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A new arrangement of galvanic anodes for the repair of reinforced concrete structures

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ABSTRACT

Discrete galvanic anodes are traditionally embedded in the patch repairs of steel reinforced concrete (RC) structures to offer corrosion prevention. This research investigated the performance of galvanic anodes installed in the parent concrete surrounding the patch repair, in order to explore the performance of such a new arrangement and identify its potential for wide-scale application.

This arrangement was tested on a RC multi-story car park and a RC bridge, with both suffering from chloride-induced corrosion of the reinforcement. The performance of the anodes was assessed using close-interval potential mapping for 215 days after installation. The results indicate that the anodes polarised the steel at a significant distance away from the patch repair interface, up to 600 mm in some cases. It illustrates that such an arrangement may be advantageous when repairing RC structures as the corrosion prevention can be targeted at the steel in the surrounding parent concrete, which is traditionally considered to be at higher risk due to incipient anode development.

Keywords

Reinforced concrete; corrosion; galvanic anodes; potential mapping

INTRODUCTION

Patch repairs of deteriorating concrete is a common approach to rehabilitate defective concrete structures. Bridge Advice Note 35 [1] suggests that areas which show chloride concentrations greater than 0.3% by weight of cement and half-cell potential measurements higher than -350mV should be removed. Concrete replacement to this extent on chloride-contaminated structures can be very onerous and expensive [2].

Galvanic anodes have been used to limit the extent of concrete replacement and extend the service life of patch repairs to RC structures [3 – 5]. They respond to changes in the environmental conditions they are exposed to [3, 6, 7]. Such an effect will be more dominant in parent concrete that has a residual level of

chloride contamination as opposed to the non-contaminated repair concrete or mortar and this has been employed to extend the use of galvanic anodes [8, 9].

This work measured the performance of galvanic anodes installed within the parent concrete around the perimeter of the repair as opposed to the traditional approach of placing the anodes within the patch repair area itself. The anodes were monitored in order to assess their performance and the results provide an improved understanding of the corrosion protection mechanism [5].

THEORETICAL BACKGROUND

Galvanic anodes operate on the principle of differential potentials of metals [3, 4]. A schematic illustration of a galvanic cathodic protection (CP) system is provided in Figure 1. For the protection of steel reinforcement in concrete, such electrochemically more active metals include zinc, aluminium and magnesium.

Figure 1: A compact discrete galvanic anode connected to the steel reinforcement which becomes the cathode of the galvanic cell that is formed [10].

Contemporary galvanic anode systems can be categorised as (Figure 2) [10]:

- i. Metal coatings applied directly to the concrete surface
- ii. Sheet anodes attached to the concrete surface
- iii. Distributed anodes embedded in a cementitious overlay
- iv. Discrete anodes embedded in cavities in the concrete

Figure 2: Galvanic anode examples (i) a thermally applied metal coating (top left), (ii) adhesive zinc sheets (top right) [4], discrete anodes in drilled holes (bottom left) [15], discrete anodes installed in patch repair (bottom right).

For galvanic anode systems, current output tends to fall with time as the anode is consumed. As a result galvanic protection is not generally achieved by sustaining an adequate level of steel polarisation, as is the case for other electrochemical treatments [9, 11].

For this reason, traditional galvanic anode systems are only installed as a corrosion prevention system and take the form of discrete anodes embedded within concrete patch repairs [3, 12]. The concrete repair process will restore steel passivity [4, 13]. Thus, embedded galvanic anodes are only required to provide a small cathodic polarisation to the steel reinforcement in the parent concrete adjacent to the repair area, which is considered to be an area of high risk [14 – 16]. This is also commonly known as “cathodic prevention” [17].

The traditional 100 mV depolarisation performance criterion for Impressed Current Cathodic Protection (ICCP) systems has also been routinely applied to galvanic anode systems [18, 19]. However, several publications note that this is not suitable for galvanic CP systems which are primarily designed to offer cathodic prevention only [9, 19 – 21]. The new International standard for CP of steel in concrete [17] has taken this into account and performance assessment of galvanic CP is preferably focused on corrosion risk assessment. In practice this is based on monitoring of changes in the condition of the reinforcement that arise as the result of the protective effects afforded by galvanic CP [11]. Examples include corrosion potential as a function of time and/or distance from an anode or edge of the repaired area and/or corrosion rate [5, 22].

There are a number of factors affecting the performance of galvanic anode systems. These are summarised in Table 1.

