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Cathodic protection on the UK's Midland Links motorway viaducts

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The Midland Links motorway viaducts (MLMV) are a series of reinforced concrete structures comprising 21 km of elevated motorway around the outer circumference of Birmingham. Deterioration was identified early in their serviceable life due to chloride induced corrosion of the steel reinforcement. An electrochemical treatment utilising an impressed current cathodic protection (ICCP) was successfully trialled in 1987 with the first large-scale commercial application of the treatment on the network in 1991. Since then it has been the principal corrosion management strategy for the MLMV, with 740 structures currently protected by ICCP. The aim of this paper is to offer a brief historical review of the MLMV network, discuss the deterioration mechanisms and review the historical developments of ICCP together with its overall performance as a corrosion-management method. Recent developments in cathodic protection technology and secondary beneficial effects of the ICCP previously not recognised are also discussed on how they can potentially result in significant cost savings for maintenance agencies for this and other similarly protected structures.

1. Introduction

Structural concrete is exposed to a myriad of environmental conditions and therefore subject to a wide variety of physical and chemical deterioration. Of these, chemical deterioration is very common, and of particular importance is the corrosion of reinforcement within concrete. Figure 1 illustrates an example of chloride-induced damage for a steel-reinforced-concrete structure.

Reinforcement corrosion is an electrochemical process. The two main causes of corrosion in concrete structures are chloride attack and concrete carbonation. Concrete, under normal circumstances, provides a highly alkaline environment for the reinforcement with pH above 13. Under these conditions, the steel remains passive owing to formation of an oxide film, which covers its surface and presents a barrier to further metal dissolution (Glass and Buenfeld, 1996; Page and Treadaway, 1982).

This paper focuses on the main cause – chloride-induced corrosion. The presence of chlorides in concrete can be a result of either bound chlorides cast in the concrete during construction or ingress of chlorides owing to exposure to a marine environment (i.e., sea water) or the use of de-icing salts. The use of calcium chloride as a concrete accelerator has been restricted since the 1970s (BSI, 1988) and therefore corrosion problems nowadays are mainly attributable to the external ingress of chlorides.

Electrochemical principles of corrosion reactions can be demonstrated with the aid of pH-potential (thermodynamic properties) and polarisation diagrams (kinetic properties). The most thermodynamically stable form of iron as a relationship of the potential and the pH can be illustrated by the simplified Pourbaix diagram in Figure 2. It can be observed that the passive oxide film is the most stable product for the conditions naturally encountered in concrete (pH of 13 or more). For corrosion to occur, this passive oxide film needs to be broken down. This will occur above a certain chloride concentration, otherwise known as the chloride threshold limit (ACI, 2001; Everett and Treadaway, 1985). A recent study by Angst *et al.*

Figure 1. Typical chloride-induced corrosion damage to a reinforced-concrete structure

(2009) illustrated that there is a very broad range of reported values of chloride threshold limits, from 0·1% chloride to in excess of 2% chloride (by weight of cement), indicating that corrosion initiation is subject to a number of factors, not just chloride concentration (Glass and Buenfeld, 1997; Glass *et al.*, 2000; Sergi and Glass, 2000).

2. The viaducts

By 1957 it was becoming apparent in the UK that a transport link was needed between the M1, M5 and M6. The detailed studies that followed resulted in what is nowadays known as the Midland Links. It comprised in total 106 km of motorway of which 69 km were rural type and 37 km urban type motorway. Out of these, 21·3 km consisted of motorway viaducts or as commonly known the Midland Links motorway viaducts (MLMV). The section between Gravelly Hill and Castle Bromwich (junctions 6 to 5 of the M6) was the longest continuous viaduct in the MLMV at a total length of 5·6 km. Part of the MLMV is the Gravelly Hill interchange, junction 6 of the M6, commonly known as the 'Spaghetti Junction' owing to its complexity and was the first of its kind. It connects the M6 with the A38M motorway, A38 and the A5127 (Figure 3).

