Incipient anodes in reinforced concrete repairs: A cause or a consequence?

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ABSTRACT

Patch repairs are a common repair technique for corrosion-damaged reinforced concrete structures. However, this repair method is sometimes associated with limited durability and in many cases further corrosion damage has been noted around the repaired patches, a phenomenon known as the “incipient anode” effect. The diagnosis of this problem is widely reported to be macrocell activity. It is deemed that the cause of incipient anodes is the loss of the natural cathodic protection provided by the corroding steel to the steel in the parent concrete adjacent to the patch repair. This diagnosis is based on very limited data. Indeed potential measurements on field structures repaired with proprietary materials have provided data that suggest that macrocell activity is not a cause of incipient anode formation but it is a consequence. Alternative mechanisms that may cause incipient anode activity include repair/parent material interface effects, residual chloride contamination within the parent concrete, and/or vibration damage to the steel/parent concrete interface during repair area preparation. The aim of the work presented here was to assess the impact of macrocell activity on the formation of incipient anodes around the perimeter of repairs in patch-repaired reinforced concrete structures. This was examined based on a major multi-storey car park and a bridge structure both located in the UK. The analysis challenges the view that macrocell activity is a cause of incipient anode formation. Indeed this work shows that the data supporting the existing diagnosis is not convincing and suggests that macrocell activity is primarily a consequence of incipient anode formation and the cause probably, results from other factors.

Keywords: corrosion, incipient anode, repairs;

1. Introduction

Corrosion of steel reinforced concrete structures is a very common phenomenon of ageing infrastructure. Replacing physically deteriorated concrete is a common repair technique known as concrete patch repair. A concrete patch repair involves the removal of physically deteriorated concrete, cleaning of the steel reinforcement and replacement with a repair mortar. This process aims to eliminate the cause of original deterioration (anodic reaction) and provide protection to the repaired area against future deterioration, thus making the steel within the repair area passive (Qian et al. 2006).

However, in many cases further corrosion deterioration has been observed around concrete patch repairs after a few months to a year following completion of the repair process (Qian et al. 2006, Nounou and Chaudhary 1999). This phenomenon is usually known as the incipient or ring anode formation (Dugarte and Sagüés 2009, Page and Sergi 2000, Broomfield 2007, Bertolini et al. 2013).

Page and Treadaway (1982) were the first to introduce the incipient anode concept with the observation that the redistribution of anodic and cathodic sites following concrete repair may affect future corrosion risk. Since then the incipient anode concept has developed and been described in a variety of ways.

The incipient anode phenomenon has been described as:
i. “The redistribution of anodic and cathodic sites in the concrete following repair (particularly in the substrate concrete) and the electrochemical between repair and substrate materials and its influence on corrosion at the interface” (Page C.L. and Treadaway 1982).

ii. “Unless all significantly chloride-contaminated material is removed from around the corroding areas, the likelihood of corrosion re-appearing and cracking the concrete adjacent to the repairs is high. The potential of the metal in these less severely contaminated areas can rise to a value at which pitting is liable to be initiated” (Page and Sergi 2000).

iii. “If only concrete near the corroded reinforcement is replaced, the attack may start in the areas near to those repaired because they no longer benefit from the cathodic polarisaiton and, moreover, pitting corrosion may even be stimulated by anodic polarization from the repassivated steel in the repaired zone” (Bertolini et al. 2013)

iv. “If a structure with extensive chloride attack is to be patch repaired then it must be recognised that patching the corroding areas can accelerate corrosion elsewhere” (Broomfield 2007).

v. “The repair of only those sites which are actively corroding in a chloride-contaminated structure is likely to stimulate corrosion at sites adjacent to the repair” (Concrete Society 2011).

vi. “When an anode develops on reinforcing steel in concrete, particularly due to chloride attack, is repaired then it becomes a cathode. This allows the previously “naturally cathodically protected” adjacent areas to start corroding” (British Standards Institution 2012).

