominal Laminate Thickness	0.04 in (1 mm)	0.01 in (0.25 mm)
Ultimate Tensile Strength in Primary Fiber Direction	121,000 psi (834 MPa)	35,840 Psi (247 MPa)
Ultimate tensile strength 90 degrees to primary fiber, psi	-	35,840 Psi (247 MPa)
Density	0.063 lbs/in ^{3} (1.74 g/cm^3)	0.092 lbs/in ^{3} (2.55 g/cm^3)
Tensile modulus	11.9 X 10 ^{6} Psi (82 GPa)	2.24 X 10 ^{6} Psi (15.4 GPa)

Carbon fibers are more expensive than glass fibers. Several grades, with varying strength and elastic modulus, are available. Carbon fibers are typically much stiffer, stronger, and lighter than glass fibers, and they are thus used in weight and/or modulus-critical applications, such as prestressing strands for concrete and FRP wraps for repair and strengthening of concrete structures. In addition, carbon fibers display outstanding resistance to thermal, chemical, and environmental effects. Carbon FRPs appear to have the best fatigue performance among the three common FRPs used in infrastructure applications.

Glass fibers (GFRP) are currently the least expensive and consequently the most commonly used fibers in structural engineering applications. They are often chosen for structural applications that are non-weight-critical (glass FRPs are heavier than carbon or aramid) and that can tolerate the larger deflections resulting from a comparatively low elastic modulus. Glass fibers are commonly used in the manufacture of FRP reinforcing bars, tubes, and structural wraps.

6.4.1 CFRP vs. GFRP at 0.75 in (18.75 mm) Depth

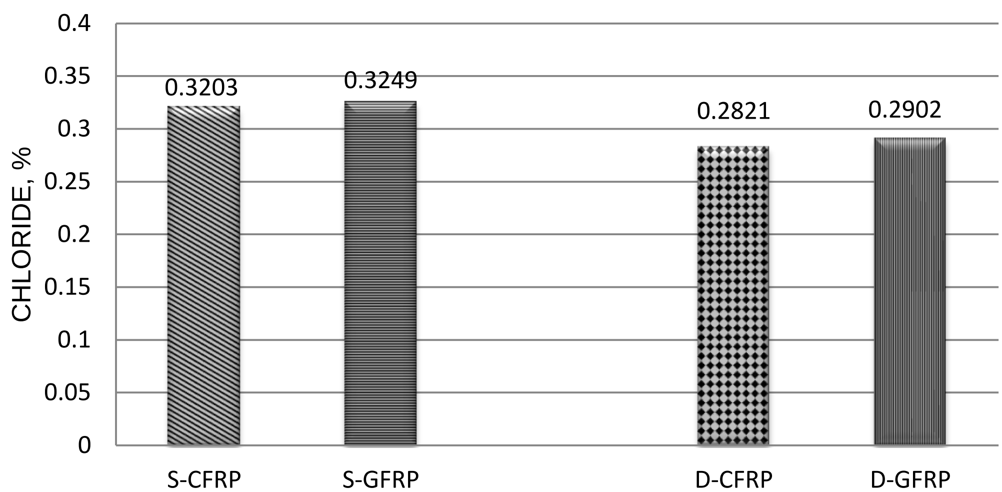

Figure 6-16 Graphical chloride percent plot between CFRP and GFRP at 0.75 in (18.75 mm) depth

