Performance of zinc sacrificial anodes for long-term control of reinforcement corrosion

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ABSTRACT

Since its development in the mid-nineties, numerous installations of the alkali activated zinc sacrificial anodes have been carried out in repairs to steel reinforced concrete structural elements suffering from corrosion. From these, several sites have been thoroughly monitored in the UK and worldwide. Results so far have been very encouraging with current densities ranging between 0.8 mA/m^2 and 8 mA/m^2 of steel surface depending on the type of application which includes cathodic prevention, corrosion control and cathodic protection. These levels of currents were shown to be sufficient to overcome any further visible corrosion of the steel reinforcement extending the service life of the repairs significantly. Some of the early field projects have now been monitored for more than ten years. This presents an opportunity for the results to be analyzed and the performance of the sacrificial anodes to be critically assessed medium to long term.

This paper reviews the performance of the anodes in terms of current output and steel polarization levels over the years in site field projects concentrating on a field study which has now completed 10 years. The prospects of further developed and improved sacrificial anode systems achieving improved performance are reviewed and discussed.

BACKGROUND

Chloride contamination of concrete structures leading to corrosion of the steel reinforcement is a major worldwide problem. Where chlorides are left in the surrounding sound concrete, traditional patch repairs of only the damaged concrete are rarely successful. Under such conditions, the corrosion cell simply moves into areas adjacent to those that have been repaired. This phenomenon is known as the incipient anode or ring effect.[1,2,3] Consequently, further repairs will be necessary within relatively short timescales. It is essential, therefore, that some form of intentional 'cathodic prevention' be reinstated within the patch repair region so that the adjacent areas remain cathodic and corrosion initiation is prevented. This can be achieved by embedding sacrificial anodes around the perimeter of the patch repair.

Galvanic anodes suitable for patch repair applications were developed in the late 1990's. Small-scale controlled laboratory trials demonstrated their medium term effectiveness in preventing corrosion initiation of the steel at the periphery of the repaired area.[1,2] The anode, in the shape of a puck, was produced from zinc metal encased in a specially formulated porous cementitious mortar (Fig. 1). A reservoir of excess LiOH maintaining a constantly high pH (>14), was shown to sustain the zinc in an active condition producing soluble zinc corrosion products that do not stifle the corrosion process of the zinc metal.[4]

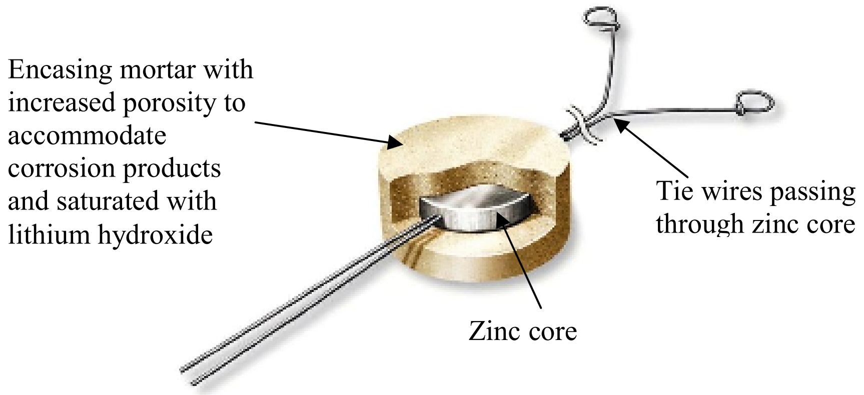


Figure 1 Puck-like anode designed to be attached to the steel around the perimeter of a patch repair

A second design of anode was subsequently developed for use in more global corrosion control applications where corrosive conditions are known to exist but repair is not yet necessary. These types of anode (Fig. 2) were designed to fit in drilled or cored holes in a grid configuration.

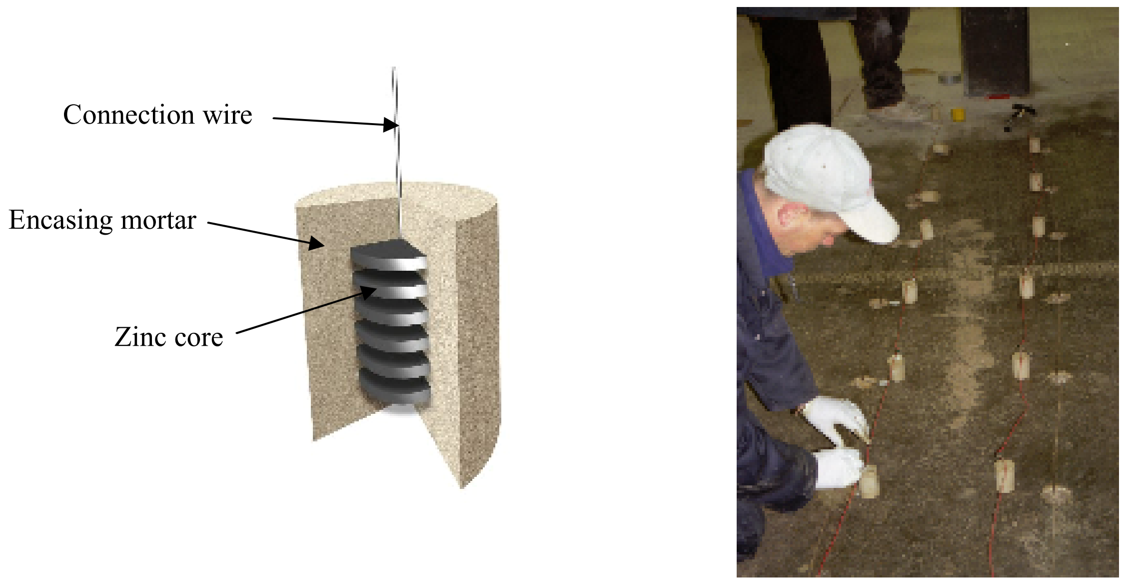


Figure 2 Cylindrical anode designed to be inserted in an array of drilled holes in concrete

