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Theoretical and experimental study of microcell and macrocell corrosion in patch repairs of concrete structures

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Abstract

Patch repair is commonly used to rectify localized corrosion induced damage in concrete structures. However, inadequate durability in patch repair systems caused by new corrosion attack is prevalent. From the prevailing understanding, the mechanism is attributed to macrocell corrosion formed between repaired area (called patch) and its adjacent unrepaired area (called substrate), and thereby ensuring electrochemical compatibility between the two areas is deemed to be the key element to reduce the corrosion risk and thus to achieve a successful repair. This paper examined the corrosion mechanism and the concept of compatibility in patch repair systems from fundamental electrochemical principles and experimental verification. It was illustrated that both macrocell and microcell corrosion mechanisms could play significant roles, and the total corrosion could be underestimated if the latter is overlooked. Although the incompatibility serves as the driving force for the macrocell corrosion, in light of corrosion kinetics, it was shown that the corrosion magnitude depends more on the individual corrosion kinetics of the anode or cathode.

Keywords: Patch repair; Corrosion; Macrocell; Microcell; Corrosion kinetics

1. Introduction

Corrosion of the reinforcing steel is a major deterioration problem of concrete structures. Corrosion prevention and repair of concrete structures will continue to be an important strategy for the rehabilitation of corrosion-damaged structures. Patch repair is a commonly used method in concrete structures, especially on highway bridge decks, for rectifying localized damage in concrete induced by corrosion of the reinforcing steel. The repair process entails removal of loose concrete that has cracked, spalled, or delaminated, often by surface treatment of the steel reinforcement and the old concrete, then replacing the defective concrete with patching materials. From an electrochemical viewpoint, a patch repair is designed to remove the anodic reaction on the reinforcing steel that existed before the repair and to prevent it from recurring by making it a passive area. The change of corrosion state in the repaired area, however, brings about new corrosion risk in the surrounding areas because they are often in electrical contact. Many patch repairs and their surrounding areas have exhibited new corrosion damage after a few months to a year.

In patch repair systems, the repaired area (called patch) and the adjacent unrepaired areas (called substrate) provide the embedded steel bars with dissimilar electrochemical environments. The protective high pH of sound concrete, such as in a newly repaired area, normally passivates the embedded reinforcing steel. If the concrete is contaminated by chlorides and/or becomes carbonated, such as in the substrate, active corrosion can initiate in the reinforcing steel. When the active steel and passive steel are put into electrical contact, macrocell corrosion can form between them, in which the former is polarized anodically and the latter polarized cathodically. In patch repair systems, active corrosion damage often occurs in the substrate or at the interface, known as incipient corrosion or ring-anode effect, because concrete

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in the substrate is normally more corrosive than in the patch. It was found that the patch repair induces or enhances the active corrosion in the substrate if its chloride content is above a threshold level and sufficient moisture is present [1,2] as supported by many experimental detections of the macrocell corrosion formed between them [1–5]. This has led to the prevailing understanding that the main corrosion mechanism in patch repair is the macrocell corrosion.

The total dissolution of the steel in the active area however, is determined by both the macrocell and microcell corrosion currents that might coexist. The role of microcell corrosion has not been fully addressed in patch repair systems. The microcell corrosion could also be induced in the substrate by the patch repair. For example, the damaged area, before the repair, was more corrosive to the steel than its surrounding substrate and served as an anodic site, with the steel in the adjacent substrate thus being cathodically protected. The repair would therefore remove the corrosive environment and consequently, the cathodic protection on the steel in the substrate. As a result, the microcell corrosion could occur spontaneously in the substrate, especially if its chloride content is higher than the threshold level [5,6]. Some limited data have enabled a comparison of the magnitude of microcell and macrocell corrosion activities. Li and Yuan [2] showed that steel bars in the substrate near the repair interface would lead to corrosion exacerbation and the influenced area increased with the increase of the repaired region. Their results conformed to the theoretical illustration that a newly induced macrocell might not necessarily surpass the existing microcell corrosion if a cathodic area is not much larger than the anodic area [7]. Note that the technique to measure macrocell corrosion cannot measure microcell corrosion, and as a result, the contribution of the latter is easily overlooked and the real degree of total corrosion could be seriously underestimated. Thus, it is essential to identify the underlying mechanism and distinguish the degree of participation of both types of corrosion as to whether the induced corrosion in the patch repair system is mainly due to macrocell or microcell corrosion or both.

