

# Long term control of corrosion of steel reinforcement by a two-stage cathodic protection method

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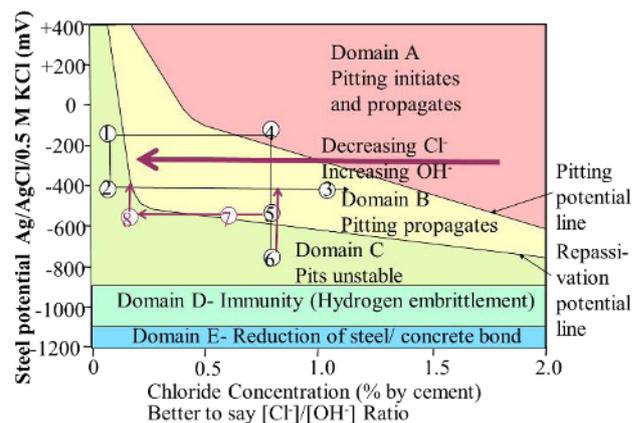
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**Abstract.** It has been shown experimentally that corrosion of steel reinforcement can be arrested if sufficient cathodic charge at a current density higher than 20 mA/m<sup>2</sup> is applied over a period of weeks. Once corrosion is arrested, a cathodic prevention current density, which requires a current density an order of magnitude lower than for conventional cathodic protection, can be applied for long-term prevention of re-initiation of corrosion. Self-contained products were developed in the laboratory according to the Two-Stage principle, each single product containing a battery-operated ICCP element which produces a high initial current output of between 20 mA/m<sup>2</sup> and 50 mA/m<sup>2</sup> of steel area during an initial polarisation corrosion arrest phase and a galvanic anode component which delivers the lower cathodic prevention current long-term. Diodes ensure that the current from the battery is delivered to the steel reinforcement and not dumped onto the galvanic anode and allow the galvanic current to flow only when the ICCP element becomes inoperable. This paper describes the principles of the technique, illustrates products developed and presents medium-term field studies to demonstrate the success of the Two-Stage CP technique.

## 1 Introduction

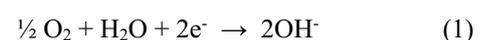
Concrete contains an alkaline pore liquid phase which protects embedded steel from corrosion by enabling, in oxygenated conditions, the development of a highly dense passive oxide film on its surface. This fortuitous protection can be lost, however, if the concrete undergoes either carbonation or chloride contamination in the vicinity of the steel. Corrosion can lead to cracking and spalling of the cover concrete.

The corrosion state of steel in chloride contaminated concrete varies with potential and chloride content, as illustrated by Bertolini et al [1] and summarised in Figure 1. Domain A represents conditions that can lead to the initiation and propagation of pits on initially passive steel. Domain B signifies conditions that allow pre-existing pits to propagate but do not favour the initiation of new pits on initially passive steel. Domain C indicates conditions that do not allow the initiation and propagation of pits, and, very importantly, any pre-existing pits tend to repassivate. Finally, Domains D and E represent conditions that lead to highly negative potentials and steel immunity but are sufficiently reducing to render the passive film unstable. In such cases, hydrogen is formed cathodically, increasing the risk of hydrogen embrittlement of pre-stressed steel tendons. Thermodynamically, therefore, forcing the potential of the steel into Domain C by applying sufficient cathodic current (1 to 4 to 6) would ensure that no new pits will propagate, and existing pits will repassivate. Even if polarisation is only sufficient to place the steel potential in Domain B (1 to 4 to 5), the development of new pits cannot occur and intensity of corrosion in any pre-existing pits will diminish depending on the level of polarisation.



**Fig. 1.** Approximate domains of electrochemical behaviour of steel in concretes with increasing levels of chloride contamination (based on Fig. A.3, ISO 12696:2016 [2])

What Figure 1 also demonstrates quite elegantly is that an increasing level of chloride reduces the steel potential at which pitting can occur (pitting potential) and at which repassivation is possible (repassivation potential) so that an increasing cathodic current is required to force the potential of the steel below these levels as the chloride contamination rises. At the other extreme, there is a minimum concentration of chloride below which pitting is not possible. This, of course, assumes a fixed level of alkali in the concrete. Applying a cathodic current to steel, however, ensures the production of hydroxyl ions on the surface of the steel from the cathodic reaction (eq. 1).



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The applied electric field also attracts alkali cations, present in the pore electrolyte, such as  $\text{Na}^+$ ,  $\text{K}^+$  and  $\text{Ca}^{2+}$ , to the now negatively charged steel. The opposite occurs with the negatively charged  $\text{Cl}^-$  anions which are repelled away from the steel. The reduction of the destructive  $\text{Cl}^-$  ions renders the surrounding electrolyte less aggressive to the steel. Aided by the increase in alkali, which maintains the steel passive, the thermodynamic equilibrium moves to the left, as indicated in Figure 1 by the thick arrow. It would be reasonable to suggest that the chloride concentration axis can be changed to a ratio of chloride to hydroxyl ionic concentration, enabling the potential passivation of the steel with time as  $[\text{Cl}^-]/[\text{OH}^-]$  reduces, even if the level of steel polarisation remains the same (5-7-8). These aspects will be elaborated further in this paper.