Factor	Effect
Concrete Resistivity	An increase in concrete resistivity reduces the protection current output of a galvanic anode which limits the protection delivered [3, 4, 17].
Current distribution	Discrete anodes distribute current poorly compared to surface applied anodes but protection can be targeted to the area of need [3, 4, 17].
Continuing corrosion	Products designed for use in a preventative role may fail when trying to arrest an active corrosion process [23].
Charge capacity / current output	The maximum theoretical life cannot exceed a period determined by the anode charge capacity and anode current output.
Anode activity / surface area	Determines protection current output and discrete anodes in particular need a method of anode activation. For alkali activated systems, anode activation is dependent on the quantity of alkali in the assembly.
Anode delamination / adhesion to concrete	Galvanic anode systems applied to concrete surfaces in particular are at risk of suffering from delamination and loss of contact with the concrete.

Table 1: Factors affecting the performance of galvanic anode systems applied to RC structures [10].

METHODOLOGY

This section describes the structures and the testing regime employed to evaluate the performance of the galvanic anodes.

Structures

The structures comprised a multi-storey car park (MSCP) with 11 stories in the East Midlands, UK and an 18 span bridge approximately 180 m long in Northern Scotland, UK. This MSCP was built in the early 1970s and it has a concrete one-way spanning ribbed type deck arrangement with 80 mm thick slab in-between the ribs (Figure 3). Due to the nature of the structure it was lightly reinforced with steel mesh. The bridge was also built in the early 1970s and comprised prestressed concrete beams supported on RC crossbeams with steel rendhex pile supports (Figure 4). Due to the nature of dealing with full-scale structures at an age of at least 40 years, full details of the concrete composition were not available.

Figure 3: MSCP structural arrangement

Figure 4: Bridge structural arrangement

Both structures suffered from chloride-induced corrosion [5] (Figure 5). The MSCP exhibited structural damage on the decks and soffits with exposed reinforcement and extensive concrete spalling. Chloride analysis, at more than 50 test locations on the concrete slabs and soffits of various floors, conducted in accordance with BSI [24], indicated that the chloride levels were up to 2.92% by weight of cement at a depth of 30 mm to 55 mm. This is high and presents a corrosion risk that should be addressed [1].

Figure 5: Chloride-induced corrosion and spalling to the MSCP and bridge structures (respectively)

The bridge also exhibited widespread areas of chloride-induced deterioration, being located in an aggressive marine environment. Chloride analysis testing at 12 locations on the RC crossbeams, in accordance with BSI [24], indicated high concentration levels of around 1.8% by weight of cement at a depth of 25 to 50mm - the depth at which the reinforcement is located. This is high and presents a corrosion risk that should be addressed [1].

Design Arrangement

The design for the structural repairs involved removing only physically deteriorated concrete by jack hammer on the MSCP and hydro-demolition on the bridge. The breakouts extended beyond the back of the reinforcement and at a minimum additional depth equal to the aggregate size of the repair mortar plus 3 mm. The steel was cleaned by means of rotary steel wire brushes [13].

The nature of commercial contracts and their risk allocation require that a contractor uses specialist repair materials conforming to a standard. Two proprietary repair materials, labelled A and B, certified as class structural repair mortars in accordance with BS EN 1504-3 [12, 25] were applied to restore the concrete profile. Because of the nature of this study it is not possible to give an equivalent material detail to that provided in laboratory experiments, although further details may be found elsewhere [13]. Table 2 provides further material details, how and where each one was applied.

Material	Structure type	Repair location	Properties	Application method
A	MSCP	Deck	Portland cement based, flowable, polymer modified, shrinkage compensated micro-concrete. Twenty five kilograms of material was mixed with 2.50 litres of water.	Poured and trowel finished
B	MSCP – Bridge	Soffits and vertical faces	Portland cement based, polymer modified, shrinkage compensated repair mortar containing silica fume. Water to cement ratio ranges 0.35 - 0.4.	Dry spray or hand applied and trowel finished

Table 2: Repair materials and location

Galvanic anodes with a diameter of 20 mm and a length of 40 mm, each containing approximately 65 grams of zinc, were installed in pre-drilled holes of 25 mm diameter and 45 mm long in the parent concrete, as close as practically possible to the edge of the patch and then filled with proprietary backfill (Figure 6). A titanium wire integrated with the galvanic anodes made a connection to the steel reinforcement within the repair area. On the MSCP, the design galvanic anode spacing was 300 mm centres, and on the bridge structures 250 mm centres.

Figure 6: Galvanic anode installation procedure, (a) repair area following breakout and with location of anode installation marked out, (b) testing for reinforcement continuity, (c) pre-drilled holes for anode installation, (d) installation of galvanic anode and (e) connection of galvanic anode to the steel reinforcement and anode hole following filling with the proprietary backfill.