Many of the references above suggest that a contributing factor to incipient anode formation is the loss of the natural cathodic protection provided by the corroding steel to the steel in the parent concrete adjacent to the patch repair. However in some cases it is suggested that patch repairs stimulate corrosion as a result of enhanced macrocell activity, where anodes and cathodes separated possibly at a considerable distance from one another are formed (Pruckner and Gjov 2002, Raupach, 2006).

The aim of the work presented here was to examine the factors affecting the formation of incipient anodes around the perimeter of repaired concrete structures. A multi-storey car park and a bridge, both of reinforced concrete, were used to evaluate the on-site performance of concrete patch repairs. The work discusses in detail the factors affecting the performance of concrete patch repairs based on observations from full scale reinforced concrete structures as opposed to laboratory specimens.

2. Methodology

This section describes the details of the structures selected and the testing regime employed.

2.1 Structures

A large multi-storey reinforced concrete car park (MSCP) in the East Midlands, UK and a 180m long multi-span reinforced concrete bridge in North Scotland, UK, were used for site trials to identify evidence for the formation of incipient anodes adjacent to concrete patch repairs. Both structures were approximately 40 years old and had suffered extensive chloride-induced corrosion damage.

The structural arrangement of the MSCP was a one-way spanning ribbed slab. The typical thickness of the slab between ribs was only 80mm and was lightly reinforced, primarily with 8mm steel mesh. The maximum cover to the reinforcement was only 20mm, although there were several areas, usually at the overlap locations, where cover was reduced to around 10mm or less.

The structural arrangement of the reinforced concrete bridge structure consisted of 18 equal simply supported spans with a total bridge length of approximately 180m. The supports consisted of steel piles connected with a reinforced concrete pile cap, supporting prestressed concrete beams with lightly reinforced concrete infill making up the deck.

Both structures were in an advanced stage of concrete deterioration and reinforcement corrosion as a result of the use of de-icing salts, the bridge structure was also exposed to an aggressive marine environment.
For the car park, deterioration affected primarily the decks, the parapets and the soffits around the areas of leaking expansion joints. For the bridge structure, concrete deterioration affected primarily the reinforced concrete pile caps due to water leaking through the joints and the ends of the prestressed concrete beams which were resting on top of the pile caps.

All areas of concrete deterioration where broken up, by jack hammer on the MSCP and hydrodemolition on the bridge, the steel cleaned by rotary steel wire brushes and repaired with proprietary cementitious materials as described below.

2.2 Testing

2.2.1 Chloride analysis
Historical data was available for chloride concentration profiles throughout the MSCP over the period 1997 to 2008. The data illustrated that for the depth band of 0–25 mm (where reinforcement was located) at least 85% of the test locations exceeded the suggested threshold of 0.3% by weight of cement (Design Manual for Road and Bridges 1990).

For the reinforced concrete bridge, 27 dust samples were taken in total, at depths of 25 mm to 125 mm at 25 mm increments, from the prestressed concrete beams and from the reinforced concrete pile caps. Chloride content of the samples was determined by an independent laboratory to BS 1881, Part 124 (Design Manual for Road and Bridges 1988). The chloride concentration of only one dust sample was below the suggested threshold 0.3% by weight of cement. Concentrations of up to 1.89% by weight of cement were identified even at depth bands of 75–100 mm.

2.2.2 Potential mapping
The performance of the repairs was assessed by means of surface potential mapping in which the steel potential was measured against the potential of a reference electrode (Concrete Society 2004, American Society for Testing and Materials 2009, Christodoulou 2013, Christodoulou et al. 2010, Christodoulou et al. 2014, Christodoulou et al. 2014b, Dodds et al. 2014). A portable Ag/AgCl/0.5M KCl reference electrode was primarily used for the testing together with a high impedance multi-meter. Direct steel reinforcement connections were not always possible and in some cases only relative values could be obtained. Notes within the Figures identify whether the steel potential values are relative or absolute values.