6.4.2 CFRP vs. GFRP at 1.5 in (37.5 mm) Depth

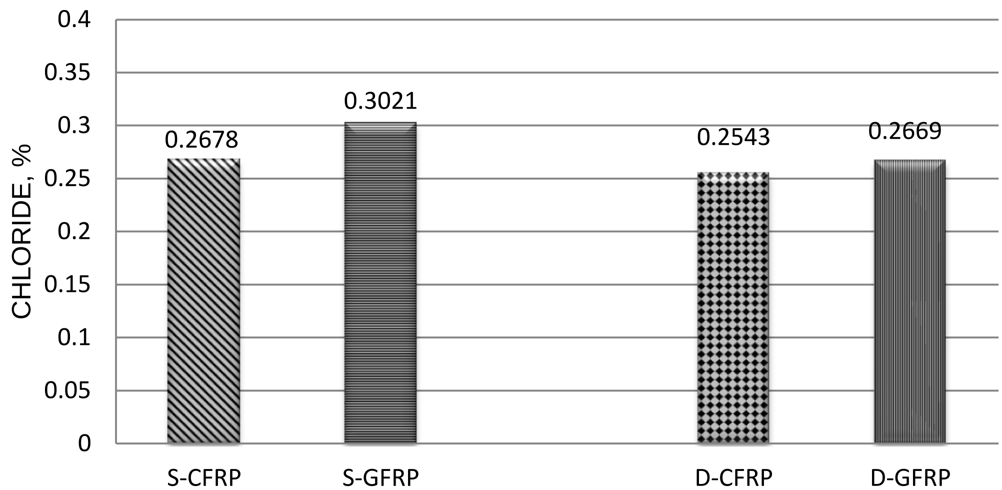

Figure 6-17 Graphical chloride percent plot between CFRP & GFRP at 1.5 in (37.5 mm) depth

6.4.3 CFRP vs. GFRP at 2 in (50 mm) Depth

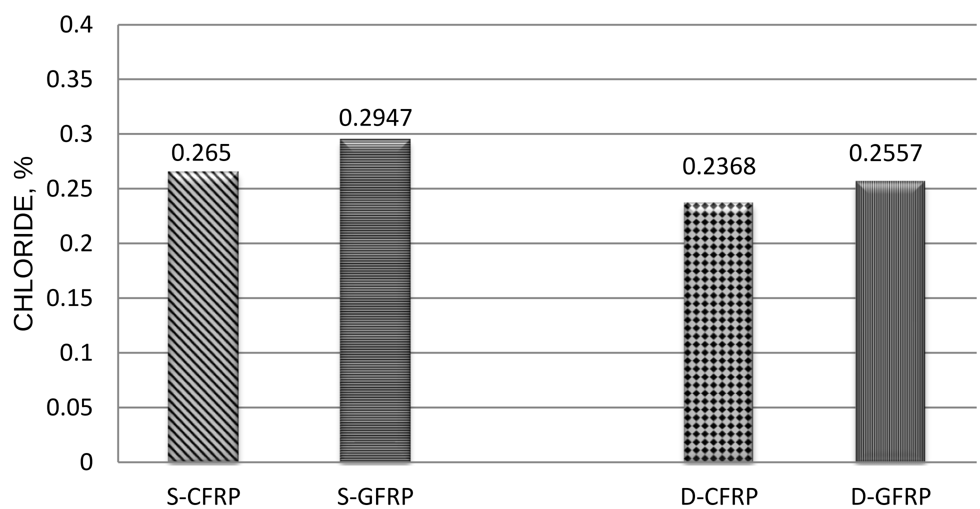

Figure 6-18 Graphical chloride percent plot between CFRP & GFRP at 2 in (50 mm) depth