Another prevailing understanding is that the compatibility of patching materials with substrate is the most critical factor for a successful patch repair [8–10], because the incompatible properties between the patch and substrate leads to an electrochemical potential difference that serves as the driving force for the formation of macrocell corrosion [11]. The incompatibility can arise from physical properties (e.g. porosity), chemical compositions and electrochemical properties. Therefore a significant incompatibility between patch and substrate will result in a larger driving force for the macrocell corrosion to occur. A larger driving force, however, does not necessarily mean a higher rate of corrosion, because the behavior of the individual active area or passive area in terms of their reaction rates often outweighs the thermodynamic driving force in determining the rate of corrosion [12]. Some experiments also showed that a seemingly "incompatible" repair, in which stainless steel was used to replace the carbon steel in the damaged area, brought about low macrocell corrosion with the carbon steel in the substrate [13–15]. This implies that the key factors affecting the characteristics of macrocell corrosion itself are not well understood and the concept of compatibility needs further examination with regards to corrosion kinetics, in addition to the thermodynamic driving force.

This paper presents a theoretical examination of the prevailing understanding of the corrosion mechanisms and their causes in patch repair systems, as well as an experimental demonstration to validate the suggested mechanisms. This study will attempt to clarify fundamental mechanism of the corrosion in concrete patch repair and enhance the current understanding of the importance of the microcell corrosion and its relation to the macrocell corrosion.

2. Theoretical consideration

2.1. Microcell corrosion

The corrosion of steel in concrete is an electrochemical process involving the transfer of electrons from one chemical species to another. Microcell corrosion refers to a corrosion process in which the mechanism is within a microscopic scale. The reactions involving consumption of metal and release of electrons are anodic reactions:

$$\mathrm{Fe} \rightarrow \mathrm{Fe}^{2+} + 2\mathrm{e}^- \qquad (1)$$

The Fe^{2+} ions react with OH^- to form ferrous hydroxide [$\mathrm{Fe(OH)_2}$]:

$$\mathrm{Fe}^{2+} + 2\mathrm{OH}^- \rightarrow \mathrm{Fe(OH)_2} \qquad (2)$$

The $\mathrm{Fe(OH)_2}$ commonly reacts further with oxygen to form various oxide species such as hydrated ferric oxide ($\mathrm{Fe_2O_3 \cdot H_2O}$) and hydrated magnetite ($\mathrm{Fe_3O_4 \cdot H_2O}$), depending on pH and availability of oxygen:

$$4\mathrm{Fe(OH)_2} + \mathrm{O_2} \rightarrow 2\mathrm{Fe_2O_3} \cdot \mathrm{H_2O} + 2\mathrm{H_2O} \qquad (3)$$

$$6\mathrm{Fe(OH)_2} + \mathrm{O_2} \rightarrow 2\mathrm{Fe_3O_4} \cdot \mathrm{H_2O} + 4\mathrm{H_2O} \qquad (4)$$

As a contrary, reactions involving consumption of electrons and dissolved chemical species are referred to as cathodic reactions, which most likely incorporate the following steps depending on the availability of oxygen, pH of the solution, and electrochemical potential:

$$2\mathrm{H_2O} + \mathrm{O_2} + 4\mathrm{e}^- \rightarrow 4\mathrm{OH}^- \qquad (5)$$

$$2\mathrm{H_2O} + 2\mathrm{e}^- \rightarrow 2\mathrm{OH}^- + \mathrm{H_2} \qquad (6)$$

In concrete, oxygen is usually able to penetrate through the pores and micro-cracks into the steel surface and the overpotential for oxygen reduction reaction (Eq. (5)) is low, thereby making this reaction the prevailing cathodic reaction. As the corrosion process becomes stable, the anodic oxidation and the cathodic reduction reactions will reach