Following reinstatement of the patches, the area was allowed to cure for at least 10 days before undertaking surface potential mapping with frequency of testing set at approximately 10 day intervals. The spacing used for the potential mapping was on a grid of 50mm by 50mm in order to easily identify the formation of macrocells.

2.2.3 Repair Materials
Details of the repair materials are included in Table 1, alongside a description of their chemical base and characteristics.

<table>
<thead>
<tr>
<th>Material</th>
<th>Structure type</th>
<th>Repair location</th>
<th>Chemical Base &amp; Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>MSCP</td>
<td>Deck</td>
<td>Shrinkage compensated, pourable, polymer modified concrete, trowel finished</td>
</tr>
<tr>
<td>B</td>
<td>Bridge</td>
<td>Soffits and vertical faces</td>
<td>Shrinkage compensated, dry sprayed, polymer modified micro-concrete, trowel finished</td>
</tr>
</tbody>
</table>
3. Results

This section describes the results of testing for both structures selected.

3.1 MSCP

Potential mapping results for a concrete patch repair using material type A after a period of 30 days are shown in Figure 1. It can be observed that following repair the potentials of the steel within the repair area have been pushed to more negative values.

![Material A](image)

**Fig 1.** Potential mapping monitoring of material type A on car park deck repair (Christodoulou 2015).

Figure 2 illustrates the potential monitoring of a repair using Material A over a period of 246 days. The early age results (15 days) show that the steel potentials within the patch repair were depressed to very negative values as a result of the fresh alkalinity provided by the repair mortar. The steel potentials shifted to less negative values as the age of the patch repair increased, however, at no point within the 246 days of monitoring did the potentials of the steel within the patch rise above the steel potentials in the parent concrete.

Similar behavior was observed for all the patch repairs monitored as part of this work, confirming consistency on the results obtained.
The surface potential mapping results before and 30 days after a concrete patch repair using material type A are shown in Figure 3. Following repair, it can be observed that the potentials of the steel within the repair area were pushed to very negative values and remained more negative than the potentials of the steel in the parent concrete for the first 30 days. In addition, it can be observed that the potentials of the steel in the parent concrete were also affected.

3.2 Bridge structure

The potential data obtained on patch repairs on the bridge structure illustrated similar behaviour to that obtained on the car park. Figure 4 shows data obtained at an area repaired with material B. The potentials of the steel within the repair material were about 200 mV more negative than the potentials of the steel in the adjacent parent concrete at the start. After 83 days the change was still greater than 100 mV.
4. Discussion

This discussion firstly considers whether the available data suggests that macrocell activity is a cause or a consequence of incipient anode formation. Factors affecting the potential that may have a bearing on the analysis are then considered. The repair material interface and other factors that may induce incipient anode activity are then described and finally the corrosion risk resulting from repairing chloride induced corrosion damage is summarised.

4.1 Cause or Consequence

The current understanding of the effect of an incipient anode on the steel in the parent concrete adjacent to the repair is based on the hypothesis that steel within the repair passivates as a result of the alkalinity of the fresh repair material, the absence of chlorides and the abundance of dissolved oxygen in the pore solution of the freshly mixed concrete or repair mortar.

Figure 5 illustrates three possible cases schematically showing the steel potential change between repair material and parent concrete in the situation where a repair has been performed to address chloride-induced corrosion damage. The effect of an incipient anode on the steel potential in the parent concrete adjacent to the repair is taken into account in the potential plot in cases 1 and 2.
Case 1 represents one textbook understanding of the cause of incipient anode formation. In this hypothesis, the steel within the repair passivates as a result of the alkalinity of the fresh repair material, the absence of chlorides and the abundance of dissolved oxygen in the pore solution of the freshly mixed concrete or repair mortar. The steel potential in the repair rises above the passive steel potential in the parent concrete resulting in a macrocell that induces passive film breakdown causing an incipient anode to form adjacent to the repair. No data was uncovered either in the measurements recorded within this study or a review of the literature to support this hypothesis.

Case 2 represents the situation where the repair results in the removal of the corrosion site that used to be an anode. Previously published laboratory data (Page and Sergi 2000) has shown that this situation may occur.

