ONSET AND RATE OF CORROSION IN CFRP WRAPPED REINFORCED CONCRETE CYLINDERS

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Abstract

An experimental investigation was conducted of the corrosion performance of steel reinforcement in small-scale concrete specimens. Each sample was treated with one of thirteen different surface treatment options, including control samples, epoxy only, and up to three layers of carbon fiber reinforced polymer (CFRP) wrap. Two different two-part epoxies were tested. Samples were subjected to an impressed current and a high salinity solution. For each sample, corrosion activity was monitored throughout the test using current flow measurements. Reinforcement mass loss was measured after the sample failed or at the end of the test period. Theoretical predictions of total mass loss were computed using Faraday's law, and correlation with actual mass loss was investigated. As strong correlation was found for total mass loss, theoretical estimates of the cumulative mass loss over time were computed, also using Faraday's law. This information was used to examine the effect of CFRP wraps on the onset and rate of corrosion.

Test results indicated that CFRP wrapped specimens had prolonged test life, decreased reinforcement mass loss, and slower corrosion rates. The performance of wrapped specimens was superior to that of either control samples or those coated only with epoxy. Epoxy type had a significant effect on the corrosion resistance of the CFRP wrapped samples. It was concluded that CFRP wraps were not only able to inhibit the passage of salt water, but were also able to confine the concrete, slowing deterioration from cracking and spalling, thereby slowing the overall corrosion rate.

1. Introduction

This paper investigates the use of CFRP composite wraps to delay the onset of reinforcement corrosion and reduce the rate of corrosion in concrete samples exposed to an aggressive chloride environment. Additionally, the effects of fabric orientation, number of wrap layers, and the type of impregnating epoxy are considered. According to Toutanji et al. composites are particularly suitable for rehabilitation because they are lightweight, durable, corrosion resistant, and high modulus and stiffness [1]. However, the application of CFRP materials to protect reinforced concrete structures from corrosion has not been widely studied, nor has the effect of different impregnating systems; thus, further research is needed. It is proposed that CFRP wrapping of concrete members will reduce or slow reinforcement corrosion by confining concrete and reducing permeability.

2. Background and Related Research

Corrosion is an electrochemical process requiring an anode, cathode, electrolyte, and a contact between the anode and cathode. Ions present in salt water that leach into concrete provide a means for active reinforcement corrosion. Detwiler et al. state that the products of the corrosion of iron can take up a volume as much as six times that of the original iron [2]. When this expansive process occurs in reinforced concrete, it induces internal stresses in concrete that can eventually lead to spalling or delamination of the concrete around reinforcing steel. The cross sectional area of the steel can be significantly reduced once corrosion starts. If the concrete can be kept from deteriorating, the migration of undesirable ions into concrete could be slowed down, and it would follow that the rate of corrosion would decrease. It has been shown that, under short-term exposure conditions, carbon fiber wraps effect the absorption of water into concrete, reducing infiltration at the surface and eliminating the penetration of water into the interior of specimens [3].

Research by Debaiky et al. on CFRP wrapped column stubs showed that CFRP wrapping reduced corrosion activity in the reinforcing steel even under harsh conditions, as measured by decreased corrosion current density, decreased mass loss, and reduced chloride diffusion from external sources [4, 5]. A study by Lee et al. monitored and tested circular reinforced concrete columns wrapped with CFRP sheets before and after being subjected accelerated corrosion [6]. In that study, the rate of post CFRP-repair corrosion was found to be reduced.

3. Experimental Investigation

3.1. Materials and Specimen Preparation

Forty-two concrete test specimens were cast in the form of lollipop samples. Each sample was 51 mm (2 in.) in diameter, 102 mm (4 in.) in height, and contained a single 12.7 mm (1/2 in.) diameter steel reinforcing bar. The reinforcement was cleaned of surface rust prior to casting, and secured such that it protruded from the top of the mold by 19 mm (3/4 in.) thus providing a uniform concrete cover of 19 mm (3/4 in.) at the sides and bottom. Portland Cement Association guidelines for the proportioning of normal concrete mixtures for small jobs were followed to establish the concrete mix design for this study [7]. Concrete mix proportions were 1:2.5:1.5:0.5 by volume of cement, wet fine aggregate, wet coarse aggregate, and water, respectively. The 28 day compressive strength was 11.5 Mpa (1670 psi).

