Performance of Concrete Patch Repairs: From a Durability Point of View

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ABSTRACT

Chloride contamination in reinforced concrete leads to the corrosion of steel bars. Concrete patch repairs are widely practiced as a remedial measure for the mitigation of such corrosion in reinforced concrete structures. The performance of the patch repairs was studied by various researchers in the past. The structural and material aspects of patch repairs have received more attention than the electrochemical consequences of patch repairs in past studies. But electrochemical changes could be the underlying cause for the failure of many patch repairs. This paper reviews the performance of patch repairs from a durability point of view. It covers the formation of incipient anodes, which are the new corrosion sites formed after a patch repair process. The prevailing corrosion mechanism at the incipient anodes is discussed. The performance of patch repairs when modified with corrosion inhibitors and sacrificial anodes is examined. The importance of the selection of repair materials from a durability point is highlighted considering the electrochemical consequences of patch repair.

1. INTRODUCTION

Patch repair is the most popular repair technique for reinforced concrete members that are affected with chloride-induced corrosion. It involves the removal of loose chloride contaminated concrete, cleaning of the steel bar, and filling the area with a patch repairing material. The generic repairing materials in use are cement-based materials, polymer-modified mortars, and resinous materials (Al-Dulaijan et al., 2002). In chloride-contaminated-reinforced concrete, reinforcement in the chloride-affected region loses its passivity and behaves as an anode, whereas the remaining portion of the steel bar enjoys passivity from the cathodic protection offered by the electrically connected anodic area. In the event of a patch repair, electrochemical conditions around the steel bar change. The previously corroding area is cleaned and exposed to fresh alkaline patch repair material, but the rest of the steel bar remains in the same substrate concrete and loses its previous cathodic protection. Repair materials differ from the substrate concrete in terms of chloride content, oxygen availability, and permeability properties. Depending on the chloride content present, steel in the substrate concrete can form new corrosion sites. These newly formed anodic sites are known as incipient anodes. Incipient anode formation is found to be the reason for the failure of many patch repairs (Pruckner & Gjørv, 2002). There is a difference in opinion about the location of incipient anodes and the underlying corrosion

mechanism. To overcome the problem of incipient anodes, conventional patch repairs were modified with the application of different corrosion inhibitors and sacrificial anodes (Castro, Pazini, Andrade, & Alonso, 2003; Glass, Davison, & Roberts, 2010). The transportation of chloride ions from the substrate concrete to the repair materials can also cause the initiation of new corrosion sites. Also, the penetration of chloride ions through the repair–concrete interface can influence the corrosion mechanism in a patch repair. There is general agreement among researchers that patch repairs do not increase the corrosion risk that is otherwise expected in a corroded reinforced concrete structure. The review of literature was focused on the following areas:

I. Incipient anode formation;

II. Corrosion mechanism at the incipient anodes;

III. Selection of repair materials;

IV. Chloride transport through a patch repair.

Failure of the patch repair can be due to one of the many reasons. Incorrect diagnosis of the underlying reason leads to the persistence of the problem even after repair. Proper diagnosis is necessary to avoid such an issue. The design of the repair should be based on the exposure conditions and loading consideration. Incorrect design will lead to short lived repairs. The selection of repair materials should be on a case-specific basis. A common repair material may not be the ideal choice

in different repair situations. The entire repair process should be done with the utmost care, including the surface preparation, cleaning of the steel bars, and the application of the repair mortar (Lukovi et al., 2006). This paper reviews the key factors affecting the durability of concrete patch repairs.