The laboratory data which provided some initial support for macrocell induced incipient anode formation is reproduced in Figure 6 (Qian et al.2006). To obtain this data a concrete slab was cast and then repaired under laboratory conditions. The parent concrete was not aged in the same way that concrete on a structure is aged and a proprietary repair material conforming to existing standards was not used to repair the damage. The reported data showed two possible areas of incipient anode formation, for a concrete slab cast and then repaired.
The benefit provided by this natural cathodic protection is questionable because corrosion of a steel anode results in expansive products that cause disruption to the surrounding concrete (Bertolini et al. 1998). This may be the reason why reinforcement corrosion tends to spread laterally along the steel bars in conditions that also result in expansive corrosion products as opposed to forming deep pits as is the case for passive metals in other environments including steel in water saturated concrete.

A related observation has been made in relation to the influence of a macrocell caused by coupling stainless steel to steel in concrete. The impact of a stainless steel/mild steel couple on inducing corrosion on the mild steel has been reported to be no different to that of a passive mild steel/mild steel couple and did not increase the corrosion damage reported on the mild steel (Bertolini et al. 1998). By the same argument, it is unlikely that a macrocell formed by coupling the steel in the repair area to steel in the parent concrete will have any substantial impact on inducing additional corrosion on the steel in the parent concrete.

4.2 Factors affecting potential

The data of the currently presented work indicated that the steel in the patch appeared to have a more negative potential than the steel in the parent concrete. Although potentials shifted to more positive values with time, they were always more negative than the potential of the steel in the parent concrete, as evidenced by Figures 1 to 3. Such an observation is not unique and has also been made by Cleland et al. (1997) and by Morgan (1996).

Some possible reasons for the observed behavior include the build-up of the oxide film or that a membrane or streaming potential exists between the parent and the patch concrete (Angst et al. 2009, Schiegg et al. 2009). However, they do not dominate the time dependence to the extent that steel potentials in the repaired area rises above that in the parent concrete over time. Thus, the data from this study, like that of Cleland et al. (1997) and Morgan (1996) provide no evidence to indicate that macrocell activity is a cause of incipient anode formation in aged concrete structures repaired with proprietary repair materials. This suggests that, on balance, macrocell activity is a consequence, not a cause, of incipient anode formation in these circumstances.

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**Fig 6.** Open circuit steel potentials of a slab following 2 months of conventional patch repair (potential vs Standard Calomel Electrode) (Page and Sergi 2000).
The change in pH between the repair material and the parent concrete can also give rise to a membrane potential. This results due to diffusion of hydroxide ions from the patch repair to the parent concrete and a resulting build-up of charge on the walls of the pore system at the repair interface (Glass and Buenfeld 2000). A residual charge on the pore walls at the repair interface results from dissimilar dissolution of the solid phase and represents a membrane.

The effect of the charge results in positive and negative ions diffusing at very different rates through the pore system and induces a membrane potential. Studies on membrane potentials in concrete suggest that large membrane effects are transient.

### 4.3 Repair material interface

Cracks may occur at the interface between the parent concrete and the repair material following patch repair of concrete structures. The presence of such cracks can be attributed to drying, or plastic shrinkage, thermal or stiffness incompatibility, poor curing, surface preparation or a combination of these (Concrete Society 2008). Admixtures can be used to increase the volume of the repair material during early age hardening of shrinkage compensated materials. However, the material will often undergo an S-shaped expansion/contraction cycle (Szilágyi 2009). Although close to zero, net unrestrained shrinkage can be achieved in such shrinkage compensated materials; there may be some limited retained shrinkage which can give rise to crack because the early expansion part of the cycle is restrained by the parent concrete.

Crack formation in reinforced concrete structures and its relationship to corrosion has been established by a number of studies (Raupach 1996, Schiessl and Raupach 1997). In particular, it has been shown that the reinforcement within and around the crack zone will start to corrode first. Chadwick (1993) also observed that the presence of construction joints in the same material resulted in corrosion initiating at lower chloride levels and concentrated at the joint interface.