The CFRP wraps consisted of a unidirectional carbon fabric (12,000 filaments per yarn, 4 yarns per cm width, ply thickness of 0.55 mm (0.022 in)) embedded in a thermoset epoxy. The fabric has a tensile strength of 3.1 GPa (450 ksi), modulus within 221-241 GPa (32-35 Msi), and an areal weight of approximately 340 g/m^2 (0.07 psf) according to manufacturer's literature [8]. Two different brands or types of epoxy were tested. Each of the two part systems incorporated a clear, pale amber, low-viscosity (approximately 1 $N{\cdot}s/m^2$ at 22°C) liquid epoxy resin combined with an aromatic hydrocarbon-blend curing agent.

The first epoxy, West System 105 (referred to henceforth as WS), is a marine grade epoxy designed specifically for reinforcing fabrics [9]. Product literature states that this epoxy offers excellent wet out and adhesion to fiberglass, carbon, and aramid fabrics. The resin is described as a Bisphenol A based epoxy resin, and the hardener is described as a modified aliphatic polyamine. This epoxy dries to a hard, clear finish and does not required a polyester gelcoat; however a clear coat of epoxy on the exterior surface is recommended.

The second epoxy, Sikagard 62 (referred to henceforth as SG), is a thick, gray epoxy designed for use as a high-build, corrosion-resistant, moisture-insensitive protective coating [10]. Product literature states that this epoxy may be applied to concrete or carbon laminates, and offers long-term protection from chlorides and water ingress. The resin is described as a modified epoxy resin of the epichlorohydrin Bisphenol A type containing suitable viscosity control agents. The hardener is described as a proprietary blend of aliphatic and cyclic amines, containing suitable viscosity control agents, pigments, and accelerators.

The CFRP wraps were applied to samples with a hand lay-up procedure. An initial coat of epoxy was applied to the bottom and sides of the samples, followed by the application of successive wetted fabric layers, then followed by a final clear coat of epoxy. Samples were cured at room temperature for 24 hours between layer applications, and for 28 days before testing. Samples were grouped into 13 categories, each receiving a different type of surface treatment as shown in Table 1. Surface coating options fell into three main classifications: control samples that were untreated, those that were only coated with epoxy, and finally those that were wrapped with CFRP composite wraps.

Table 1. Sample Designations and Surface Treatment Options

Category/ Designation	Number of Samples	Number of CFRP Wrap Layers	Epoxy	CFRP Wrap Fiber Strong Axis Alignment
CTRL	3	0	None	None
WS0E	3	0	West System	None
WS1A	3	1	West System	Axial-90°
WS1R	3	1	West System	Radial-0°
WS2R	3	2	West System	Radial-0°
WS3R	3	3	West System	Radial-0°
WS2B	3	2	West System	Bias-±45°
SG0E	3	0	Sikagard	None
SG1A	3	1	Sikagard	Axial-90°
SG1R	3	1	Sikagard	Radial-0°
SG2R	3	2	Sikagard	Radial-0°
SG3R	3	3	Sikagard	Radial-0°
SG2B	3	2	Sikagard	Bias-±45°

3.2. Exposure Conditions

Specimens were placed in a tank and partially immersed in a 5% NaCl by weight solution, approximately double that of typical seawater, at a room temperature of approximately 24°C (75°F). Figure 1 shows a schematic of the test configuration, with samples connected to a 12-volt DC power supply, thus impressing a current such that the reinforcing bars are anodic. The high salinity and the impressed current were both used to create an especially aggressive environment by providing an abundance of chloride ions and by stimulating an increased flow of electrons, respectively.