Understanding of these principles was essential for the development and evolution of CP of reinforcing steel in concrete. As an example, the recognition that the primary objective of CP, unlike cases such as buried pipelines and submerged steel structures where total immunity is required (Domains D and E in Fig. 1), is simply to reduce the susceptibility of the metal to pitting in the presence of chloride ions was a major development. To achieve adequate CP in a structure in which chloride-induced corrosion has been occurring for some time, it is only necessary to polarize the steel from its condition of pitting (Domain A) to Domain C where pitting is unstable. Thus, complete repassivation of the steel can be achieved.

A development in Italy, which demonstrated a clear understanding of the principles of CP in reinforced concrete, was the application of CP on prestressed concrete viaducts as a means of preventing the initiation of corrosion. In such cases, even though the structures may be exposed to chlorides, their low concentrations near the reinforcement as they are being repelled away are unlikely to cause depassivation, so only modest polarization is needed, typically an impressed current density of about 0.4-2  $\text{mA}/\text{m}^2$  (1 to 2 in Fig. 1), to maintain the steel at a potential where pits cannot initiate. Bertolini et al termed this process Cathodic Prevention [1]. As chloride penetration progresses, it must of course be ensured that the potential remains below the upper boundary of the imperfect passivity domain (2 to 3 in Fig. 1) but much higher chloride levels can be tolerated at the steel before corrosion can initiate.

Another interesting application, is the use of sacrificial anodes to protect both susceptible regions of the reinforcement following a conventional patch repair in chloride-contaminated concrete and as a means of reducing the corrosion activity of the reinforcement [3,4], but the use of galvanic anodes following a short period of ICCP where corrosion is arrested is perhaps the major recent development in the technology which may drive the future of CP.

### 1.1 Two-Stage CP Process

ISO EN 12696:2016 [2] has clear performance criteria that need to be continuously satisfied to ensure that the system is working. A much-used criterion is that a

depolarisation potential of 100 mV should be achieved when the system is temporarily turned off for a period of 24 hours. The standard also defines that a successful CP system either passivates the steel or reduces the corrosion rate of the steel reinforcement to low levels which implies, correctly, that achieving 100 mV of polarisation does not necessarily mean that corrosion has been arrested short-term. Nonetheless, it has been shown in several cases that if a CP system is running for an extended period, e.g. 5 years, and is then turned off, corrosion of the steel does not reinitiate over a significant time period [5]. As briefly mentioned earlier, this phenomenon is believed to be caused by some secondary effects, primarily, the increase in alkalinity and reduction in chloride concentration at the steel/concrete interface [6] which in effect reduces the  $[\text{Cl}^-]/[\text{OH}^-]$  ratio considerably below the critical ratio for initiation or maintenance of corrosion. It has also been suggested that realkalisation of the acidified pits occurs which allows steel repassivation within them [7]. Once repassivation of the steel is achieved, the application of cathodic prevention can then maintain the passive conditions long-term (6 to 2-3 in Fig.1) [8].

It was soon realised that a system that can arrest steel corrosion relatively early and can then switch to cathodic prevention mode over the longer term is realistically possible. It was important, however, to identify the desired current density and overall charge delivery to the steel reinforcement for successful corrosion arrest to occur before the current density is reduced to the lower cathodic prevention current density levels (0.4-2  $\text{mA}/\text{m}^2$ ) which have been shown to be easily achieved by galvanic anodes [8,9].

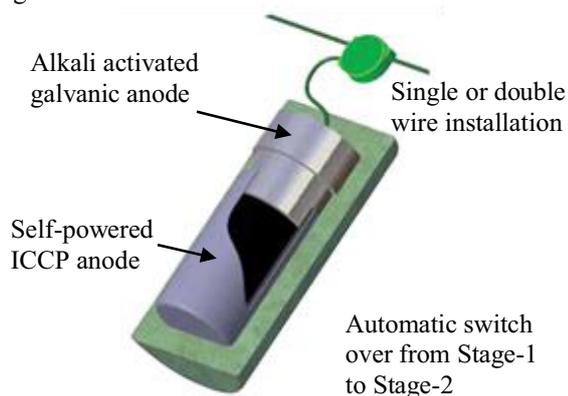
To develop a viable Stage-1 procedure in which corrosion arrest of steel can be achieved, a series of experiments were conducted, the results of which are published elsewhere [10]. What was discovered was very interesting. At two constant current levels, 30  $\text{mA}/\text{m}^2$  and 50  $\text{mA}/\text{m}^2$ , the corrosion of pre-corroded steel plates in mortars containing increasing doses of chloride by weight of cement as NaCl, was arrested after a length of time under polarisation. The required charge (current multiplied by time) delivered to the steel until passivation of the steel was achieved increased with the level of chloride but was lower at the higher current density of 50  $\text{mA}/\text{m}^2$ , as summarised in Table 1. Passivity of the steel was assumed when the 24-hour depolarised potential had reached -150mV vs Ag/AgCl, 0.5M KCl as indicated in ISO 12696:2016 [2].

