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Controlling past and future deterioration of reinforced concrete

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CONTROLLING PAST AND FUTURE DETERIORATION OF REINFORCED CONCRETE

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Abstract

The durability of concrete structures is affected by a number of factors such as environmental exposure, electrochemical reactions, mechanical loading, impact damage, mix design, and poor construction, amongst others. Corrosion of the reinforcement is the main consequence for the deterioration of steel reinforced concrete structures with the cause often related to environmental exposure, poor design or placement and others.

Corrosion management is becoming increasingly necessary as a result of the growing number of aging infrastructure assets internationally (e.g. bridges, tunnels etc.) and the increased requirement for unplanned maintenance in order to keep these structures operational throughout their design life (and increasingly commonly, beyond).

A recently completed research programme by the authors investigated the long-term performance of the most common corrosion management techniques by means of in-situ and laboratory testing focused on full-scale reinforced concrete (RC) bridge structures in order to collect a variety of rigorous empirical data. Consequently analysis enabled improvements to be recommended for the corrosion management of steel reinforced concrete structures through changes in design and maintenance requirements.

This paper provides an overarching review of how the findings of this recent research on a) patch repairs and incipient anodes, b) Impressed Current Cathodic Protection, c) galvanic and hybrid cathodic protection and d) hydrophobic impregnations on full-scale RC structures can form part of a wider corrosion management strategy in order to enhance durability and extend the service life of RC structures.

1. INTRODUCTION

Reinforced concrete (RC) structures are an essential part of society's infrastructure and the number of these types of asset has increased considerably with over three quarters of the current UK bridge stock built after 1960 [1]. However, their long-term performance is affected by various factors such as environmental exposure, electrochemical reactions, mechanical loading, impact damage and others. In a survey of 200 bridge structures in the UK, it was identified that at least 30% of those examined where in poor conditions as a result of spalling, rusting and cracking [1]. Chloride-induced corrosion of the reinforcement is

considered the main deterioration cause of RC structures [2]. This is associated with the currently high use of de-icing salts during winter maintenance which is reported to be as much as seven times as in early 1960s [1].

Corrosion management started to be exercised more rigorously in the UK in the 1980's as a result of an increasing bridge stock requiring maintenance and deterioration affecting a large number of bridges which were only in the first 20 years of their design life. It was at this time that Impressed Current Cathodic Protection (ICCP) was successfully trialled in the Midland Links Motorway Viaducts (MLMV) [3]. ICCP benefited a large number of ageing transportation infrastructure assets (i.e. bridges, tunnels etc.) which required unplanned maintenance in order to keep them operational throughout their design life.

This paper provides an overarching review of a recently completed research programme by the authors which investigated the long-term performance of a) patch repairs, b) Impressed Current Cathodic Protection, c) galvanic cathodic protection and d) hydrophobic impregnations by means of in-situ and laboratory testing focused on full-scale RC structures in order to collect rigorous empirical data which can then be used into overarching corrosion management strategies to enhance durability and extend the service life of RC structures.

2. CORROSION MANAGEMENT STRATEGIES

2.1 Monitoring

Monitoring can take various forms. In the UK, highway structures undergo a General Inspection every 2 years and a Principal Inspection every 6. This provides useful information about their condition and possible deterioration. It is essential that regular monitoring takes place to ensure that historical records about a structure's condition are available which will be of great importance in developing relevant maintenance strategies.

2.2 Repairs

Patching of RC is the most common repair technique and involves the removal of physically deteriorated concrete, cleaning of the steel reinforcement and replacing the cover with a repair mortar. The aim is to eliminate the cause of original deterioration and provide protection to the repaired area against future deterioration, thus making the steel within the repair passive [5]. If the approach is targeted to only physically deteriorated areas, the fundamental cause of corrosion initiation may not be always properly addressed. 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 [5]. This phenomenon is usually known as the incipient or ring anode formation [6].

In 2010, a research programme which formed part of full refurbishment works to a multi-storey car park and a bridge was undertaken to assess the impact of macrocell activity on the formation of incipient anodes around the perimeter of repairs in patch-repaired RC structures [7]. Both structures suffered extensive corrosion-induced damage resulting from reinforcement corrosion due to exposure to de-icing salts, with both structures requiring extensive concrete repairs. Three proprietary repair materials (labelled A, B and C in this work) were used to restore the concrete profile [7].

The performance of the repairs was assessed by means of concrete surface potential mapping [8]. Potential maps were obtained on a 50 mm square grid to detect macrocell activity. Typically the steel potential was measured against the potential of a portable reference electrode (Ag/AgCl/0.5M KCl) using a high impedance multi-meter. When a direct

steel connection was not possible relative measurements were taken to determine the change in the potential within the concrete as previously described [9].