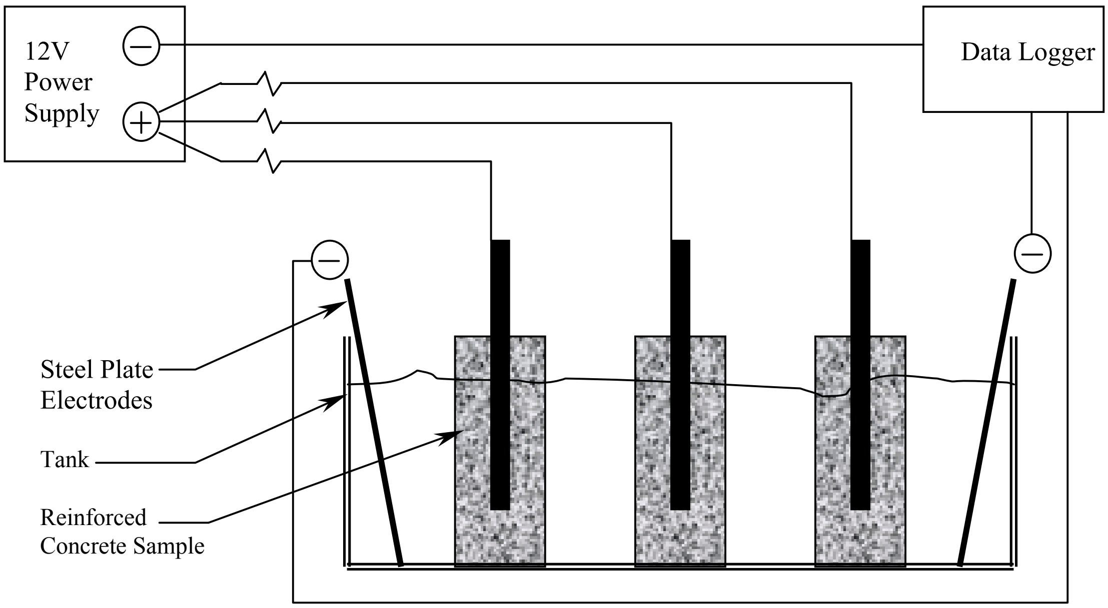

Figure 1. Test Configuration Schematic

3.3. Corrosion Monitoring and Testing

3.3.1. Current Measurements

The current flow was measured regularly to monitor the impressed current. Twice a day, approximately every 12 hours, impressed current measurements were taken with an ammeter in each of the parallel electrical circuits. Due to the potential hazard posed to the electrical circuitry from excessive current flow, a current reading in excess of 320 mV was designated as a type of sample failure, and subsequently the sample was disconnected. A current spike or rapid increase in current flow was typically caused by a short circuit and indicated that enough cracks had formed in a sample that failure was imminent.

3.3.2. Sample Failure and Rebar Mass Loss

Samples were visually inspected for cracks daily and removed from the tank when the concrete cracked, the wrap failed, and/or the current flow in the reinforcement spiked. The type of failure and number of days to failure were recorded. The reinforcing bar was extracted from the concrete and placed in a 10% solution of muriatic acid for a week. Following the cleaning, the bars were weighed to the nearest 0.01 gram. The extent and distribution of localized corrosion were recorded.

4. Results and Discussion

4.1. Theoretical Mass Loss

Corrosion is an electrochemical process whereby the amount of corrosion is related to the electrical energy consumed, which is a function of voltage, amperage, and time interval. The amount of corrosion can be estimated using an equation based on Faraday's Law as follows:

$$\Delta m_{theoretical} = \frac{t \cdot i \cdot M}{z \cdot F}$$

where: t = time (*sec*)

i = current (*Amperes*)

M = atomic weight of iron (*55.847 g/mol*)

z = ion charge (*assumed 2 for* $Fe \rightarrow Fe^{2+} + 2e^{-}$)

F = Faraday's constant (*96,487* $Amp \cdot sec$).

The amount of steel consumed over time was approximated using the experimental values of the recorded current flow (average) within a known time interval. In a similar manner Debaiky et al. used Faraday's Equation to accurately estimate mass loss in CFRP wrapped samples subject to an impressed current [5].

4.2. Comparison of Theoretical and Actual Corrosion Mass Loss

The cumulative theoretical mass loss was compared to the actual mass loss for each sample. Figure 2 plots the actual versus theoretical mass loss for all samples in the study; each point represents the total mass loss for a single sample. The solid black line was calculated using a linear regression analysis. When current is passed through a bare steel bar exposed to water, chlorides, and oxygen, the correlation between actual and predicted mass loss should theoretically be equal to 1. However, once the steel bars are embedded in concrete that is wrapped with CFRP, this correlation changes, as shown in Figure 2.