**Table 1.** Cathodic Charge required to passivate steel at the chloride levels and current densities shown [10]

Current Density ( $\text{mA}/\text{m}^2$ )	30			50	
	1	2	3	2	4
% Cl <sup>-</sup> in Mortar					
Cathodic Charge ( $\text{kC}/\text{m}^2$ )	15	120	190	74	108

As revealed in the introduction, work by Pedeffferri [11] and Presuel-Monreno et al [12] had demonstrated that passivity of the steel can be maintained in a corrosive environment for considerable periods, by Cathodic Prevention, by applying a current density of 0.4-2 mA/m<sup>2</sup>. In part of their work, constant exposure to highly corrosive environments could not initiate corrosion at a current density of 1.6 mA/m<sup>2</sup> even if the chloride concentration near the steel approached 3% by weight of cement [13]. Thus, once corrosion is arrested, it would appear reasonable to suggest that a second stage of a process, based on Cathodic Prevention, is likely to protect the steel from further corrosion. A CP system, therefore, based on a Two-Stage process appears to be a viable corrosion mitigation method.

This understanding formed part of a process that has enabled the recent development of a simple to install and operate Two-Stage Corrosion Mitigation system [14,15]. A schematic prototype of the anode is illustrated in Figure 2.



**Fig. 2** Schematic of a Two-Stage anode

## 2 Installation of anodes at two sites

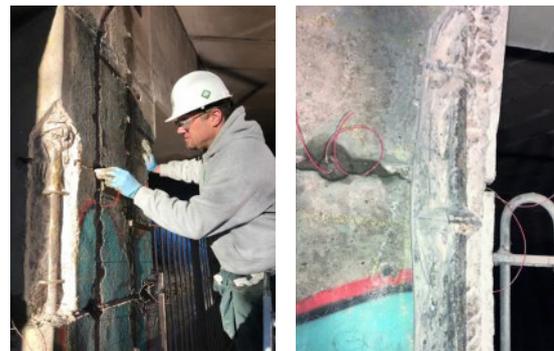
Following developmental and lab experimental work [10] a trial was conducted on a column of a bridge pier in Leicester, followed by a full installation of a structure in South Wales, both in the UK.

### 2.1 Trial in Leicester, UK

The outer two steel bars of a column had suffered from corrosion leading to cracking of the cover concrete (Fig. 3). Chloride levels were found to vary between 0.5% and 2.1% by weight of cement at the depth of cover. To determine an appropriate chloride concentration and allow an estimation of the level of charge that may be required for corrosion arrest based on Table 1, the mean value from 11 dust samples taken from the column was determined and one standard deviation from the mean was added. This gave a value of 1.77 % Cl<sup>-</sup> by weight of cement which translated to a charge requirement of 100 kC/m<sup>2</sup> by steel area. To achieve such a level of charge on all areas of the steel, it is important to account for the reduced current delivery at the points furthest away from four surrounding anodes in a grid. From modelling, current delivery at these points is about half the calculated

mean, so a charge of the order of 200 kC/m<sup>2</sup> was planned to be delivered to the steel.

All cracked concrete that was present on two edges of the column had been removed and repaired with an appropriate repair mortar. A total of six anodes were installed in a grid formation at a spacing of 600 mm so as to surround the repaired areas. Two silver/silver chloride standard reference electrodes were embedded within the test areas in-between the anodes to enable monitoring of the steel potentials both during application of the current and following disconnection. A junction box connected the anodes to the steel externally, so disconnection of the anodes was possible at any stage. Current delivery to the steel, on-potentials and 24-hour depolarisation potentials were recorded at different stages.

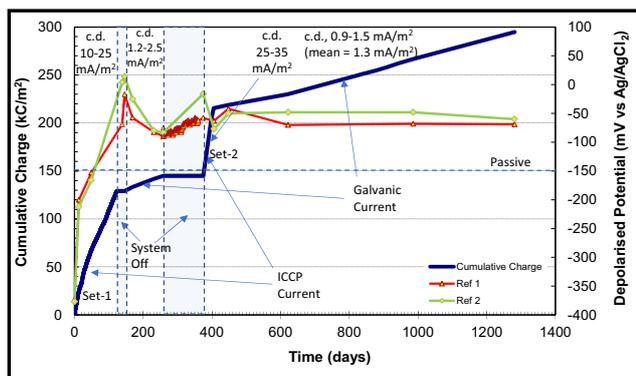


**Fig. 3** Installation of a Two-Stage anode system in a column suffering from reinforcement corrosion from up to 2.1% chloride by weight of cement.