FIELD STUDY RESULTS

Following the successful laboratory trials,[1,2] several field studies were set up, forming at least a part of the repair regime undertaken for the rehabilitation of structural elements. Both types of anode were used, the puck-like anode around the perimeter of patch repairs in a cathodic prevention mode (Photo 1), and the cylindrical anodes in a grid configuration in susceptible areas of reinforced concrete in a corrosion control mode (Fig. 2).

Photo 1 Puck-type galvanic anodes positioned around the periphery of a repair at Leicester, UK

All the anodes were connected to the steel reinforcement via a junction box to enable the current output to be monitored with time (Photo 1). In some field studies, depolarisation potentials were determined and instant-on currents (the current output of the anode 5 seconds after reconnection to the steel) were measured. The results of the current output measurements are summarised in Tables 1 and 2.

Table 1 Summary of field study results of the puck-like galvanic anode

No.	Field Study (UK unless otherwise stated)	Length of monitoring (years)	Anode Current over period shown (μA)			No of anodes	Mean Anode Overall Current	
			0-1 year	1-2 years	2 years+		Per anode (μA)	Per unit area of steel (mA/m^2- approximate)*
1	Parking Garage Deck, Northampton	8	700	60	20	4	120	0.8
2	River Bridge, Northampton	5	450	320	90	1	210	N/A
3	Parking Garage Deck, Runcorn	7	280	290	150	6	200	Not Known
4	Parking Garage Beam, Blackpool	7	360	360	220	7	275	1.5
5	Parking Garage Column, Blackpool	7	450	470	380	5	410	0.8
6	Bridge Beam, Leicester	10	190	200	260	12	200	1.4
7	Bridge Column, Leicester	10	450	250	180	6	210	1.0
8	Bridge, Vrbenského, Czech Rep.	4	60	50	60	18	55	Not Known
	Mean		365	250	170		210	1.1

* The steel area was assumed to be that contained within the patch and in a surrounding area in the periphery within a distance of 200-300mm of the boundary of repair to parent concrete

Table 2 Summary of field study results of the cylindrical-type galvanic anode

No.	Field Study (UK unless otherwise stated)	Length of monitoring (years)	Mean Anode Current over period shown (μA)				Mean No of anodes per string	No of anodes	Mean Anode Overall Current		Anode centres (mm)
			0-1 year	1-2 years	2 years+	No of Strings			Per anode (μA)	Per unit area of steel (mA/m^2- approximate)†	
1	Housing Balcony, USA	5.0	660	400	150	8	6	47	340	8.0	500-1100
2	Parking Garage Deck, Wakefield,	5.0	280	180	100	4	5	20	165	1.5	700
3	Bridge, Seaham Seaton,	4.5	600	400	250	6	5-6	33	393	2.7	500
4	Pavillion, Norwich,	4.5	350	300	250	2	6	12	300	3.2	600
5	Power Station, Rugeley,	2.5	1200	550	N/A	2	6	12	875	2.5	500
6	Abutment, Ivy Street,	4.5	450	650	200	2	9	18	415	4.5	300
7	Columns, South Clutterbridge,	4.5	500	380	150	2	9-10	19	380	4.1	300
	Mean		580	410	185				410	3.8	

Current levels were seen to be related to the exposure conditions and the level of chloride contamination around the periphery of the repair in the case of the puck-like anodes and in the bulk of the concrete in the case of the cylindrical anodes. The current output was also strongly influenced by the ambient temperature (Fig. 3).

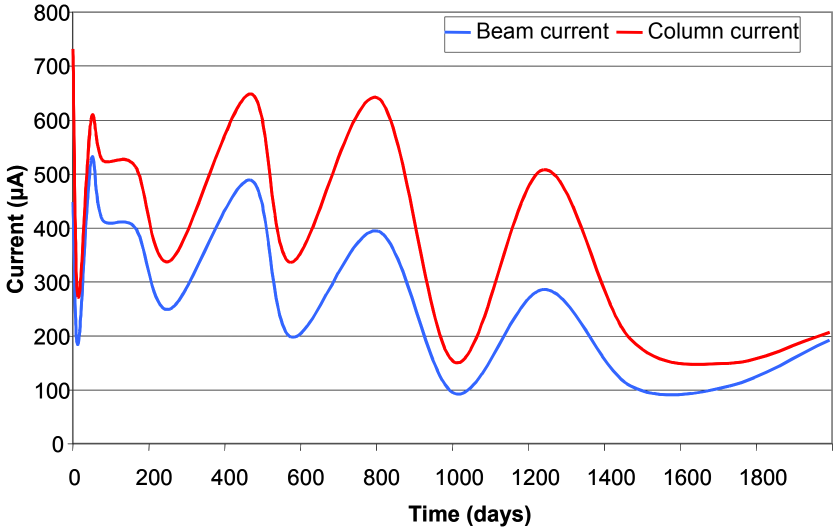


Figure 3 Mean current over time of individual puck-like anodes fixed on steel in patch repairs performed on a concrete beam and column in a car park in Blackpool, UK, contaminated from coastal spray chlorides showing strong seasonal variation owing to temperature (No's 4 & 5 in Table 1).

