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RESEARCH ARTICLE

EFFECT OF FRP WRAPPING ON CONCRETE CHLORIDE INGRESS

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ABSTRACT

Fiber Reinforced Polymer (FRP) wrapping is being successfully used to strengthen deteriorated and/or under-designed concrete structures for flexure, shear, axial, blast and impact capacities. The technique is economic, labor friendly, durable and space saving. In this study, the effect of various FRP wrapping parameters, such as type, fiber orientation, number of layers and the role of the epoxy adhesive, were investigated on the ingress of chloride ions inside the concrete substrate. A surface saline ponding approach for 16 weeks and chemical determination of chloride contents of powder concrete at various concrete depths were utilized. FRP wrapping was found to provide excellent barrier against chloride ingress (28% reduction on average). The chloride resistance came from the composite FRP laminate and not from epoxy only. The chloride content decreased rapidly and linearly with the penetration depth. Carbon FRP (CFRP) was more effective than the thinner glass FRP (GFRP), and double layers more effective than single layer. The FRP fiber directionality had no bearing on chloride penetration. Although less expensive, the less strong GFRP is at a disadvantage in providing long-term durability to concrete structures, as compared to CFRP wrapping.

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INTRODUCTION

Increasing resistance to carry higher design loads, addressing strength loss due to deterioration, or increasing the durability of the structure are some of the reasons to reinforce structures using externally applied materials (ACI 2002a). Traditionally available methods to externally reinforce structures include steel or concrete jackets, external post-tensioning and externally bonded steel plates. Fiber Reinforced Polymer (FRP) rebars and FRP sheets are some alternative methods to externally reinforce concrete structures (Uomoto, 2001). FRP wrapping can be used in areas where existing conventional methods may have limited access and are difficult to implement. Retrofitting reinforced concrete structures may preclude total reconstruction as an alternative (Fyfe 2015). Figure 1 shows application of external FRP wrapping to strengthen a building slab. The very small thickness of cured FRP systems are often desirable in applications where space saving is a concern (ACI 2007). Moreover, it increases the flexural, shear, axial and torsion strengths and also improves the ductility of strengthened members. The effects of harsh environment conditions on the long term performance of FRP wraps and FRP-concrete bond were studied previously. Results indicated 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 (ISIS Canada 2006). A recent study investigated the effects of different surface treatments on the chloride resistance of concrete in marine environments. The concrete permeability was evaluated according to the ASTM standard for rapid chloride penetration (ASTM 2010). Surface protection significantly reduced the sorptivity of concrete (reduction rate< 70%) (Christodoulou *et al.*, 2013) However, only the polyurethane coating was highly effective in reducing the chloride diffusion (reduction rate of 86%). The most effective was the single layer protective system with a chloride reduction of 86%. In contrast, the double layer FRP system provided a reduction of 33 - 41%. Oh and Jang (2007) developed a model predicting chloride penetration in concrete that includes parameters such as the age of concrete, temperature, relative humidity, chloride binding and chloride convection. The model showed that the ingressed chloride accumulates near the surface of the concrete. The durability related strength loss of carbon fiber reinforced polymer (CFRP) applied to concrete beams was investigated through an NCHRP study (ISIS Canada 2006). The developed design guidelines include a durability strength reduction factor for LRFD for both wet and dry conditions. Another study focused on the durability of CFRP wrapped concrete beams under

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accelerated and natural aging (Prachasaree *et al*., 2011). Variation in mechanical properties due to aging through water immersion, salt and alkaline solution immersion at elevated and freeze-thaw temperature variation were studied. Results of experimental theoretical load (moment) ratios indicated a trend of reduction in load (moment) capacity with increasing temperatures.