2. INCIPIENT ANODE FORMATION

Incipient anode formation is generally explained using the two events that take place after a patch repair. First, macrocell corrosion formation within the repaired structure due to the electrochemical potential difference created between the repair material and substrate concrete. The repaired part will be different from the substrate concrete in terms of the chloride content, permeability properties, and the electrical resistivity. This creates two different environments around the steel bar in the repair and substrate concrete. The part of the steel bar with least electrochemical potential will serve as the anode, while the part with higher electrochemical potential acts as the cathode. Electron transfer takes place between these locations, resulting in the formation of macrocells. These resulting corrosion sites are called as incipient anodes. Second, chloride ion transport takes place from the substrate concrete to the repair and on through the repair–substrate interface. Movement of chloride ions can depassivate the new steel bar areas. This could act as new anodes. Also, the penetration of chlorides through the interface creates new corrosion sites at the interface. Hence, the new corrosion sites after a repair could be formed in any one of the following three areas: on the substrate concrete, on the substrate–repair interface and within the repair itself (Barkey, 2005; Mailvaganam & Zhang, 2006; Soleimani, Ghods, Isgor, & Zhang, 2010).

There are differences in opinion about the location of incipient anode among different researchers. Incipient anodes are formed at the intersection of repair and substrate concrete and the majority of the cathodic sites are situated in the repair material with few in the concrete substrate. However, another study has reported that incipient anode formation is identified in the substrate concrete. The location of an incipient anode could be in the 2–5 cm range near the interface. Anodic current density is found to have a peak near the repaired concrete and asymptotically approaches to the corrosion density observed in the substrate before patch repair. It is interesting to note that both researchers adopted different kinds of specimen geometry for their experimental studies (Barkey, 2005; Zhang & Mailvaganam, 2006). The macrocell current generated at the incipient anode location is ohmic controlled; the existing potential gradient accelerates

the transport of chemical species. It can be either chlorides or a corrosion inhibitor. The interface between the repair and original concrete remains passive due to the transport of chlorides away from the interface against the macrocell potential gradient that exists. This provides an opportunity to engineer-durable patch repairs for better performance.

Incipient anode formation can also be explained related to the chloride ion transport in a repaired member. Macrocell activity may not be the only reason for the development of incipient anodes but also can be the interface features at the substrate–repair boundary, existing chloride in the parent concrete, and the vibration effects created during the repair process. The potential gradient between steel in the repaired parts to steel bars in the parent concrete is not very high. Both possess similar potential values. This shows that the residual chloride content present in the parent concrete can alone form further corrosion sites, macrocell formation phenomena is not necessary. Normally, the permeability of repair materials is very low, but parent concrete is more permeable to the attack of chlorides; more chlorides are present at the interface that also contributes to the corrosion initiation (Christodoulou, Goodier, Austin, Webb, & Glass, 2013).

Concrete resistivity is another major factor that influences the magnitude of macrocell corrosion, followed by the availability of the oxygen in the patch. Electrical resistivity of the electrolyte is an important parameter that decides the magnitude of the corrosion current at the incipient anode. The total corrosion current in the repaired member decreases as the patch resistivity increases. Hence, a repair material with higher resistivity than that of the substrate is a better repair strategy. A patch with high resistivity diminishes the incipient anode effect. But if the quality of the repair and the substrate considerably differs, then there is a chance for the mechanical incompatibility between the two. If the resistivity of the substrate is low, the incipient anode effect will be predominant irrespective of the patch quality. Substrate concrete with low resistivity experiences the most significant incipient anode effect, regardless the resistivity of the patch used cover thickness and the size of the patch does not significantly affect the incipient anode formation, since it is a localised phenomenon. It was expected that the limiting oxygen concentration will result in lower microcell and macrocell current. But incipient anode effect was present at low oxygen concentrations also (Soleimani et al., 2010). Researchers agree that the incipient anode formation appears in the patch repairs as a cause for its failure, but there is no unanimous opinion about the locations of its appearance and the factors that trigger its formation.