6.4.4 CFRP vs. GFRP at 3 in (75 mm) Depth

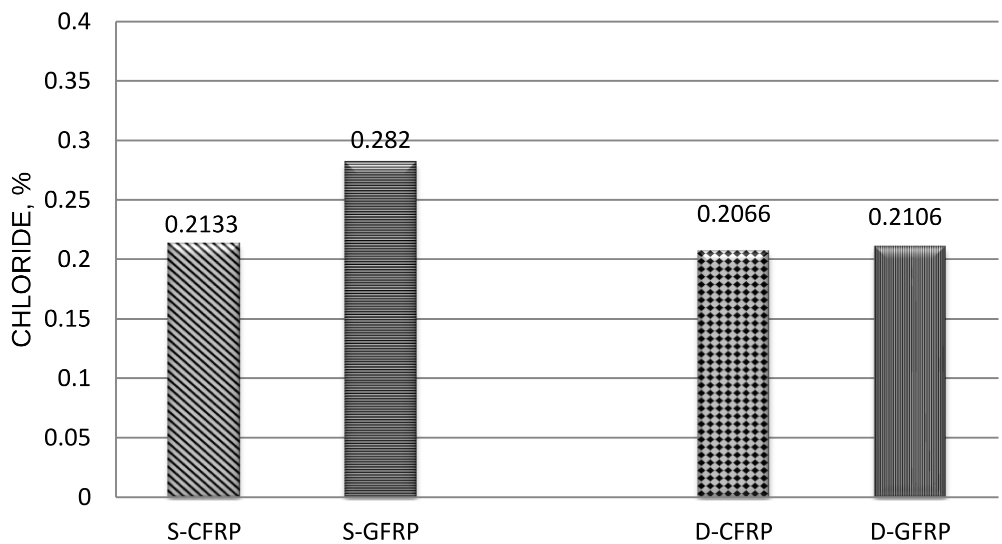

Figure 6-19 Graphical chloride percent plot between CFRP & GFRP at 3 in (75 mm) depth

6.5 Trend line equations for specimens installed with FRP, layers of FRP and EPOXY

Trend line equations for specimens installed with single layer carbon FRP, double layer carbon FRP, single layer glass FRP, double layer glass FRP, EPOXY and normal control specimens are listed in the Table 6-8. Below figure shows the trend line equation and R^2 (coefficient of determination) for specimens installed with single layer carbon FRP. Using this trend line equations we can find the chloride percentage of different specimens at required depths.

Table 6-8 Trend line equations for specimens with FRP, layers of FRP and Epoxy

SPECIMEN	Trend line equation	R^2 (Coefficient of determination)
Single layered CFRP	y = -0.0453x + 0.3487	0.9569
Double layered CFRP	y = -0.0335x + 0.3056	0.9969
Single layered GFRP	y = -0.0185x + 0.3345	0.9417
Double layered GFRP	y = -0.0351x + 0.3194	0.9813
EPOXY	y = -0.0181x + 0.3778	0.9010
Control specimen	y = -0.0232x + 0.4103	0.7603

y : chloride percentage x : depth, in

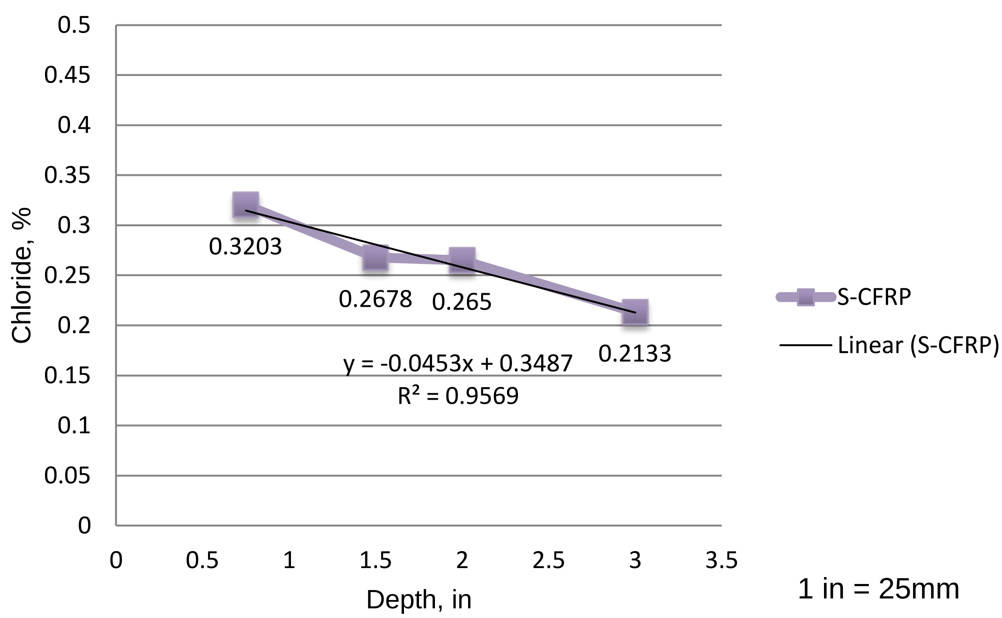

Figure 6-20 Trend line equation and R^2 (coefficient of determination) for specimens installed with single layer carbon FRP