Fig. 1. FRP application on concrete beams

An experimental research project evaluated the long-term effectiveness of FRP wraps in preventing corrosion of concrete elements in severe environments (ISIS Canada 2006). Partially wrapped versus unwrapped elements were studied. Other parameters included: cast-in chlorides, cracked versus uncracked elements, and corrosion inhibitors. Another experimental project assessed the use of FRP wraps with fibers oriented in the hoop direction for corrosion-damaged columns (Harichandran and Baiyasi, 2000). The results of the accelerated corrosion experiments indicated that wrapping reduced corrosion depth in the reinforcing bars by 46 to 59% after 190 days. Both glass and carbon wraps were equally effective in slowing down corrosion. CFRP wraps were used to repair corrosion-damaged reinforced concrete columns in aggressive environment (ISIS Canada, 2006). The experiment incorporated electrochemical chloride extraction treatment on the columns followed by CFRP wrapping. The FRP decreased the steel corrosion rate and restored the structural integrity. FRP may potentially be damaged by the alkaline environment within concrete through several interrelated mechanisms. In the specific case of GFRP materials, moisture that penetrates the fibers may extract ions from the fiber and result in etching and pitting, causing deterioration of tensile strength and elastic modulus (Prachasaree *et al*., 2011) Certain chemicals such as sodium hydroxide and hydrochloric acid can cause severe hydrolysis of fibers. Decrease in FRP strength and increases in moisture uptake are greater when exposed to 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 FRP introduced to non-saline solutions show only very slightly less degradation than those in saline solutions (ISIS Canada 2006).

GFRP sheets are typically less than half the cost of CFRP sheets. However, CFRP is typically stiffer, stronger and lighter than GFRP, and they are thus used in weight and/or modulus-critical applications, such as prestressing strands and FRP wraps for repair and strengthening of concrete structures. In addition, carbon fibers display outstanding resistance to thermal, chemical and environmental effects, and also fatigue loading (ISIS Canada 2006). It has been established from previous studies that FRP wrapping for retrofitting concrete structures offer high resistance to corrosion causing agents, such as chloride ions and water, leading to reduction of rebar corrosion. Yazdani and Garcia (2014) showed that the required minimum cover for unprotected concrete, based on ACI 2014 criteria, can be reduced significantly with FRP external wrapping, to achieve similar levels of chloride protection (ACI 2014). Corrosion of steel in concrete may lead to reduced bond strength, cracks and spalling of concrete members, severely reducing the service life and strength of a member. However, the effect of FRP type, number of FRP layers and the role of epoxy adhesive in reducing the infusion rate of external chlorides inside concrete members has not been extensively studied. The corrosive agents for concrete rebars are chlorides, acids, sulfates moisture and oxygen. Among the chemical agents, chlorides are the major cause of rebar corrosion (ACI 2002a). External FRP wrapping of concrete members is currently undertaken to strengthen the underlying members, provide additional ductility, impact resistance and also confinement. The durability issue needs additional investigation, such as the current study, in order to better assess the various FRP related parameters and their effect on concrete chloride penetration and associated long term durability of concrete. Quantitative estimation of the role of the epoxy layer, number of FRP wrapping and FRP type in reducing chloride ingress will be useful for practical applications. For this study, ASTM C1543, ASTM C1152 and ASTM C114 methods were used to determine the resistance of FRP wraps in affecting the penetration of sodium chloride solution into concrete (ASTM 2010, ASTM 2012, ASTM 2015). ASTM C1543 provides a procedure to determine the ingress of sodium chloride solution into concrete by surface ponding method over a period of time. Afterwards, ASTM C1152 and ASTM C114 provisions were used to find the acid soluble chloride profiling for each concrete specimen at various penetration depths.

MATERIALS AND METHODS

A standard concrete mix based on ACI guidelines was chosen for this study (ACI 2002a). The mix design details are presented in Table 1. The obtained slump of 90 mm was within the range specified by ACI (75 to 100 mm). Commonly used FRP fibers are carbon, glass and aramid. The properties of the cured FRP laminate depend on the properties of both epoxy and dry FRP. In this study, two types of common FRP, a CFRP and a GFRP from the same manufacturer, were used. The CFRP had unidirectional laminates, while the GFRP has bidirectional laminates. However, laminate direction is not likely to affect the chloride ingress levels in concrete. The epoxy used was a two component type that is compatible with the two FRPs. Relevant dry fiber and composite laminate properties of the selected CFRP and GFRP are presented in Table 2, while properties of the selected epoxy are presented in Table 3. The design strength of the composite is based on a combination of the raw carbon fiber and epoxy formulation.

