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CORROSION RISK OF REINFORCED CONCRETE STRUCTURES FOLLOWING 3 YEARS OF INTERRUPTED CATHODIC PROTECTION

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SUMMARY: Impressed Current Cathodic Protection (ICCP) has contributed significantly to the repair and maintenance of motorway structures in the U.K. By polarising the steel reinforcement it can arrest and prevent corrosion activity and can take away the necessity to remove chloride contaminated but otherwise sound concrete. The aim of this research was to collect data from full-scale motorway reinforced concrete structures which had ICCP systems applied for a range of years and to assess their performance with regards to corrosion. It was found that for structures which had received a protective current for 5 years or more, the steel reinforcement retained a residual passive corrosion condition for at least 3 years following interruption of the protective current. This was despite the fact that in several structures the residual corrosion risk was high, based on the concentration of chlorides that was found at the depth of the reinforcement. It can be concluded that the application of ICCP on reinforced concrete structures for more than 5 years transforms the steel-concrete interface.

Keywords: Corrosion, Cathodic Protection, Concrete, Steel

1. INTRODUCTION

Impressed Current Cathodic Protection (ICCP) is a well-established repair method for corroding reinforced concrete elements with a track record of more than 30 years worldwide. The single largest application of ICCP in Europe is in the United Kingdom on the Midland Links Motorway Viaducts where over 700 concrete structures are currently protected.

Long-term monitoring of field structures suggests that after steel passivity has been induced then the protection current may be interrupted, as illustrated by Figure 1. The technical reason for this is that the application of ICCP has resulted in an increase in the reservoir of inhibitive hydroxide ions at the metal surface which will stifle the corrosion process.
A study undertaken in the U.S.A. by Presuel-Moreno et al. (2005) on the effect of long–term cathodic polarisation of reinforced concrete columns in a marine environment also illustrated the persistent effects of ICCP. The structures tested were partially submerged with the splash zone exposed to very high chloride contamination levels, in cases up to 4.7% by weight of cement and they have been protected by ICCP for an approximate period of 9 years. A more recent report by the Transportation Research Board, U.S.A. (2009) surveyed National Transportation Agencies in the USA to identify where ICCP is used, the reasons for its selection and explanations why it is not used by other States. They concluded that the technique is not used because of disappointing past experience, ICCP being more expensive than other options, and because monitoring and maintenance was a significant burden.

It is apparent that although ICCP is a respected repair method offering extended life service it is more expensive than other methods and there is also a greater degree of complexity. Further exploration is needed of the issues associated with ICCP, to quantify the true effect offered by long-term protection and if possible refine the ICCP method to make it more competitively in the current market conditions. This study therefore sought to identify the existence of long-term effects from the use of ICCP in a number of field structures. The objective was to systematically collect data from in-service structures that can be compared to published laboratory testing and hence establish if field evidence exists for the effect of long-term ICCP application (Christodoulou et al. 2010).

2. THEORETICAL BACKGROUND

This section discusses the corrosion mechanism for chloride induced attack to atmospherically exposed steel reinforced concrete structures and the principles of operation and protection of Impressed Current Cathodic Protection.

2.1 Corrosion Mechanism

It is well known that chloride contamination can induce severe localised corrosion of the reinforcement (Alvarez 1984). Chloride ions may be cast into the concrete due to poor construction materials or due to the use of accelerators. Such problems are not commonly encountered in new build structures and chloride induced corrosion is a direct result of exposure to marine environments, water spray and the penetration of de-icing salts which are applied on the moist surface of the structure during winter maintenance.

Concrete offers a highly alkaline environment and under these conditions the steel will develop a protective passive oxide film. Figure 2 Error! Reference source not found. illustrates the most thermodynamically stable iron products for different levels of alkalinity-acidity based on an interpreted Pourbaix diagram. It can be therefore understood that the oxides making up the passive protective film are the most stable products for the typical alkaline conditions encountered...
in concrete. Furthermore, it is evident that a significant reduction in pH is required to make these oxides unstable and therefore for corrosion to occur.

