Monitoring Results of a Range of Galvanic Sacrificial Anodes in Steel Reinforced Concrete for up to 18 Years

George Sergi, David Simpson, Nikita Rathod & Gamini Seneviratne

Vector Corrosion Technologies Ltd.
27A Upper High Street, Cradley Heath, West Midlands, B64 5HX, UK
Tel: +44 (0)1384 671 400

e-mail: GeorgeS@Vector-Corrosion.com

Summary

Sacrificial anodes, both for patch repair enhancement and for more extensive corrosion control, have now been used successfully for more than 15 years. Several sites have been monitored with results confirming their effectiveness in either preventing corrosion initiation around the periphery of the repairs or controlling corrosion in larger protected areas.

This paper reviews the performance of the anodes installed at several UK sites and in one site in USA. It follows on from a ten-year analysis (2009) and demonstrates, from results of current output, steel polarisation levels and estimated corrosion rates, that the repair systems are all still functioning adequately. The repaired areas remain intact with no significant signs of deterioration. The oldest anodes continue to deliver a reduced but significant current complying with accepted criteria. On average about 50% of the original zinc has been consumed over an 18.5-year period. The corrosion control and distributed anode systems are still delivering current outputs after 15 and 10 years respectively at levels comparable to their early life performance and appear to have substantial residual life expectancies.

Considerable knowledge has been gained from the results of the long-term monitoring which has enabled the development of new, more flexible anodes that are now appearing in the market intended for more effective and design-based corrosion control.

Introduction

Chloride induced corrosion of steel reinforcement in concrete structural elements is a major worldwide problem. Chlorides can be introduced into the concrete via deicing salts or seawater. This leads to localised breakdown of the normally passive steel reinforcement in the form of pitting corrosion.

Enhanced patch repairs, where galvanic anodes are attached to the steel around the perimeter of the patch, have now become common practice in the UK and the process is fast being accepted as an essential part of repair works worldwide. The anodes are necessary to deal with the phenomenon of incipient anode formation or ring effect [1,2,3,4], where corrosion is quickly transferred to the patch periphery. The anodes act as an essential form of intentional 'cathodic prevention' so that the adjacent steel remains cathodic and corrosion initiation is prevented.

The galvanic anodes were developed in the late 1990's and are produced from zinc metal encased in a specially formulated porous cementitious mortar saturated with lithium hydroxide (pH >14.5). Such an environment, with a reservoir of excess LiOH maintaining a constantly high pH, was shown to sustain the zinc in an active condition producing soluble zinc corrosion products that do not stifle the corrosion process of the metal [1].

Similar ‘point’ anodes but with a higher current output capability were used in a grid formation to protect larger susceptible areas which had not yet suffered from cracking and spalling. A third type was developed as a distributed anode system in areas where most of the cover concrete had been replaced with fresh concrete or where additional cover was required.

Several trials were set up as part of the repair regime undertaken for the rehabilitation of structural elements over the last 18.5 years both in the UK and the USA. Some of the early results have been reported elsewhere [3,5]. Current densities of the order of 0.3-10mA/m^2 of steel surface were recorded depending on the type of application.

Ten-year results of the oldest site trial at a bridge in Leicester, UK, (Photo 1) were reported earlier [6]. The anodes used at the time were designed for a 10-year minimum life so the results were seen as a milestone. The trial is now 18.5 years old and, as the current output is now diminishing and the anodes are reaching the end of their useful lifespan, it was thought appropriate to present the results over the trial’s lifetime.

The trials

Enhanced Patch Repair

As verification for the performance of anodes embedded within patch repairs in the Leicester bridge structure, a total of 12 commercial anodes were installed in an otherwise conventional patch repair [7] on spalled and cracked areas of a beam section of the bridge (Photo 2). This formed part of a repair scheme with anodes at the perimeter of the repairs for the whole bridge which contained two abutments and two piers each consisting of a long cross beam sitting on 8 columns (Photo 1). The trial was set on the soffit of a section of the beam between Columns 6 and 7 on the west pier (Fig. 2). The performance of these anodes was monitored with time.

Photo 1 South side of the Leicester bridge (west pier on the left)

Photo 2 Installation of anodes within the repaired area of a beam showing also control box and wiring

The extent of deterioration of the beam section that was chosen for the trial is summarised in Figures 2 and 3 which show the chloride contamination at increasing depths and the potential map prior to repair respectively. The chloride concentration at the depth of the steel was over 2% by weight of cement in location C, close to the most negative recorded potential within the area. In location D, the chloride concentration was just below 1%. Both concentrations are overall higher than the range of chlorides found in this particular part of the pier outside the area of repair and the mean for the west pier but lower than the maximum concentration found in the pier (Fig. 2).

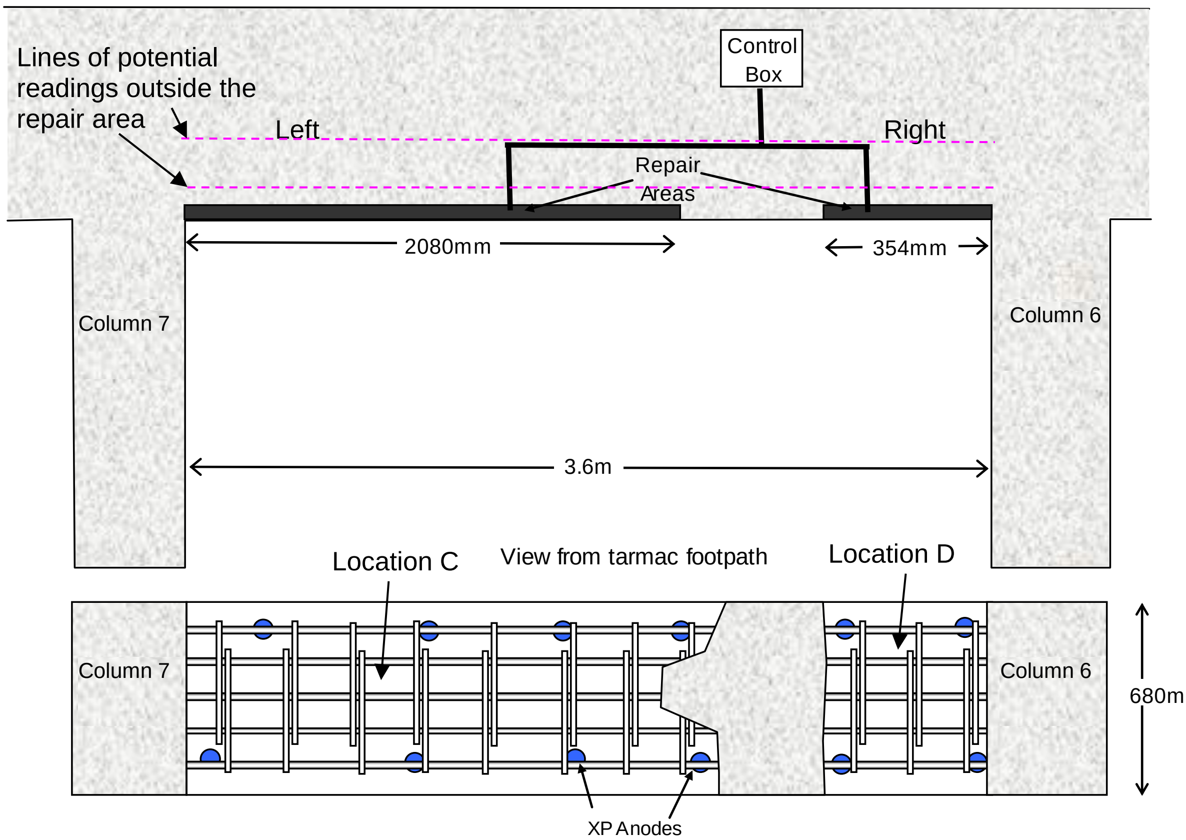

Figure 1 Schematic of the repaired area of the beam soffit

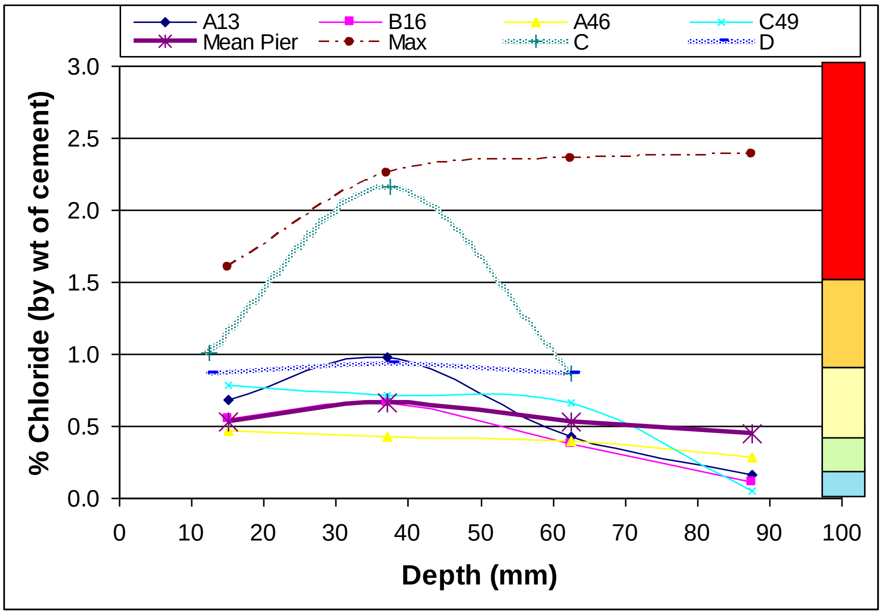

Figure 2 Chloride concentration profiles at positions C and D within the subsequently repaired area of the beam compared to around the beam (A13, B16, A46 & C49) and the maximum and the mean for the whole west pier prior to repair[i] [8].