The MLMV had to pass through a number of urban and rural areas and as a result there was a variety of natural and man-made obstructions to overcome. These obstructions included several canals, the River Tame, River Rea, several reservoirs, the Birmingham–Peterborough train line, the Chase (also known as Walsall) train line, other cross-city train lines, 18 in (0·46 m) diameter high-pressure gas mains, 440 kV overhead electricity lines and many others. Where possible a standard arrangement of a 15·24 m (50 ft) span was adopted with simply supported steel beams and reinforced-concrete composite deck slabs, supported on reinforced-concrete crossbeams, in turn supported on reinforced-concrete columns (Figure 4). Across the entire MLMV there are over 1300 spans, crossbeams and expansion joints and more than 3600 columns.

There were occasions however, where this typical arrangement could not be adopted owing to access issues posed by the

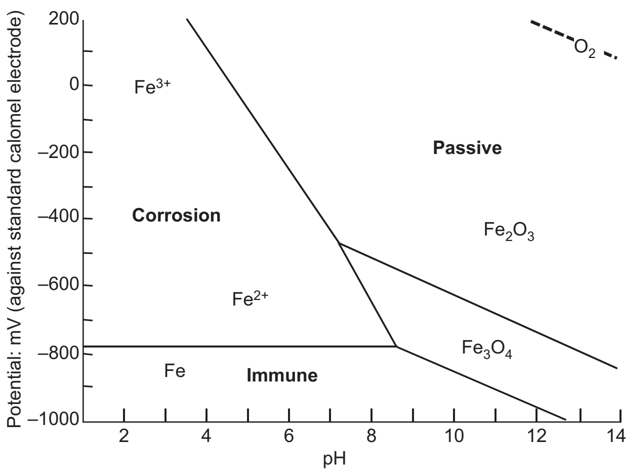

Figure 2. Modified Pourbaix diagram showing the stability of iron as a function of pH and potential (Pourbaix, 1990)

Figure 3. Aerial photograph of Gravelly Hill interchange on the MLMV, J6 of the M6 – known as 'Spaghetti Junction'

aforementioned natural and man-made obstructions. Several alternative solutions were therefore adopted such as

- varying depth I-beams
- steel crossbeams
- longitudinal steel box beams
- continuous deck structures.

Over the years however, the MLMV have suffered from structural deterioration, primarily corrosion of the reinforcement owing to chloride attack. The chlorides can be traced back to the de-icing salts used during winter maintenance to keep the motorways open. The chloride contamination of the substructure can also be attributed to the leakage that occurred through the original expansion joints but also through subsequent expansion joints once they were damaged. Damaged expansion joints allowed water to fall onto the reinforced-concrete crossbeams; concrete delamination has mainly occurred on the top faces but also the elevations of the crossbeams.

Several different actions were taken in order to implement corrosion management on the structures. These included installing gutters, increasing the inspection and testing regimes, using urea as an alternative de-icing agent to normal road salts, structural assessments, hydrophobic treatments such as silanes, concrete repairs and cathodic protection. The use of cathodic protection to arrest active corrosion and lower the risk of further concrete deterioration owing to chloride-induced corrosion became more widespread over the last 25 years and the experiences from its use are discussed below (Cropper *et al.*, 1998).

3. Cathodic protection

The first electrochemical treatments of reinforced concrete elements date back to 1959 when the California Department of Transport (Caltrans) experimented with the first impressed current cathodic protection (ICCP) system (Stratfull, 1959). The first known full-scale ICCP system to be installed on a reinforced concrete bridge was on the Sky Park bridge in Placerville, California in 1972 (Stratfull, 1973).

The principle of ICCP is based on the passage of an electric current from a conductive material (anode) installed either on the surface, or embedded within the concrete, through an electrolyte (concrete) to the steel reinforcement (cathode) which opposes 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 5 illustrates a schematic representation of a typical ICCP system.