† The steel area was assumed to be that contained within the treated area plus an additional half of the calculated anode spacing beyond the outer edge of the anodes

Currents averaged around 200µA per puck-like anode (Table 1) and more than 400 µA per cylindrical anode (Table 2) which has a larger surface area than the puck. Converted to current density of steel surface it was found to be of the order of 0.8-8mA/m^2 depending on the type of application, spacing of the anodes and local conditions.

The oldest field study, at a bridge in Leicester, UK, (Photo 1) has now completed ten years of life (No. 6 Table 1), a milestone, as the anodes were designed for a minimum life of ten years. The results of part of this field study are discussed in more detail in the following section.

LEICESTER FIELD STUDY

A total of 12 prototype commercial puck-like anodes were installed in an otherwise conventional patch repair on spalled and cracked areas of a beam section of the bridge (Photo 1). The repair was made on the soffit of a section of the beam between Columns 6 and 7 on the west pier (Photo 2). The repaired area was found to be contaminated with about 1-2% chloride by weight of cement. All the spalled and cracked concrete was removed until clean steel was exposed but the remaining concrete around the repair still contained around 0.4-1.0% chloride by weight of cement at the level of the steel reinforcement. These were ideal conditions for incipient anode formation, where the cathodic steel in the fresh patch repair induces corrosion around its periphery as this steel, originally protected by the corroding steel, becomes anodic.

This formed part of a repair scheme for the whole bridge which contained two abutments and two piers each consisting of a long cross beam sitting on 8 columns. The overall repair system was made up of patch repairs containing puck-like anodes around their perimeter and included impressed current cathodic protection with discrete anodes at the more deteriorated areas at the top of the abutments. The performance of the 12 anodes was monitored with time.

Photo 2 North side of the Leicester bridge (west pier on the right)

The ten year results of the current output of each anode are presented in Figure 4. They indicate a variable current depending on the moisture content in the concrete but primarily on temperature (see also next section). For example, Anode 7, which long-term was the most active, could generate up to 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.

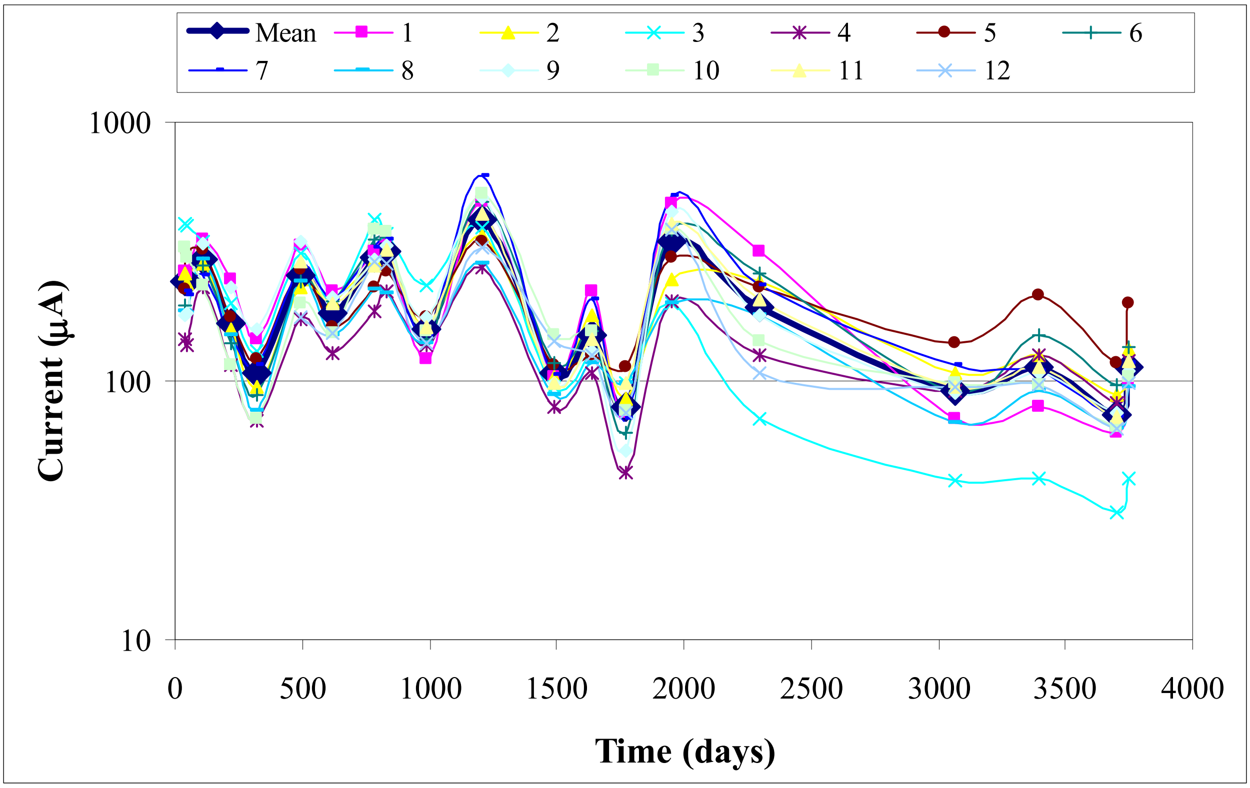


Figure 4 Current output of the 12 individual anodes and the mean output with time