[i] Colour bars on the side of the graph indicate approximate degree of risk of reinforcement corrosion for the particular chloride concentration range as indicated in BRE Digest 444 Part 2 [8]. Blue and red indicate the extremes in significance of risk of steel corrosion initiation with 'insignificant' and 'extremely high' respectively.

The potential map suggested the presence of corrosion activity of the steel reinforcement which was accompanied by some cracking and delamination. The range of potentials within the test area (Fig. 3), is similar to the whole west pier, a significant proportion of the potentials indicating the presence of some corrosion activity (Fig. 4). The concrete was broken out to behind the steel and to beyond any corroding steel as shown in Photo 2 and Figure 1. No attempt was made to ensure that chloride contaminated concrete areas were removed, the level of chloride in the adjacent un-removed concrete and at depth beyond the steel was known to be significant, as suggested by Figure 2. These are classic conditions for the formation of new anodic sites at the periphery of a conventionally repaired area causing corrosion of the steel and cracking of the concrete within a few years [1,2].

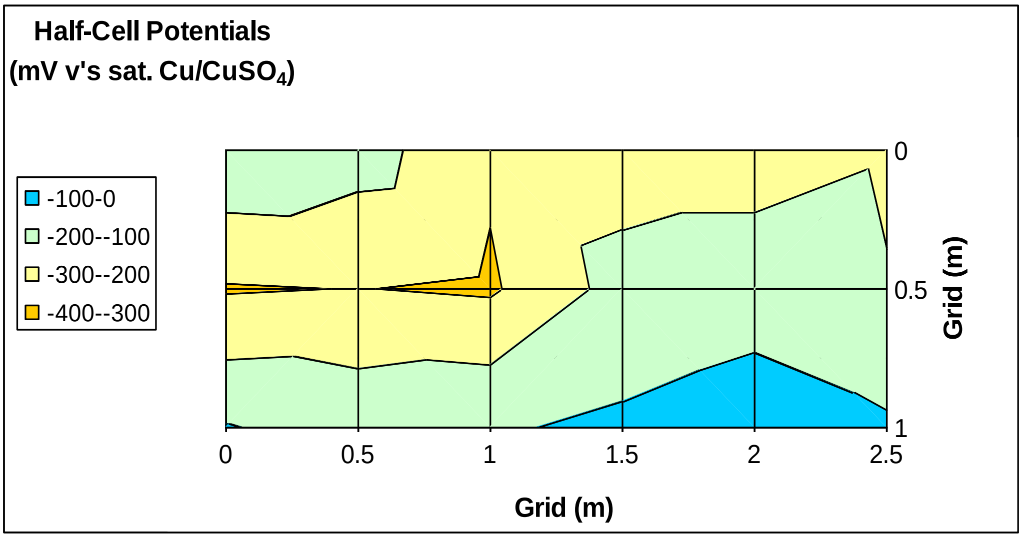

Figure 3 Potential map of the left repaired area of the beam prior to repair

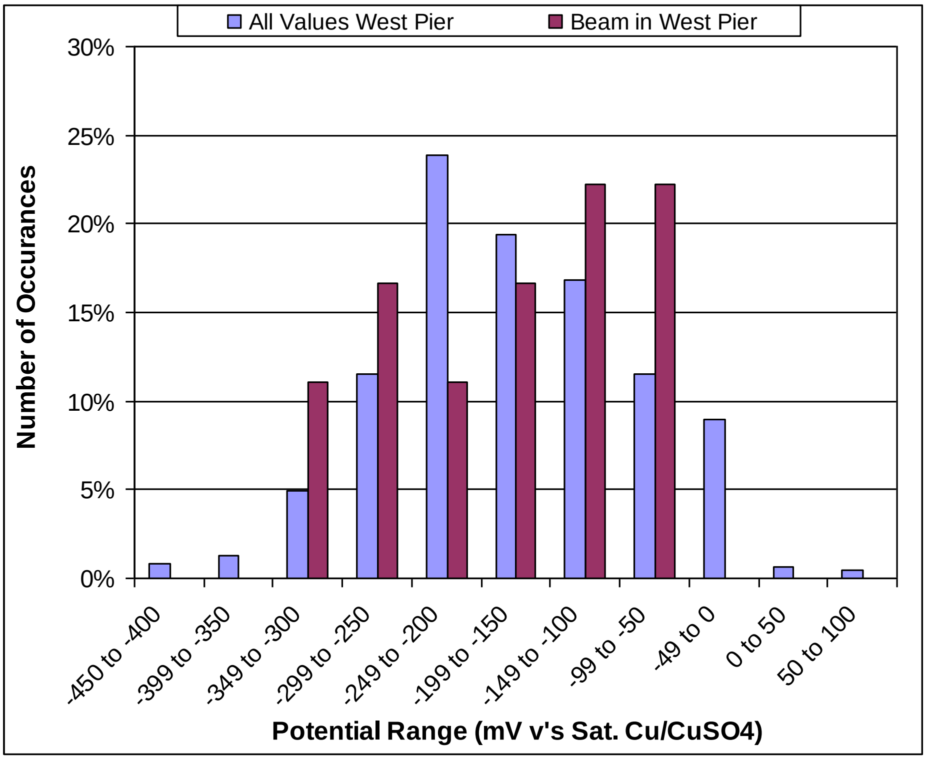

Figure 4 Range of potential values recorded within the area of the soffit of the beam chosen for repair compared to all the values recorded over the whole west pier.

A total of eight anodes were inserted around the perimeter of the left hand repair area and four anodes were inserted in the right hand area at between 600mm and 700mm centres (Photo 2 & Fig. 1). The anodes were specially adapted to enable monitoring. A single wire from each anode was connected to a control box so that connection could be made individually to the steel reinforcement via the box. All other similarly cracked, delaminated or spalled areas of both piers were likewise repaired with anodes positioned at approximately 600-700mm centres around the perimeter of each area. These were directly connected locally to the steel reinforcement using the four tie wires available [7].

Monitoring of the twelve anodes was by a combination of current output measurements for each installed anode and, normally, a depolarisation potential over 4 or 24-hour periods after disconnection of the anodes. Monitoring started in April 1999.

Corrosion Control

Two separate Corrosion Control protection designs were required by the respective clients to be monitored for the early part of their life. Permission by them to return on occasions for additional monitoring allowed a relatively clear picture of their behaviour over a period of around 15 years.

Site-1 Leeds
This was an abutment of a bridge that had shown signs of corrosion owing to leaking joints and partial chloride migration into the concrete. Following a potential mapping survey, it was decided to protect the top and bottom areas of the abutment. As there was no significant deterioration, a decision was taken to embed CC100 corrosion control galvanic anodes in drilled holes in a grid configuration at 300mm spacings both in the vertical and horizontal direction.

Photo 3 Abutment of bridge in Ivy Street, Leeds, showing areas where corrosion control was applied and the two monitored zones

Two zones from each protected area consisting of a chain of 9 anodes in a 3 x 3 configuration were monitored for current delivery. Two reference electrodes one positioned equidistantly between 4 anodes and one in-between two adjacent anodes (Fig. 5) monitored the on, instant-off and depolarised potentials following disconnection of the anodes from the steel over a 24 hour period.

