MONITORING CORROSION ACTIVITY IN CHLORIDE CONTAMINATED CONCRETE WRAPPED WITH FIBER REINFORCED PLASTICS

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Abstract

Damage to concrete due to corrosion of steel reinforcement is a costly maintenance problem that affects infrastructure. Reinforced concrete structures located in an aggressive environment are susceptible. Fiber reinforced plastic composite wraps have recently been used to rehabilitate structures that have experienced damage due to corrosion. Little is known about the long-term performance of FRP composites in corrosion prevention. Fourteen reinforced concrete specimens were subjected to an accelerated corrosion environment consisting of wet/dry cycles of saline water. The specimens were designed to represent conditions that may be found in rehabilitated concrete. Ten of the specimens were wrapped with GFRP, and four were left unwrapped. The specimens were monitored using half-cell potential testing. After the specimens were removed from exposure, chloride content determination and linear polarization were performed. The specimens were then opened and evaluated for corrosion activity.

Introduction

Corrosion of steel reinforcement in concrete structures is the single most expensive corrosion problem in the United States. It affects the integrity of thousands of bridges, roadbeds, and overpasses.[1] Concrete is typically a strong, durable, and long lasting building material. However, a concrete structure may experience premature deterioration due to exposure to an aggressive environment.

Aggressive environments include marine environments and exposure to deicing salts. This type of environment may cause concrete to become chloride contaminated. The most commonly quoted threshold for chlorides is 1 lb of chloride per cubic yard of concrete, which is approximately 0.03% chlorides by weight of concrete and 0.22% chlorides by weight of cement. Chloride contamination typically results from chloride ions becoming diffused into the concrete due to repeated exposure to saltwater or deicing salts. Some other sources of chlorides include the use of chloride containing additives in the concrete mix or the use of chloride contaminated water or aggregate.[2] Chloride contaminated concrete is highly susceptible to corrosion activity when sources of moisture and oxygen are available. The corrosion process will eventually cause cracking, spalling, and delamination of the concrete. This type of damage may lead to structural problems and requires expensive rehabilitation.

Common repair techniques for corrosion damage involve removing the cracked and spalled concrete over and around the reinforcing bars, cleaning or replacing badly corroded reinforcement, and replacing the concrete with a patch. It is necessary to remove all chloride contaminated or other unsound concrete from the repair area before it is patched. The repair material should be similar to the existing sound concrete to reduce electrochemical differences due to oxygen permeabilities of the two materials. This is to prevent a localized corrosion cell, known as macrocell corrosion, from forming between the

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[1] Denny A. Jones, *Principles and Prevention of Corrosion.* (Upper Saddle River, NJ: Prentice Hall, 1996).
[2] John P. Broomfield, *Corrosion of Steel in Concrete.* (London: E.& F.N. Spon, 1997).

existing concrete and the patch. Macrocell corrosion accelerates the corrosion process in the repair area, which often leads to spalling of the patch.[3]

Fiber Reinforced Plastic (FRP) composite wraps, which are commonly used in seismic retrofits have been considered for repairing corrosion damage in chloride contaminated concrete. FRP materials have very high strength-to-weight and strength-to-stiffness ratios. They are corrosion resistant and have a low axial coefficient of thermal expansion. The material is ideal for retrofits because it is easy to handle, can conform to the shape of existing elements, and can be applied quickly. Some disadvantages of FRP composites are high initial costs, and limited knowledge exists regarding long-term behavior of the material properties and long-term durability.

Laboratory Study

The purpose of this study, sponsored by the Texas Department of Transportation, was to evaluate the long-term performance of FRP composite wrap in preventing corrosion of steel reinforcing in chloride contaminated concrete. Concrete specimens were constructed to replicate the worst case scenarios found in the field.

The specimens consisted of two shapes, cylinders and rectangular blocks. The cylinders were modeled to represent bridge columns, and the rectangular blocks were modeled to represent portions of bridge bents located at points where bridge deck runoff exposes the bent to water containing deicing salts. The cylinders were 36 in. long and 10 in. in diameter. The rectangular blocks were 36 in. long with a 10 in. by 10 in. cross section. The reinforcement consisted of four #6 grade 60 bars. The transverse reinforcing for the cylinders consisted of nine ¼-in. plain steel wire circular hoops spaced at 4 in. The rectangular blocks have ¼-in. plain steel wire that form three U-shaped stirrups spaced at 10 in. The steel cage was tied together with metal ties in order to assure electrical continuity. The reinforcement extended 3 in. past the concrete to allow easy access for making electrical connections to the steel. The specimens had 1 in. of concrete cover that was maintained by using plastic chairs.