By applying a sufficient magnitude of constant direct current the steel is polarised and is made cathodic – that is, only cathodic reaction occurs on the steel reinforcement – hence, the term cathodic protection (Broomfield, 2007; Christodoulou *et al.*, 2009). For atmospherically exposed reinforced concrete the requirements for adequate protection relate to

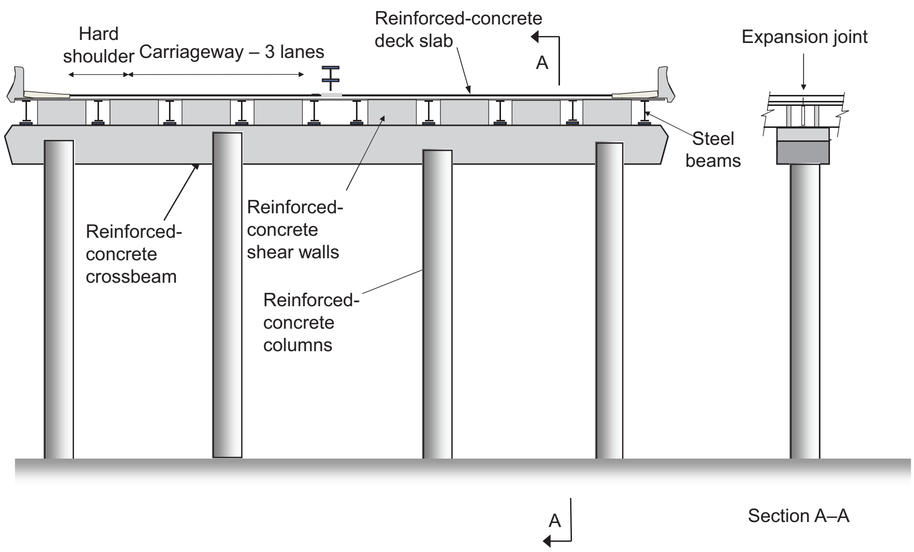

Figure 4. Schematic representation of a typical MLMV structural arrangement

- between 0·1 and 1·0 s following interruption of the protective direct current (instant off), the steel reinforcement should retain a potential more negative than −720 mV with respect to a Ag/AgCl/0·5M KCl (silver/silver chloride/potassium chloride) reference electrode
- the potential shift of the steel reinforcement measured between when the current was applied and up to 24 h off following its interruption should be at least 100 mV
- an extended potential shift of the steel reinforcement measured between when the current was applied and interrupted of at least 150 mV for measurements beyond 24 h.

Under these conditions the reinforcement is deemed sufficiently polarised and corrosion cannot occur (BSI, 2012; NACE, 2007).

4. ICCP on the MLMV

The first trial of ICCP on the MLMV took place in 1986 for the Department for Transport. This trial was performed on the Gravelly Hill Interchange over an area of 200 m^2 of reinforced-concrete structure. The trial was successful and over the years ICCP was employed as one of a wide range of corrosion-management options and only used where appropriate. As well as ICCP, other options included concrete replacement (with no CP), concrete repairs (with or without sacrificial anodes) and complete replacement of structural elements.

The first fully operational ICCP repair contract was installed and commissioned by July 1991; it utilised a conductive coating impressed current anode system. This particular anode system is still operational today (Figure 6). Since then it is estimated that ICCP has been installed on 740 crossbeams of the MLMV and more than 100 000 m^2 of concrete surface area have been protected.

All ICCP systems on the MLMV were monitored on a quarterly basis up until 2010 when a field study of the long-term performance of ICCP uncovered new evidence allowing monitoring intervals to be increased to annual (for systems that are in operation for more than 5 years). This is discussed further in Section 7 below. The monitoring included performance assessment of the ICCP systems to ensure compliance with the relevant design standard (BSI, 2012) and ensure adequate corrosion protection is provided to the structures.

The following sections discuss the various anode systems that have historically been used on the MLMV.

5. Anode systems

As explained earlier, an anode is required to deliver the protective current to the reinforcing steel. The following subsections provide details of the various types of (impressed current) anode systems applied on the MLMV and a brief overview of their performance. A full summary of the anode systems discussed and the number of structures to which they have been applied is provided in Table 1.

5.1 Conductive coatings

The majority of the systems installed have utilised the conductive coating impressed current anode due to the system's low capital costs and ease of installation. They are brush- or spray-applied coatings which contain graphite in order to improve their conductivity. 660 structures on the MLMV have received this type of anode system.

In total, there are 450 structures which received solvent-based coatings and 210 structures which received water-based coatings. Over the years, the MLMV maintenance agencies have experienced varying long-term performance levels for these systems and some of the disadvantages of this particular anode system are discussed later in this paper.