6.6 Limitations of the Study

1. This study was focused mainly on one corrosive agent by making an assumption that chloride ingress is the major component responsible for steel corrosion.
2. This study is based on chloride ingress data from 16 weeks duration. It is recommended that the concrete be exposed to the chemical reagent for a period of at least 12 months or more. With the prolonged exposure, there is the possibility of the chloride solution breaking down the epoxy in the wrap system, which would allow space for chloride transport into the concrete beneath the FRP wrap.
3. The standard test method used in this study to find the chloride ingress percentage is ASTM C1543. But there are few methods like laser induced breakdown spectroscopy (LIBS) to find the chloride ingress percentage. In this LIBS method we can have very accurate chloride percentage at any depths.
4. The chloride ponding test used herein is based on the static ponding of a chloride solution on the concrete surface. This situation changes when the concrete structures are subjected to coastal structures in contact (constant) with saline sea water, such as bridge piers, concrete piles, steel pipelines etc.
5. In this study only one epoxy material (Tyfo S) is used. Use of different epoxy materials in combination with different FRP materials may find any differences when establishing the clear cover depths.
6. In this study only single layer and double layers of FRP are used. In order to obtain additional moment capacities try to use more layers of FRP and control corrosion.

Chapter 7

Conclusions and Future Research

7.1 Conclusions

The following conclusions are made based on the findings from this study. Table 6-1 and table 6-2 gives the results of specimens installed with FRP, epoxy and normal concrete specimens. The significance of this study is to reduce the chloride ingress in to concrete from FRP and epoxy installation. With the effects of FRP application there can be increase in concrete durability and also reduction in minimum concrete clear cover.

1. FRP wrapping was effective in reducing corrosion activity in the test specimens. The FRP provided a barrier to the migration of chlorides. The migrating chloride concentrations in the wrapped specimens were less than the normal concrete specimens.

2. Application of FRP and epoxy on concrete surfaces reduces the chloride penetration percentage, when compared to normal concrete specimens without any application of FRP. The chloride ingress percentage is absorbed maximum at top of concrete specimen and decreased at higher depths (based on ACI and AASHTO clear cover requirements). The reduction of chloride ingress for FRP application varied between 0.08% and 0.15% with normal concrete specimens. However, the reduction of chloride ingress percentage for epoxy application varied between 0.03% and 0.04% with Normal concrete specimen. Therefore, it may be concluded that decreased chloride percentage should reduce the corrosion rate and loss of load capacity. FRP application can be used to extend the design life of a concrete structure.

3. In this study, carbon FRP, glass FRP and epoxy are installed on different concrete specimens to reduce the chloride percentage. The permeability of chloride in concrete has lesser rate for specimens with application of carbon FRP (Tyfo SCH-41) than glass FRP (Tyfo WEB) and only epoxy.

4. In this case study, the concrete specimen installed with layers of FRP have resulted lesser chloride penetration than specimens installed with FRP. The reduction of chloride ingress for layers of FRP application, reduction was mostly seen near the surface and decreased at increasing depths. The penetration of chloride ion in the concrete specimen decreased with increase in layers of FRP confinement thus causing the reduction of corrosion there by increasing the strength.

5. In this case study, the specimens are installed with FRP composites and also specimens are installed with epoxy (Tyfo S saturate) only. This study is done to know the reduction of chloride ingress is due to epoxy or FRP composite. From the results, it can be inferred that specimens installed with only epoxy have the highest rate of chloride ingress than specimens installed with FRP and layers of FRP. From the above results, we can conclude that specimens installed with FRP composites saturated with epoxy works in reduction of chloride ingress where as the reduced chloride ingress for specimens installed with only epoxy is almost same as normal concrete specimens.