Figure 2: Interpreted Pourbaix diagram, showing the thermodynamic stability of iron oxides in varying conditions (Glass et al. 2007)

Chloride attack tends to be localised and the passive oxide film breakdown tends to follow the model of pitting corrosion followed by pit growth (Glass et. al 2000). For corrosion continuum the pits need to grow and this will be achieved by a sustained fall in the local pH and increase in the chloride content at the pit site. As can be illustrated in Figure 2, the reduction in the pH will render the passive oxide film unstable and the presence of chloride ions promotes the dissolution of iron and production of hydrochloric acid – HCl (Glass & Buenfeld 1997). This is also commonly called acidification of the metal – concrete interface.

2.2 ICCP Principles

The principle of ICCP relies on the passage of an electric current from an inert anode, through the electrolyte to the corroding metal surface (cathode) which reverses the direction of the electric current produced by the corrosion reactions. To achieve an electrical circuit a power source is required where the anode is connected to the positive terminal, the steel is connected to the negative terminal and anode and cathode are separated by an electrolyte, which in this case will be the concrete. Figure 3 illustrates a schematic representation of a typical ICCP system and Figure 4 illustrates a typical ICCP installation on concrete structures.

The polarity is reversed by applying a sufficient magnitude of direct current and the steel potentials are driven negatively. For atmospherically exposed reinforced concrete the requirement for adequate protection will be to achieve a depolarisation potential shift of 100mV from instant off up to 24 hours off. Under these conditions the reinforcement is deemed sufficiently polarised and corrosion cannot occur (Wyatt 2009).
3. FIELD STUDY AND METHODOLOGY

The following section describes the bridge structures and the methodology for their selection. In addition, it discusses the testing employed and particular on-site testing arrangements.

3.1 Structures Selection

Figure 5 illustrates a typical arrangement of the sub-structure for the Midland Links Motorway Viaducts in the UK. Each span of the viaduct is simply supported on a reinforced concrete crossbeam. In total there are approximately 1200 crossbeams in the network and about 700 of them have been protected by means of ICCP over the last 20 years.

Ten beams were selected based on the age of the installed CP system, accessibility and chloride levels indicating a residual corrosion risk. In addition, the ICCP system on each beam had a different age (Table 1). On every beam, two locations (called segments) were selected for monitoring based on the chloride analysis, with a total number of monitored locations being 20. Figure 6 illustrates one of the beams that were tested to assess the long-term benefits of ICCP.
All the structures were constructed in the period of 1966 to 1970. A chloride sampling analysis was undertaken to identify areas of residual risk. The locations of testing were in original un-repaired concrete and the chloride contents are expressed as weight percent of cement and for a 25 to 50 mm cover depth. No chloride contents above 2% were detected at this depth. The anode system comprised a conductive coating which was provided by different suppliers in order to compare their individual performance.

**Table 1. Details of the selected structures**

<table>
<thead>
<tr>
<th>Structure Reference</th>
<th>Year of Installation</th>
<th>Locations with Cl- greater than 1%</th>
<th>No of test locations</th>
<th>Locations with Cl- greater than 0.4%</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>1991</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>A2</td>
<td>1995</td>
<td>2</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>A3</td>
<td>1995</td>
<td>2</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>B1</td>
<td>1996</td>
<td>3</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>B2</td>
<td>1998</td>
<td>1</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>B3</td>
<td>1998</td>
<td>2</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>B4</td>
<td>1998</td>
<td>2</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>C1</td>
<td>1999</td>
<td>0</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>C2</td>
<td>2002</td>
<td>0</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>C3</td>
<td>2000</td>
<td>0</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>
3.2 Methods of Assessment
A number of tests were undertaken to assess the potential of corrosion activity in the structures. These were:

a) corrosion potential measurements, undertaken monthly and in some cases continuously
b) polarisation resistance, undertaken monthly to calculate corrosion rates
c) impedance testing for corrosion rates, undertaken monthly where possible

Measuring steel potentials against the potentials of a standard reference electrode was firstly established by Stratful (1957). In general measurements more positive than approximately -200mV are considered to be in the area of small corrosion risk and measurements more negative than -350mV are considered to be in the area of high risk of ongoing corrosion (BA35/90).

Corrosion rates are usually expressed as a current density or a rate of section loss. A corrosion rate of 1 mA/m$^2$ when expressed as a current density is approximately equal to a steel section loss of 1µm/year. The calculation of corrosion rates through the polarisation resistance method is a well established technique and its feasibility has been demonstrated in numerous occasions (Stern & Geary 1957, McDonald & McKubre 1981, Polder et. al 1993, Andrade & Alonso 2004). Rates below 2 mA/m$^2$ (500 years to lose one mm of steel section) are considered negligible and corrosion development is highly unlikely. At a higher rate, localised corrosion activity becomes increasingly likely.