3.   CORROSION MECHANISM AT PATCH REPAIRS

Macrocell corrosion and microcell corrosion are the two different corrosion mechanisms that are found at any corrosion site. The distance between the anode and cathode locations, their respective surface areas, and the electrochemical environment around it are the factors deciding the type of corrosion. In a uniform corroding environment, microcell corrosion is expected in the steel bars. In case of patch repair, steel bars are subjected to a non-uniform environment; hence, microcell corrosion is not examined in most of the previous studies conducted in concrete patch repairs. Before patch repair, steel bar in the concrete is actively undergoing microcell corrosion. During patch repair, fresh alkaline repair material provides passivity to the area of steel bar present in the repair, but the rest of the steel bar in the adjacent chloride contaminated concrete continues to undergo microcell corrosion. Also, macrocell corrosion can additionally develop due to the electrochemical potential difference that arises between the repair material and substrate concrete (Soleimani et al., 2010). Both of the above corrosion mechanisms could play an important role in the failure of patch repairs. Also, there are chances for the coexistence of both the corrosion mechanisms (Zhang & Mailvaganam, 2006). Macrocell and microcell corrosion in concrete is schematically represented in Figure 1. Anodic (A) and cathodic (C) locations are closely situated in a microcell corrosion scenario, whereas they are located at a large distance apart in a macrocell corrosion scenario. Anodic current and cathodic current are represented as I_A and I_C, respectively.
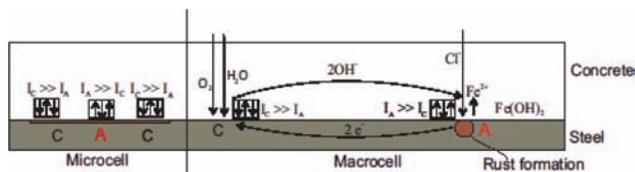

Figure 1. Schematic representation of the formation of corrosion sites.

Raupach (1996) has explained the corrosion risk after a patch repair focusing on the macrocell corrosion mechanism. The importance of surface preparation before patch repair was highlighted. All the weak contaminated concrete over the steel bar should be removed. The presence of chlorides adjacent to the repair material can initiate new macrocell sites for corrosion. A coating of affected area of steel bar reduces the cathodic reactions, but overall, it is not very effective since other passive areas are available in the steel bar as cathodic locations. Application of coating systems that can reduce the water content in concrete could increase the electrical resistivity and thereby reduce corrosion current flow. Differences in the availability of oxygen can also cause macrocell formation in patch repairs. Generally, the repair materials have very low permeability and dense microstructure than the old substrate concrete. This will create differences in the concentrations of available oxygen between the patch and the substrate concrete. It can also contribute to the generation of an electrochemical potential gradient and macrocell formation. There was one such study stating that microcell corrosion is the predominant corrosion mechanism, when an active steel bar is connected to the passive steel bar. High potential gradient may not cause high macrocell current flow, and it could be controlled by the individual anodic–cathodic kinetics. In such cases, replacement of carbon steel bars with stainless steel bars in the patch repairs could be an economical solution to reduce the failure of repairs (Qian, Zhang, & Qu, 2006).

3.1 Microcell corrosion

Microcell corrosion is more uniform in its nature. Anodic and cathodic locations are situated very closely in this kind of corrosion mechanism. Penetration of chloride ions to the concrete and further depassivation of the steel bars creates anodic sites. Areas of steel bar, which have access to the oxygen and water, will serve as the cathodic sites.

Anodic reaction at the active steel in the substrate concrete,

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

Cathodic reaction is at the passive steel in repair material,

$$2H_2O + O_2 + 4e^- \rightarrow 4\ OH^- \qquad (2)$$

Further OH^- reacts with Fe^{2+} to form $Fe\ (OH)_2$; this further reacts with oxygen to form a series of oxide compounds. They appear as rust in the steel surface.

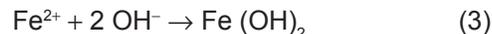$$Fe^{2+} + 2\ OH^- \rightarrow Fe\ (OH)_2 \qquad (3)$$