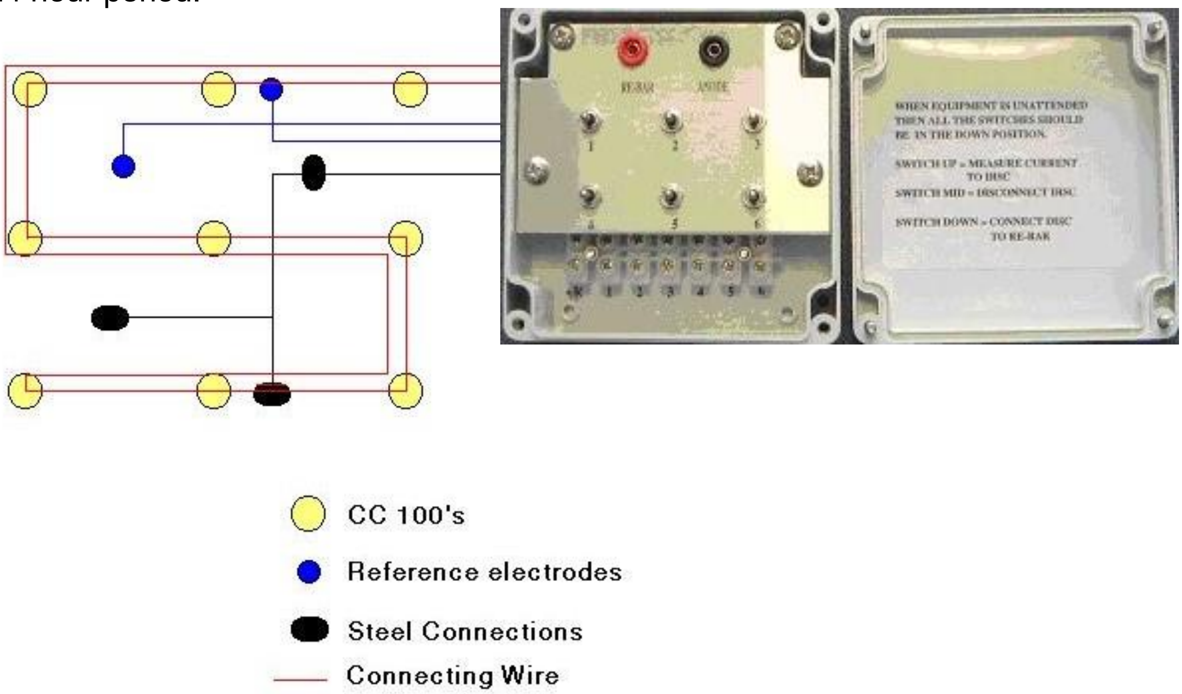

Figure 5 Configuration of anodes, silver/silver chloride reference electrodes, steel connections and connecting wire for the monitored zones showing also the monitoring box.

Site-2 South Clatteridge over M53

Corrosion control was also applied in two adjacent piers of a bridge in South Clatteridge crossing over the M53 motorway in Northwest England. There was concern by the owners that spray from the adjacent frequently de-iced motorway had introduced chlorides to the base of the piers. Even though no significant corrosion was detected, it was thought that deterioration would have occurred in the near future so it was necessary to prevent corrosion of the reinforcement. It also provided an opportunity to compare the CC65 with the CC100 anodes which were both set at 300mm spacings.

 

Photos 4 & 5 Two adjacent piers of a bridge in South Clatteridge crossing over the M53 Motorway with CC100 anodes embedded in the left-hand side pier and CC65 anodes inserted in the right-hand side pier

Distributed Anode System (DAS)

An opportunity arose to install long continuous lines of anodes able to distribute the current better than point anodes when an abutment in Ohio, USA had suffered reinforcement corrosion from leaking of a joint (Photo 6) as, in addition to repairs, it required strengthening. A substantial amount of the concrete was removed, especially near the top of the abutment, and a new thicker layer of concrete, reinforced with epoxy coated steel, was applied as part of the repair and strengthening scheme. DAS anodes were aligned horizontally along the whole length of abutment, as depicted in Figure 6 and Photo 7. These were required to protect primarily the existing chloride contaminated steel susceptible to corrosion.

Photo 6 Deteriorated abutment wall caused by chlorides from a leaking joint above

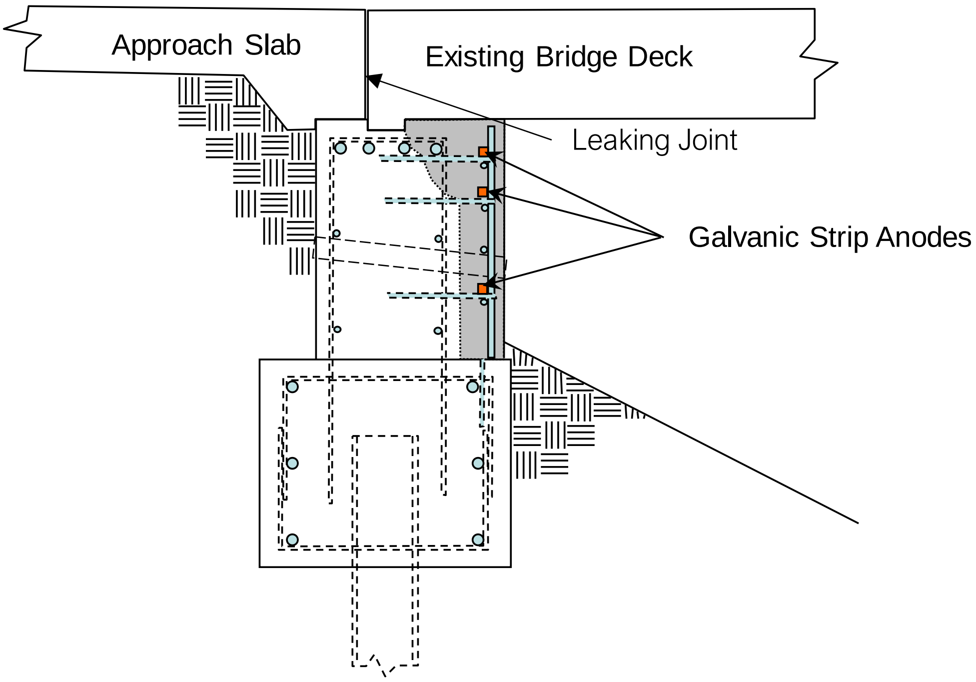

Figure 6 Cross section of the abutment showing its repair and widening (grey area) and the position of the added epoxy bars (green) and the galvanic anodes (red)

Photo 7 DAS anodes positioned as a continuous line along the abutment.

Results and discussion

Enhanced Patch Repair

The 18.5-year results of the current output of each anode are presented in Figure 7. They indicate a variable current depending on the moisture content in the concrete but primarily on temperature (see also next section). For example, the same anode could generate up to 400-600μA of current during hot periods and less than 100μA during cold spells. Corrosion of the steel is expected to have similarly varying corrosion rates so that the current output of the anodes is thought to be self-regulating, producing higher levels when the steel is corroding most.