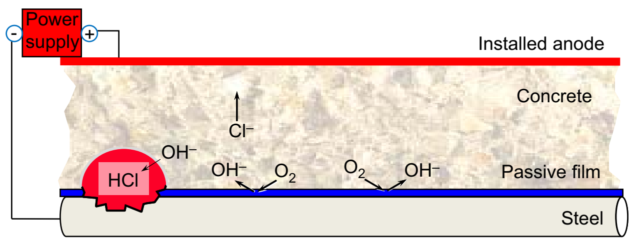

Figure 5. Schematic representation of a typical ICCP system

Figure 6. The first operational ICCP system on the MLMV installed in 1990 as seen on 14/03/2012

Anode system	Number of installations
Solvent-based conductive coatings	450 structures
Water-based conductive coatings	210 structures
Mixed metal oxide/titanium (MMO/Ti) and cementitious overlay	75 structures
Cementitious conductive overlay	75 structures
Discrete impressed current anodes	10 structures
Mixed metal oxide/titanium (MMO/Ti) ribbons	6 structures

Table 1. Summary of anode systems used on the MLMV and number of structures installed

The conductive coatings are in general considered to provide adequate corrosion protection but the current densities delivered are usually limited to 20 mA/m^2 of concrete surface area. With the steel reinforcement to concrete surface ratio exceeding 2 at certain critical locations this equates to a maximum protective current density of 10 mA/m^2 of steel surface area. For cathodic protection design it is recommended to use current density values ranging 5 mA/m^2 to 20 mA/m^2 of steel surface area (BSI, 2012).

As a general rule, ICCP systems are usually commissioned at a quarter of their maximum capacity, and their performance is assessed based on the criteria of BS EN ISO 12696 (BSI, 2012), discussed previously. Such an approach is usually sufficient to meet the performance requirements of the standards. Although the design standards recommend higher current densities than the ones usually used to commission conductive coating anode systems, this approach has not caused any issues and the systems met their performance criteria at all times during commissioning. Over the last 25 years, the annual performance monitoring for every structure protected by ICCP has indicated that conductive coatings have been performing satisfactorily and within the requirements of the design standards. It appears that conductive coatings have been providing the necessary current to protect the substructures on the MLMV, suggesting that potentially lower protective design current densities may be appropriate.

5.2 Mixed metal oxide titanium mesh and cementitious overlay

Over the last 7 years, designs have favoured the use of mixed metal oxide/titanium (MMO/Ti) mesh anodes. It is essentially a mixed-metal-oxide-coated titanium mesh fixed at the surface of the concrete with plastic clips and then covered with a spray-applied cementitious overlay, typically 30 mm thick (Figure 7). In total, there are 75 structures which currently utilise this anode system. This is primarily attributable to greater current outputs from the anodes themselves and improved durability characteristics. The MMO/Ti anode can deliver a higher current to the reinforcement (approximately 110 mA/m^2) which can be very beneficial in cases where the steel reinforcement is extremely dense or deeply embedded in the concrete. A study by Broomfield (2004) illustrated that this type of anode can actually offer corrosion protection to the steel reinforcement of a bridge's half-joint, even at steel layers located 800 mm away from the concrete surface.

Figure 8 illustrates a bridge half-joint exhibiting chloride-induced deterioration. These areas are highly stressed and are heavily congested with steel reinforcement. Access is severely limited and thus the application of traditional concrete repairs can be undertaken only in accessible areas. Following repairs of the physically deteriorated concrete, an ICCP system utilising an MMO/Ti mesh anode was installed to arrest ongoing corrosion activity and prevent further structural deterioration.

The MMO/Ti mesh system utilises a cementitious sprayed overlay mortar to embed the anode and the corresponding cabling. The cementitious overlay, typically 30 mm in thickness, serves as protection to the anode and all the associated cables. MMO/Ti mesh anode with an overlay offers increased durability against environmental conditions compared with conductive coating anodes, partly due to the increased durability of the MMO/Ti anode, and partly owing to the more rigorous surface preparation and interfacial bond. The MMO/Ti mesh serving as an anode for the ICCP system is fixed firmly to the structure and also acts as a light reinforcement to the overlay material (Figure 7). There is also a mechanical bond

Figure 7. A MMO/Ti mesh fixed to a concrete beam prior to the application of the cementitious overlay

Figure 8. Chloride induced corrosion deterioration of a bridge half-joint

of the cementitious overlay with the mesh in addition to the chemical bond between the parent concrete and the overlay.

