Corrosion management of reinforced concrete structures

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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]. Their long-term performance however, is affected by several factors such as environmental exposure, electrochemical reactions, mechanical loading, impact damage and others. Chloride-induced corrosion of the steel reinforcement is usually considered the main deterioration cause of RC structures [2], associated with the ongoing high use of de-icing salts during winter road maintenance, which is reported to now be as much as seven times as in the early 1960s [1].

Corrosion management began to be exercised more rigorously in the UK in the 1980’s as a result of an increasing bridge stock requiring maintenance, as well as 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 on the Midland Links Motorway Viaducts (MLMV), near Birmingham, England, UK [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.

Various techniques have been established and followed by asset owners and their managing agent contractors. These can be categorised in five main groups (Figure 1).
This article provides an overarching review of a recently completed research programme by the authors [4] which investigated the long-term performance of a) patch repairs, b) hydrophobic impregnations and c) ICCP, by means of in-situ and laboratory testing focused on full-scale RC structures in order to collect rigorous empirical data. These findings were then inputted into overarching corrosion management strategies to enhance the durability and extend the service life of the RC structures studied.

CORROSION MANAGEMENT STRATEGIES

Patch 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 the 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 the 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 (Figure 2) [6].
In 2010, a research programme, which formed part of the full refurbishment works to a multi-storey car park and a bridge, investigated the impact of macrocell activity on the formation of incipient anodes around the perimeter of repairs in patch-repaired RC structures [7].

The findings indicated that the steel potential within the patch remained more negative than the steel potential in the parent concrete. 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.

The 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 this, 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 often develop at the repair/substrate interface, even with shrinkage-compensated repair materials, providing an easier and more direct path for chlorides to penetrate into the substrate.
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 [8]. They offer simplicity of application, low material cost and low maintenance requirements. Several studies have investigated the beneficial effects in reducing the rate of chloride diffusion in concrete by employing silanes [9 – 11]; there is scarce data however, on their long-term performance.

In 2009, a research programme was established to gather empirical data from full-scale RC structures on the MLMV on the long-term durability of silanes [8]. 12 cross-beams were investigated, 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 [12].

Figure 3: A typical view of the Midland Links Motorways Viaducts (MLMVs).
The results identified that silane impregnations provided a residual hydrophobic effect even after 20 years of application. The effect was reduced with the increasing age of the silane, but still provided hydrophobic protective effects when compared to control non-treated specimens. Statistical analysis indicated at least 97% confidence in the results.

**Impressed Current Cathodic Protection (ICCP)**

ICCP is generally regarded as the only solution that can directly stop corrosion, even in the most corrosive environment [13]. As a technique it has developed extensively and is now 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 [14].

In the UK, the biggest application of ICCP systems on RC structures is located on the MLMV with over 700 of them already installed, primarily on the RC crossbeams [15]. Figure 4 shows a typical sub-structure arrangement. 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 (Figure 5). Under such conditions the protective current is no longer applied and the structure is considered at risk of corrosion.

![Figure 4: Typical sub-structure arrangement of the Midland Links Motorways Viaducts.](image-url)
In 2007, a research programme was established to investigate the long-term performance of ICCP in the MLMVs and the effects that loss of protective current may have on the overall corrosion risk of individual structures [16]. 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.

Results indicated that in all cases examined there was no corrosion activity despite the absence of any protective current for a period of 33 months, as well as residual high levels of 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 can and 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.

CONCLUSIONS

This article provided an overview of a recently completed research programme [4] which investigated the long-term performance of a) patch repairs, b) hydrophobic impregnations and c) ICCP, and the following conclusions can be drawn:

- Incipient anode formation is a consequence rather than a cause of macrocell activity;
- Silane hydrophobic treatments have a residual protective effect on RC structures, even after 20 years of in-service;
- ICCP arrests corrosion and has persistent protective effects in the absence of a negative potential shift.
These findings can be utilised to help develop more efficient corrosion management strategies and associated technologies to extend the service life or ageing RC structures. In addition, lessons learnt regarding repair and maintenance can also be transferred to the design and codes of practice for new RC structures.

REFERENCES