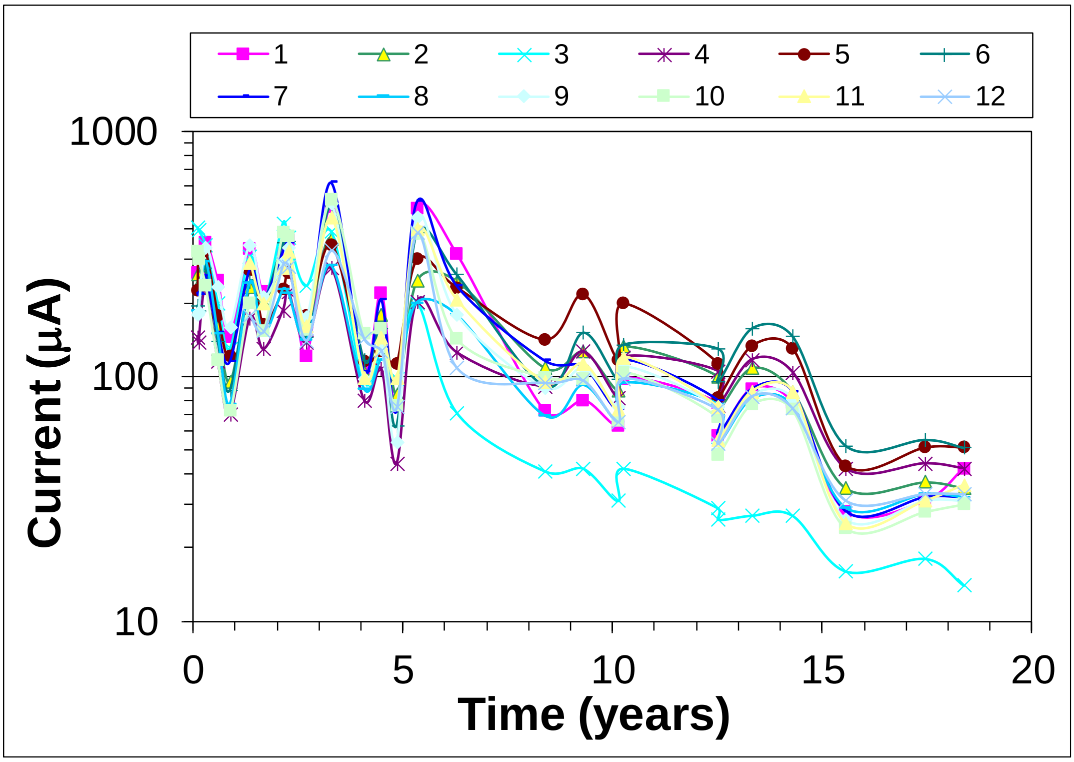

Figure 7 Current output of the 12 individual anodes with time

The total estimated current output of each anode could be converted to a charge delivered to the steel. Fig. 8 shows the mean cumulative charge density. Using Faraday's law, and assuming an efficiency and utilisation rate for the metal, the total consumption of the zinc metal could be estimated. For an efficiency of around 85% the level of consumed metal varied between 35% and 57% (Fig. 9).

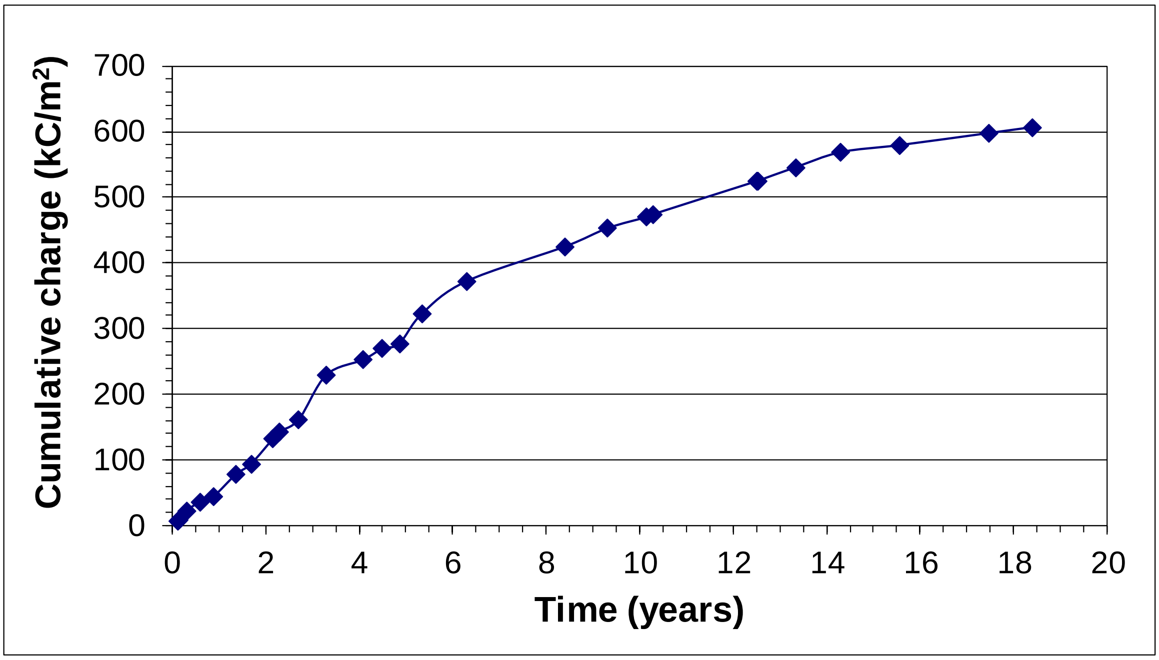

Figure 8 Total mean charge density produced by the anodes in 18.5 years of exposure

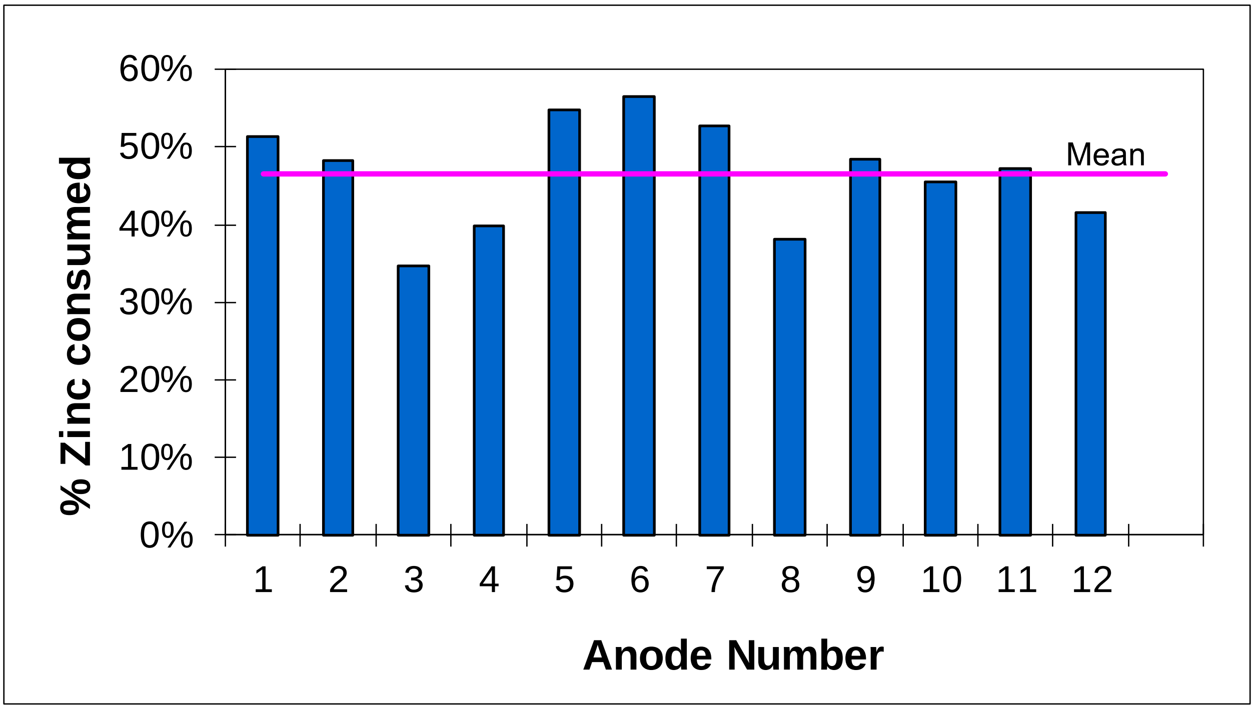

Figure 9 Approximate amount of zinc consumed based on the charge produced and an 85% efficiency

Confirmation of the approximate efficiency was provided by visually assessing removed anodes from an adjacent patch repair in the west pier. These removed anodes had been in operation for 10 years and the exposure conditions were similar to the 12 monitored anodes. Exposure of the zinc core revealed a thickness of corrosion product at the interface of the zinc and encasing mortar. No more than 25-30% of the original zinc metal was lost, a level within the range calculated for the 12 monitored anodes after 10 years, suggesting that the assumed efficiency of 85% is likely to be a fair estimate. There was clear evidence also that the pores of the encasing mortar extending several millimetres away from the zinc/mortar interface, were partly filled with white corrosion products (Fig. 10). This supports the assertion that the zinc corrosion product, likely to be zinc oxide, remains soluble, owing to the pH of the pore solution exceeding 14 as a result of saturated solution of LiOH present in the encasing mortar, and can migrate through the pores before super-saturation and precipitation occurs. The porosity of the encasing mortar is deliberately designed to be high enough to accommodate this kind of corrosion product movement. The mechanism ensures that no stresses and no expansive forces build up around the zinc core and cracks are avoided. It also allows continual exposure of the zinc substrate to the alkali pore solution ensuring its high activity.