A further 12 anodes were embedded in the column also at 600 mm spacings but were not connected to the circuit. They remained dormant in the structure and were only going to be used if passivation of the steel had not been achieved with the six anodes.

The main results are detailed in Figure 4. The range of current densities applied either during Stage-1 (ICCP anodes) or Stage-2 (galvanic anodes) is indicated at the top of the graph. All potentials shown are 24-hour depolarised potentials, i.e. the current was interrupted for 24 hours before the steel potential was recorded. The anodes were disconnected for two longer periods starting at 130 days and 260 days to allow extended depolarisation of the steel. At 260 days all 18 anodes were cored out of the concrete. Only the 6 active anodes were replaced with smaller capacity anodes and were connected to the steel on Day-360. The cumulative charge delivered to the steel obviously accrued much faster during the application of current from the ICCP component which occurred on separate occasions at zero and 360 days from the two sets of anodes.

It was already evident that even after the initial 130 kC/m<sup>2</sup> of charge the steel had clearly passivated (>-150mV vs Ag/AgCl<sub>2</sub>, 0.5M KCl) and remained passive throughout even after a lengthy lower current delivery from the galvanic anodes at cathodic prevention mode. It was justifiable, therefore, that the remaining anodes were removed for further laboratory studies and for examination and analysis of the different components.



**Fig. 4** Details of the monitoring results since the installation of the system indicating current density, cumulative charge and 24-hour depolarised potentials of the steel as measured by two standard embedded silver/silver chloride reference electrodes.

The charge delivered by the six lower capacity anodes starting at Day-360 did not appear to influence the steel reinforcement potentials any further which remained stable and indicated passivity of the steel throughout.

Depolarisation levels during the ICCP periods were in the range of 150-200 mV as the current density was maintained at high levels of up to 35 mA/m<sup>2</sup> but it is this higher current density that changes the electrolyte around the steel to low, passive-inducing ratios of [Cl<sup>-</sup>]/[OH<sup>-</sup>]. Depolarisation during the galvanic current delivery was considerably lower (50-75 mV) but passivation of the steel had already been achieved so a 100 mV depolarisation was not necessary during this cathodic prevention stage.

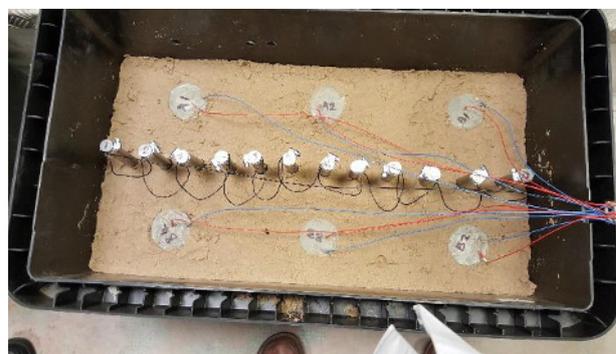
### 2.1.1 Supportive laboratory tests

The 18 removed anodes were returned to the laboratory for investigation. The six used anodes were dismantled, and the different components carefully examined. Cables, connectors, diodes and galvanic anode elements all remained intact and in good working order. One important finding was that the stainless-steel cans that were used as the anode current carriers for Stage-1 remained intact with no evidence of corrosion despite the substantial delivery of current (Fig. 5). They had been encased in a saturated lithium hydroxide-based mortar to maintain high alkalinity and prevent pitting corrosion of the cans.