Figure 1 pictorially explains the above reactions. In the microcell corrosion scenarios, the corrosion rate is determined by the intersection of the anodic and cathodic polarisation curves as shown in Figure 2 (Qian et al., 2006). Steel bar in the repair material benefits from the passivation, as observed by a more positive half-cell potential values ($E_{mi,\ c}$) and less corrosion current ($I_{mi,\ c}$). Steel bar in the substrate concrete depassivates in the presence of chlorides and more negative half-cell potential ($E_{mi,\ a}$) and high corrosion currents ($I_{mi,\ a}$) are observed. The magnitude of microcell corrosion taking place in the patch repair materials and in substrate concrete can be represented as $I_{mi,\ c}$ and $I_{mi,\ a}$. In both scenarios, the anodic current
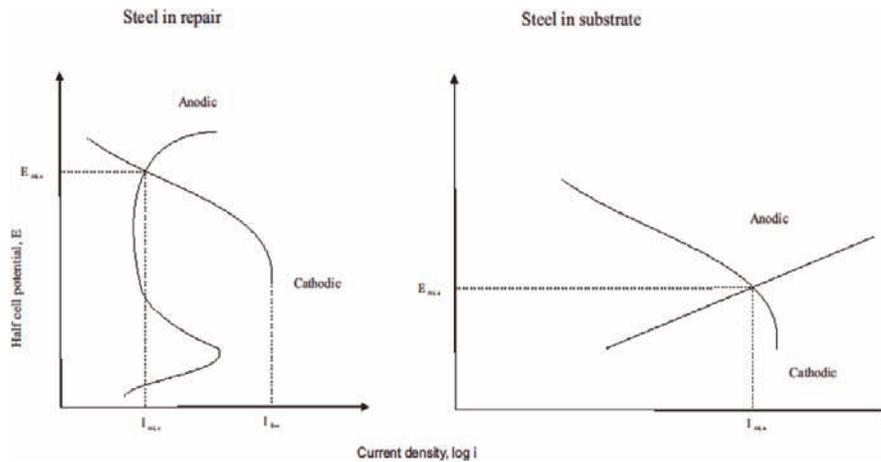
Figure 2. Microcell corrosion formation in patch repair.

is equal to the cathodic current since all the electrons released by the anodic area are consumed at the cathodic area. The corroding part will show a uniform corrosion potential, such as $E_{mi, c}$ and $E_{mi, a}$, in cathodic and anodic areas, respectively.

3.2 Macrocell corrosion

Macrocell corrosion is the predominant corrosion mechanism found in chloride contaminated concrete. The macrocell formation in patch repairs can be theoretically explained using a macrocell model circuit (Maruya, Takeda, Horiguchi, Koyama, & Hsu, 2007). When there are a number of anodic and cathodic sites created because of an electrochemical potential difference such as in the case of a patch repair, the microcell corrosion alone cannot explain the whole process. There are a number of anodic and cathodic sites connected at the incipient anodes. Since the anodic and cathodic areas of the steel bars are electrically connected in a concrete patch repair, the redistribution of electrochemical potentials is observed after a patch repair. The difference between the final potentials of anodic and cathodic sites is the driving potential, which is responsible for the macrocell corrosion current. The initial half-cell potential values of the anodic and cathodic sites are represented by $E_{mi, c}$ and $E_{mi, a}$ in Figure 3. Polarisation of the anodic and cathodic sites was observed once the electrodes are connected. A shift in the potential values was observed at both the anode and cathodic sites due to this polarisation. The final half-cell potential values are represented by $E_{ma, c}$ and $E_{ma, a}$. It was observed that the potential of the cathodic site is moving in the more positive direction, whereas the anodic site is moving in the more negative direction. The difference between the $E_{mi, c}$ and $E_{mi, a}$ is the driving potential responsible for the macrocell current generation.

The possible threats to the durability of a patch repair are graphically shown in Figures 4A–D.
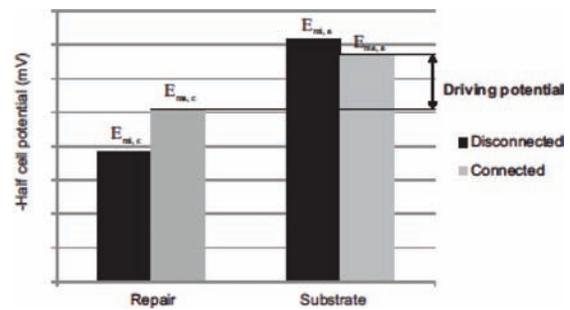