Table 1. Concrete mix design, one cu. m. mix

Ingredient	Amount
Coarse aggregate, crushed stone of 2.65 specific gravity	1008 kg
Fine aggregate, river sand of 2.61 specific gravity	773 kg
Type II Portland cement	460 kg
Water/cement ratio	0.4

Table 2. Properties of selected FRPs

Typical Dry Fiber Properties		
Property	CFRP	GFRP
Tensile Strength (GPa)	3.79	3.24
Tensile Modulus (GPa)	230	72.4
Ultimate Elongation	1.7%	4.5%
Density (g/cm^3)	1.74	2.55
Minimum weight (g/m^2)	644	915
Composite Gross Laminate Properties		
Property	CFRP	GFRP
Ultimate tensile strength in both fiber directions (MPa)	834	247
Elongation at break	0.85%	1.3%
Tensile Modulus (GPa)	82	15.4
Nominal Laminate Thickness (mm)	1.0	0.25

Table 3. Properties of selected epoxy

Property	Value
Glass Transition Temperature	82° C
Tensile Strength	72.4 MPa
Tensile Modulus	3.18 GPa
Elongation Percent	5.0%
Flexural Strength	123.4 MPa
Flexural Modulus	3.12 GPa

A total of 12 concrete specimens were cast for this study. As shown in Table 4, wrapping configurations with single/double layers of CFRP/GFRP, only epoxy and no wrapping at all (control) were used. Two replicate samples for each configuration were cast. Plywood molds with exposed top surface and 175 by 175 by 200 mm in dimension were prepared and used for the concrete casting. Within each mold, a 100 mm deep sample was cast. The mold dimensions complied with the requirements from ASTM C 1543 specifications. The samples within the molds were cured for a period of 28 days at a temperature of 28^o c. Three cylindrical concrete samples (150 by 300 mm) were cast concurrently with the brick shaped samples, and were tested for compressive strength at seven days. The average concrete strength at seven days was found to be 30.09 MPa, exceeding the minimum strength of 24.1 MPa as specified in ACI (ACI 2002b). After 28 days of curing, the concrete was ready to have the FRP composite material installed at the top surface.

Table 4. Sample designations

Wrapping Type	Designation	Description	No. of Samples
CFRP/epoxy	S-CFRP	One CFRP layer	2
	D-CFRP	Two CFRP layers	2
GFRP/epoxy	S-GFRP	One GFRP layer	2
	D-GFRP	Two GFRP layers	2
Epoxy only	EPOXY	Only epoxy layer	2
None	CONTROL	No FRP or epoxy	2
Total Number of Brick Samples			12

Each FRP system manufacturer has developed application procedures that may differ slightly in some cases. The end goal of the surface preparation activities is typically to provide a freshly-exposed, clean, sound, open, dry and roughened texture. The exposed concrete surfaces were lightly sandblasted to expose the fine and coarse aggregate surfaces, and also to achieve the ICRI Surface Profile 3 configuration, as required by the FRP manufacturer (ISIS 2006). The epoxy material was mixed with 500 ml component A and 210 ml of component B in a small mixing machine. A 7% silica powder was added to the mixed epoxy in order to thicken it. The manufacturer recommended application of epoxy layers of approximately the same thickness as the FRP fabric (1.0 mm for CFRP and 0.25 mm for GFRP). For EPOXY specimens, the mix was evenly distributed on the concrete surface. For S-CFRP and S-GFRP specimens, a layer of epoxy was evenly applied on the concrete surface. The FRP fabric was also saturated with epoxy on both sides. The saturated fabric was then placed on the concrete surface with even hand pressure to ensure good bonding and removal of any air bubbles (Fig. 2). For D-CFRP and D-GFRP specimens, after applying the first layer, the second saturated layer was immediately placed with pressure on top of the first layer. All FRP and epoxy specimens were allowed to cure for a period of 72 hours at room temperature.