A low quality, highly permeable mix was used for the specimens. In order to insure permeability, the selected water-cement ratio was 0.7. An air entrainment additive was also added to the mix. In order to simulate chloride contaminated concrete, half of the specimens had cast-in-chlorides added to the mix. The chloride content was 1.5% chlorides per weight of cement.

In order to simulate existing cracks within a structure, some of the specimens were subjected to flexural cracking prior to being wrapped. The cracks were created by applying a point load in the center of the specimen using a Universal Testing Machine. The specimens were loaded until crack widths of 0.01 to 0.013 in. were observed, which is the maximum crack width allowed for exterior exposure by ACI 10.6.4.[4] The cylinders were loaded on two sides; the rectangular blocks were only loaded on the topside.

Two types of repair material, an epoxy grout and a latex-modified concrete, were chosen. Portions of concrete on the specimens were removed to the level of the reinforcing with a chipping hammer. The area was then patched with the repair material. A surface applied corrosion inhibitor was applied to four of the cylinder specimens.

Ten specimens were wrapped with three layers of glass FRP (GFRP). The FRP was applied by the hand layup method. Four specimens were not wrapped in order to serve as controls. The specimen parameters are listed in Table 1.

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[3] Ping Gu, et al., "Electrochemical Incompatibility of Patches in Reinforced Concrete," *Concrete International*, August (1997), pp. 68-72

[4] *Building Code Requirements for Structural Concrete (ACI 318-95) and Commentary (ACI 318R-95).* (Farmington Hills, MI: American Concrete Institute, 1995).

Table 1. Specimen Parameters

Specimen	Cast-in-Chlorides	FRP Wrap Length, in.	Initial Concrete Condition	Concrete Repair Materials[5]	Corrosion Inhibitor
Cylinder 1	Chlorides	24, water line	Cracked		
Cylinder 2	Chlorides	Unwrapped	Cracked		
Cylinder 3		Unwrapped	Cracked		Yes
Cylinder 4		24, water line	Cracked		Yes
Cylinder 5		36, full wrap	Cracked		Yes
Cylinder 6		24, water line	Uncracked		
Block 1	Chlorides	Unwrapped	Cracked		
Block 2	Chlorides	30	Cracked		
Cylinder 7	Chlorides	24, water line	Uncracked	EG	
Cylinder 8	Chlorides	36, full wrap	Cracked	EG	
Cylinder 9	Chlorides	36, full wrap	Cracked	EG	Yes
Cylinder 10		24, water line	Cracked		
Block 3		30	Cracked	LMC	
Block 4		Unwrapped	Cracked		

The specimens were exposed to an accelerated corrosion environment, consisting of alternating wet and dry cycles of 3.5% saline water. The wet/dry cycle consisted of a soaking (wet) period of one week in a 3.5% saline solution followed by a two-week drying period. During the wet period, the lower one-foot of the cylinders (columns) was immersed in salt water. During the drying cycle, the water was removed to a level below the bottom of the cylinder specimens. This was to create a splash zone effect for the cylinder specimens. The rectangular block specimens (bents) had saline water irrigated over the top surface. Mats were placed over the tops to provide even distribution of the water. The blocks were placed at a slight incline, allowing for the water runoff to flow towards the downstream end.

Findings

The specimens were divided into two groups. Group A, Cylinder 1 – Cylinder 6, Block 1, Block 2, were exposed to fifteen wet-dry cycles. Group B, Cylinder 7 – Cylinder 10, Block 3, Block 4, were exposed to twenty-six wet-dry cycles.

The laboratory specimens were monitored by half-cell potential using a saturated calomel reference electrode. The procedure followed ASTM Standard C 876. The readings were then converted to equivalent copper/copper sulfate results. Readings were taken after every four wet/dry cycles for the wrapped specimens during the exposure period. Readings were taken after every cycle for the unwrapped specimens for the first eighteen months of exposure. The results for each group are plotted in Figure 1 and Figure 2. The ASTM interpretation of half-cell potential readings is as follows:

0 to -200 mV	Low risk, 10% probability of corrosion
-200 to -350 mV	Intermediate risk, corrosion activity in uncertain
< -350 mV	High risk, 90% probability of corrosion
< -500 mV	Severe corrosion, corrosion induced cracking may occur

[5] The notation EG represents the epoxy grout, and the notation LMC represents the latex-modified concrete.

