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Corrosion process and abatement in reinforced concrete wrapped by fiber reinforced polymer

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The corrosion performance of steel reinforcement embedded in concrete samples encased by carbon fiber reinforced polymer (CFRP) wraps was investigated experimentally. Concrete samples were wrapped with 0–3 fabric layers impregnated with one of two different epoxies. To accelerate corrosion, samples were subjected to an impressed current and a high salinity solution. Current flow measurements dynamically monitored corrosion activity during exposure, while reinforcement mass losses were measured following exposure. Theoretical predictions of total mass loss were compared with actual corrosion mass loss values. Test results indicated that CFRP wrapped specimens had prolonged test life, decreased reinforcement mass loss, and lower corrosion rates. The performance of wrapped specimens was superior to that of either control samples or those coated only with epoxy. Results indicated that the level of corrosion abatement provided by the CFRP wraps was influenced both by the type of epoxy used and the number of wrap layers.

1. Introduction

The use of carbon fiber reinforced polymer (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 was experimentally investigated. Additionally, the effects of number of wrap layers and the type of impregnating epoxy were considered. According to the American Concrete Institute, composites are particularly suitable for rehabilitating structures because they are lightweight, corrosion-resistant, customizable, and have high tensile strength [1]. The application of CFRP materials specifically to protect reinforced concrete structures from corrosion, specifically bridge foundations (i.e. piers and piles) exposed to harsh chloride environments, has not been widely studied, nor has the effect of different impregnating systems.

2. Background

2.1. Related research

The corrosion of steel in a concrete environment is an electrochemical process requiring an anode, a cathode, an electrolyte, and a contact between the anode and cathode. Ions present in salt water that leach into concrete can provide a means for active reinforcement corrosion. Normally, concrete cover provides both chemical and physical barriers to corrosion of embedded reinforcing steel. Fig. 1 shows a model for the natural corrosion process of steel encased by concrete adapted from Bentur et al. [2]. In this natural corrosion model, the initiation stage describes the time period required for the conditions for steel depassivation to occur; that is, the time where aggressive agents, such as chloride ions, migrate through the concrete to the surface of the steel and buildup sufficient concentration to breakdown the steel passivation layer. The corrosion rates at the propagation stage, or stage where active corrosion has already initiated, are shown to accelerate significantly once the concrete cover has cracked. Depending on their composition and degree of hydration, the products of the corrosion of iron can take up a volume as much as six times that of the original iron [3]. 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, particularly during the later stage of corrosion propagation.

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 [4]. A study to evaluate steel reinforcement

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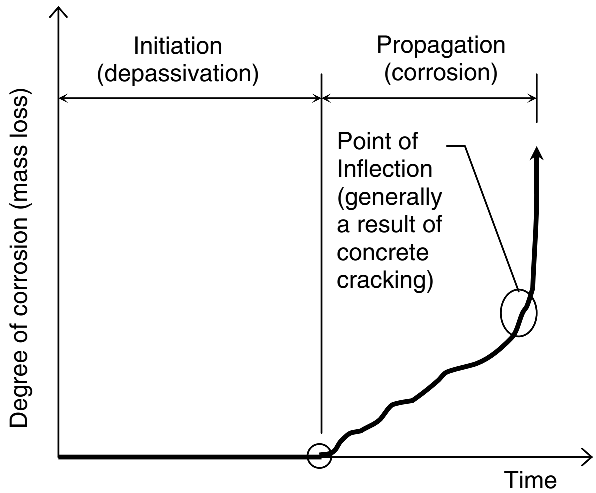

Fig. 1. Corrosion process model for steel in concrete.

corrosion and the properties of concrete specimens coated with waterproofing coatings concluded that the water absorption capacity was a simple physical property that could be considered to predict the protection performance of coating systems against corrosion [5].

Research by Debaiky et al. [6–8] 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. It was found that increasing the number of CFRP layers did not significantly enhance the protection. The research concluded that the CFRP wraps applied over corrosion-damaged reinforced concrete columns will decrease the corrosion rate of the reinforcement and restore the structural integrity of the column. A combination of electrochemical chloride extraction and wrapping was found to provide the best protection against future corrosion.