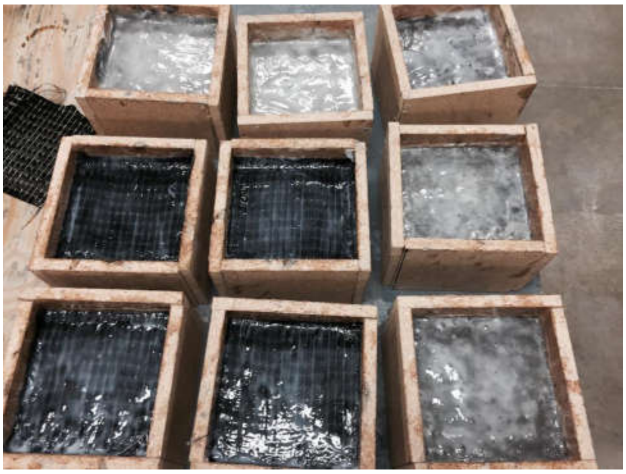

Fig. 2. Concrete specimens with applied FRP/Epoxy

After the FRP curing, the saline solution ponding process was initiated to a depth of 25 mm on top of the samples, as per ASTM C1543 procedure. A 4% sodium chloride solution was used herein. The specimens were thereafter covered with a thick polyethylene sheet on the top surface of the molds and sealed around edges to minimize water evaporation. The specimens were stored indoors at a room temperature of below 23 ± 2^{0}C and inspected every two days for 16 weeks duration. It is recommended in ASTM C1543 that the initial sampling be performed after three months of ponding. If any evaporation loss was detected, fresh saline solution was used to replenish the loss. All samples were drained and fresh saline solution added after eight weeks (halfway in the ponding process. Figure 3 shows a few ponded and sealed specimens.

Fig. 3. Specimens with saline ponding

In order to collect powder concrete samples, the ponding solution was removed and specimens allowed to air dry. A rotary impact hammer was used to collect powder concrete samples (Fig. 4), as specified in ASTM C1152.

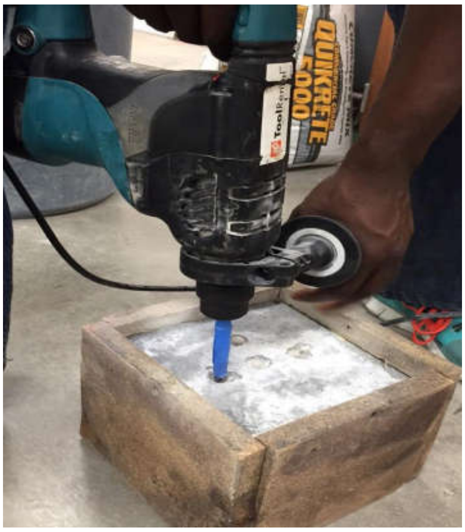

Fig. 4. Collection of powder concrete samples

The sampling points were spaced at least 25 mm from the exterior edge or another sampling point. Approximately 10 g of sample was collected from each depth, and samples were collected from three different locations on each specimen for replication purposes. To conform to the ACI 318 minimum cover requirements for durability, as shown in Table 5, samples were collected from four depths of 18.75, 37.5, 50 and 75 mm (ACI 2014).

Table 5. ACI minimum concrete covers

Exposure	Concrete cover, mm
Concrete cast against and permanently exposed to earth	75
Concrete exposed to earth or weather	
No.6 through No.18 bars	50
No.5 bar and lesser	37.5
Concrete not exposed to weather or in contact with ground	
Slabs, walls, joists	37.5
No.14 and No.18 bars	18.75
No.11 bar and lesser	
Interior Beams, Columns	
Primary reinforcement, ties, stirrups, spirals	37.5

ASTM C1152 procedure was followed for the chloride determination of the concrete sample. The collected concrete powder sample was weighed and transferred to a 250 mL beaker and diluted with 75 mL reagent (deionized or blank) water. Then, 25 mL of 1:1 nitric acid was added slowly to the diluted sample. A 3 mL 30% hydrogen peroxide solution was added to the sample to avoid the interference of sulfides. After this step, 3 drops of methyl orange indicator was added and mixed. If the solution was not turning pink, small amount of nitric acid was added dropwise until the pink color appeared. Once the pink color was seen, 10 more drops of nitric acid were added, and the beaker was heated rapidly to boiling and immediately removed from the hot plate. A two mL of 0.05 N sodium chloride solution was thereafter added to the cooled sample. 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 beaker, making sure that the stir bar did not touch the electrode, as shown in Fig 5.