The estimated current output was converted to a total charge produced per anode (Table 3). The mean cumulative charge over time is shown in Figure 5. It demonstrates that there is a slowly diminishing trend but the anodes are continuing to produce significant charge.

Table 3 Total charge produced by each individual anode in ten years of exposure

Anode Number	Charge (coulombs)	Anode Number	Charge (coulombs)
1	63141	7	65194
2	55696	8	43619
3	46621	9	59459
4	41135	10	56333
5	61228	11	57205
6	60825	12	48989
		Mean	**54954**

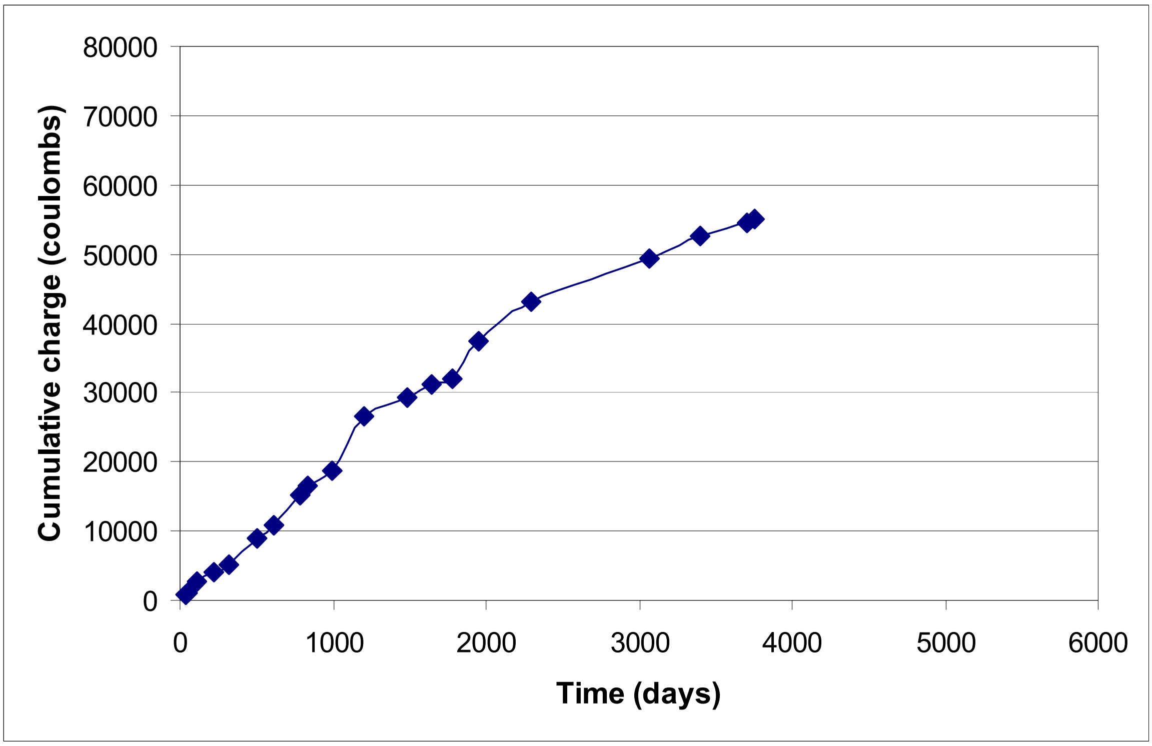


Figure 5 Mean Cumulative charge with time produced by the anodes indicating a continued charge capacity

Using Faraday's law, and assuming 85% efficiency the level of consumed metal was estimated as shown in Figure 6.