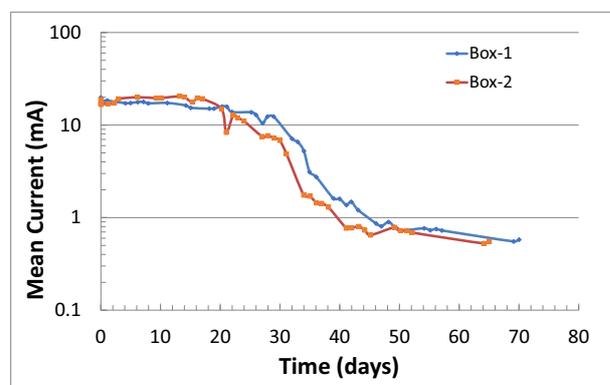


**Fig. 5** An anode removed from the Leicester column showing good condition of the stainless-steel ICCP anode

Analysis of the can encasing mortar showed that there was still substantial LiOH close to the can which continued to buffer the pore liquid at pH 14.6, that of a saturated solution of lithium hydroxide. These anodes were provided with a second connection to the can so that further current from an external power source could be delivered to the steel, if required, using the cans as ICCP anodes with little risk of pitting. During this charge delivery process, the galvanic anodes, and therefore the batteries, are disconnected from the circuit and the cans, forming a separate circuit of linked ICCP type anodes, are connected to the external power source. The 12 removed cored anodes, which had not been connected to the reinforcement on site, were buried in a sandbox in groups of six around the perimeter of the sandbox. The sand contained alkalis and sodium chloride to simulate concrete pore solution and connected to a row of buried steel bars running half-way between the anodes (Fig. 6). Each anode was connected to the steel bars via a shunt to enable monitoring of the current delivery to the steel. The results are detailed in Figure 7. During Stage-1 the mean current output of each anode was of the order of 20 mA and, after a gradual reduction beyond 40-50 days, the current output, now solely delivered by the galvanic component, settled at around 0.5 mA per anode.



**Fig. 6** Set-up of anodes embedded in a sandbox and connected to steel bars for monitoring of current delivery.



**Fig. 7** Variation of the mean current output of anodes per sandbox with time, clearly showing the gradual transition from Stage-1 ICCP current to Stage-2 galvanic anode current.

## 2.2 Full installation of system, South Wales, UK

Two piers in a Bridge in South Wales had suffered from typical steel reinforcement corrosion with cracking and spalling of the concrete in places. The damage, caused by chlorides leaking from a joint above the crossbeams, affected the abutments, the top of the piers and parts of the columns (Fig. 8). A survey, which included extended potential mapping, chloride analysis and a steel depth survey, was utilised along with the visual survey to design a Two-Stage CP system. By calculating the surface area of steel and assuming an average charge delivery requirement during Stage-1 based on a mean plus one standard deviation level of chloride content of ~2.4% for Abutment-1 and ~1.3% for Abutment-2, a mean minimum charge requirement for Stage-1 of 150 kC/m<sup>2</sup> and 70 kC/m<sup>2</sup> respectively was calculated. Current delivery at the points furthest from the anodes is about half the calculated mean so the charge requirement is expected to be double the calculated levels. An anode spacing of 500 mm on centre was expected to exceed considerably the minimum charge requirement of around 300 kC/m<sup>2</sup> and 150 kC/m<sup>2</sup> and was chosen as the standard spacing for both piers for installation convenience and to ensure sufficient current for Stage-2.



**Fig. 8** Part of Pier-2 in the bridge in South Wales showing Abutment-2 in the background (left) and typical damage of the structure from chloride-induced corrosion of the steel reinforcement (right)

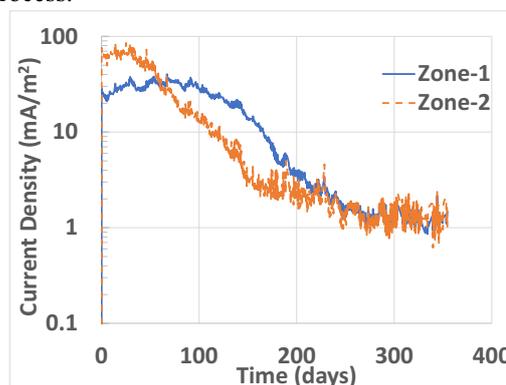
For monitoring purposes and for validation of the success of the system, two areas per abutment had the anodes laid out in a grid formation in a 5 x 5 arrangement, giving a total number of 25 anodes per area, all of which were connected to the steel via a validation box. The box was specially designed to accept two cables from each string of anodes, 5 connections to the steel reinforcement and two silver/silver chloride 0.5M KCl reference electrodes per monitoring area.

The parameters measured automatically by the validation boxes were, on-potentials, instant-off potentials, and current delivery from each set of anodes. Periodically, after the instant-off measurements, the system was allowed to depolarise for 24 hours whilst monitoring the depolarised potential which also allowed calculation of the 24-hour depolarisation potential, being the difference between the instant-off potential and the 24-hour depolarised potential.