Fig. 5. Powder concrete sample titration

The sample was titrated by adding a 0.05 N silver nitrate ($AgNO_3$) solution in 0.2 mL increments. At each increment, voltage was monitored with a volt meter. As the equivalence point approached, the additions caused increased changes in meter readings. Past the equivalence point, the voltage change per increment decreased. Titration was continued for three readings past the equivalence point. The precise sample equivalence point was calculated based on ASTM C114 procedure. Next, the reagent water (blank) was treated as sample of the same volume, and the precise blank equivalence point was determined using the above procedure.

The chloride content in each powder sample was calculated by Eq. 1:

$$CL\% = \frac{3.545[(V1-V2)N]}{W} \tag{1}$$

Where:
CL % = percentage of chloride in the sample
V_1 = $AgNO_3$ solution needed to reach the equivalence point in sample solution, mL.
V_2 = $AgNO_3$ solution needed to reach equivalence point in blank solution, mL.
N = normality of the $AgNO_3$ solution (0.05)
W = mass of sample, g.

RESULTS

Chloride content (CC) results at each depth from the two replicate brick samples and the three different locations on each brick sample for each FRP/epoxy configuration were close. Therefore, the average of six total sampling for each FRP/epoxy configuration (two replicate brick samples, three locations on each sample) is reported herein. Figures 6, 7, 8 and 9 present the CC in various sample arrangements at 18.75, 37.5, 50 and 75 mm depths, respectively. It is noted that all single and double FRP wrapped samples showed lower CC than the control concrete sample with no protection at all depths, clearly showing the protective benefits of FRP wrapping.