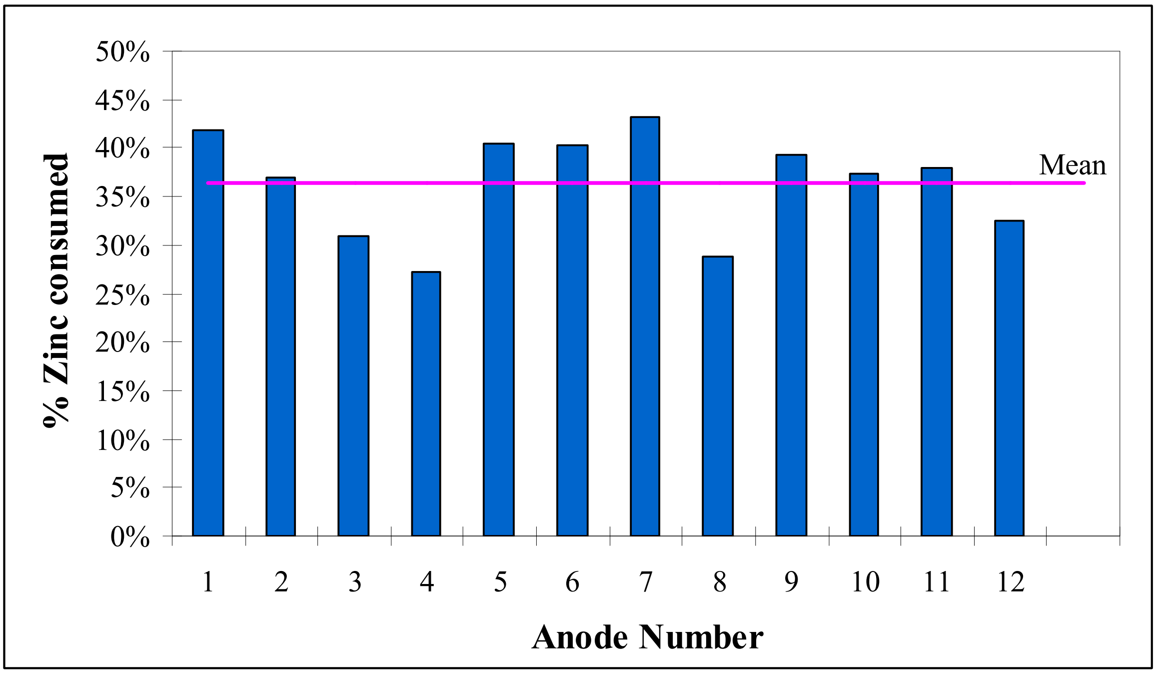
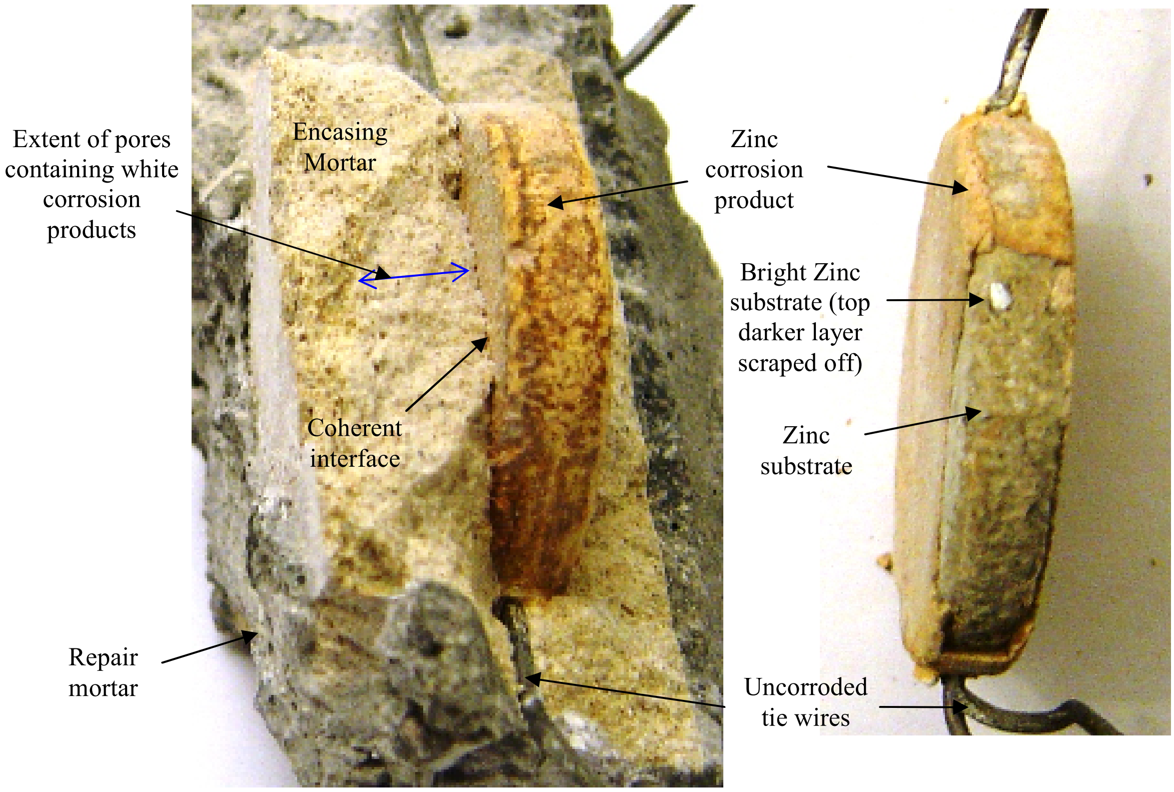


Figure 6 Approximate amount of zinc consumed based on the charge produced and an 85% efficiency level

Visual assessment of removed anodes from an adjacent patch repair in the same west pier confirmed the estimated efficiency level. These anodes were installed at the same time 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. About 25-30% of the zinc metal was consumed, a level at the lower end of those calculated for the 12 monitored anodes (Fig. 5). There was evidence also that the pores of the encasing mortar extending several millimetres away from the zinc/mortar interface, were partly filled with white zinc corrosion products. This corrosion product, likely to be zinc hydroxide, remains soluble, owing to the high pH of the pore solution present in the encasing mortar which is saturated with lithium hydroxide, and can travel 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 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.