3.3 Testing Arrangement
The arrangement to assess steel passivity is outlined in Figure 7. Briefly, the main elements were the existing ground level power supply, the existing high level cabinet for the CP system, the anode system and a new high level unit to facilitate the new connections to the system.

Firstly, a segment of the anode (patch) was isolated from the rest of the anode system. This isolated area was cleaned and a new anode installed locally, coloured black as seen in Figure 8. A reference electrode located in the middle of the anode segment was used to assess the steel potential shift. The new electrodes were installed to monitor high chloride concentration areas that were not previously monitored from the original electrodes installed during the installation of the ICCP system.
4. CORROSION ASSESSMENT RESULTS

This section discusses the results from the steel potentials measurements, corrosion rates assessment by polarisation resistance testing and impedance testing.

4.1 Steel Potentials

Figure 9 illustrates the steel potentials for all the monitoring locations for the 10 beams for a period of 36 months with respect to the newly installed reference electrodes. In accordance with BA 35/90, values more positive than -200mV indicate a low probability corrosion risk. All but one out of twenty values was more negative, which would suggest a residual corrosion risk. The readings suggest that in the majority of locations the corrosion risk is negligible and the one location identified as a potential risk was further monitored and also checked with polarisation resistance testing.

Figure 10 illustrates the steel potentials from all the 9 original reference electrodes (marked R1.1 to R1.9) for structure B2 with the addition of the 2 new reference electrodes (marked N.R. 1 and N.R. 2). It can be observed that in all cases the values recorded were substantially more positive than -200mV indicating a negligible probability for corrosion. In addition, the old and new reference electrodes have similar fluctuations over time confirming that these are primarily attributed to the change in environmental conditions.
Figure 9: Steel potentials for all monitoring locations of the 10 beams monitored over a period of 36 months.

Figure 10: Steel potentials from the original 9 reference electrodes for structure B2.
4.2 Polarisation Resistance Testing
Manual polarisation resistance testing was undertaken monthly on every structure. However, for some structures, continuous monitoring was undertaken to obtain a better understanding of their behaviour while the ICCP system was switched off. Two structures were selected based on their accessibility, security for installing equipment, age of the ICCP system and opted for structures with a deteriorated system.

![Corrosion rates summary - Segment 2](image)

Figure 11: Corrosion rates summary from polarisation resistance testing over a period of 36 months

Figure 11 provides a summary of corrosion rates calculated from the manual polarisation resistance testing undertaken on every structure monthly. It can be observed that in all cases the corrosion rates have been well below the threshold level of 2mA/m², reinforcing the view that cathodic protection will have persistent long-term effects. Occasional peaks can be seen but these are primarily associated to changes in the environmental conditions.

4.3 Impedance Testing
Impedance is an alternative way to calculate corrosion rates of reinforced concrete structures. It is different from polarisation resistance in that it involves only a small and brief pulse to the structure as opposed to a constant potential applied over a prolonged period. The depolarisation following the pulse is recorded and it can be associated with corrosion rates (Glass et al. 1997).
Figure 12: Raw data for impedance analysis of structure C2

Figure 12 illustrates the data obtained during an impedance testing and the anticipated depolarisation curves. The current applied over a period of time and the depolarisation over time can then be combined to represent impedance. In other words impedance is a frequency dependent resistance characteristic that includes phase angle information. Figure 13 shows typical examples of impedance data for corroding and passive reinforcement. The point of intercept at the x axis gives the resistance and can be translated to a corrosion rate. The higher the scale of the x-axis the lower the corrosion rate of the particular structure. The peak of the curve is the characteristic frequency and in general the lower the frequency the better the condition of the passive film. Higher frequencies indicated actively corroding steel.