Researchers at the University of Toronto and colleagues conducted several studies into the behavior of reinforced concrete columns wrapped with CFRP and GFRP sheets before and after being subjected accelerated corrosion [9,10]. In one study, large-scale circular concrete columns were subjected to an accelerated corrosion regime then repaired using CFRP sheets [9]. In that study, the repairs were shown to greatly improve the strength and ductility of repaired corroded members and reduced the rate of post-repair corrosion. Moreover, subjecting the repaired column to extensive, post-repair corrosion resulted in no loss of strength or stiffness and only a slight reduction in the ductility of the repaired member. In a second study, GFRP wraps were used in combination with grouting the voids between the jacket and the original surface of the specimen [10]. Different types of diffusion barriers were used to protect the GFRP wraps from exposure to alkali activity of the fresh grout, and to reduce the supply of oxygen and water to the mechanism of corrosion. Increasing the number of GFRP layers and providing sufficient wrap anchorage was found to improve performance, while prestressing with expansive grouts compromised performance.

Suh et al. [11] examined the effect of CFRP and GFRP wraps on scale model prestressed piles exposed to simulated tidal cycles for nearly three years. This study also showed that corrosion rates decreased in wrapped specimens and while increasing in control specimens. Metal losses were also much lower in wrapped specimens compared with controls. The results showed that the FRP-concrete bond was largely unaffected by exposure and both CFRP and GFRP-repaired specimens significantly outperformed the controls.

2.2. Theory

The objective of this research is to investigate the effect of various configurations of CFRP wraps and two-part epoxies on the corrosion-induced mass loss of steel rebar in reinforced concrete. One experimental technique to expedite reinforcing bar corrosion in concrete samples uses exposure to aggressive conditions while forcing corrosion activity through galvanostatic corrosion. In this technique, direct current is impressed into the steel reinforcement so that it becomes the anode while an auxiliary element serves as a cathode. When a constant voltage is maintained between the anode and cathode, the current level is proportional to the speed of the corrosion process. An accurate representation of the corrosion current activity and speed of corrosion acceleration is the corrosion current density i_{corr}, expressed as current divided by the total surface area of the polarized steel ($\mu A/cm^2$). 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 Eq. (1) which is based on Faraday's Law.

$$\Delta m_{\text{theoretical}} = \frac{t \cdot i \cdot M}{z \cdot F}, \tag{1}$$

where t is the time (s), i the current (A), M the atomic weight of iron (55.847 g/mol), z the ion charge (assumed 2 for $Fe \rightarrow Fe^{2+} + 2e^-$) and F the Faraday's constant (96,487 A s).

This technique was successfully used by researchers studying the bond behavior of corroded reinforcing bars in concrete samples who found that when current was passed through a bar suspended in salt solution the correlation between actual and predicted mass loss was almost perfect [12]. Furthermore, they found that when a bar was embedded in concrete, mass loss based on Faraday's law overestimated the actual mass loss, but that, by passing external current, it is still possible to induce predetermined accelerated corrosion. In a similar manner, Debaiky et al. [7] used Faraday's equation to accurately estimate mass loss in CFRP wrapped reinforced concrete samples subject to an impressed current.

3. Experimental program

3.1. Materials

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 [13]. 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 24.5 MPa (3560 psi), which is within the anticipated range of 20.7–34.4 MPa (3000–5000 psi) for the mix design. The CFRP wraps consisted of a unidirectional carbon fabric (12,000 filaments/yarn, 4 yarns/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 [14]. Two different brands or types of epoxy were tested. Each of the two-part systems incorporated a clear, pale amber, low-viscosity (approximately 1 $N s/m^2$ at 22 °C, according to manufacturer's data) liquid epoxy resin combined with an aromatic hydrocarbon-blend curing agent. The two epoxies were selected because of their adherence to concrete and carbon fibers and because of their resistance to moisture.

The first epoxy, West System 105 (referred to henceforth as WS), is a marine grade epoxy designed specifically for reinforcing fabrics [15]. 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