(a) (b)

Photo 3 (a) Removed 10 year old anode showing corrosion product around zinc and intact encasing mortar (b) Zinc core with part of the corrosion product broken off exposing the zinc substrate

The level of depolarisation was recorded at 12 points within the repaired area and at 8 points outside the repair. 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. 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 (24 hours for the 3400 day results). The actual values are tabulated in Table 4.

Table 4 Mean depolarisation values at 4 hours (24 hours at 3400 days)

No. of days from switch-on	Beam soffit within the repaired area, midway between anodes (mV)	West vertical face of beam at shown distance from edge of repair (mV)	
		50mm	300mm
21	56	58	56
41	27	47	31
50	22	55	28
112	24	48	11
3400	95	184	Not determined

The depolarisation values are very low initially but approach or exceed 100mV after 9 years (3400 days) of polarisation of the steel. It is interesting to note that the level of depolarisation tends to be higher outside the repaired area and appears to be still significant up to 300mm away from the edge of the repair. An estimated level of corrosion under such conditions can be made from equation-1 (see later) which shows that the corrosion intensity averages around 0.7mA/m^2 up to day 112 and diminishes substantially to 0.2mA/m^2 on day 3400. These levels are considerably lower than the 1-2mA/m^2 which is assumed to be the limit below which corrosion intensity is insignificant.

The fact that the depolarisation level increased substantially and the estimated level of corrosion decreased over the ten year period, indicating a good level of protection of the steel reinforcement, and that the patch repair is still intact and operating well, it is reasonable to suggest that the 100mV depolarisation criterion is not applicable for this type of cathodic prevention system. Such systems are only required to cathodically prevent the onset of corrosion of the reinforcement and not to control existing corrosion as is the case in 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[5] and Pedeferri[6] and adapted in the European Standard.[7]

A more useful way of determining the effectiveness of the repair system is by monitoring the depolarised potential of the steel in the vicinity of the repair with time. This is indicated by Figure 7, which shows the mean depolarised potential with time both within and outside the repaired area. It is clear that the recorded mean potential is continuously moving to a more noble level with time indicating increasing passivation of the steel.

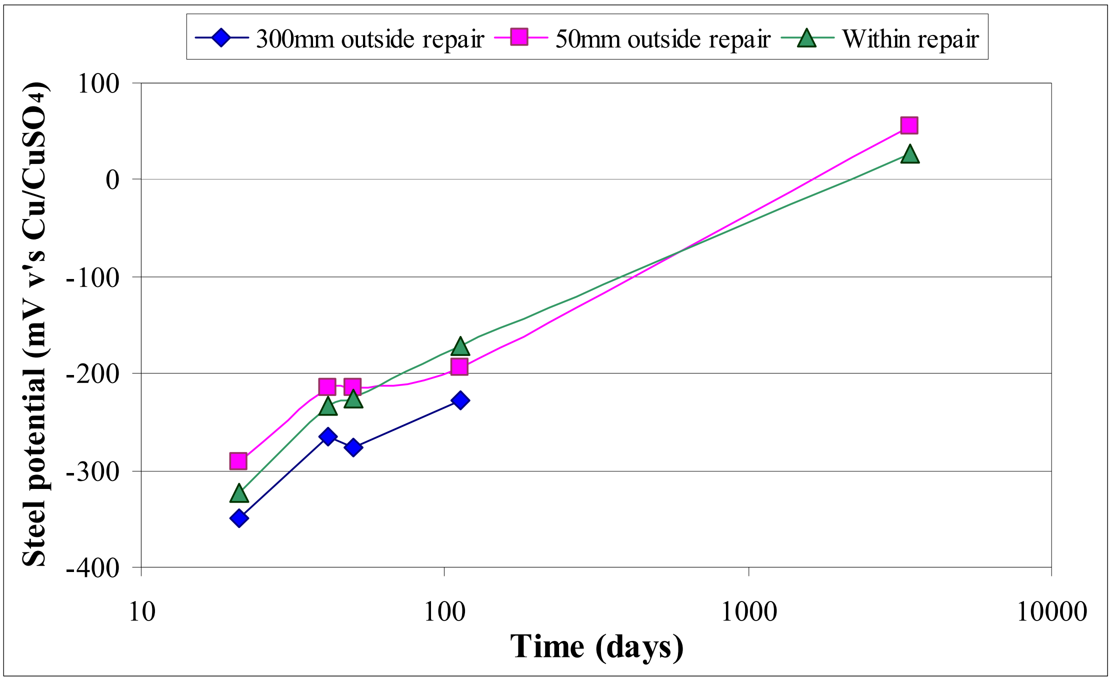


Figure 7 Mean depolarised steel potentials with time (4 hours or 24 hours after disconnection of the anodes)