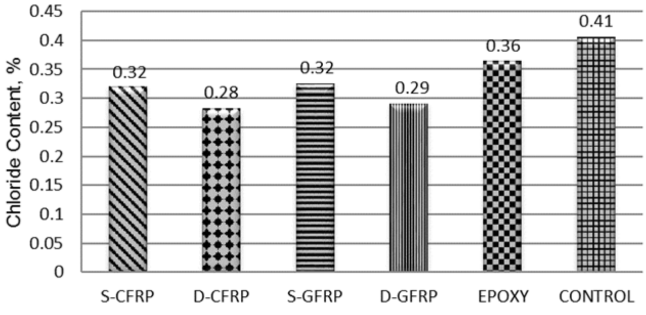

Fig. 6. Chloride contents at 18.75 mm depth

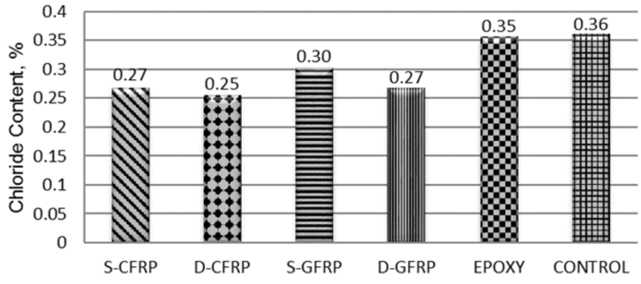

Fig. 7. Chloride contents at 37.5 mm depth

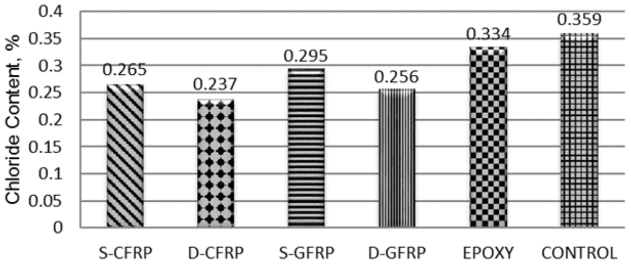

Fig. 8. Chloride contents at 50 mm depth

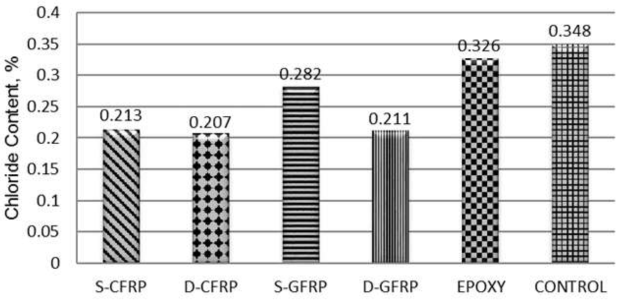

Fig. 9. Chloride contents at 75 mm depth

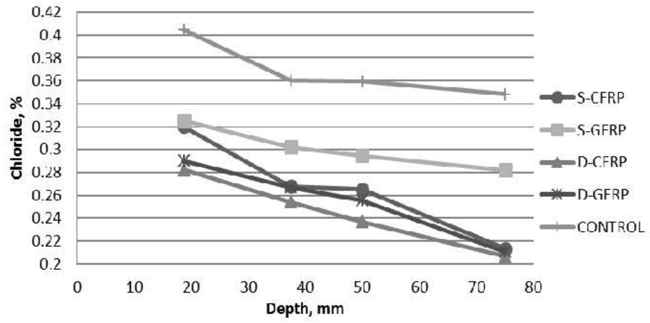

Fig. 10. Chloride content vs. Depth

Table 6. Chloride content decreases compared to control, %

Depth, mm	FRP/Epoxy Configuration				
	EPOXY	S-CFRP	D-CFRP	S-GFRP	D-GFRP
18.75	10	21	30	20	28
37.5	1	28	31	16	26
50	6	26	34	18	29
75	6	40	41	19	39

Table 7. Trend line equations for chloride content

Specimen	Trend line equation (y = chloride content, %, x = depth, mm)	Correlation coefficient, R^2
CONTROL	$y = -0.0009x + 0.4103$	0.76
S-CFRP	$y = -0.0018x + 0.3487$	0.97
D-CFRP	$y = -0.0013x + 0.3056$	0.99
S-GFRP	$y = -0.0007x + 0.3345$	0.94
D-GFRP	$y = -0.0014x + 0.3194$	0.98
EPOXY	$y = -0.0007x + 0.3778$	0.90

The percentage decrease in CC, as compared to the control sample and shown in Table 6, varies from 16% to 41%, with an average of 28% for all wraps at all depths (excluding epoxy only), an impressive decrease. This should result in lower corrosion potential of embedded steel rebars, leading to increased durability and service life. To understand the role of FRP type and number of layers, the CC in the various FRP wrapped samples were plotted as functions of the depth. It is apparent that the CC in all sample configurations decrease rapidly with increasing depths, as expected. However, the CC decrease is not similar for all FRP configurations. It is observed that the FRP type has an appreciable effect on the CC. For a single layer application, the CFRP wrap performed much better than the GFRP wrap in reducing chloride intrusion at depths larger than 18.75 mm. At 75 mm depth, the S-CFRP sample CC is about 33% less than that in the S-GFRP sample. The effect of FRP type for double layered samples is not that significant, although the D-CFRP performed better than the D-GFRP.

DISCUSSION

It is evident from Figs 6 - 9 and Table 6 that the epoxy coating by itself did not decrease the CC to a large extent; the CC in EPOXY samples was close to that in the control concrete samples. It is apparent that the barrier to chloride ingress in concrete is provided by the FRP layers only. The role of the epoxy adhesive is important in bonding the FRP material to the concrete, but not in adding durability aspect to the member. The number of layers made an appreciable difference in the CC for GFRP samples, with the D-GFRP showing much better protection than the S-GFRP case, especially at greater depths. For CFRP specimens, the double layers were also more effective than the single layer in concrete protection, although at not that large an extent as for the GFRP wrapping. The directionality of the FRP fabric did not have any bearing on the CC reductions found in this study. The unidirectional CFRP fabric performed better than the bidirectional GFRP fabric in general. For interior slabs, walls and joists, the minimum ACI 318 concrete cover is 18.75 mm. At this shallow depth, the double layered protection for GFRP and CFRP samples outperformed the single layered samples by about 10% in terms of CC reduction. At 50 mm depth, the minimum ACI 318 concrete cover for exterior exposure, the D-CFRP performed best, followed by D-GFRP and S-CFRP. At this depth, the D-CFRP helped reduce the CC by about 16% more than the S-GFRP. For concrete cast against and permanently exposed to earth (ACI 318 minimum cover of 75 mm), the S-CFRP, S-GFRP and the D-CFRP wrap configurations all performed similarly and quite a bit more efficiently in reducing CC, as compared to the S-GFRP wrapped samples. A review of Table 2 information can help shed some light on the relatively lower performance of GFRP laminates in reducing the chloride ingress in concrete elements. It is observed that the composite gross GFRP laminate was 0.25 mm, ¼ of the CFRP laminate thickness of 1 mm. The GFRP fabric was denser than the CFRP fabric by about 43%. It has been shown in the current study that the epoxy layer by itself was not effective in providing appreciable additional protection to the concrete structure. Therefore, the chloride protection was primarily due to the FRP fabric. The significantly thinner GFRP fabric was not as efficient as the thicker CFRP fabric in protecting the concrete surface, despite it being denser than the CFRP fabric. It is also noted from Table 2 that the GFRP composite laminate had significantly less strength than its CFRP counterpart. Therefore, the GFRP wrapping is at a disadvantage in terms of structural strength contribution to concrete structures, as compared to the CFRP wrapping, in addition to the lower durability contribution as well. The higher initial cost of CFRP wrapping may be offset by the additional benefits of the CFRP wrapping usage over GFRP wrapping and also the durability related maintenance and rehabilitation savings over the long term. Figure 10 data shows that the data are more or less clustered around straight lines for each surface wrapping configuration. To prove this, trend line (linear regression) equations in EXCEL for each configuration were developed herein, and presented in Table 7. The very high correlation coefficients for all cases (except the control specimens) show that the CC data can be effectively expressed as simple linear functions. This means that the CC increases almost linearly with the penetration depth in concrete for various wrapping configurations.