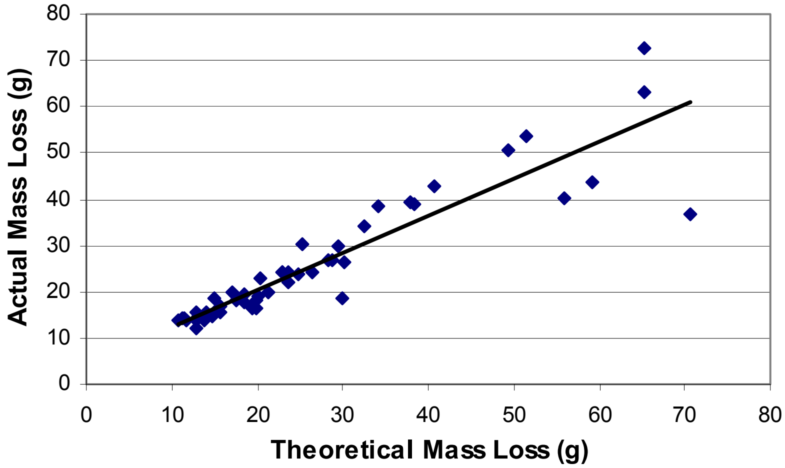

Figure 2. Total Mass Loss – Theoretical vs. Actual

The best-fit relationship for the given data is:

$$\text{actual percent mass loss} = 0.80 \text{ theoretical percent mass loss} + 4.41 \quad (1)$$

Most of the data points fit this trend quite well: the R^2 value for this trendline is 0.837.

Possible factors that may have lead to a difference between the actual and theoretical mass loss values are:

- Composition of the bar: It is assumed that the bar is made of pure iron;
- Faraday's law is based on the original cross-section, so more error is expected as the cross-section diminishes;
- A certain amount of energy is needed to initiate corrosion in steel bars embedded in concrete as reasoned by Auyenung et. al. [11];
- Natural corrosion may have occurred while samples were disconnected from the impressed current circuitry (samples were disconnected from the circuit for approximately 2 to 2-1/2 hours a day for maintenance and testing, and samples that failed early were removed from the tank but were not cleaned and weighed until the end of the test);
- The muriatic acid used to clean the bars might have resulted in a small additional mass loss.

The integrity of the concrete in the sample also appears to play a role in the magnitude of the actual corrosion, and thus in the percent error between actual and theoretical values. This can be seen in Figure 3, which shows the percent error between the cumulative actual and theoretical mass loss, grouped by treatment style for each of the samples. It is expected that concrete that is sound and not deteriorated will undergo less corrosion than predicted. In Figure 3 it can be seen that, on average, samples with 2 or more CFRP wraps generally have negative percent errors. The negative value means that theoretical mass loss is greater than the actual mass loss (less corrosion than predicted). This implies that some of the current did not contribute to corrosion and may have been consumed while passing through the concrete and wrap. Conversely, concrete that is deteriorated from corrosion damage will have cracks and decreased resistance resulting in corrosion that is closer to predicted levels.