Although the initial capital costs for this type of anode are higher, as opposed to conductive coating and conductive overlays (see below), over the whole life cycle of the ICCP system the anode does not need to be replaced as it is fully encapsulated and thus protected from environmental effects. In the long term, this approach can provide a very cost-effective solution.

5.3 Cementitious conductive overlays

This type of anode comprises a cementitious material with conductive fibres to provide electrical conductivity. It is spray applied and also contains a strip (ribbon) of MMO/Ti as the primary current feeder to the overlay. The current is then evenly distributed through the overlay as a result of the conductive fibres.

The structures did not originally have bearing stiffeners and transverse restraint was provided by thin and wide reinforced-concrete shear walls (Figure 4). These shear walls were cast integrally with the reinforced-concrete crossbeams and hinged to the reinforced-concrete deck slab above.

These shear walls also received the conductive coating anode system. However, the introduction of the MMO/Ti mesh anodes with a cementitious overlay for the crossbeams was not considered appropriate for shear walls on the MLMV owing to their flexural movement which could cause considerable cracking of the thick overlay material.

Continuing the application of the conductive coatings to the shear walls was also a possibility but an alternative design solution was required which would improve the durability in a similar way as for the crossbeams. In this case spray-applied cementitious conductive overlays formulated to offer electrical conductivity in a similar way to the conductive coatings were used. Electrical current is delivered to the overlay by an MMO/Ti ribbon which can be embedded within the overlay. With regards to the output current densities, conductive overlays provide similar outputs to conductive coating anodes (maximum of 20 mA/m^2 of concrete surface area).

The advantage of this conductive overlay anode system is derived from its increased flexural strength as a result of the added fibres which improve control of structural micro-cracking owing to vibrations. In addition, the thickness of the system (up to 8 mm) is considerably less when compared to the thickness required for the cementitious overlays accompanying the MMO/Ti anodes.

Spray-applied conductive coatings are a recent development on the MLMV, applied to help provide cathodic protection to the shear walls after the introduction of an ICCP system using mesh and overlay less than 10 years ago. To date, no issues have been reported with the long-term performance of these conductive overlays.

5.4 Discrete impressed current anodes

These anodes are usually cylindrically shaped tubes inserted into pre-made cavities within the reinforced-concrete structure and connected together to form an array of anodes acting in unison over a specific area. The number of anodes installed is varying depending on the steel density, with higher amounts of steel requiring a greater amount of anodes.

In the MLMV, discrete anodes have been used on a limited number of MLMV structures, mainly utilised in cases where access for installation is extremely restricted. Typically, they have been used for additional protection of the intermediate layers of reinforcement on half-joints and also for protecting the reinforcement in the bearing plinths. To date, where discrete anodes have been employed they are usually together with other anode systems such as MMO/Ti mesh and overlay.

Installation of discrete anodes to protect very large concrete surfaces with high amounts of steel reinforcement can be a tedious, time-consuming and could be an expensive approach. This is attributable to the fact that very large numbers of anodes are required to be installed in pre-drilled holes together with associated wiring to connect those anodes to the power supply. In view of this, surface-mounted anodes could become more cost-effective and easier to install.

Very importantly, the anodes should have no physical contact with the steel reinforcement in order to ensure that they are electrically isolated. Otherwise, the anodes will form a short-circuit with the reinforcement and no corrosion protection will exist.

Discrete anodes tend to offer high design current densities and are usually installed in areas of high corrosion risk which have difficult accessibility. Thus, the anodes are usually operated on high current densities not far from their capacity as opposed to an MMO/Ti mesh anode and overlay.

5.5 Mixed metal oxide/titanium (MMO/Ti) ribbons

More recently MMO/Ti ribbon anodes installed in concrete chases or embedded within a cementitious overlay have also been used on six MLMV structures. As discussed previously, MMO/Ti ribbon anodes installed on the surface of shear walls and then covered with a conductive overlay has successfully been used. Extending the use of these types of anodes on other parts of structures was therefore considered feasible and anodes were subsequently installed on the crossbeams, column tops and abutment walls.