Figure 13: Published impedance data illustrating passive and corroding steel (Glass et al. 1997)

Corrosion rates can be calculated from these graphs in the usual manner as the x-axis is providing resistance. Therefore, impedance testing is an alternative technique to polarisation resistance capable of providing accurate corrosion rates. By looking at the results from Table 2 it can be observed that in most cases the two different test methods will produce similar results. There are some variances in magnitude occasionally, however both methods suggest that the corrosion rate threshold of 2mA/m² was never exceeded and the steel remained passive.
Table 2. Corrosion rates for August 2010 based on impedance and polarisation resistance testing

<table>
<thead>
<tr>
<th>Structure Reference</th>
<th>Segment</th>
<th>Polarisation Resistance Corrosion rate (mA/m²)</th>
<th>Impedance Testing Corrosion rate (mA/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>1</td>
<td>0.23</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.25</td>
<td>0.32</td>
</tr>
<tr>
<td>A2</td>
<td>1</td>
<td>0.05</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.039</td>
<td>0.08</td>
</tr>
<tr>
<td>A3</td>
<td>1</td>
<td>0.05</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.02</td>
<td>0.10</td>
</tr>
<tr>
<td>B1</td>
<td>1</td>
<td>0.3</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.54</td>
<td>N/A</td>
</tr>
<tr>
<td>B2</td>
<td>1</td>
<td>0.01</td>
<td>0.23</td>
</tr>
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<td></td>
<td>2</td>
<td>0.006</td>
<td>0.17</td>
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<td>0.16</td>
</tr>
<tr>
<td>B4</td>
<td>1</td>
<td>0.09</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.08</td>
<td>0.26</td>
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<tr>
<td>C1</td>
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<td>0.38</td>
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<td>2</td>
<td>0.46</td>
<td>N/A</td>
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<tr>
<td>C2</td>
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<td>0.007</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.003</td>
<td>0.1</td>
</tr>
<tr>
<td>C3</td>
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<td>0.04</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.05</td>
<td>0.15</td>
</tr>
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</table>

5. DISCUSSION

From the outset of this study the structures were showing signs of good condition with no corrosion induced damage or signs of distress despite the fact that substantial chloride levels still remained in several location as shown by Table 1. Looking at the trends of corrosion rates from polarisation resistance testing and the trend of the steel potentials, they all suggest that the structures are not actively corroding despite the current being interrupted for a period longer than 36 months. In the case of structure B1, anode deterioration was so severe that the anode connections were visibly hanging from the structure and the system was not operational at the initial stages of this study. The current was interrupted at an unknown point in time but the 36 month monitoring data suggest that the structure has been passive for a very long time.
The ten ICCP systems investigated included older designs with single anode zones for the entire structure and newer multizone systems. Furthermore, three different proprietary products were used for the conductive coating anode systems. Based on the monitoring all anodes were capable of inducing steel passivity despite mixed performance results with regards to adhesion. Also, the larger anode zones of the earlier systems did not seem to affect performance and passivity was induced.

Conductive coating anodes for ICCP have in general been associated with low costs but in addition with poor long term performance due to the anode deterioration. In this study apart from the difference in the age of systems, the structures also had different proprietary anodes. In the case of structure A1 where the conductive coating was installed in 1991, it showed very good adhesion until today, with no signs of deterioration and the anode was still operational. By contrast structures A2 and B1 which where installed in 1995 and 1996 respectively, showed extensive anode deterioration. Although the study did not focus on the examination why conductive coatings were deteriorating it is apparent that deterioration is a product specific issue, with some performing substantially better than others.

Looking at the performance specification of conductive coating anodes, they are capable of delivering up to 20 mA/m² at the concrete surface when they are run at their full anode current density which is also 20 mA/m². At areas where the structures had a highly dense reinforcement arrangement, approximately steel surface area to concrete surface area ratio equal to 2, this would equate at a maximum design current density of no more than 10 mA/m² to the steel, which is still within the required limits set by BS EN 12696:2000.

It is common practice that commissioning of any ICCP system will be substantially lower than the design current density and the CP specialist will monitor the system for a period of 28 days after initial energising and will at this point check whether the protection criteria, typically the 100mV depolarisation shift from instant off up to 24 hours off for atmospherically exposed concrete, are satisfied. Only in cases of failure to meet these criteria the CP specialist will increase the current. It can be understood that although BS EN 12696:2000 requires a minimum design current density of 5 mA/m² to be delivered to the steel, in many cases these older systems have delivered lower protective currents, satisfied the 100mV depolarisation criterion and the present study has illustrated that the steel is passive and not corroding.