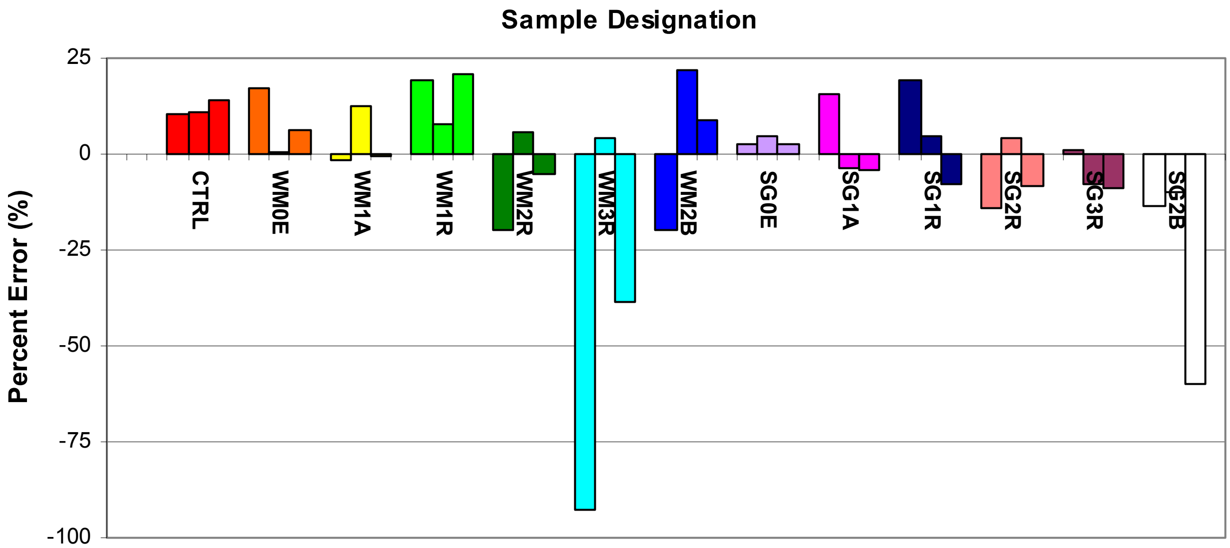

Figure 3. Percent Error – Theoretical vs. Actual Mass Loss

In both Figure 2 and Figure 3, it is apparent that, while most samples have relatively good correlation between actual and theoretical mass loss, with low percent errors, three samples have a much higher percent error. Although no specific experimental cause could be identified for the high rate of error in these samples, it is worth noting that all three are wrapped samples that exhibited less corrosion than predicted. However, because the error in these samples was so extreme, they were examined specifically for fit. Using a technique identified by Vining, these three values were identified as outliers [12]. When the three samples were removed from the data set, the best-fit relationship for the remaining data becomes:

$$\text{actual mass loss} = 1.02 \text{ theoretical mass loss} + 0.10 \tag{2}$$

This trendline matches the ideal case almost perfectly. In addition, the R^2 value is 0.97, much higher than the previous trendline.

In this study, the theoretical mass loss values based on Faraday's law correlate well to actual recorded mass loss values, regardless of sample style. This indicates that neither the wraps (number of layers and layer orientation) nor the epoxy (type and thickness) has a significant effect on the validity of the theoretical predictions. In addition, because of the strong correlation, the theoretical mass loss values can be used to examine the corrosion behavior of the samples over time.

4.3. Accumulative Theoretical Corrosion Mass Loss Over Time

Theoretical mass loss predictions were used to examine accumulative mass loss over time, as shown in Figures 4 through 7. Mass loss predictions were averaged for samples of the same style. Failure of all the samples of a particular style led to a horizontal leveling. This is apparent in the graphs due to the lack of any further mass loss accumulation from impressed current. The generally accepted corrosion process model for steel in concrete is exponential in nature. After active corrosion has been initiated, corrosion rates accelerate once the concrete cover has deteriorated due to larger volume of the corrosion byproducts [13]. Control samples and WS epoxy wrapped samples follow this trend; however, SG epoxy wrapped samples behave more in a linear fashion with more constant rates of corrosion.