Another useful parameter that could be used as a criterion for establishing the continued effectiveness of galvanic anodes is the current output at switch on. This was measured five seconds after reconnecting each individual anode to the steel while all other anodes were disconnected following the 4 hour or 24 hour depolarisation period. The mean current appears to have increased with time right up to ten years (Figure 8). The magnitude of this current is likely to be related to the potential difference between the zinc anode and the steel, which may be thought of as a 'drive potential'. The zinc potential was not measured but a plot of the 'instant-on' current versus the mean potential of the steel within and around the repaired area just before switch-on, a parameter related to the 'drive potential' if the potential of the zinc is assumed to be reasonably stable, suggests a good correlation (Fig. 9). In addition to Figure 5, both Figures 8 and 9 also suggest that the anodes are still able to perform to a very high level after 10 years of operation. The generally decreasing current output of the anodes shown in Figure 4 may thus be related primarily to the changing conditions of the concrete, as drying of the pier has been occurring owing to the repair of leaking joints, and 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.[8]

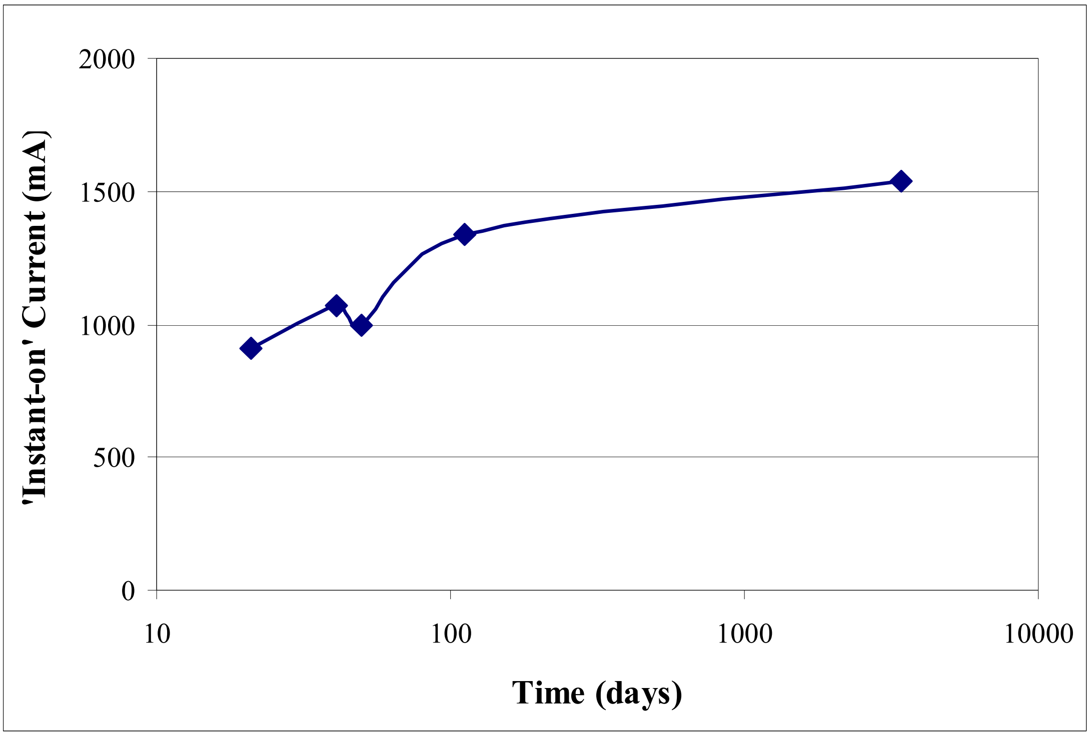


Figure 8 Variation of mean current output with time of anodes at switch-on after depolarisation