### 4.4 Incipient anode formation

Factors that may cause incipient anodes to form include repair material interface effects, residual chloride contamination and damage to the steel-concrete interface during repair preparation. Furthermore, cracks and interfacial effects between parent concrete and repair material provide an easier path for the chlorides to penetrate into the substrate. The parent concrete may have a higher permeability than the new repair material and this will aid the diffusion process. The parent concrete is also likely to have some residual chloride contamination that may promote corrosion. The preparation of the repair area usually requires the mechanical removal of concrete that can cause damage to (or defects at) the interface between the unexposed steel and the parent concrete adjacent to the repair area. This increases the corrosion risk by lowering locally the chloride threshold level (Glass et al. 2007).

The repair of corroding areas removes the anode in this location and any “sacrificial” cathodic protection effects that were previously applied to the steel in the surrounding regions. However, it has been suggested that the detrimental effect of a corroding steel anode in concrete probably outweighs any beneficial effects that were provided previously by such an anode (Glass et al. 2007, Bertolini et al. 1998, Christodoulou 2013). In other words, a corroding steel anode causes more damage than it prevents.

### 4.5 Corrosion risk

This analysis has suggested that there is no obvious increase in corrosion risk following patch repair of reinforced concrete structures that result from macrocell activity, beyond what would be the case if the steel had remained passive (i.e. there is no increase in the macrocell voltage). Indeed, steel reinforcement in an aged parent concrete may remain cathodic relative to steel in proprietary repair materials for a substantial period after the repair is undertaken. The results of this study are in line with previously reported findings by Bertolini et al. (1998) and Qian et al. (2006) on the corrosion risk presented by a galvanic couple of stainless steel to carbon steel. The damage caused by a corroding steel anode in an
unrepaired area probably outweighs any electrochemical protective effects that such a corroding area may deliver (Bertolini 1998, Glass et al. 2007).

Incipient anodes may form around patch repairs and their presence can be detected with potential mapping. As noted above, alternative causes of incipient anodes include a permeable interface between the parent and repair materials, residual chloride contamination of the parent concrete and damage to the steel interface within the parent concrete during the preparation of the repair area.

The results of this research help to inform the development of corrosion management strategies that may include rehabilitation methods such as cathodic protection, surface coatings and hydrophobic impregnations, to increase durability of reinforced concrete structures.

5. Conclusions

While the incipient anode effect often occurs on repaired reinforced concrete structures, potential measurements taken on structures repaired with a variety of proprietary repair mortars over a period of up to 250 days suggest that macrocell activity does not stimulate incipient anode formation. No evidence was found from potential measurement data obtained in this work to support the hypothesis that macrocell activity is a cause of incipient anode formation.

The use of cementitious proprietary repair materials may permanently depress steel potentials within the repair area. Reasons for this include the common low permeability and high pH of these types of materials. A high pH in an area of repair would result in a negative shift in steel potentials because equilibrium potentials of steel in concrete are more negative at the high end of the pH range.

Cracks can develop at the repair/substrate interface even when using shrinkage compensated repair materials, which may provide an easier path for chlorides to penetrate into the substrate. This is due to the fact that the shrinkage compensated material undergoes an “S” shaped strain curve, even in an unrestrained case where no net strain occurs, which can result in shrinkage during the final phase. The extent of these cracks will be dependent upon surface preparation, application techniques, material properties, adhesion between the repair material and parent concrete and curing conditions. Such cracks may be obscured by trowel finishing of the repair, or a coating (if applied).

An increased number of incipient anodes adjacent to areas of concrete repair may arise from one or more of the following reasons:
- chlorides may enter the concrete through the interface between the parent and repair material,
- parent concrete adjacent to the repair area may have an above average level of residual chloride contamination that is sufficient on its own to cause corrosion, and/or
- preparation of a repair area may result in vibration damage at the steel interface with the adjacent parent concrete.

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