6. Simple interpolations based on the plotted chloride ingress results at various depths can establish the required clear cover for rebar's (based on equivalency

of chloride ingress between unprotected concrete and FRP protected concrete) can be conveniently reduced for concrete with FRP application. These reductions are based on type of FRP used. The CFRP and the GFRP wraps yielded almost same results but CFRP showing slightly more benefits than GFRP wraps and also layers of FRP showing more benefits than single layer FRP.

7. FRP wraps is the best alternative among all the traditional methods on controlling corrosion. Traditional steel repairs are heavyweight, time consuming and heavy welding works which restrain their use in pipelines located underground and in water. With lower cost and no heavy weights FRP wraps has proven to be an effective alternative while repairing corroded steel pipelines, concrete piles when exposed to tidal water, bridge columns etc.

8. FRP sheets are capable of containing the expansive forces generated from the corrosion product. For existing structures like bridges have snow and ice problems and for chemically deicing tons of salt is used, which causes steel corrosion in a concrete member. From this study we can conclude that for repair and rehabilitation, FRP applications provides protection and containment of chlorides. The multi-layered FRP wraps are also proven successful in keeping chlorides levels constant within the structure after exposing to deicing salts and this multi-layered process reduces chloride ingress more than single layered process. This project utilized both carbon and glass FRP wraps for chloride barrier systems.

9. For many existing structures, the requirement of minimum clear cover values does not satisfy with the ACI and AASHTO minimum clear cover values. The change of clear cover in existing structures is not possible. The FRP strengthened structures could be made code amenable with the reduced cover requirements (As shown in Chapter 6, 6.3).

10. Corrosion of steel reinforcement significantly reduces the serviceability of RC beams, yield and ultimate loads of RC beams. Reduction in yield load decreases the steel mass loss. On application of FRP to the beams of existing or new structures, controls the reduction of serviceability of RC beams, yield and loads of RC beams.

11. After application of FRP composites, the deflection of corroded and repaired beams reduced when compared to corroded and unrepaired beams. This behavior is seen in beams because FRP application reduces chloride ingress and also reduces corrosion (known from this research).

12. Overall, all FRP wrap systems and only epoxy have kept the chloride level below the corrosion threshold. To date, from the observed results indicate that single layered carbon FRP and multi-layered carbon, glass FRP are effective barrier to chlorides. Each of these FRP wraps has lesser rate of chloride ingress. The results so far indicate that multi-layered FRP wraps are most effective.

7.2 Future Research

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

1. In this case study the exposure of sodium chloride solution on concrete specimen is done for 16weeks, 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 or more. With the prolonged exposure, there is the possibility of the chloride solution breaking down the epoxy in the wrap system, which would allow space for chloride transport into the concrete beneath the FRP wrap.
2. Using different epoxy materials in combination with different FRP composites to find any differences when establishing the clear cover depths.
3. Examine concrete with FRP wrapping exposed to other possible corrosion causing agents besides chloride, such as water, other chemicals and elevated temperatures.
4. 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.
5. With the geometry of members and existing properties try to use more layers of FRP to achieve additional moment capacity.
6. Use different methods to reduce the chloride penetration other than FRP composites like using denser concrete or by applying any coating other than FRP, etc.

Appendix A

Sample Calculations On Chloride Percent Determination

The following equation given below determines the chloride ingress percentage in concrete using the values obtained from the titration process of powdered samples obtained from concrete specimens.

$$\mathrm{CL\%} = \frac{3.545[(V1 - V2)N]}{W}$$

Where:

V_1=ml of 0.05 N AgNO3 solution used for sample titration (equivalence point).

V_2=ml of 0.05 N AgNO3 solution used for blank titration (equivalence point).

N=normality of the 0.05 N AgNO3 solution

W=mass of sample in grams.