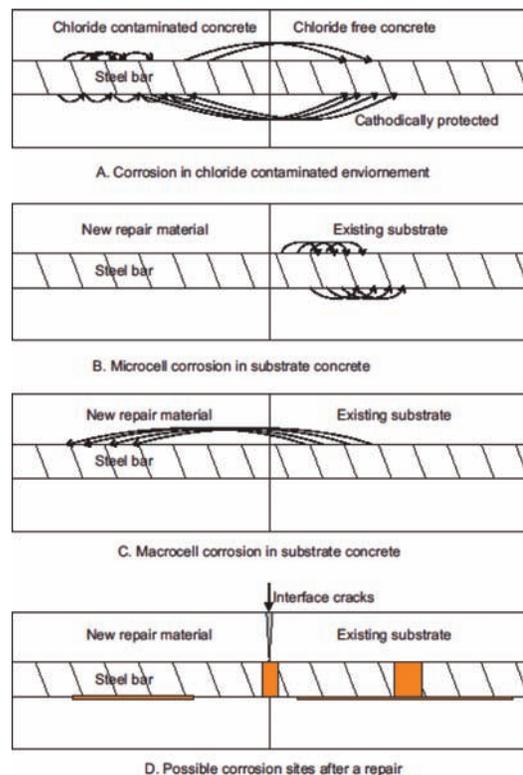**Figure 3.** Formation of macrocell corrosion and the driving potential in a patch repair.

Figure 4. (A–D) Different possible scenarios after a patch repair.

Figure 4A: corrosion in chloride-contaminated environment can be because of either microcell or macrocell formation. Also both of these can coexist in a corroding steel bar. Steel in the chloride-free concrete enjoys the cathodic protection.

Figure 4B: when the chloride-contaminated concrete is replaced with a fresh repair mortar, the steel in the old substrate concrete loses its passivity, and microcell corrosion cells can be initiated there.

Figure 4C: the electrochemical potential difference between the repair material and the substrate concrete can lead to the formation of macrocells in a repaired structure. Steel in the substrate concrete can act as the anode, and the steel in the repair material will serve as the cathode.

Figure 4D: the possible corrosion sites after a patch repair can be located in the substrate concrete, repair material, or at the interface between the substrate concrete and repair material. In a patch repair exposed to a chloride-contaminated environment, the interface cracks can serve as the entry point for the chlorides. This leads to the formation of corrosion sites at the interface.

4. SELECTION OF REPAIR MATERIALS

A comprehensive guide dealing with the protection of concrete structures using different repair methods is available with the European code EN 1504. This review is restricted to the properties of repair materials, which are important from the electrochemical consequences of patch repair. Hence, large amounts of literature dealing with the structural properties of repair mortars are not included. Cementitious mortars, polymer-modified cementitious mortar, and resin-based mortars are the commonly available generic repair materials on the market. The compatibility of the repair material with the substrate concrete is the most important feature for the selection of repair materials. Compatibility should be matched in terms of mechanical, electrochemical, and dimensional properties (Emmons, Vaysburd, & McDonald, 1993; Vaysburd, 2006).

There are inherent differences in properties between the polymer based repair materials and traditional construction materials. The properties of polymer-based materials are highly dependent on the temperature and application methods (Kosednar & Mailvaganam, 2005). Proper application methods and curing procedures need to be followed for those repair materials. Polymeric repair materials also exhibit a reduction in their water permeability (Mangat & Limbachiya, 1995). Fibre-reinforced repair mortars reduce the microcracking in repairs. Repair materials with migrating inhibitors are new developments in the repair industry. In such repair materials, inhibitors can diffuse through the concrete *via* diffusion. They make

a monomolecular protective layer upon contact with the steel bar and this protects them (Batis, Routoulas, & Rakanta, 2003). Creep and shrinkage properties of the repair material are also important since they control the cracking and bond failure at the repair–concrete interface (Mangat & Limbachiya, 1995). The penetration of chlorides to the repaired structure after the repair can take place mainly through such weak areas.