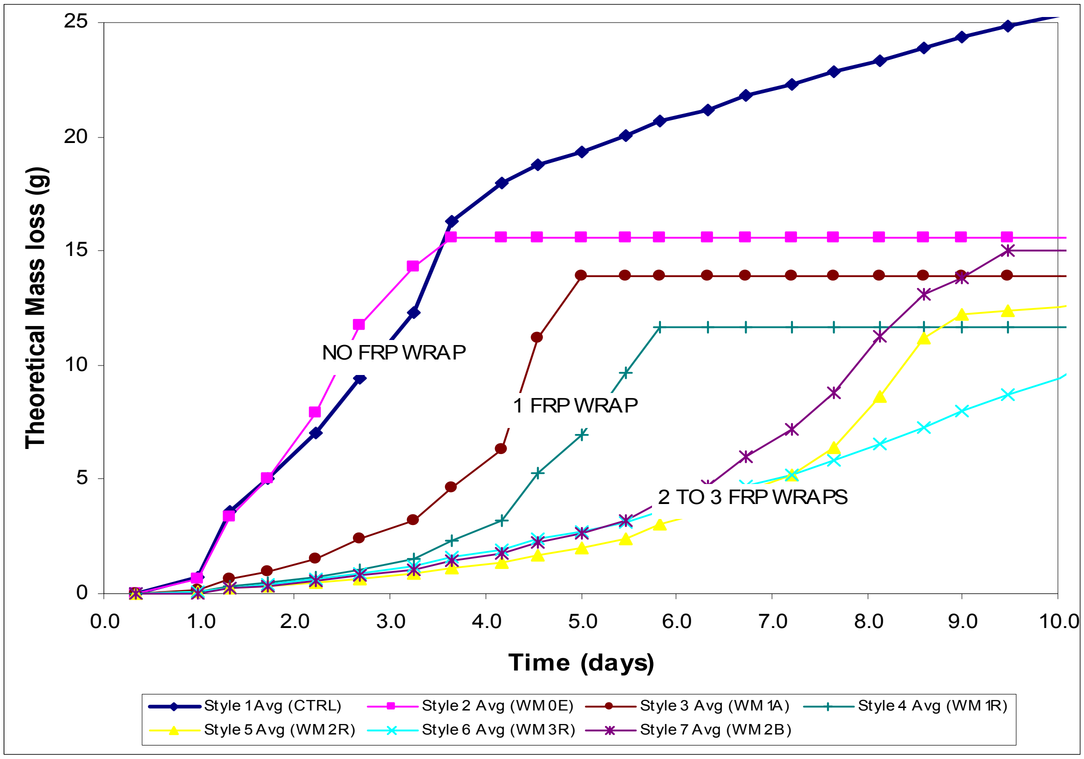

Figure 4. Mass Loss Averages vs. Time – WM Epoxy (10 Days)

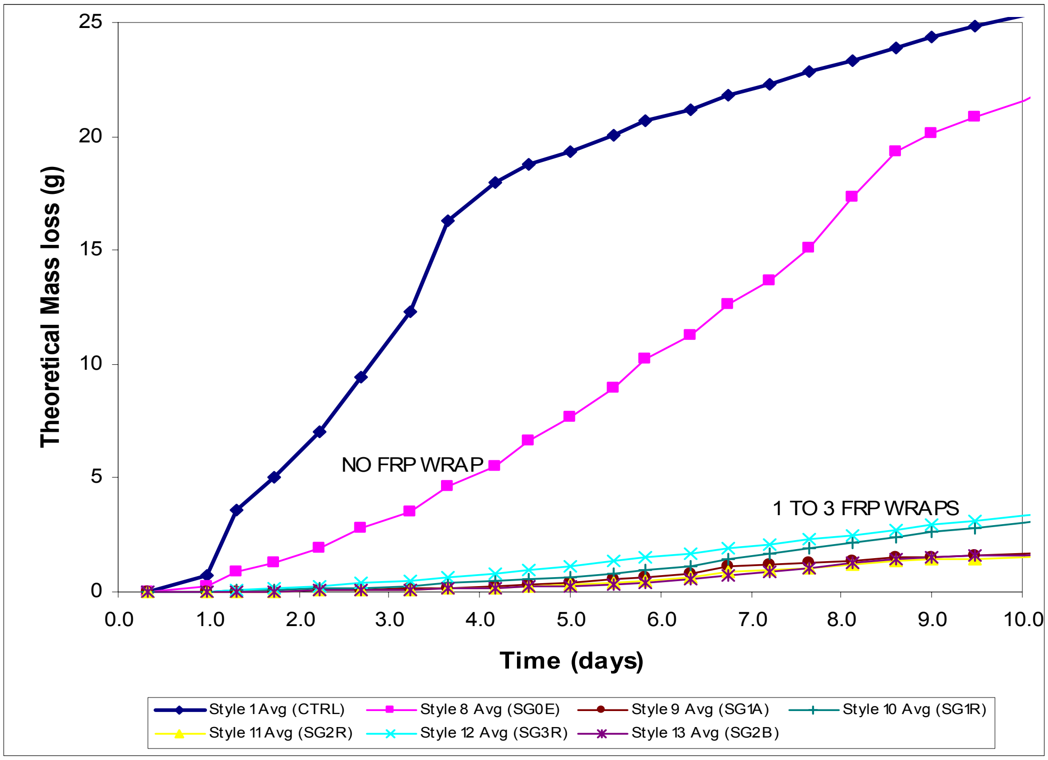

Figure 5. Mass Loss Averages vs. Time – SG Epoxy (10 Days)