The findings indicated that the steel potential within the patch remained more negative than the steel potential in the parent concrete up to 250 days following placement of the repair material (Figure 1). While the measurements were obtained on real structures made with different concretes repaired using different proprietary repair materials that were exposed to a variety of environmental conditions and subject to many other unknown variables associated with repair contracts, there was not a single instance where the potential within the repaired area rose to or above that in the parent concrete.

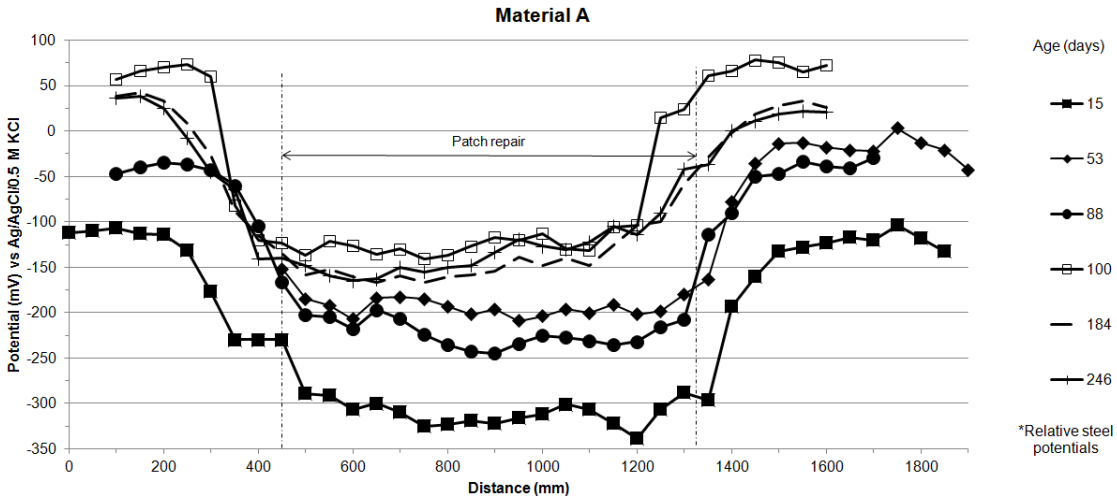

Figure 1: Surface potential mapping with material A over a period of 246 days [7].

Such an observation is not unique and has also been made by Cleland et al. [10] with data over a period of 2 years and by Morgan [11] when testing proprietary repair materials under laboratory conditions. These results support the hypothesis that, on balance, macrocell activity is a consequence, not a cause, of incipient anode formation in repaired concrete structures. The detrimental effect of a corroding steel anode in concrete outweighs any beneficial effects that were provided previously by such an anode.

From all of the above it can be summarised that the use of proprietary repair materials may permanently depress steel potentials within the repair area. The reasons for this include the typically low permeability and high pH of these materials. In addition, cracks can develop at the repair/substrate interface, even with shrinkage-compensated repair materials, providing an easier path for chlorides to penetrate into the substrate.

2.3 Surface Solutions

Hydrophobic Impregnations

Hydrophobic treatments have been used in various forms in the construction industry to help prevent water and chloride ingress into concrete. They can be divided into three categories: coatings, pore blockers and pore liners. The most common pore liners are silanes, a group of silicones containing one silicon atom [12]. They offer simplicity of application, low material cost and low maintenance requirements. Hydrophobic impregnations are covered under BS EN 1504-9 principles 1, 2, 5 and 8 [2] and the required performance characteristics

defined by BS EN 1504-2 [13]. Several studies have investigated the beneficial effects in reducing the rate of chloride diffusion in concrete by employing silanes [14, 15].

Although there are extensive trials assessing silane performance in reducing water absorption, data on their long-term performance under real environmental conditions is quite scarce. Work by Polder and de Vries [15] provided preliminary evidence that silanes were still effective even after five years of outdoors environmental exposure. Work undertaken by the Transport Research Laboratory in the UK [16] also provided a basis for the durability of silanes by examining specimens extracted from full-scale silane treated structures which have been in service for up to four years.

In 2009, a research programme was established to gather empirical data from full-scale RC structures of the Midland Links Motorway Viaducts (MLMV) on the long-term durability of silanes [17]. 12 cross-beams were selected, of which eight had previously received a silane treatment 20 years following their construction, whereas the remaining four had not, hence were acting as control specimens. The silane treatment itself had been in service for a period between 12-20 years. Four cores (diameter and length of 80mm) were extracted for testing from each cross-beam, all from the top surface, which represented the most critical area for water ingress. The effectiveness of the silane treatment was investigated by means of capillary absorption following the procedure outlined in BS EN 13057 [18].