New designs of ICCP systems in the UK are mainly utilising Mixed Metal Oxide/Titanium mesh system buried in a cementitious overlay. These proprietary products offer varying current densities which can be substantially higher than what could be offered by the conductive coatings. It is also common practice that anode selection is based upon steel to concrete ratio and a selection of the protective current to be delivered to the steel, which is subjective to the design engineer’s perspective. Therefore, in many cases the proprietary anode selected will be delivering a higher current density than what the conductive coatings could achieve.
The findings of this study illustrate that although the old conductive coating systems had limited current output, they have been capable of arresting corrosion and sustaining corrosion prevention. Based on these results, new ICCP design can be refined to use less powerful anode systems than currently used, with similar outputs to the conductive coatings and as a result less powerful power supplies. This would assist to reduce the initial capital costs of ICCP which has been identified as one of the main reasons why some states in the U.S.A. do not use the method.

A basis now exists to use conductive coatings in some structures where durability will not be difficult to achieve. In other terms, where a proprietary product with a good track record exists and the structure is not continuously exposed to rain then the use of conductive coatings is very attractive. Furthermore, in cases where preventative maintenance is applied by terms of replacing an anode system which has reached its service life, conductive coatings are again a very attractive solution as the steel has been sufficiently polarised and the purpose of the refurbished ICCP system will be cathodic prevention.

Finally, this research has illustrated that monitoring of structures is not as critical is previously thought. The structures after their first few years of protection with ICCP are in general sufficiently polarised that corrosion will take a substantial amount of time to re-occur. By extending monitoring intervals substantial cost savings can be achieved, without the Maintaining Agency incurring substantial risks from this action.

6. CONCLUSIONS

Based on the testing undertaken over a period of over 36 months, all structures selected for monitoring are showing that the steel is passive and in some cases where the current was interrupted at an unknown point in time the steel has been passive substantially longer than 36 months. The structures monitored included older single zone ICCP systems, newer multizone ICCP systems and 3 different anode types. No difference in performance between these systems was observed with regards to steel passivation, despite current practice guidance for more zones in a structure.

From the long term performance evaluation of conductive coatings it can be concluded that despite several reported adhesion
issues and early age failures, they have all achieved to sufficiently polarise the steel during their initial operational days. A basis now exists to revise current designs to take into account reduced design current requirements (i.e. less powerful anodes) and therefore reduce installation costs to make ICCP more attractive to Maintaining Agencies when compared with alternative repair methods.

Passivation of steel by the earlier ICCP treatment should be taken into consideration during refurbishment schemes. The refurbished ICCP system should mainly target to prevent corrosion and lower design requirements can be adopted to reduce maintenance costs.

Monitoring can be reduced into extended intervals which can result into substantial cost savings in the long term. It is becoming apparent that refinements are needed in the design of ICCP systems for atmospherically exposed reinforced concrete in order to make the method more cost effective when compared with alternative methods.

7. ACKNOWLEDGMENTS
The authors would like to thank the Highways Agency, AECOM and ESPRC for supporting the lead author throughout the duration of this project.

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9. AUTHOR DETAILS

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</tr>
</thead>
<tbody>
<tr>
<td>John Webb is a Regional Director of AECOM UK and project manager in the structures team in their Birmingham office. After several years of supervision of construction he now manages a wide range of projects including maintenance management and refurbishment of structures, cathodic protection, concrete durability and other associated matters.</td>
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<td>Dr Gareth Glass BSc(Hons) MSc PhD is a Corrosion Consultant with extensive experience in materials technology, durability and rehabilitation of structures. Rehabilitation techniques that have been evaluated and used include various forms of cathodic protection, various temporary electrochemical treatments, galvanic protection, corrosion inhibitors, coatings and novel combinations of these techniques. He is a leading expert in the repair of corrosion damaged concrete and he has over 100 to his name in the area of corrosion protection.</td>
</tr>
<tr>
<td>Prof Simon Austin BSc PhD CEng MICE is Professor of Structural Engineering in the Department of Civil and Building Engineering at Loughborough University. Prior to this he worked for Scott Wilson Kirkpatrick &amp; Partners and Tarmac Construction. He has undertaken industry-focused research for over 30 years into the design process, integrated working, value management, structural materials and their design.</td>
</tr>
<tr>
<td>Dr Chris Goodier PhD MICT MCIOB FHEA is a Lecturer in the Structures and Materials Group in the School of Civil and Building Engineering at Loughborough University, having worked previously at the Building Research Establishment (BRE) and Laing Civil Engineering. His areas of expertise include concrete technology and repair, offsite construction, community energy and construction futures.</td>
</tr>
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