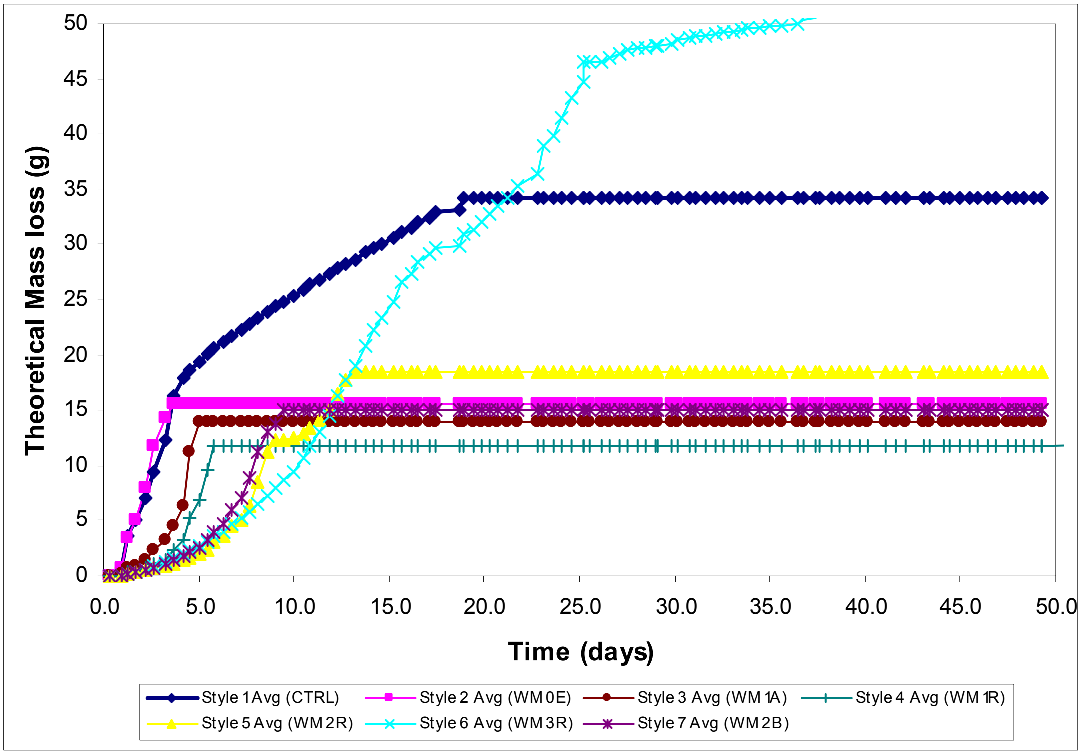

Figure 6. Mass Loss Averages vs. Time – WM Epoxy (50 Days)