The ribbons are in principle a type of very condensed and tightly arranged strip of mesh coated with a MMO. Ribbons offer the same advantages as MMO/Ti mesh with high current densities and ease of installation. Where ribbons are installed in concrete chases, they do not require large amounts of cementitious overlays as they are installed in cavities and covered by a grout. Nonetheless, there is still a need for good accessibility in order to saw-cut the chases and achieving good cover to the ribbon anodes is critical for the durability of the cathodic protection system.

In the MLMV ribbons have just started to be applied and therefore their track record is not long. They have been used in areas such as the bearing shelf where availability of space is very limited for the installation of a MMO/Ti mesh and the concrete top is heavily congested with reinforcement, which makes the installation of discrete anodes very difficult. They have also been applied within a cementitious overlay to protect crossbeams and column tops.

Overall, all the anode systems utilised have slowed ongoing corrosion activity and reduced risk of future corrosion damage. This was also illustrated by a recent study which is examined later. ICCP is a technique capable of extending the service life of chloride contaminated concrete structures without the necessity to remove contaminated but otherwise sound concrete.

6. Disadvantages

Although the application of ICCP has been very successful on the MLMV with several hundred reinforced-concrete structures already protected, there have also been a number of issues. Figure 9 illustrates an example of an ICCP system (utilising a conductive coating) exhibiting signs of severe anode deterioration which subsequently resulted in the loss of the protective current.

Deterioration of the conductive coatings may be attributed to a number of reasons. Good surface preparation is very important in ensuring durability as it can affect the bond strength between the parent concrete and the coating. The prevalent environmental conditions such as sunlight and rain can seriously affect the durability of the conductive coatings. Long-term exposure to cycling drying and wetting is a major issue for durability and it has been observed that the majority of the anode deterioration has occurred on the more exposed areas of the structures as a result of loss of bond between the concrete and the conductive coating anode. In addition, these conductive anode coatings have been supplied by a number of manufacturers and their performance has been variable. It should be noted that these anodes were initially envisaged to have 10 years design life which in all cases have been met.

Only conductive coating anodes have suffered in this way and no evidence currently exist with regards to anode deterioration for the conductive cementitious overlays and the MMO/Ti anodes with a cementitious overlay.

Electrical shorts can also affect the operation of the ICCP system. When the anode is in direct physical contact with the reinforcement or tie wires which are attached to the reinforcement then the electrical circuit is shorted and no protective current is being passed. Such occurrences have tended to be

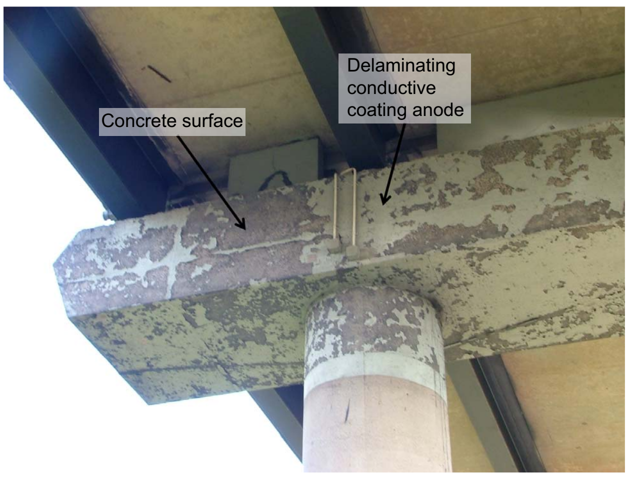

Figure 9. An original water-based conductive coating ICCP system from a section of the M5 motorway, installed in 1993 showing severe delamination of the conductive coating

rare and quickly repaired as there is a very rigorous quality assurance (QA) regime applied on the MLMV at the time of the installation of the CP systems.

A vital element of each ICCP system is the power supply. Initially, these were located at ground level to enable good access, with the cables rising to the crossbeams by way of cable trays attached to the columns of the structures. However, vandalism of the electrical cabling is becoming more common and results to a loss of the protective current to the structures. Several structures have been affected from vandalism and required expensive repairs to replace the electrical wiring and the power supplies. Power supplies, cabling and monitoring equipment now tends to be installed at high level to reduce the risk of vandalism.