Testing Regime

Measuring steel potentials against the potential of a standard reference electrode (i.e. absolute potentials) is a well established non-destructive monitoring technique [26 – 29]. An alternative to this, are electrode to electrode potentials (i.e. relative potentials) which provide information on the electric field in concrete and as such locating areas of actively corroding steel by considering spatial variation of potentials [27, 31]. While the use of relative potential differences in reinforced concrete galvanic CP is recent, such analysis has been used for sometime in pipeline CP [28, 30].

Potential maps were obtained on a 50 mm square grid using a portable Ag/AgCl/0.5M KCl reference electrode and a high impedance multi-meter. The size of each grid varied in accordance to the size of the repair but in general it extended up to 700 mm in the parent concrete when measured from the edge of the repair. All the potential values herein are reported relative to the most positive value obtained at the time of the measurement.

In a number of areas with ease of access, the anodes were connected to the steel reinforcement with a 10 Ohm resistor bridge, in a junction box mounted at the surface of the repair (Figure 7). This arrangement was used to facilitate galvanic current densities.

Figure 7: Typical galvanic anode installation at monitoring station to facilitate galvanic current measurements.

RESULTS

Approximately seventy patch repairs of various sizes were monitored for both structures. In all cases examined, both for the MSCP and the bridge structure, the performance of the galvanic anodes was consistent, and similar polarisation effects were observed. For this reason, only a representative number of randomly selected repairs are reported here in order to demonstrate the range of polarisation effects afforded by the galvanic anodes in each structure examined.

MSCP

The typical polarisation effects afforded by the anodes at a distance away from the edge of the patch repair in the MSCP with material type A, between 110 and 195 days following installation are shown in Figure 8. It can be observed that the anodes affected the potentials to a distance of approximately 500 mm from the edge of the repair after 195 days. The time dependant trends observed in Figure 8 were attributed to changes in the weather conditions.

Figure 8: Polarisation effect of the anodes at a distance from the edge of a patch repair in the MSCP with material type A between 110 and 195 days following installation.

Figure 9 shows the polarisation effect afforded by the anodes at a distance away from the edge of a different patch repair in the MSCP with material type A over a period of 215 days. In this case, the anodes affected the potentials to a distance of approximately 600 mm away from the edge of the repair after 215 days.

Figure 9: Polarisation effect of the anodes at a distance from the edge of a patch repair in the MSCP with material type A over a period of 215 days.

A typical repair together with a schematic illustration of the location of the galvanic anodes is shown in Figure 10. The potential mapping around this particular repair over a period of 195 days is demonstrated in Figure 11. It can be observed that the anodic points identified in the mapping, coincided at all times with the location of the galvanic anodes (anodic points have been circled over). It can be observed that the potentials never rose higher than the imaginary lines connecting the anodic spots, suggesting that there are no other anodic spots between the galvanic anodes.

Figure 10: Typical concrete repair (left) and schematic illustration of the location of the galvanic anodes (right).

Figure 11: Potential mapping around a repair location with Material A up to 195 days following installation of the galvanic anodes.

Contour plots showing potential mapping results both before and after repairing an area of corrosion damage with material A are shown in Figure 12. The repair material had cured for 30 days when the data for the post repair contour plot was recorded. It is evident that before the repair (Figure 12 (a)), the potential in the area of the corroding steel was about 100 mV more negative than the potential in the adjacent parent concrete. 30 days after the repair this difference increased to approximately 200 mV.

Figure 12: Surface potential mapping on car park repair with Material A (a) before and (b) 30 days after repair [13]. Dashed line in (b) illustrates extent of patch repair.

Contour plots of potential mapping following concrete replacement before and after connection of the galvanic anodes are provided in Figure 13. The application of a cementitious repair mortar initially depressed steel potentials within the patch repair to more negative values than the parent concrete (Figure 13 (a)). After the anodes were connected to the reinforcement, it can be observed that the polarisation effects afforded extended at least 250mm to the steel in the parent concrete (Figure 13 (b)) and further depressed steel potentials by close to 100 mV. The galvanic current output varied from 1.5 mA/m² to 1.0 mA/m² of steel surface area, demonstrating a responsive behaviour with time.

Figure 13: Surface potential mapping on car park repair with Material B (a) following concrete replacement and (b) after connection of the galvanic anodes. Dashed lines illustrate extent of patch repair.

Bridge

Typical polarisation effects afforded by the anodes at a distance away from the edge of the patch repair from the bridge structure with material type B, between 110 and 195 days following installation are shown in Figure 14. The anodes affected the potentials to a distance of at least 400 mm away from the edge of the repair at 30 days after their installation.