Attempts have been made to modify conventional patch repairs to improve their performance. The macrocell corrosion in patch repairs that is modified by the application of reinforcement primers was studied. Four different types of primers offering barrier protection, cathodic protection, inhibition, and passivation were considered for the study. Results showed that the primers are effective in the initial months. In the long term, the primers that offer barrier protection exhibited better performance. Zinc sacrificial coating was found to be not long lasting and not effective for protection in the longer duration. It enhances the corrosion of the non-repaired zones in the long run (Castro et al., 2003). Modified patch repair techniques were also patented by various researchers. Weyers patented the patch repair technique in which corrosion inhibitors were sprayed initially to the repairing location after the removal of loose concrete. The area is saturated with corrosion inhibitor before back filling is done with the concrete overlay modified with a corrosion inhibitor (Weyers & Prowell, 1995).

Glass demonstrated the application of sacrificial anodes in the patch repairs. Repair materials of high resistivity will reduce the effectiveness of the sacrificial anode if it is placed in the repair. Hence, a methodology involving the insertion of sacrificial anodes into the substrate concrete itself was proposed by Glass (Glass et al., 2010). The effectiveness of sacrificial anodes in a patch repair was also demonstrated using finite element modelling (Cheung & Cao, 2013). Sacrificial anodes placed in the parent concrete influences the potential of the steel bar in the repair. The reach of protection is higher than that offered by a sacrificial anode embedded in the repair itself. Properties of the repair materials affect the performance of sacrificial anodes, when they are embedded in the repair material, but they are not effective when the anodes are embedded in the substrate concrete. An alternative criterion to the 100-mV depolarisation is verified to assess the performance of sacrificial anodes in patch repairs. According to this, parts of the steel bar away from the anode should have a significant polarization to at least a distance equal to half of the spacing between adjacent anodes (Christodoulou, Goodier, Austin, Glass, & Webb, 2014). The influence of the corrosion inhibitors in limiting the failure of patch repairs was also studied. Corrosion inhibitors are classified based on their protection mechanism. An active type of corrosion inhibitor encourages the formation of a passive layer

around the steel bar, whereas a passive type reduces the chloride ion migration. Organic inhibitors, primarily amines and esters, provide a protective coating around the steel bar and delay the penetration of chlorides to the steel surface (Söylev & Richardson, 2008). The application of corrosion inhibitors to improve the patch repairs is not a guaranteed solution to avoid the long-term problems (Smith & Virmani, 2000). Long-term stability and performance of the corrosion inhibitors are questionable.

There is a methodology proposed for the selection of repair materials to be used for the repair of carbonation-induced corrosion. The method suggests the selection of repair materials based on its tendency to form a macrocell corrosion cell when attached to the substrate concrete (Ribeiro, Panossian, & Selmo, 2013). The combination of tests, such as the resistance to chloride ion penetration, electrical resistivity, water absorption, and the potential to form macrocell corrosion, can provide the comprehensive idea about the suitability of a repair material when it is to be applied in chloride-contaminated concrete. The curing conditions are also important to ensure the success of a patch repair. Chloride penetration to the repair material is dependent on its permeability. The microstructure and permeability are highly influenced by the curing conditions provided to the patch repair (Mangat & Limbachiya, 1999). In practical repair locations, provision of a proper curing environment for a long duration is often not possible. Hence, repair materials should be assessed under practical curing conditions in laboratory to get a realistic idea of their behaviour and performance.

5.   CHLORIDE TRANSPORT THROUGH A PATCH REPAIR

Chloride ion transport takes place from the substrate concrete to the new repair material after a patch repair. The transportation becomes easier in cases of poor-quality substrate concrete. High water-to-cement ratio in the substrate concrete favours this chloride transport. The mechanism and duration of chloride transport is not exactly known (Skoglund, Silfwerbrand, Holmgren, & Trägårdh, 2007). The interface between the concrete and repair material also acts as a way for the entry of chlorides. The presence of microcracks accelerates the transport. Such microcracks can be formed due to various reasons such as drying, thermal or stiffness incompatibility, poor curing, surface preparation, or their combined effect. Substrate concrete, which is more permeable than the repair material, accommodates the chloride ions and corrosion sites tend to form within the substrate material itself (Christodoulou, Goodier, Austin, Glass, & Webb, 2012). In many repair situations, the residual chloride content in the substrate concrete itself is sufficient to create a new corrosion site (Christodoulou et al., 2013).