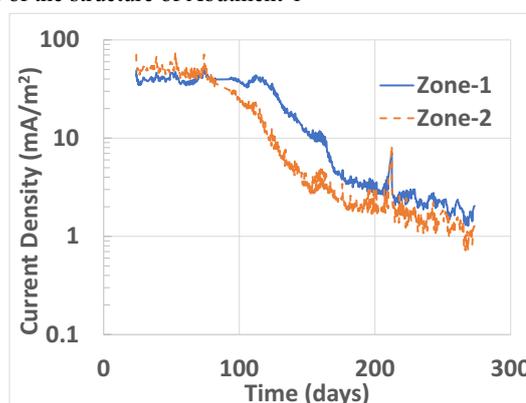
### 2.2.1 Analysis of the measurements

The current density for the two abutments recorded over a period of up to a year is shown in Figures 9 and 10. In all cases, Stage-1 was completed within some months and

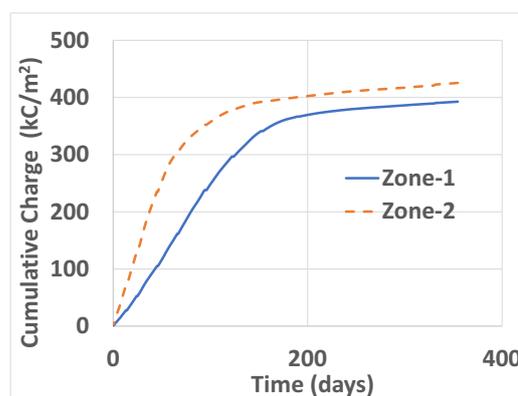
the current delivery gradually changed to that originating from the galvanic anode components. The cumulative charge delivered with time (Figs. 11 & 12) confirmed that the minimum charge delivery per area was well in excess of that estimated to be an appropriate minimum in order to repassivate the steel reinforcement during Stage-1 of the process.



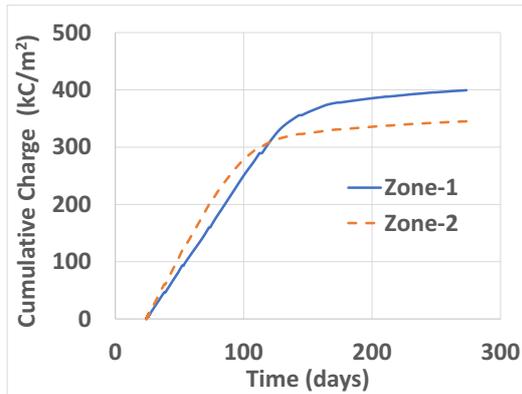
**Fig. 9** Current density delivered to the steel within the monitored areas of the structure of Abutment-1



**Fig. 10** Current density delivered to the steel within the monitored areas of the structure of Abutment-2

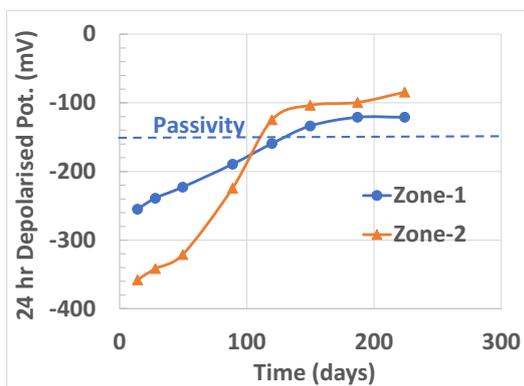


**Fig. 11** Cumulative charge delivered to the steel within the monitored areas of the structure of Abutment-1

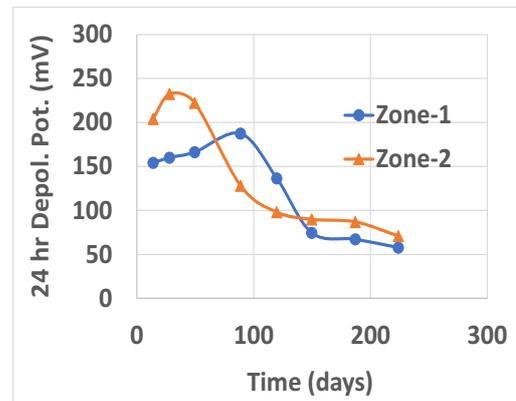


**Fig. 12** Cumulative charge delivered to the steel within the monitored areas of the structure of Abutment-2

That the steel had re-passivated after Stage-1 was confirmed by the 24-hour depolarised potential which became more noble with time as the charge delivery increased. Figure 13 shows the decreasing tendency of corrosion for Abutment-2, as indicated by the steel potential becoming more noble with time within around 100-120 days, the steel becoming passive (>-150 mV vs Silver/silver Chloride, 0.5M KCl). Similar behaviour was observed in the case of Abutment-1. Figure 14 gives an indication of how the level of 24-hour depolarisation potential varied with time and, therefore, charge delivered, for Abutment-2. During Stage-1 (up to 100-130 days) the level of depolarisation always exceeded 100 mV and early on, at the peak of the current density, it ranged between 150 mV and 240 mV. Naturally, the level of depolarisation diminished to between 50 mV and 80 mV as current from Stage-1 diminished and Stage-2 current delivery from the galvanic anode component of the anode was established.