Table A-1 Recorded Values from SCFRP-1, SCFRP-2. SGFRP-1 and SGFRP-2 Specimens at 0.75 in (18.75 mm)

SPECIMEN	DEPTH (in)	WEIGHT(lb)	Silver Nitrate Used($AgNo_3$ ml)	CHLORIDE (%)
SCFRP-1	0.75 in(18.75 mm)	0.01764 lb(8 gm)	14.5	0.3212
SCFRP-2	0.75 in(18.75 mm)	0.01631 lb(7.4 gm)	13.3	0.3194
SGFRP-1	0.75 in(18.75 mm)	0.02028 lb(9.2 gm)	16.6	0.3269
SGFRP-2	0.75 in(18.75 mm)	0.01873 lb(8.5 gm)	15.5	0.3230

Using equation from ASTM 1152, Percentage of chloride ingress is calculated for

SCFRP-1(1st sample at 0.75 in (18.75 mm) depth)

$$\mathrm{CL\%} = \frac{3.545[(\mathrm{V1} - \mathrm{V2})\mathrm{N}]}{\mathrm{W}}$$

$$\mathrm{CL\%} = \frac{3.545[(14.5\mathrm{ml} - 0\mathrm{ml})0.05\mathrm{N}]}{8}$$

Then

CL% = 0.3212 %

SCFRP-2 (2nd sample at 0.75 in (18.75 mm) depth)

$$\mathrm{CL\%} = \frac{3.545[(\mathrm{V1} - \mathrm{V2})\mathrm{N}]}{\mathrm{W}}$$

$$\mathrm{CL\%} = \frac{3.545[(13.3 - 0\mathrm{ml})0.05\mathrm{N}]}{7.4}$$

Then

CL% = 0.3194%

SGFRP-1 (1st sample at 0.75 in (18.75 mm) depth)

$$\mathrm{CL\%} = \frac{3.545[(\mathrm{V1} - \mathrm{V2})\mathrm{N}]}{\mathrm{W}}$$

$$\mathrm{CL\%} = \frac{3.545[(16.6 - 0\mathrm{ml})0.05\mathrm{N}]}{9.2}$$

Then

CL% = 0.3269%

SGFRP - 2 (2nd sample at 0.75 in (18.75 mm) depth)

$$\mathrm{CL\%} = \frac{3.545[(\mathrm{V1} - \mathrm{V2})\mathrm{N}]}{\mathrm{W}}$$

$$\mathrm{CL\%} = \frac{3.545[(15.5 - 0\mathrm{ml})0.05\mathrm{N}]}{8.5}$$

Then

CL% = 0.3230%

Average value of the Single layered CFRP specimens at 0.75 in (18.75 mm) depth:

Average % = (0.3212+0.3194)/2 = 0.3203%

Average value of the Single layered GFRP specimens at 0.75 in (18.75 mm) depth:

Average %= (0.3269+0.3230)/2 = 0.3249%

The following calculation is shown to determine the percentage of chloride ingress for the samples collected from ASTM C 1152 for the single layered CFRP and GFRP specimens at 0.75 in (18.75 mm) depth only. The normality of the silver nitrate solution was 0.1893 mol/US gal (0.05 mol/L). The blank titration value, V2, 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 CI, chloride percentage, values obtained for each sample taken at the 0.75 in (18.75 mm) depth. The double layered CFRP, double layered GFRP, epoxy and control specimen's average values were calculated in a similar manner as described here for the single layered CFRP and GFRP specimens.

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Biographical Information

Vinod Reddy Kamagani Kuntla was born in Telangana, India in 1992. He graduated from Jawaharlal Nehru Technological University Hyderabad, India earning a bachelor of technology in civil engineering on May 24, 2013. During the last semester of his undergraduate studies in 2013, he applied for master's program at University of Texas at Arlington in the structural engineering area. His admission for masters in university of Texas was approved for the structural engineering and applied mechanics program after successfully completing the required courses. This opened a window for vinod to start his education at University of Texas at Arlington. In August 2015 he graduated and obtained his master of science in civil engineering degree with structural engineering and applied mechanics emphasis. Vinod reddy's future plans are to start working in order to obtain professional license and then start an own company for construction purposes.