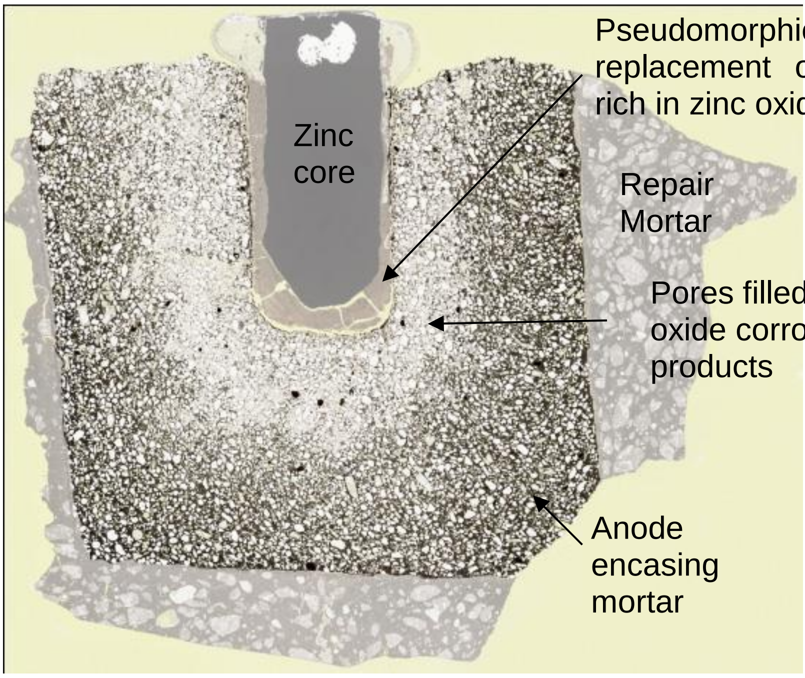

Figure 10 Polished cross section of 10-year old anode, illuminated by filtered light, highlighting zinc oxide corrosion products distributed throughout the encasing mortar

The level of depolarisation was recorded at 12 points within the repaired area and at 8 points outside the repair. In the repaired area this was a 3 x 4 grid at 500mm intervals along the length of the beam and 250mm intervals across the beam but away from the anodes. Outside the repair, the points were along two lines on the vertical face of the beam at 50mm and 300mm from the edge of the repair (Fig. 1). The values recorded were the difference between the potential at the nodes whilst the anodes were connected (not the instant off potential) and the depolarised potential at the same nodes 4 hours after disconnection of all the anodes up to Year-5 and 24 hours subsequently. The potential drop caused by the ir drop was mainly indeterminable as it was very low (0-2mV as read by a multimeter) owing to the low current density delivered by the anodes. The actual depolarisation values ranged between less than 10mV to 95mV, depending on the level of the current measured. The mean over the whole period was 33mV within the repaired area, 47mV at 50mm outside the repair and 23mV at 300mm outside the repair. The results appear to suggest that greater current was delivered at 50mm outside the repair, most likely because of the relatively high resistivity of the repair material in relation to the parent concrete, than within the repair and that a significant current was received by steel 300mm outside the repair.

Systems such as this are designed to cathodically prevent the onset of corrosion of the reinforcement and not to necessarily control existing corrosion as is the case with cathodic protection systems. As such, a much lower current density (0.2-2mA/m^2) is necessary for cathodic prevention, as reported by Bertolini et. al [9] and Pedeferri [10] and adapted in the European Standard EN 12696:2012 [11]. Estimation of the steel surface area within the repaired and affected adjacent area shows that the mean current density ranged between 0.6 mA/m^2 and 3.0 mA/m^2 with an overall mean of around 1.4 mA/m^2 over the first 10 years, generally within the suggested range for cathodic prevention. Beyond 10 years the current density dropped significantly to between 0.3 mA/m^2 and 0.8 mA/m^2 but was still within the cathodic prevention current density criterion for Cathodic Prevention. It is worth mentioning that had the spacing been designed on latest criteria, for the level of chloride (>0.8%) and steel density of over 0.6, it would have been between 400mm and 500mm leading to an overall increased current density even with these embryonic anodes. Considering that the depolarised potentials demonstrate steel passivity (~-50mV to -200mV) and that after 18 years life the patch repair is still operating well, it is reasonable to suggest that the 100mV depolarisation criterion is not applicable for this type of cathodic prevention system. Other criteria for determining the effectiveness of a cathodic prevention system may be necessary.

Monitoring the depolarised potential of the steel in the vicinity of the repair with time may be a more effective way of determining the effectiveness of the system. Figure 11, showing the mean depolarised potential with time both within and outside the repaired area, indicates this. It is clear that the recorded mean potential is continuously moving to a more noble level with time indicating increasing passivity of the steel.

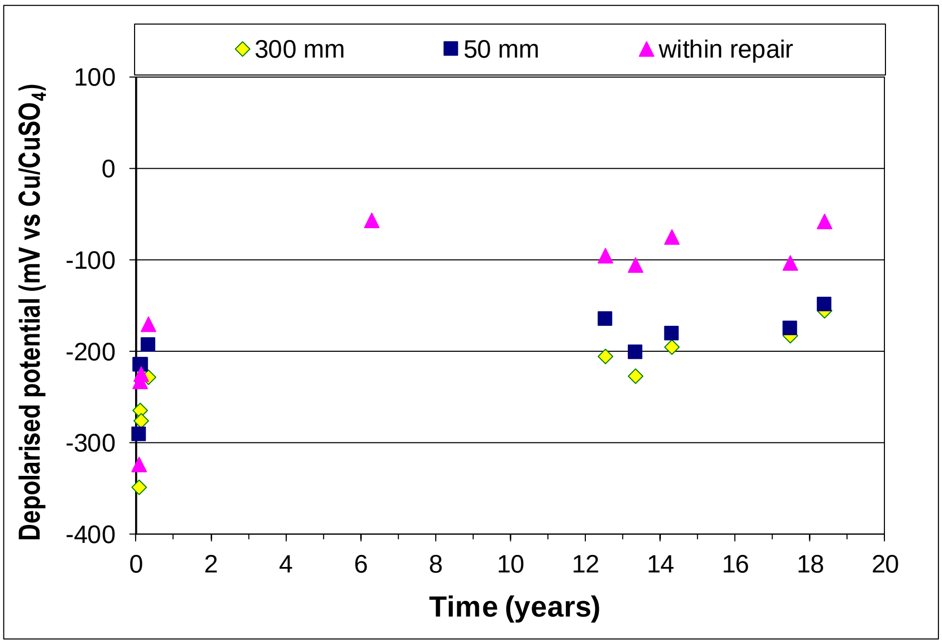

Figure 11 Mean depolarised steel potentials with time (4 hours or 24 hours after disconnection of the anodes)

How the depolarised potential varies over the whole recorded area is illustrated by the potential map at 18.5 years shown in Figure 12.

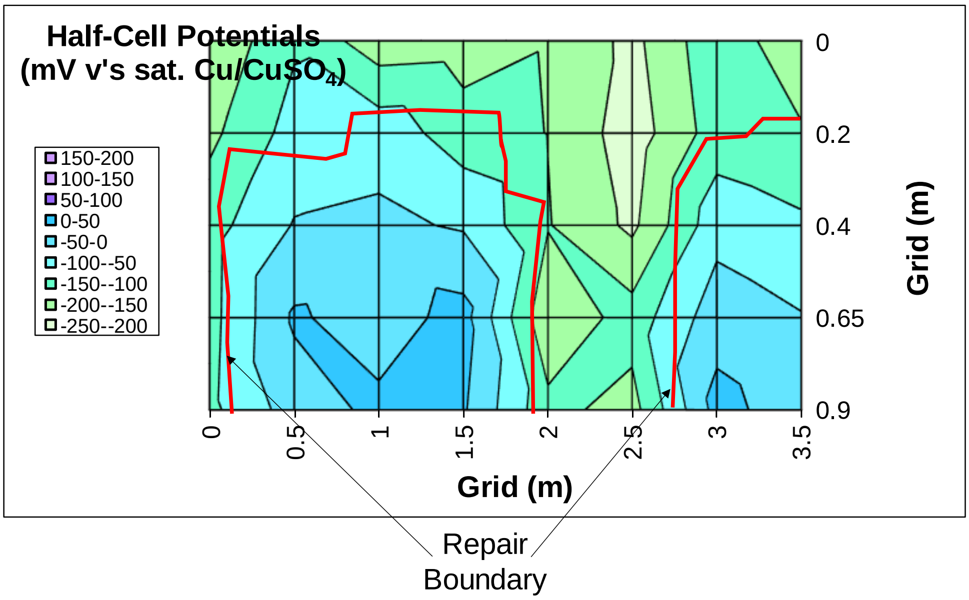

Figure 12 Potential Map after 24 hour depolarisation of the whole area at 18.5 years

An alternative criterion that relates the current applied to the level of depolarisation at any instance has been applied recently [12,13]. This allows an estimate of the mean corrosion current of the steel reinforcement with the use of the Butler Volmer equation.

$$i_{corr} = \frac{i_{appl}}{\exp\left(\frac{2.3\eta}{\beta a}\right) - \exp\left(\frac{-2.3\eta}{\beta c}\right)} \qquad \text{eq. 1}$$

where,

i_{corr} = corrosion current density,
i_{appl} = applied current, i.e. current density,
η = potential shift, i.e. depolarisation potential,
βa = Anodic Tafel Constant (assumed as 120mV),
βc = Cathodic Tafel Constant (assumed as 120mV)

Although the depolarised potential over 24 hours underestimates the total polarisation for the equivalent applied current density, empirically the equation appears to give a fair estimate of the corrosion current density and corresponds well with the depolarised potential. Applying equation 1 to the results, a corrosion current rate with increasing time reveals a decreasing trend of the level of corrosion over the 18.5-year period (Fig. 13).