For the older ICCP systems, one power supply provided the required protection to each structure. For this reason they were classified as single zone systems. However, over the last decade multi-zone systems have been favoured with a number of power supplies protecting different parts of each structure. Although this approach offers better control of the operating system, it has also resulted in higher capital costs owing to the greater number of power supplies now required and the increase in monitoring locations (as each zone needs to be monitored for its individual performance).

7. Recent developments and discussion

ICCP has generally been associated with high initial capital costs and recently its cost effectiveness has been questioned. A recently completed study by some of the authors investigated the long-term benefits of the early conductive coating anode systems with a view to improving the design approach, reduce maintenance requirements and ultimately reduce initial capital costs (Christodoulou *et al.*, 2010, 2012). This study examined a number of conductive coating anode systems for their long-term performance, including systems which were until today operational and others which where exhibiting significant anode deterioration and as such loss of protective current.

The study interrupted the protective current to ten structures for a period of 3 years and monitored on a monthly basis the condition of the steel reinforcement at critical locations for the initiation of corrosion. The age of the ICCP systems that were selected for this study ranged from 17 years for the oldest to 6 years for the youngest, at the time of the interruption in 2008. The corrosion condition of the reinforcement was assessed by non-destructive electrochemical measurements including steel potentials and corrosion rate measurements (Christodoulou *et al.*, 2012).

Measuring steel potentials against the potential of a standard reference electrode is a long-established technique (Elsener, 2003; Stratfull, 1957). The observed steel potentials can then be assessed against published values and an estimate can be made on the corrosion risk and corrosion probability. In accordance with BA 35/90 (BSI, 1990) and Concrete Society Technical Report 60 (Concrete Society, 2004) values more positive than -200 mV $Cu/CuSO_4$ (saturated copper/copper sulfate) reference electrode indicate a low probability of corrosion. Overall, steel potentials can give a good approximation of the corrosion risk of steel but they are affected by various other factors such as temperature, humidity and oxygen availability.

Corrosion rates are usually expressed as a current density, a rate of weight loss 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 weight loss of 10 g/m^2/year or a steel section loss of 1 μm/year (Concrete Society, 2004). In general, corrosion rates less than 6 μm/year are considered to be low to moderate (Concrete Society, 2004). Therefore, monitoring is required to ensure that they do not increase to much higher values. Corrosion rate measurement can be undertaken on site with various types of proprietary equipment based on the polarisation resistance technique.

For the study, the critical locations for each structure were selected following chloride analysis at the depth of the reinforcement. The locations of testing were in original un-repaired concrete which was now protected by an ICCP system. In the majority of the test locations, chloride concentration at the depth of the reinforcement exceeded 0·4% by weight of cement – a level at which there is a 50% probability of corrosion initiation (Concrete Society, 2004). In fact, several locations even exceeded chloride concentrations of 1·0% by weight of cement – a level at which there is a 95% probability of corrosion initiation. Such locations posed a high residual corrosion risk following the interruption of the protective current provided by the ICCP system.

The results of this 3-year experimental study demonstrated that in all cases examined, no corrosion was initiated despite the structure having a residual corrosion risk owing to the presence of chlorides at the depth of the reinforcement and despite receiving no protection from the installed ICCP system. The youngest ICCP system examined during this study was only 6 years old. Figure 10 illustrates the typical output of long-term corrosion monitoring data from this 3-year period. It can be observed that in all cases, the conservative threshold level of 2 mA/m^2 (i.e., 2 μm/year) was not exceeded.

The findings of this experimental field study from the MLMV provide long-term data with regards to the corrosion performance of chloride-contaminated concrete structures following interruption of the protective current provided by the ICCP system. These results confirm previously published data and hypotheses by Broomfield and Tinnea (1992), Presuel-Moreno *et al.* (2002) and Polder *et al.* (2009), that long-term application of ICCP renders the steel passive and has a persistent protective effect.

The results illustrate that ICCP is not only providing protection by means of a potential shift, as required by the relevant European and international standards (BSI, 2012; NACE, 2007), but there are other secondary beneficial protective effects which were probably responsible for the observed passivity and non-corroding condition of the steel reinforcement at these ten reinforced-concrete crossbeams from the MLMV.