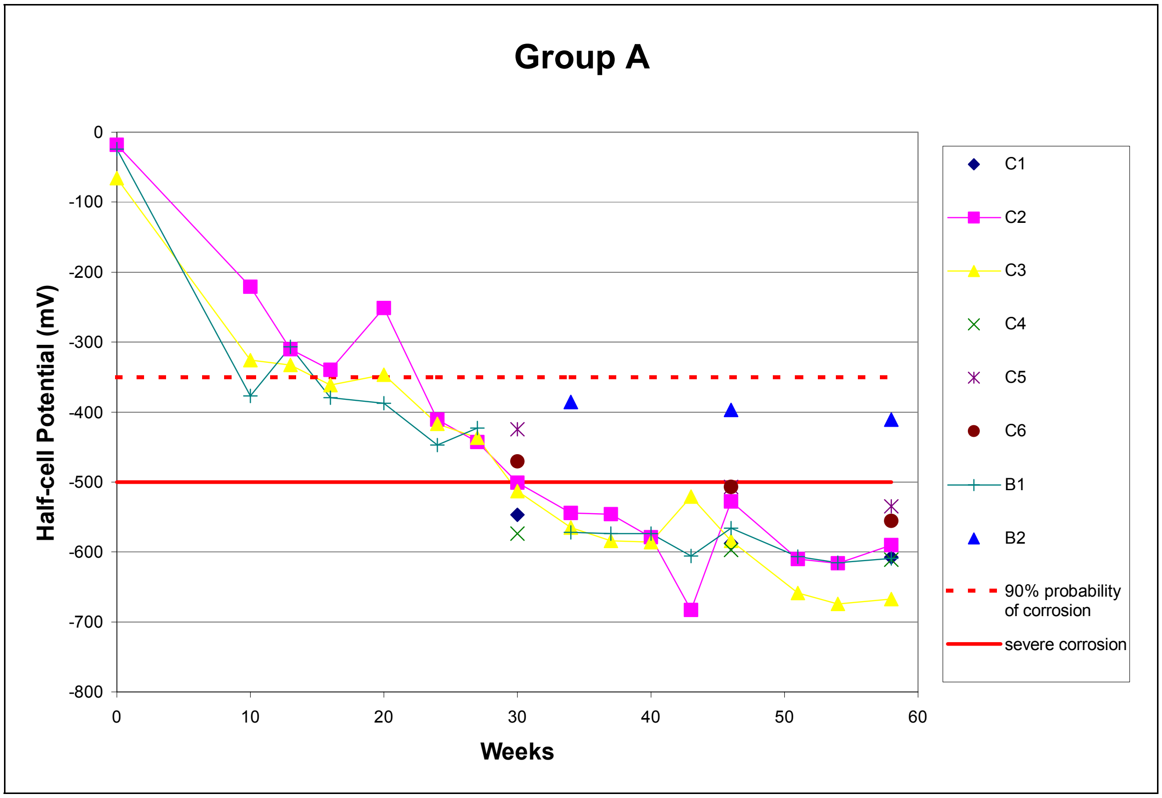

Figure 1. Half-cell potential readings for Group A.