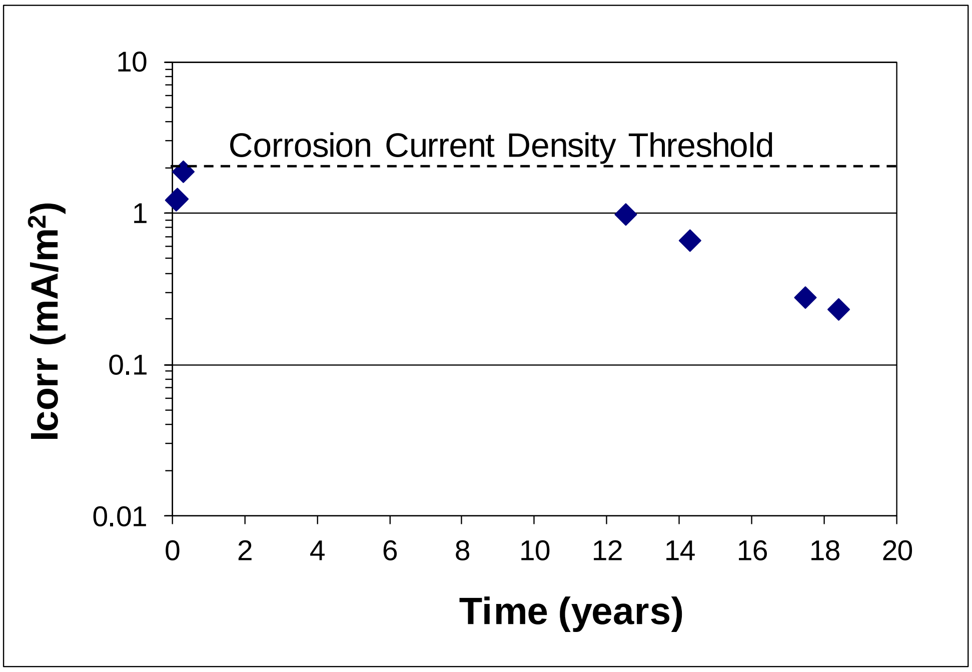

Figure 13 Decreasing trend of the estimated corrosion rate (i_{corr}) of the steel reinforcement with time

This decrease in corrosion rate was shown to be related to possible changes to the steel concrete interface such as increased alkalinity and enhancement of the passive oxide film or localised deposition of solid phases owing to the continuous polarisation of the steel [14].

Corrosion Control

The recorded current density delivered by CC100 anodes in the monitored Zones 1 and 2 at the Ivy Street site are shown in Figure 14. As would have been expected, the current diminished overall with time but remained significant after 15 years. From Faraday's Law, the approximate mean consumption of the anodes assuming 85% efficiency was 38% in Zone-1 and 60% in Zone-2.

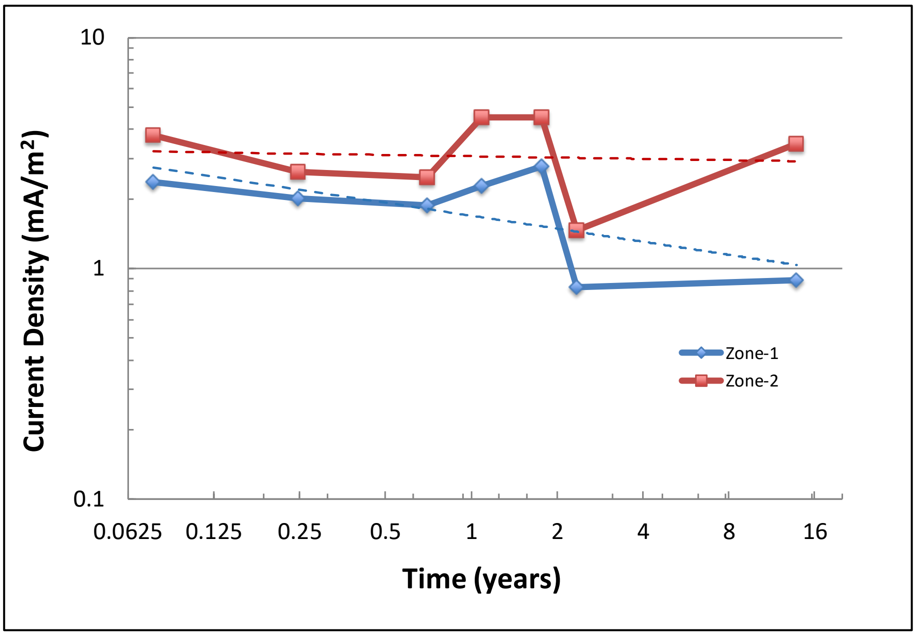

Figure 14 Current density delivered by CC100 anodes in the monitored zones over 15 years

The depolarisation potentials, taking into account the ir drop, over the same period is plotted against the equivalent current density (Fig. 15). The results are interesting in that, overall, a higher current density achieves a greater depolarisation level, as would be inferred by the Butler Volmer equation (eq. 1).

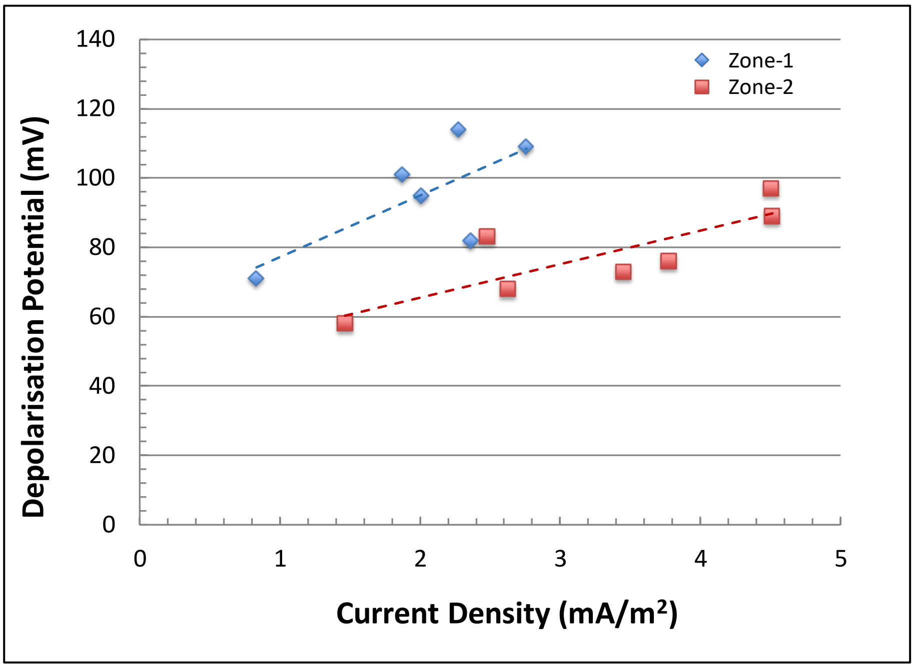

Figure 15 Depolarisation level as a function of current density

The fact that higher depolarisation is achieved in Zone-1 with a lower current density indicates that the steel in Zone-1 is more passive than in Zone-2, a fact that is confirmed by the corrosion current density calculations (Fig. 16). What is also evident, is that the corrosion current has diminished with time in Zone-1 whilst it remained essentially unchanging, but below the threshold of 1-2mA/m^2 in Zone-2. This is very revealing as it is now known that if the correct level of current is applied, the corrosion rate of the steel diminishes over time as the positive effects described earlier (increased alkalinity, reduction of chlorides and build-up of solid phases at the steel-concrete interface) take effect. The figure suggests that there may be a critical current density for any condition (e.g. Zone-1 at Ivy Street and the patch repair at Leicester) above which reduction in corrosion rate can be achieved.