Drying shrinkage, permeability of the repair material and substrate concrete are the two most important factors that influence the chloride transport after a patch repair. Drying shrinkage in the repair materials leads to the formation of interface cracks. Newly emerged repair materials, such as Engineered Cementitious Composites (ECC), has the potential to become a repair material with minimum problems related with shrinkage (Li & Li, 2006). Substrate concrete normally has a high permeability compared to the repair material. Chloride transport from the surrounding environment to the concrete and through the concrete to the repair material is possible in such cases. This movement of chlorides can trigger the depassivation of steel bars, thereby forming new corrosion sites.

6.   CONCLUSION

*   The electrochemical consequences of patch repairs should not be neglected while choosing the repair material. The macrocell corrosion formation potential of the repair and substrate combination should be checked before the patch repair. Incipient anodes could be developed in a patch repair due to the electrochemical potential difference, chloride ion transport, and the interface effects. Proper application of corrosion inhibitors, sacrificial anodes, and surface coatings in the patch repair could mitigate formation of such macrocells, but more studies are needed to understand their mechanism of action.

*   The corrosion mechanism at the failed patch repairs could be a combination of the microcell and macrocell corrosion mechanisms. The synergic effect of both the mechanisms could lead to the failure of patch repairs.

*   The repair–substrate concrete interface requires more attention in a patch repair to avoid the entry of chlorides to initiate corrosion. Movement of chlorides from the substrate material to the repair and from the outside environment to the repair–substrate interface can influence the location of incipient anodes.

REFERENCES

Al-Dulaijan, S., Al-Zahrani, M., Saricimen, H., Maslehuddin, M., Shameem, M., & Abbasi, T. (2002). Effect of rebar cleanliness and repair materials on reinforcement corrosion and flexural strength of repaired concrete beams. *Cement and Concrete Composites*, *24*(1), 139–149.

Barkey, D. P. (2005). Corrosion of steel reinforcement in concrete adjacent to surface repair. *ACI Materials Journal*, *101*, 266–272.

Batis, G., Routoulas, A., & Rakanta, E. (2003). Effects of migrating inhibitors on corrosion of reinforcing steel covered with repair mortar. *Cement and Concrete Composites*, *25*(1), 109–115.

Castro, P., Pazini, E., Andrade, C., & Alonso, C. (2003). Macrocell activity in slightly chloride-contaminated concrete induced by reinforcement primers. *Corrosion*, *59*(6), 535–546.

Cheung, M. M. S., & Cao, C. (2013). Application of cathodic protection for controlling macrocell corrosion in chloride contaminated RC structures. *Construction and Building Materials*, *45*, 199–207.

Christodoulou, C., Goodier, C., Austin, S., Webb, J., & Glass, G. K. (2013). Diagnosing the cause of incipient anodes in repaired reinforced concrete structures. *Corrosion Science*, *69*, 123–129.

Christodoulou, C., Goodier, C. I., Austin, S. A., Glass, G. K., & Webb, J. (2012). *Investigations on the incipient anode phenomenon following patch repairs for reinforced concrete structures*. Loughborough, England: Loughborough University.

Christodoulou, C., Goodier, C. I., Austin, S. A., Glass, G. K., & Webb, J. (2014). A new arrangement of galvanic anodes for the repair of reinforced concrete structures. *Construction and Building Materials*, *50*, 300–307.

Emmons, P. H., Vaysburd, A. M., & McDonald, J. E. (1993). A rational approach to durable concrete repairs. *Concrete International*, *15*, 40–45.