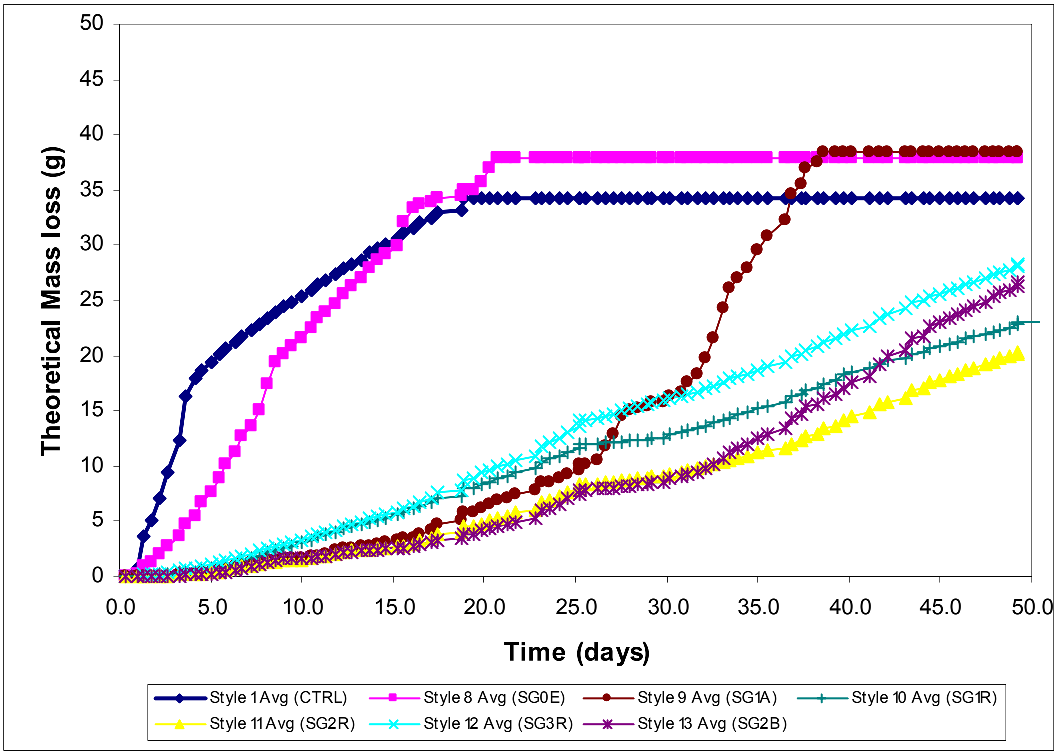

Figure 7. Mass Loss Averages vs. Time – SG Epoxy (50 Days)

Figures 6 and 7 show the accumulative mass loss for the entire interval of sample exposure. A comparison of these two graphs clearly reveals that the SG epoxy was more effective at delaying the onset and rate of corrosion than the WS epoxy. The slope of the curves, which is rate of corrosion, is lower for all wrapped SG samples than all other samples. In Figure 7 the two curves that exhibit high rates of corrosion are the control samples and those that have only an epoxy coating. It took around 4 to 8 times longer for the samples using SG epoxy to have the same level of corrosion (10 to 15 grams) as the samples using the WG epoxy. It is also apparent that the SG samples had longer test lives.

Figures 4 and 5 provide additional detail showing the first 10 days of sample exposure. In Figure 4 the effect of the number of wrap layers is distinguishable. An increase in the number of wraps decreases the onset of corrosion, as evidenced by the shifts apparent in the graph. Additionally, an increase in the number of wrap layers also decreases the rate of corrosion. The better performance of samples with more wraps is thought to be attributed to both the higher radial confinement provided by the greater number of CFRP layers and the increased ability to inhibit the passage of chlorides. Radial confinement of the concrete by the wraps would slow deterioration from cracking and spalling, thereby explaining the lower corrosion rates.

Figure 5 shows that the SG epoxy coating alone does not have a significant effect on delaying the onset of corrosion, or reducing the total amount of mass loss, nonetheless it does somewhat slow the rate of corrosion in the early stages. However, Figure 5 does clearly show that the effect of CFRP wraps on lowering the rate of corrosion is considerable and easy to identify. Unlike the WG samples, there is not a distinction between the performance of more than one wrap layer. It is probable that, in conjunction with the SG epoxy, even a single CFRP layer was enough to inhibit the passage of salt water, protect the concrete from deterioration and slow the overall corrosion rate.

5. Conclusions

A comparison of the accumulative theoretical corrosion mass loss over time was performed for control samples and those using one of two different types of epoxies. Based on the results reported in this paper and the observations made during the experimental investigation, the following conclusions can be drawn:

- It is possible to induce accelerated corrosion on reinforcing bars imbedded in concrete wrapped with CFRP wraps using an impressed current;
- For samples with CFRP wraps, the theoretical mass loss based on Faraday's Law correlates reasonably well to actual mass loss measured. Although the concrete and other factors may affect the theoretical predictions the calculated mass loss can be used to examine mass loss over time;
- CFRP wrapping reduces the rate and onset of corrosion;
- Epoxy type has a significant effect on the corrosion resistance of the CFRP wrapped samples. One type of epoxy used for CFRP wraps (SG) was significantly more effective at delaying both the onset and rate of corrosion than another (WS).

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