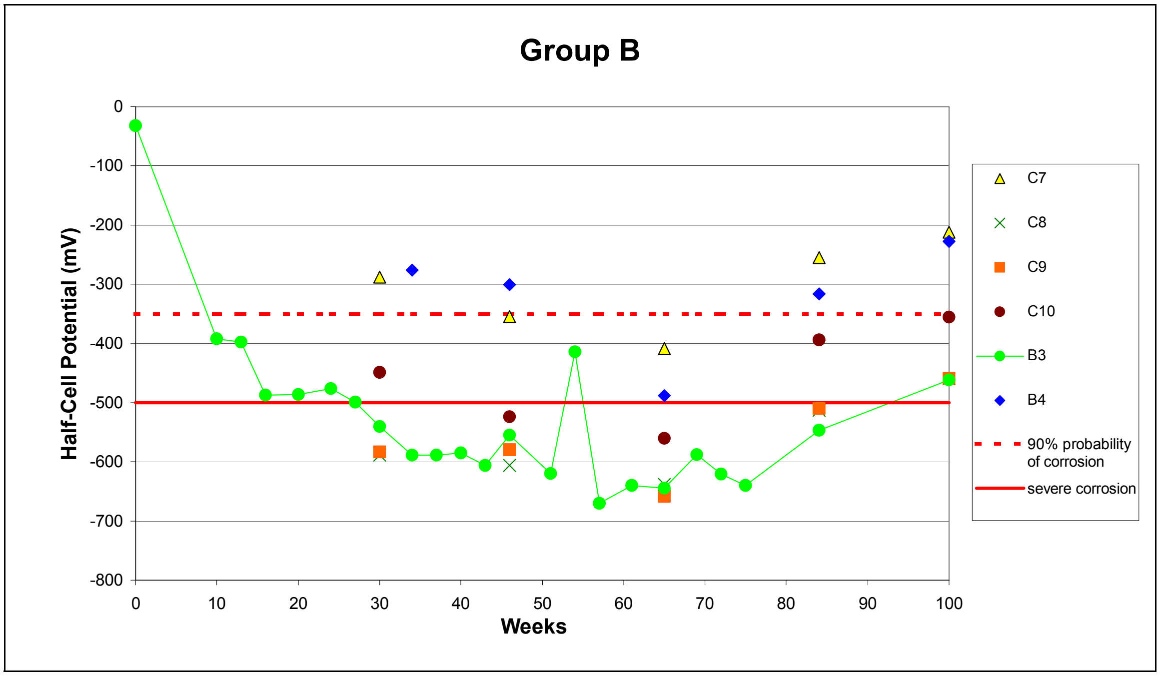

Figure 2. Half-cell potential readings for Group B.

After the specimens were removed from the exposure tank, chloride content tests were run on each specimen. A James Instruments CL-500 test was used. The chloride levels for the wrapped rectangular blocks were very close to the predicted value based on the assumption that the FRP would act as a barrier and prevent future ingress of chlorides. The unwrapped rectangular blocks had chloride levels significantly higher than the wrapped blocks. The cylinders showed similar behavior above the splash zone, but increased chloride levels were found below the splash zone. This indicated that while FRP does prove an effective barrier for chlorides, capillary action might draw salt water up into wrapped portions of a column.

Linear polarization was used on the cylinder specimens in Group B in order to determine the corrosion rate of the steel reinforcing. The testing was performed with a PR-Monitor. The PR-Monitor uses a copper/copper sulfate reference electrode with a sensor controlled guard ring. Linear polarization was performed at two locations on each specimen. The first location was at 4 in. above the waterline. The second location was in the middle of the splash zone, 6 in. above the bottom of the specimen, which is where the most corrosion activity was expected to occur. The testing was performed after the FRP composite wrap had been removed from the specimens. The test could not be performed on the lower portion of Cylinder 7 because the epoxy resin from the composite had encased the entire portion of concrete below the wrap. The E_{corr} from the linear polarization agreed well with the E_{corr} from the half-cell potential testing. The data from the linear polarization is listed in Table 2.

Table 2. Linear Polarization Data from Group B

Specimen	Location	
	Splash zone	4 in. above the waterline
Cylinder 7		
E_{corr} (mV)	N/A	-248
I_{corr} (μA/cm^2)	N/A	0.74
Rate (mpy)	N/A	0.34
Cylinder 8		
E_{corr} (mV)	-475	-411
I_{corr} (μA/cm^2)	4.88	4.27
Rate (mpy)	2.23	1.95
Cylinder 9		
E_{corr} (mV)	-504	-458
I_{corr} (μA/cm^2)	3.09	5.23
Rate (mpy)	1.41	2.39
Cylinder 10		
E_{corr} (mV)	-549	-275
I_{corr} (μA/cm^2)	8.45	1.27
Rate (mpy)	3.86	0.58

The specimens were opened and the reinforcing was examined for signs of corrosion. Very little corrosion activity was found in portions of uncontaminated concrete that were free of cracks and repair material. However, corrosion activity was present throughout the wrapped portions of the chloride contaminated specimens. Corrosion activity was also accelerated by the formation of macrocells between the existing concrete and repair material. Corrosion activity was found in the splash zones of all of the cylinder specimens.

Moisture was found trapped under the FRP wrap in four out of five of the fully wrapped specimens. Accelerated corrosion was found in the reinforcing located near the trapped moisture. For the cylinder specimens, it resulted in corrosion activity taking place in the splash zone. For the rectangular blocks, the area of corrosion activity due to trapped moisture was found at the upstream end rather than the downstream end. As a result, the activity did not register on the half-cell potential monitoring since the downstream end was the area being monitored. The results from the linear polarization showed that the half-cell potentials varied depending on the location where they were taken. The ASTM standard suggests an interval of 4 ft. for a bridge deck. In the case of the laboratory specimens, the half-cell potentials sometimes vary substantially in an interval of 10 in.

Conclusions

The amount of corrosion activity found corresponded well with the linear polarization testing. The corrosion activity was more substantial at the locations with the higher corrosion rates. The location with the lowest corrosion rate had the least amount of corrosion activity out of the test locations.

In this study, FRP composite wrap did not prevent corrosion activity in chloride contaminated concrete. FRP did serve as an effective barrier for chlorides, and did prevent corrosion activity from taking place in the wrapped portions of the specimens that were free of cracks and chlorides. In order to fully evaluate the effectiveness of FRP composite wrap in corrosion prevention, more long-term testing is required on specimens that have been adequately repaired.

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