Figure 14: Polarisation effect of anodes at a distance from the edge of a patch repair from the bridge structure, with material type B, 30 days following installation.

Figure 15 shows the polarisation effect afforded by the anodes at a different repair, with material B, from the bridge structure 45 days following their installation. It can be observed that the anodes affected the steel potentials again to a distance of at least 400mm away from the edge of the repair.

Figure 15: Polarisation effect of anodes at a distance from the edge of a patch repair from the bridge structure, with material type B, 45 days following installation.

From the above figures it can also be observed that the potentials of the steel in the parent concrete did not always reach a plateau, which suggested that the anodes may still be effective at greater distances. Access restraints generally restricted potential mapping on the bridge structure being generally restricted to a distance of 500 mm in length.

The above, are typical and re-occurring findings on the polarisation effect afforded by the anodes to steel in parent concrete at a distance from the edge of a patch repair both for material type A and B on both structures. The exact polarisation distance varied between 250 mm and 600 mm depending on the age of the anodes, the prevailing environmental conditions at the time of testing and steel density. For the MSCP, readings could not be obtained for longer than 215 days as thereafter the slabs received a surface applied waterproofing and no longer than 45 days for the bridge structure due to access restrictions.

DISCUSSION

This study investigated the performance of galvanic anodes installed in parent concrete on two major RC structures in the UK. Monitoring was performed by close-interval relative potential mapping around the perimeter of the repairs to verify that the anodes were still active, and at staged distances away from the repairs to assess the polarisation effect afforded by the anodes to the steel in the parent concrete.

The performance monitoring data indicates that the galvanic anodes affected steel potentials in parent concrete as a distance away from the edge of the patch. For the MSCP, with steel mesh reinforcement only, the polarisation effect was to a distance of approximately 600 mm away from the edge of the patch. For the bridge structure, which inherently had a higher amount of reinforcing steel, the polarisation effect afforded was

reduced to approximately 400 mm from the edge of the patch. This indicates that galvanic anodes have limitations and their beneficial effects are reduced with an increasing density of reinforcement.

Repair materials that conform to standards for structural repairs such as BS EN 1504 [29] did not affect the performance of galvanic anodes installed in parent concrete around the edge of the repair, although they are not generally considered suitable for use together with galvanic anodes due to their high resistivity [17]. By contrast, such materials will improve the quality and longevity of the repair itself, and due to their higher resistivity will preferentially direct current from the galvanic anodes to steel in the parent concrete, which is considered to be at higher risk.

Traditionally, half-cell potential mapping in the UK is undertaken based on a 500 mm grid and for rapid corrosion assessment spacing up to 1.2 m is occasionally employed [29]. Undertaking relative potential mapping at a small grid (50 mm), as in the case of the present study, has the advantage of collecting time-dependent spatial variation information about the condition of the reinforcement which is particularly suited to galvanic systems which are often installed without any monitoring facility (including a connection to the steel reinforcement).

A new criterion, to that of 100 mV depolarisation, may be adopted for assessing the performance of galvanic anode systems by means potential mapping to obtain spatial variations. Potential mapping around the perimeter of a patch repair with galvanic anodes installed in the parent concrete, should demonstrate that the anodes afford a dominant (i.e. be dominant over any effect of a steel anode) influence on the steel potentials away from the area of patch repair that is at least equal to half the spacing between anodes. This alternative performance criterion is also in line with the work of Holmes et al. [8].

CONCLUSIONS

The results of this work lead to the following conclusions:

1. Galvanic anodes installed in pre-drilled cavities formed in the parent concrete exposed within an area of patch repair can provide substantial protection to the steel reinforcement in the parent concrete outside the repair. The anodes had a dominant effect on potentials within the concrete to a distance of between 250 mm and 600 mm from the edge of the patch repair. An important factor affecting the extent of the protective effect is the steel density (quantity).
2. A repair material that conforms to standards for structural repairs such as BS EN 1504 [29] will not affect the performance of galvanic anodes installed in parent concrete around the edge of the repair. By contrast, it will improve the quality and longevity of the repair itself and will preferentially direct current from the galvanic anodes to steel in the parent concrete, which is considered to be at higher risk.
3. Close-interval potential mapping (50mm spacing) is an effective technique to assess the performance of galvanic anodes. It has the additional advantage that localised active corrosion spots can also be detected if present.

4. An alternative criterion, to that of 100 mV depolarisation, is proposed for assessing the performance of galvanic anodes: the anodes should afford a dominant (i.e. be dominant over any effect of a steel anode) influence on the steel potentials away from the area of patch repair that is at least equal to half the spacing between anodes.

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