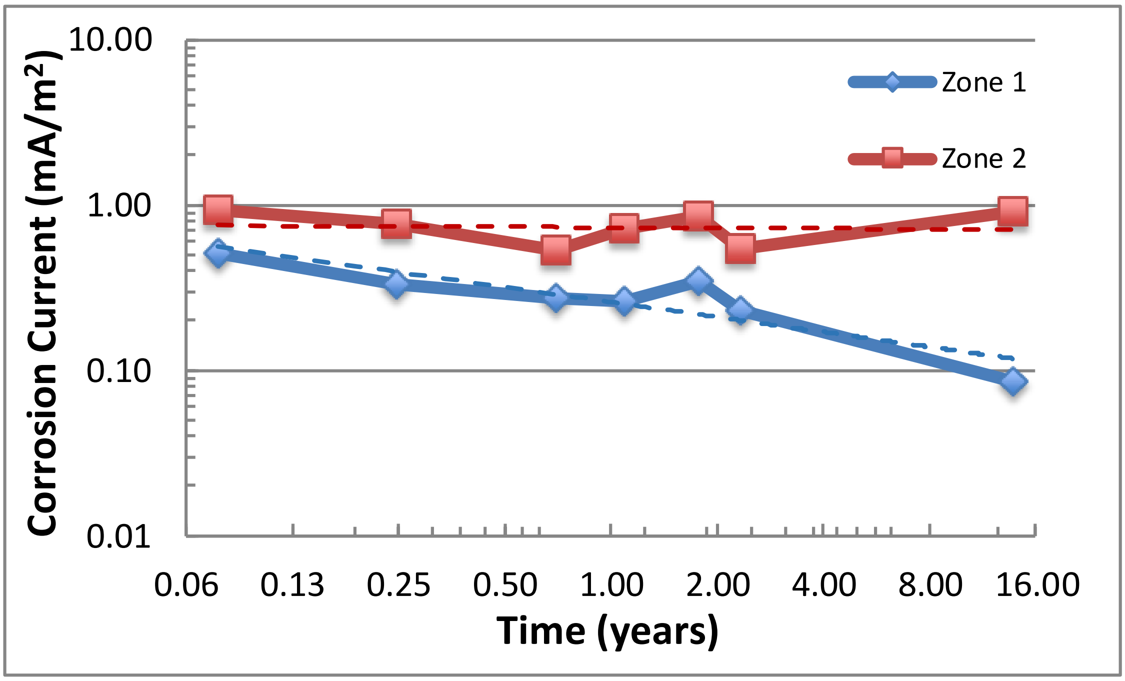

Figure 16 Estimated mean corrosion current density in Zones 1 & 2 over time

Very similar results were observed at South Clatteridge as shown in Figures 17-19. As expected, the current output of the CC100 anodes, having double the surface area of the CC65 anodes, was consistently higher (Fig. 17). The mean estimated consumption of the CC65 anodes was 58% and of the CC100 anodes 52%.

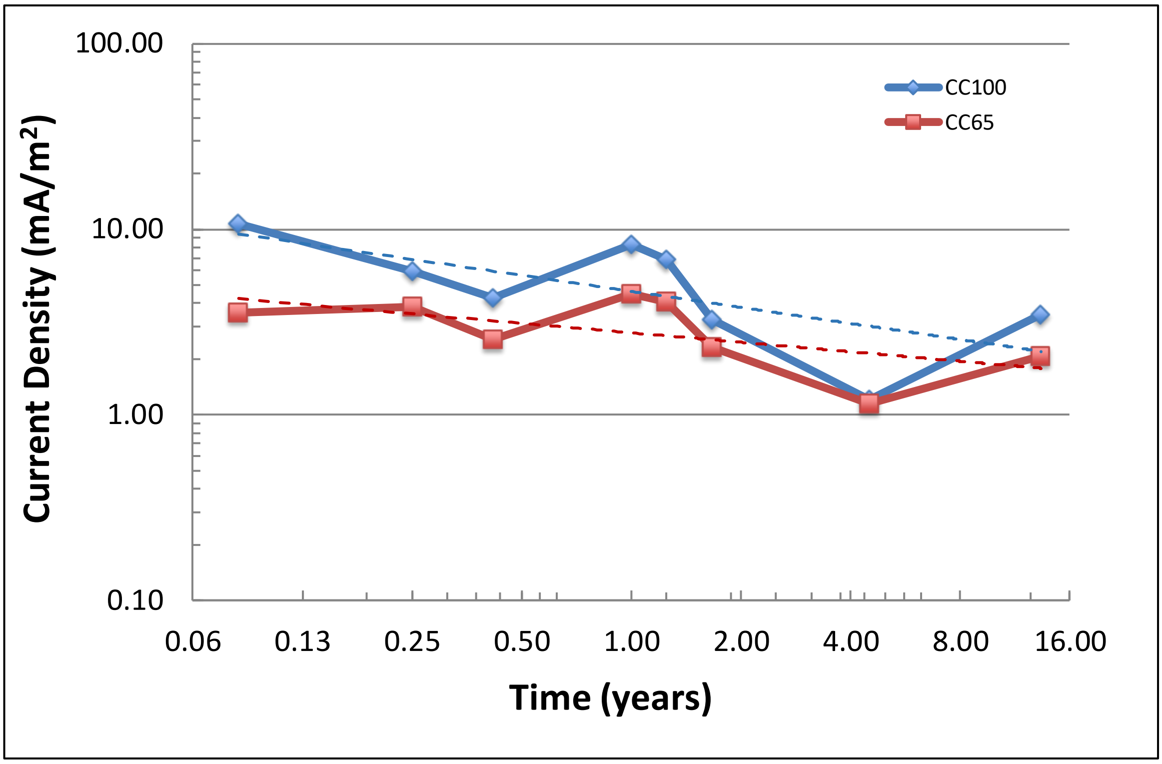

Figure 17 Current density delivered by CC65 and CC100 anodes at South Clatteridge

Similarly, the level of depolarisation was frequently higher with the CC100 anodes (Fig. 18). The resulting estimated corrosion current density remained very low (0.3-0.8 mA/m^2)

reflecting the relatively low corrosion rate of the steel reinforcement prior to the applied protection (Fig. 19).

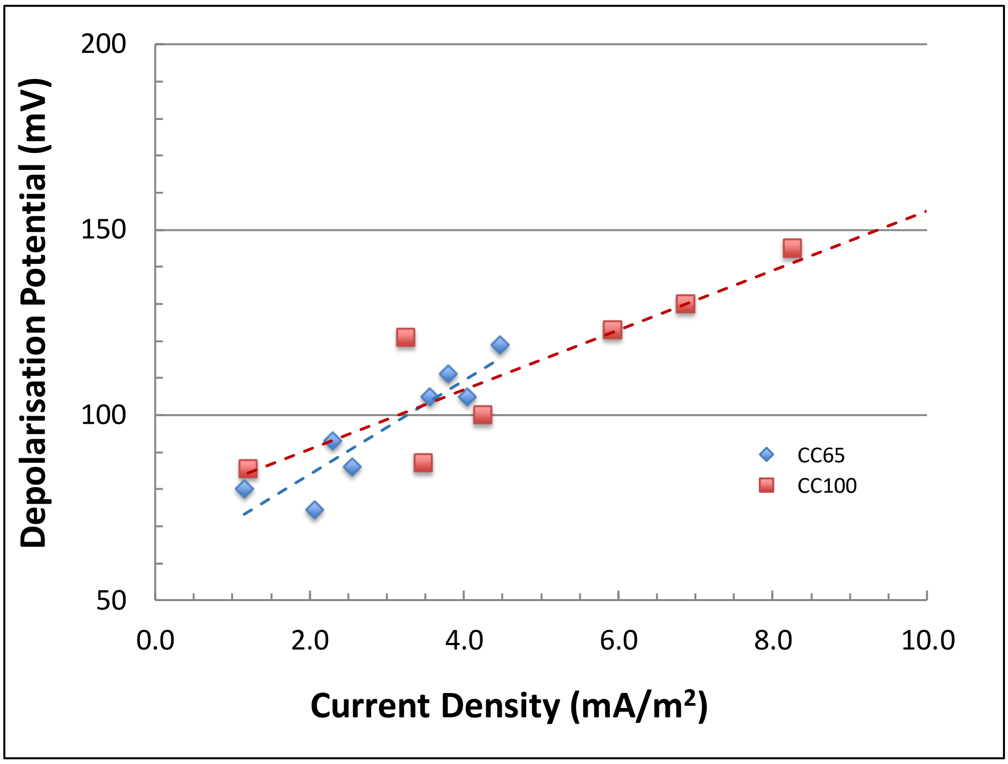

Figure 18 Change in depolarisation with increasing current density at South Clatteridge