**Fig. 13** Change in the mean depolarised potential of the steel in Abutment-2, as recorded 24 hours after disconnection of the anodes



**Fig. 14** Change of mean 24-hour depolarisation potentials with time in Abutment-2

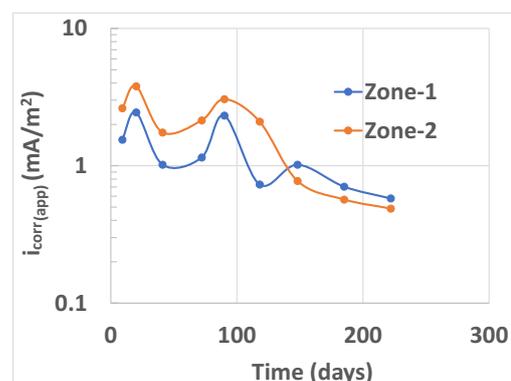
Earlier experimental and site work [9] suggested that an apparent corrosion current density ( $i_{corr(app)}$ ) could be estimated using the Butler Volmer equation (eq. 1).

$$i_{corr(app)} = \frac{i_{appl}}{\exp\left(\frac{2.3\eta}{\beta a}\right) - \exp\left(\frac{-2.3\eta}{\beta c}\right)} \quad (1)$$

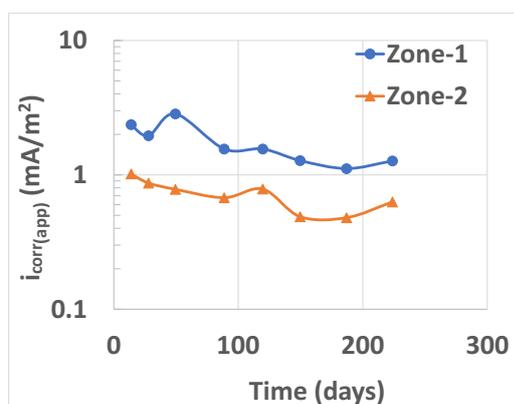
Where,

- $i_{corr(app)}$  = apparent corrosion current density,
- $i_{appl}$  = applied current, i.e. current density,
- $\eta$  = potential shift, i.e. depolarisation potential,
- $\beta a$  = Anodic Tafel Constant (assumed as 120 mV),
- $\beta c$  = Cathodic Tafel Constant (assumed as 120 mV).

Owing to factors such as the uncertainty of the steel area to which the current is delivered, variations in current throw with changing concrete resistance, uncertainty of the level of polarisation and unreliability of potential measurements, such calculations can only offer a rough estimation of corrosion current density but, as the parameters are measured in a reproducible way, the trend of the measurements can offer confirmation of a reducing corrosion rate which, in combination with the depolarised potential (Fig. 13) can offer confidence in the success of this type of CP technique. The mean apparent corrosion current densities of the two piers are depicted in Figures 15 and 16. Both show an overall decreasing trend in the corrosion activity of the steel reinforcement.

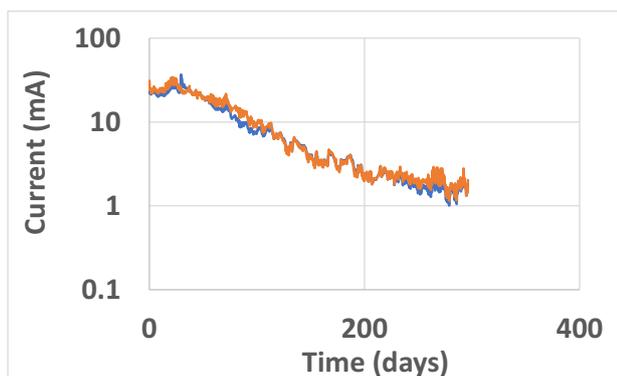


**Fig. 15** Apparent corrosion current density of Abutment-1 showing an overall decreasing trend with time indicating a reduction in corrosion activity

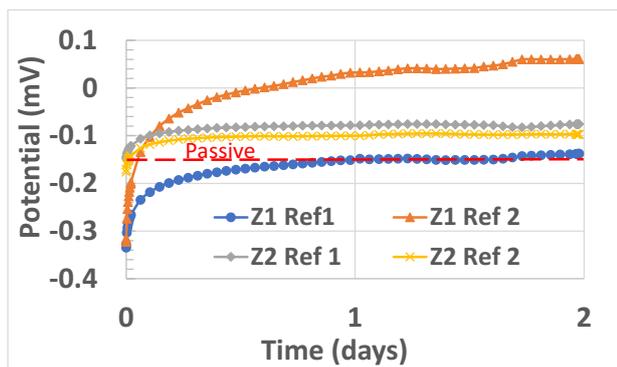


**Fig. 16** Apparent corrosion current density of Abutment-2 showing an overall decreasing trend with time indicating a reduction in corrosion activity.