From Figure 2, it can be observed that all specimens initially had a high rate of water absorption over the first 15 minutes of testing. After this time, for the silane treated cross-beams, in most cases the rate of water absorption was significantly reduced or almost eliminated, indicating steady state conditions. For the control cross-beams, in most cases, the rate of water absorption was reduced but never eliminated. It can be observed that control cross-beams D2, D3 and D4 exhibited high rates of water absorption for the initial, secondary and average rates of water absorption. Although all control structures (D series) initially performed better than silane treated cross-beam B6, the later quickly reached near steady state conditions whereas control cross-beams continued their water absorption.

The variance in the rate of water absorption observed may be partly explained by changes in the micro-structure of the specimens as water progress from the cover zone (where concrete may be more porous and exhibit surface cracking) towards the core of the specimens. The thickness of this cover zone is affected by quality control on-site and curing conditions. In addition, as all the specimens were extracted from the top of the cross-beams, this effect may be exaggerated as concrete in this area will be more prone to bleeding.

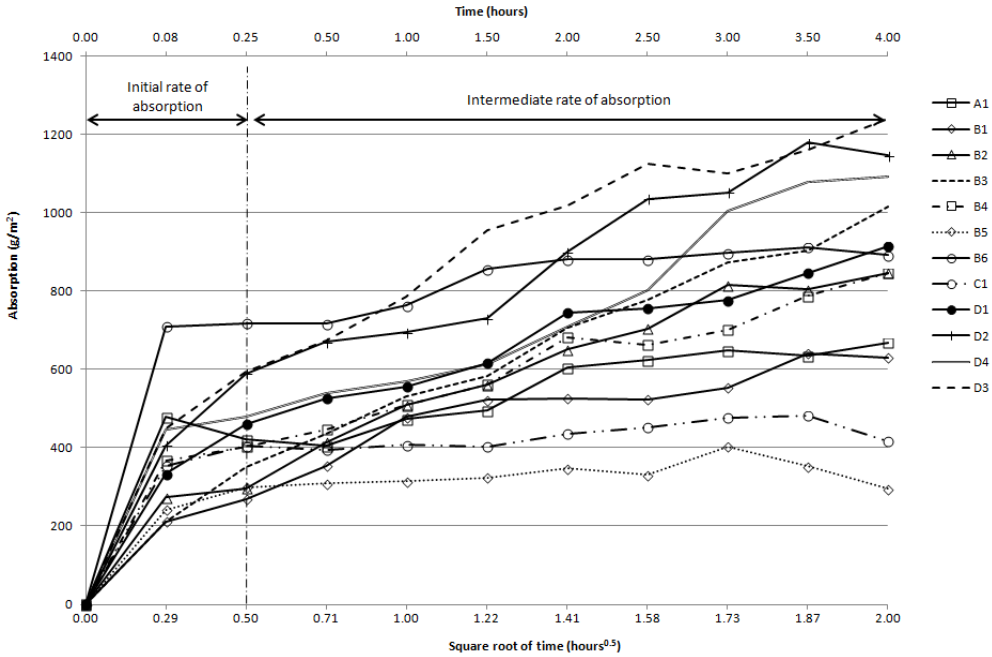

Figure 2: Average cumulative absorption for each cross-beam's group of specimens over 4 hours of capillary absorption testing [17]. The references types (A to D) are only used to differentiate different years of silane application, with type D being control specimens.

Cross-beam C1, with the youngest silane treatment at 12 years at time of testing, had a relatively high initial rate of water absorption but thereafter reached steady state conditions and was the best performer in the intermediate period. Cross-beam B5, with the silane treatment at 18 years at time of testing, was one of the best performing based on initial, secondary and average rates of water absorption and reached near steady state conditions after 15 minutes of testing. From the results of this study it can be concluded that silane impregnations can provide a residual hydrophobic effect even after 20 years of application. Statistical analysis indicated with at least 97% confidence that the variance observed between the silane treated and control specimens was due to a residual protective effect.

2.4 Electrochemical solutions

Impressed Current Cathodic Protection (ICCP)

ICCP is generally regarded as the only solution that can directly stop corrosion, even in the most corrosive environment [19]. It has developed extensively and is considered as one of the main 11 principles and methods for the protection and repair of RC structures [2] and is covered under international standard ISO BS EN 12696 [20]. Broomfield and Tinnea [21] and Glass and Chadwick [22] provided evidence that following a period of continuous ICCP application, there is an increase in the tolerance to chloride contamination. The observation that electrochemically treated structures are more tolerant to chloride contamination is countered by an observation that in very heavily chloride-contaminated concrete, corrosion may initiate again.

In the UK, the biggest application of ICCP systems on RC structures is located on the MLMV with over 700 of them already installed [23]. With an application history of 25 years, a large number of these systems were reaching the end of their design life, while in many

cases failures were also noted due to material deterioration, vandalism, or improper material selection. Under such conditions the protective current is no longer applied and the structure is considered at risk of corrosion.