Conclusions

The following conclusions are made based on the findings from this study:

1. External FRP wrapping provides excellent protective barrier against chloride ingress in concrete substrate. The percentage decrease in chloride infusion varies from 16% to 41%, with an average of 28%.
2. Epoxy adhesive by itself does not decrease chloride intrusion in concrete. The barrier to chloride ingress in concrete is provided by the FRP layers only. The role of the epoxy adhesive is important in bonding the FRP material to the concrete, but not in adding durability aspect to the member.
3. Chloride contents in FRP wrapped concrete surfaces decrease rapidly with increasing depths. The minimum chloride content was found at 75 mm depth, the greatest depth investigated in this study.
4. FRP type has an appreciable effect on the level of protection. For a single layer application, the CFRP wrap performs much better than the GFRP wrap in reducing chloride intrusion at depths larger than 18.75 mm, out-performing the GFRP wrap by about 33% at 75 mm depth.
5. The number of layers makes a significant difference in the chloride protection for GFRP samples, with the double layers showing much better protection than the single layers, especially at greater depths. For CFRP, the double layers is also more effective than the single layer in concrete protection, although at not that large an extent as GFRP wrapping.
6. Bi-directional wrapping fabrics do not necessarily perform better than unidirectional fabrics in concrete chloride protection. The unidirectional CFRP fabric performed better than the bidirectional GFRP fabric in general in this study.
7. For interior slabs, walls and joists, the minimum ACI 318 concrete cover is 18.75 mm. At this shallow depth, the double layered protection for GFRP and CFRP samples outperformed the single layered samples by about 10% in terms of chloride reduction. At 50 mm depth, the minimum ACI 318 concrete cover for exterior exposure, the double layered CFRP performed best, followed by double layered GFRP and single layered CFRP. At this depth, the double layered CFRP helped reduce chlorides by about 16% more than the single layered GFRP. For concrete cast against and permanently exposed to earth (ACI 318 minimum cover of 75 mm), single layered GFRP wrap was widely out-performed by all the other three FRP configurations.
8. The GFRP-epoxy laminate is typically denser (by 43%) and thinner (by 75%) than the corresponding CFRP-epoxy laminate. The GFRP laminate is not as efficient as the thicker CFRP laminate in protecting the concrete surface, despite its density. With less strength, the GFRP is at a disadvantage in terms of strength contribution to concrete structures, as compared to the CFRP, in addition to the lower durability contributions. The higher initial cost (50%) of CFRP may be offset by its additional benefits over GFRP, and also the durability related maintenance and rehabilitation savings over the long term.
9. Chloride content variations with depth data in FRP protected concrete members are more or less clustered around straight lines for all configurations. Best fit trend line (linear regression) equations models developed herein with very high correlation coefficients show that the chloride content data can be effectively expressed as simple linear functions.

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