A third structural element of the bridge, a pier in-between the abutments (Fig. 8) was also protected utilising the same Two-Stage system. Two areas of monitoring were also selected. Although not all results were available for inclusion in this paper, the mean current output per anode in each area was determined and is shown in Figure 17. Depolarisation potentials on Day-210, when the current output per anode was of the order of 1.5-2 mA, i.e. at the beginning of Stage-2, are also detailed in Figure 18. The 24-hour depolarised potentials varied between +30 mV and -150 mV indicating passivity of the steel reinforcement. Depolarisation potentials over the same timescale were of the order of 65 mV and 345 mV.



**Fig. 17** Mean current output per anode in the 2 zones showing gradual switch over from Stage-1 and a high of around 20-30 mA to Stage-2 and a current of around 1.5-2 mA.



**Fig. 18** Depolarisation potentials vs silver/silver chloride at Day-210 signifying passivity of steel reinforcement in the monitored areas.

### 3 Discussion of Results

In both structures the results point to a successful repassivation of the steel reinforcement during Stage-1 of the process resulting in 24-hour depolarised potentials above -150 mV vs Silver/silver Chloride 0.5M KCl. The level of mean charge required to achieve passivity was as little as 130 kC/m<sup>2</sup> for the column in Leicester but as high as 300 kC/m<sup>2</sup> for the bridge in South Wales. At Leicester, cover concrete cracking from corrosion was limited to just two lengths of bar either end of the column and there was no spalling. At the bridge in South Wales, significant cracking and spalling had occurred and some areas had been repaired in earlier years signifying perhaps a longer history of prolonged corrosion. Even though the levels of maximum chloride were similar in both structures, other mitigating factors such as quality of concrete, local environment etc. may have influenced the degree of corrosion. This suggests a cautious approach when choosing the level of required charge for arresting corrosion and should be based on sound engineering judgement.

The level of polarisation, determined as a 24-hour depolarisation potential, easily exceeded 100 mV during the Stage-1 treatment but fell below 100 mV during Stage-2. Although this second stage does not always satisfy the ISO 12696:2016 [2] criteria for cathodic protection, the steel potential signifies passivity so only cathodic prevention is subsequently required at a current density above 0.4 mA/m<sup>2</sup>. The early Stage-2 current density was of the order of 1-2 mA/m<sup>2</sup> although it is expected to diminish with time.

Apart from the monitoring of steel potential as a parameter for performance verification, the calculation of an apparent corrosion current density of the steel within the monitored area can offer an additional validation parameter, as it can confirm the reduction in corrosion activity of the steel with time. This uses already available results of current density and 24-hour depolarisation values.

### 4 Conclusions

A Two-Stage anode comprising of a battery operated ICCP component and a galvanic anode component was designed based on earlier laboratory research. It was shown to deliver sufficient early current to arrest corrosion and maintain a current output consistent with cathodic prevention in two separate structures.

Removed anodes from one site were analysed after completing Stage-1 and were found to remain intact. Crucially, the stainless-steel cans used as the ICCP current carriers showed no sign of pitting despite the substantial charge delivered by each anode. There was sufficient lithium hydroxide content remaining around the steel cans to maintain a high buffered pH so that if a subsequent stage of charge delivery was required to repassivate the steel this could be done utilising the stainless-steel cans as ICCP anodes in combination with an external power supply.

Steel passivity was established after delivery of less than 130 kC/m<sup>2</sup> of charge by steel area in the Leicester structure but nearer 300 kC/m<sup>2</sup> of charge was required for the structure in South Wales, even though the maximum chloride content was established to be around 2% by weight of cement in both cases. The assertion that for Stage-1 of the process a charge applied to the steel reinforcement of only 50 kC/m<sup>2</sup> will achieve steel passivation [16-18] is clearly erroneous as that level of charge is, in most cases, a gross underestimation. The degree of corrosion and damage to the structure must, therefore, be assessed by more parameters other than just chloride content and be based on sound engineering judgement.

Monitoring of the 24-hour depolarised potential of the steel and establishing when passivation is reached is a good way of assessing the performance of this corrosion mitigation system. A potential more noble than -150 mV vs a standard silver/silver chloride electrode is suggested as a level indicating passivity and was shown to have been established around the time Stage-1 of the process was completed.

Depolarisation levels during Stage-1 were substantially higher than 100 mV as the current density easily exceeded 20 mA/m<sup>2</sup>, an upper limit for CP according to ISO 12696:2016, but dropped to 50-80 mV during the cathodic prevention stage when the steel potential was already shown to be in a passive state.

A supportive parameter that can be easily calculated by the Butler Volmer equation is the apparent corrosion current density. It uses the already recorded values of 24-hour depolarisation and applied current density. Although its magnitude is unlikely to be adequately valid owing to several assumptions, the measurement's reproducibility still allows the establishment of a decreasing trend in the steel corrosion activity which is a requirement for this type of system.

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