In 2007, a research programme was established to investigate the long-term performance of ICCP in the Midland Link Motorway Viaducts (MLMV) and the effects that loss of protective current may have to the overall corrosion risk of individual structures [24]. Ten RC cross-beams from the MLMV were selected in such an order to represent RC with a high risk of chloride induced corrosion that had been subject to cathodic protection for a range of protection periods, from 5 to 16 years.

The corrosion activity in these structures was assessed by a) corrosion potential measurements, undertaken monthly and in some cases continuously, b) polarisation resistance determination of corrosion rates, undertaken monthly to calculate corrosion rates and c) impedance measurement of corrosion rates initiated after 6 months

Figure 3 illustrates a summary of corrosion rate measurements based on polarisation resistance testing over a period of 33 months. It can be observed that in all cases the corrosion rates were well below the Concrete Society [8] threshold level of 2 mA/m2, emphasising the view that ICCP may have persistent long-term beneficial effects. Occasionally, peaks of higher corrosion activity can be observed. These are primarily associated with galvanic currents during wet weather conditions when parts of the structures were wet whereas others remained dry. Overall, there was no trend of increasing corrosion rates after 33 months of no protection.

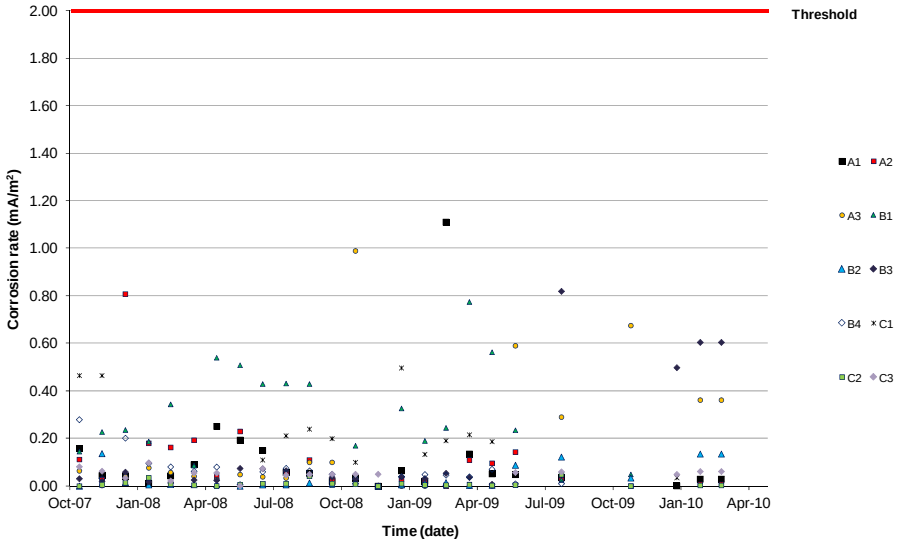

Figure 3: Corrosion rates from polarisation resistance testing over a period of 33 months [24].

Furthermore, the steel potentials have also shifted towards more positive values and have remained passive after 33 months of no protective current. On the whole, a number of the structures investigated had high levels of residual chlorides which represented a substantial corrosion risk. The absence of corrosion supports the hypothesis that ICCP arrests ongoing corrosion and has a persistent protective effect in the absence of a negative potential shift, and that this should be taken into account when repairing old CP systems. The replacement anode systems need only to deliver a low current density to achieve polarisation and prevent future corrosion initiation.

3. CONCLUSIONS

This paper provided an overview of four distinct research packages (Figure 1) relating to the corrosion management and durability of RC structures. From these, the following conclusions have been drawn:

- Incipient anode formation is a consequence rather than a cause of macrocell activity
- ICCP arrests corrosion and has persistent protective effects in the absence of a negative potential shift
- Silane hydrophobic treatments have a residual protective effect to RC structures even after 20 years of in-service

From the above it can be deducted that corrosion management of existing RC structures can be focused to the electrochemical process of corrosion and preventing contamination of concrete structures with corrosion inducing species. This is in line with the observation that ICCP is the most successful and commonly applied electrochemical treatment for RC structures.

Another observation arises from investigations in the performance of patch repairs. They are usually considered as a separate repair technique to electrochemical treatments however, they have an electrochemical effect to the environment they are applied to. This arises from the alkalinity of the repair material which can passivate the steel reinforcement within the repair area.

The observations above can be utilised to develop lean corrosion management strategies and associated technologies to extend the service life or ageing RC structures. In addition, lessons learnt from repair and maintenance can successfully be transferred to the design and codes of practice for new structures. The effect of the concrete's alkalinity can be engineered to produce design mixes which are more tolerant to corrosion inducing species such as chlorides while at the same time provides increased resistance to their absorption and diffusion.

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