Based on these findings the maintenance requirements of ICCP systems older than 6 years can be reduced, alternative anode systems can be used and the design requirements for high levels of protective current to ensure adequate protection can also be reduced. These findings can result in significant maintenance and initial capital investment savings for maintenance agencies.

On the MLMV, the findings of this study have provided the scientific evidence to reduce the monitoring intervals of all the ICCP systems older than 6 years from quarterly to annually. In addition, the results help to prioritise the repair, refurbishment or replacement of the ICCP systems which have reached the end of their design life, are affected by vandalism or are affected by durability issues such as anode de-bonding.

Overall, the performance monitoring of all the ICCP systems over the past 25 years has illustrated that the ICCP has been providing continuous corrosion protection to these structures, has extended their service life by preventing further concrete and steel deterioration, and have reduced the maintenance requirements for the asset owner.

8. Conclusions

- ICCP has been one of the many corrosion management strategies on the MLMV over the past 25 years and was only used for the structures in most need. ICCP ensured that for these structures, their ongoing corrosion activity was arrested and extended their service life.
- Durability of the ICCP systems has been variable, depending mainly on the type of anode system employed and the environmental exposure conditions. In particular, conductive coating anodes have been occasionally affected by poor bonding with the parent concrete surface, with subsequent de-bonding of the anode. Additionally, vandalism of the power supplies and the cabling/equipment has also affected

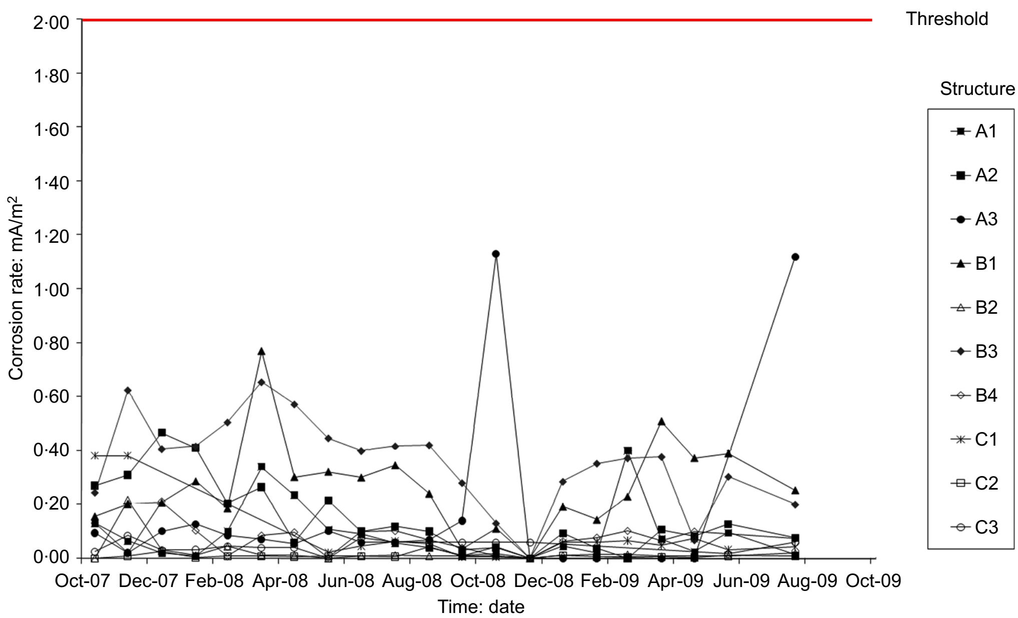

Figure 10. Corrosion rate monitoring of structures in the Midland Links motorway viaducts following interruption of the protective current

the durability of some of the ICCP systems. Improvements in recent designs have significantly reduced the impacts of these issues.

- Research on ICCP on the MLMV has also identified secondary beneficial effects that were previously not recognised. The long-term application of ICCP has provided secondary beneficial protective effects, even when the protective current was interrupted for 3 years; with consequent potential for significant cost savings for maintenance agencies. The results have readily been used on the MLMV to reduce maintenance costs associated with long-term monitoring and also help to prioritise future repair and replacement of the ICCP systems.

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