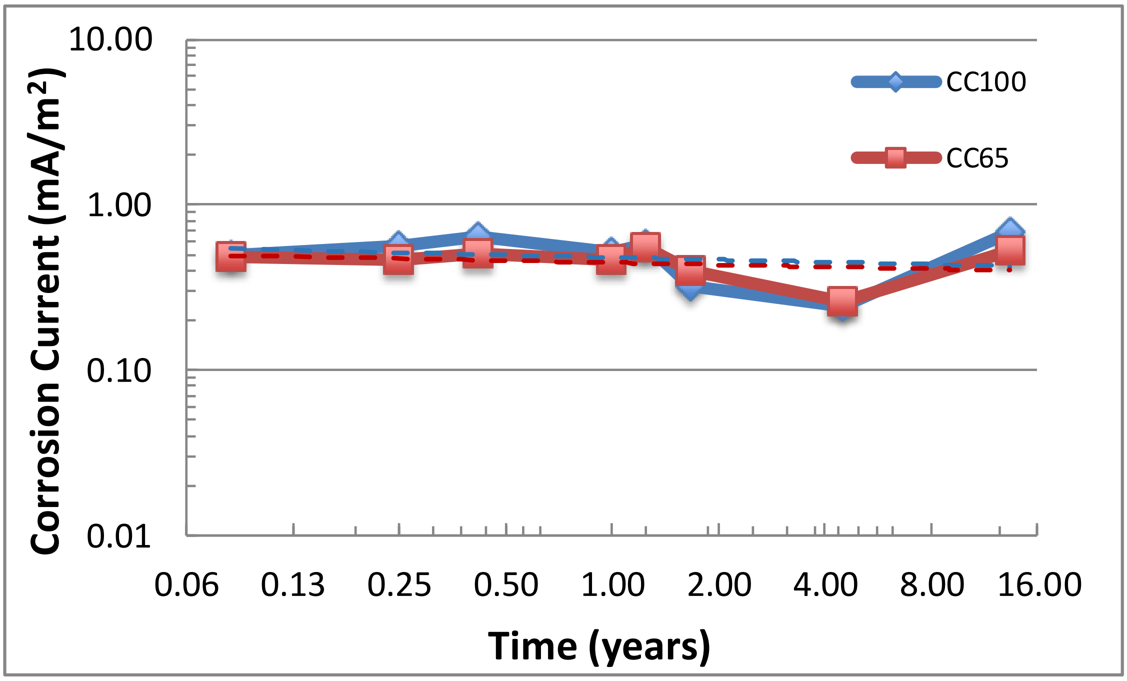

Figure 19 Estimated corrosion current density with time at South Clatteridge

Distributed Anode System

The recorded current density of the DAS rod anodes at Ohio has been consistently around an order of magnitude higher than that produced by the XP point anodes at the Leicester trial (Fig. 20). The same seasonal variation in the current density level is also evident in this case.

Overall, apart from a few minima during cold periods, the current density is compliant with cathodic protection criteria (2-20mA/m^2) with polarisation well in excess of 100mV.

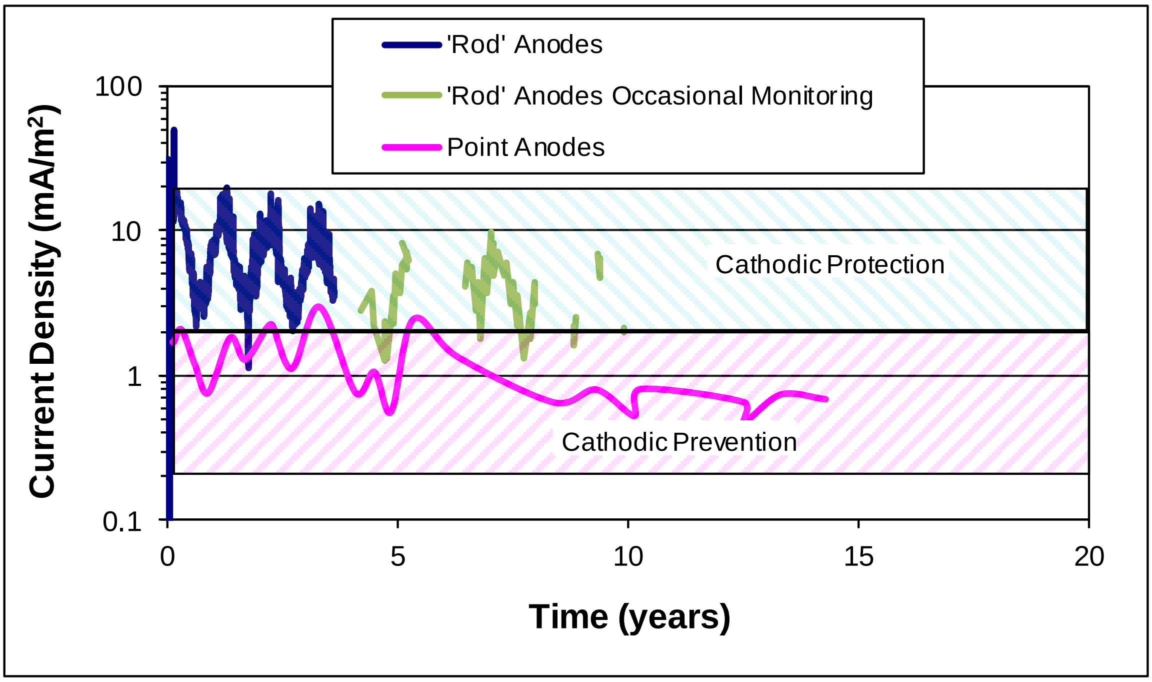

Figure 20 Current density of the DAS rod anodes compared to the Leicester Trial point anodes

New developments

Understanding that the corrosion rate of steel reinforcement can be reduced if a sufficient charge is delivered to the steel, i.e. a known level of current density over a specified period, has led to research to improve the understanding of this phenomenon [15,16,17]. The results indicated that a minimum charge delivered at a current density of the order of 30mA/m^2 is sufficient to arrest corrosion. The magnitude of this charge varies depending on the level of existing corrosion and corrosivity of environment but around 135kC/m^2 of steel area was shown to be adequate in laboratory conditions in concrete dosed with 2% chloride.

It is thus possible to apply a two-stage protection process. Stage-1 involves the arrest of existing corrosion and Stage-2 the prevention of any subsequent corrosion initiation. Stage-2, as a cathodic prevention application, only requires a current density of 0.2-2mA/m^2. Such systems are now in the development stage and will soon appear in the marketplace.

Conclusions

Zinc galvanic anodes, activated by a lithium hydroxide saturated mortar, were shown to be successful in providing adequate cathodic current to the steel reinforcement around the periphery of a patch repair for a period of 18.5 years. This ensured that no incipient anodes were formed on the steel adjacent to the repaired area and the repair as a whole remained intact and free from corrosion of the steel reinforcement. The current density of these anodes has diminished substantially but still produce sufficient preventative current and have far exceeded their 10-year design life. Their longevity can be improved further by better engineering. In fact, the second-generation anodes have been developed with long life in mind.

Depolarisation levels of the steel reinforcement after disconnection of the anodes for periods of either 4 hours or 24 hours rarely exceeded 50mV around the periphery of the repair. The 100mV depolarisation criterion, which applies to cathodic protection systems, is unlikely therefore to apply for cathodic prevention systems of this type. Alternative more realistic criteria may be the monitoring of the depolarised potential with time and the estimation of the corrosion current density from the relationship of the level of depolarisation with the applied current density as described by the Butler-Volmer equation.

Anodes in a grid configuration were also shown to provide adequate corrosion control with depolarisation levels on occasions exceeding 100mV. Corrosion current densities were estimated, as 24-hour depolarisation levels and applied current density were two of the monitored parameters and indicated continued passivity of the steel reinforcement. Where the delivered current density was high enough, a reduction in the estimated corrosion current was observed suggesting that a limiting current density for any specific condition may exist that would allow complete arrest of the steel reinforcement corrosion. This understanding has led to the development of 2-stage processes where corrosion arrest could be achieved early on followed by low current maintenance of the steel passivity.

The technology was shown to be very flexible and by utilising long, better current distributing anodes affixed along the steel reinforcement, it was possible to provide depolarisation levels exceeding 100 mV, and to achieve current densities compatible to conventional impressed current cathodic protection systems.

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