EN, N. 1504-3. (2006). *Products and systems for the protection and repair of concrete structures. Definitions, requirements, quality control and evaluation of conformity. Structural and non-structural repair*. Lisbon, Portugal: IPQ.

Glass, G. K., Davison, N., & Roberts, A. C. (2010). *U.S. Patent No. 7,731,875*. Washington, DC: U.S. Patent and Trademark Office.

Kosednar, J., & Mailvaganam, N. P. (2005). Selection and use of polymer-based materials in the repair of concrete structures. *Journal of Performance of Constructed Facilities*, *19*(3), 229–233.

Li, M., & Li, V. C. (2006). Behavior of ECC/concrete layer repair system under drying shrinkage conditions. *Proceedings of ConMat'05*, Vancouver, BC, 22–24.

Lukovic, M., Ye, G., & Van Breugel, K. (2012). *Reliable concrete repair: A critical review*. 14th International Conference Structural Faults and Repair, Edinburgh, Scotland.

Mailvaganam, N. P., & Zhang, J. (2006). Structural and patch repair in concrete structures. *Cement and Concrete Composites*, *28*(8), 669–670.

Mangat, P. S., & Limbachiya, M. C. (1999). Effect of initial curing on chloride diffusion in concrete repair materials. *Cement and Concrete Research*, *29*(9), 1475–1485.

Mangat, P. S., & Limbachiya, M. K. (1995). Repair material properties which influence long-term performance of concrete structures. *Construction and Building Materials*, *9*(2), 81–90.

Maruya, T., Takeda, H., Horiguchi, K., Koyama, S., & Hsu, K. L. (2007). Simulation of steel corrosion in concrete based on the model of macro-cell corrosion circuit. *Journal of Advanced Concrete Technology*, *5*(3), 343–362.

Pruckner, F., & Gjørv, O. E. (2002). Patch repair and macrocell activity in concrete structures. *ACI Materials Journal*, *99*(99), 143–148.

Qian, S., Zhang, J., & Qu, D. (2006). Theoretical and experimental study of microcell and macrocell corrosion in patch repairs of concrete structures. *Cement and Concrete Composites*, *28*(8), 685–695.

Raupach, M. (1996). Chloride-induced macrocell corrosion of steel in concrete – Theoretical background and practical consequences. *Construction and Building Materials*, *10*(5 SPEC. ISS.), 329–338.

Ribeiro, J. L. S., Panossian, Z., & Selmo, S. M. S. (2013). Proposed criterion to assess the electrochemical behavior of carbon steel reinforcements under corrosion in carbonated concrete structures after patch repairs. *Construction and Building Materials*, *40*, 40–49.

Skoglund, P., Silfwerbrand, J., Holmgren, J., & Trägårdh, J. (2007). Chloride redistribution and reinforcement corrosion in the interfacial region between substrate and repair concrete – A laboratory study. *Materials and Structures*, *41*(6), 1001–1014.

Smith, J. L., & Virmani, Y. P. (2000). *Materials and methods for corrosion control of reinforced and prestressed concrete structures in new construction* (No. FHWA-RD-00-081). Washington, DC: Federal Highway Administration.

Soleimani, S., Ghods, P., Isgor, O. B., & Zhang, J. (2010). Modeling the kinetics of corrosion in concrete patch repairs and identification of governing parameters. *Cement and Concrete Composites*, *32*(5), 360–368.

Söylev, T. A., & Richardson, M. G. (2008). Corrosion inhibitors for steel in concrete: State-of-the-art report. *Construction and Building Materials*, *22*, 609–622.

Vaysburd, A. M. (2006). Holistic system approach to design and implementation of concrete repair. *Cement and Concrete Composites*, *28*(8), 671–678.

Weyers, R. E., & Prowell, B. D. (1995). *U.S. Patent No. 5,427,819*. Washington, DC: U.S. Patent and Trademark Office.

Zhang, J., & Mailvaganam, N. P. (2006). Corrosion of concrete reinforcement and electrochemical factors in concrete patch repair. *Canadian Journal of Civil Engineering*, *33*(6), 785–793.