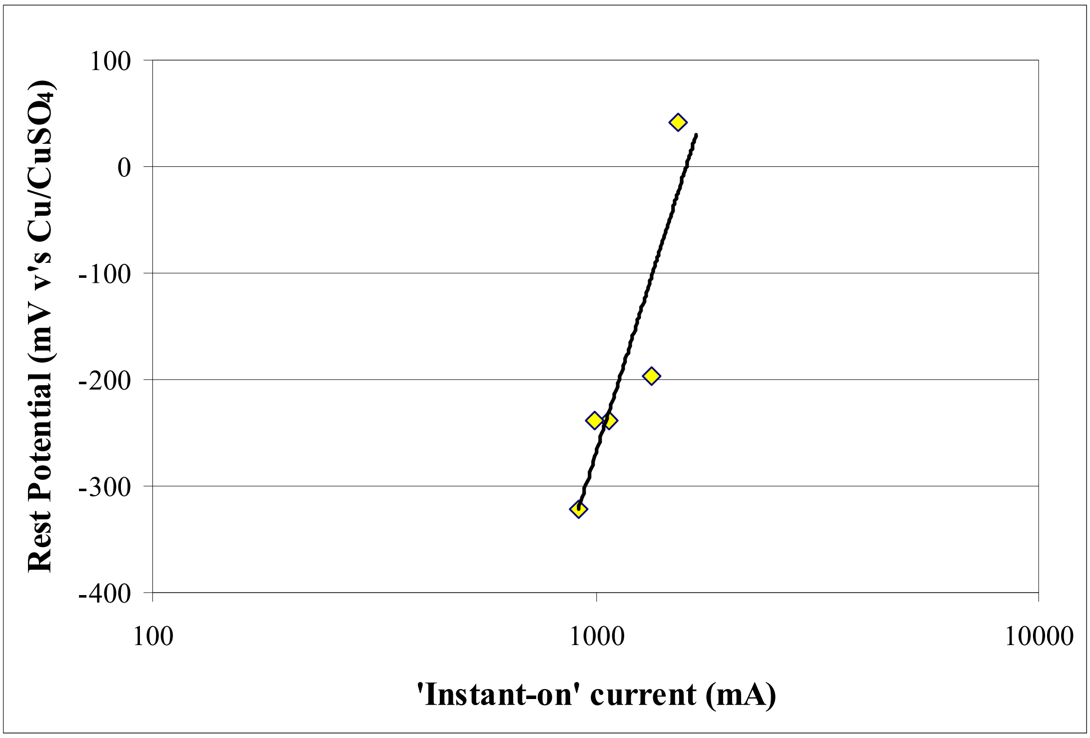


Figure 9 Relationship between mean ‘instant-on’ current and mean rest potential of steel within and around the repair area

FURTHER DEVELOPMENT OF THE ANODES

Where chlorides were present, the level of depolarisation achieved for the cylindrical anodes at 300mm anode spacings was found to be dependant on the degree of ongoing corrosion of the steel reinforcement (No's 6 & 7, Table 2). This is illustrated well in Figure 10 where the depolarisation levels versus the current output at the two locations are shown.

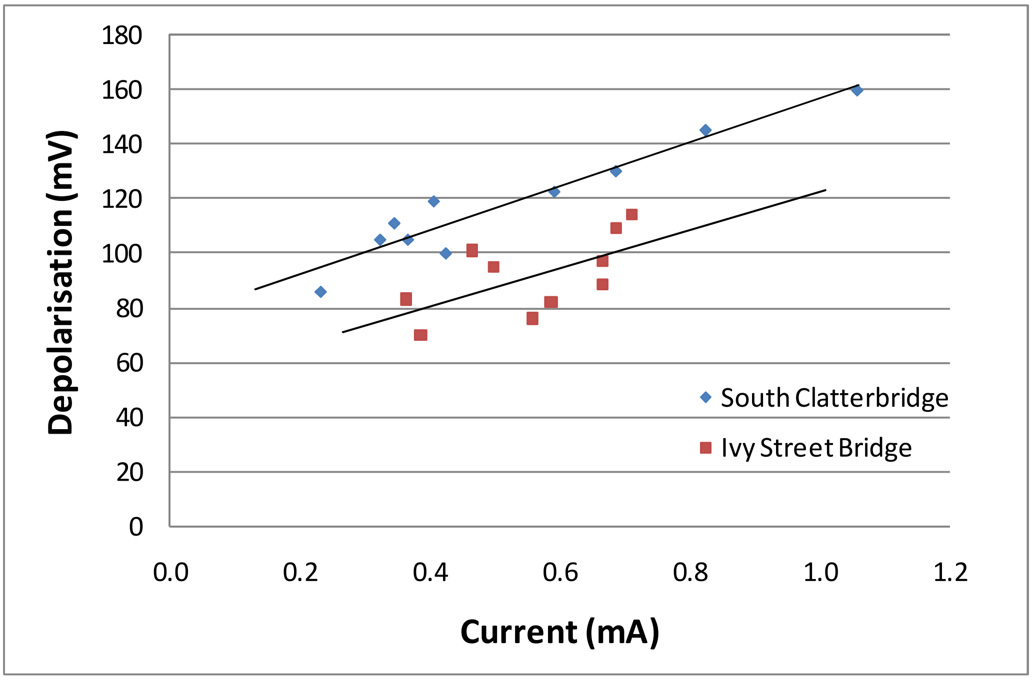


Figure 10 Level of depolarisation achieved at various mean current outputs from anodes at two locations in UK

Each protected area had a group of nine cylindrical anodes placed in a 3 x 3 array protecting steel arranged in a mesh configuration of surface area between $1.1m^2$ and $1.4m^2$. At South Clatterbridge, where 100mV depolarisation was achieved regularly, the conditions were mildly corrosive. At Ivy Street the concrete contained significant levels of chloride and had suffered from a degree of corrosion but no cracking of the concrete prior to remediation. This meant that, even though the anode configuration was the same and the steel density was similar, the 100mV criterion was only met at the higher current output values. This is borne out of the relationship between open circuit corrosion rate and potential shift at increasing applied currents (Fig. 11) derived from equation-1 if activation controlled cathodic kinetics are assumed.[9,10]

$$i_{corr} = i_{appl}/[\exp(2.3\eta/\beta_c) - \exp(2.3\eta/\beta_a)] \qquad \text{(eq. 1)}$$

Where,

i_{corr} = corrosion rate
i_{appl} = applied current
η = observed potential shift
β_c = cathodic Tafel slope (assumed as 120mV)
β_a = anodic Tafel slope (assumed as 60mV)

The early current density at these two sites ranged between 5.7mA/m^2 and 6.0 mA/m^2 of steel area. From equation-1 and according to Figure 12, such current densities can achieve polarisation levels of 100mV when the corrosion current density is of the order of 1-2 mA/m^2, a level that represents very low to insignificant corrosion activity. For a more corrosive environment the applied current density should be increased in order to achieve adequate depolarisation levels. This could be achieved in practice, either by decreasing the spacing between anodes or increasing the current output of each anode. Alternatively, an anode design that can distribute the current to the steel better could also provide increased protection (see next section).

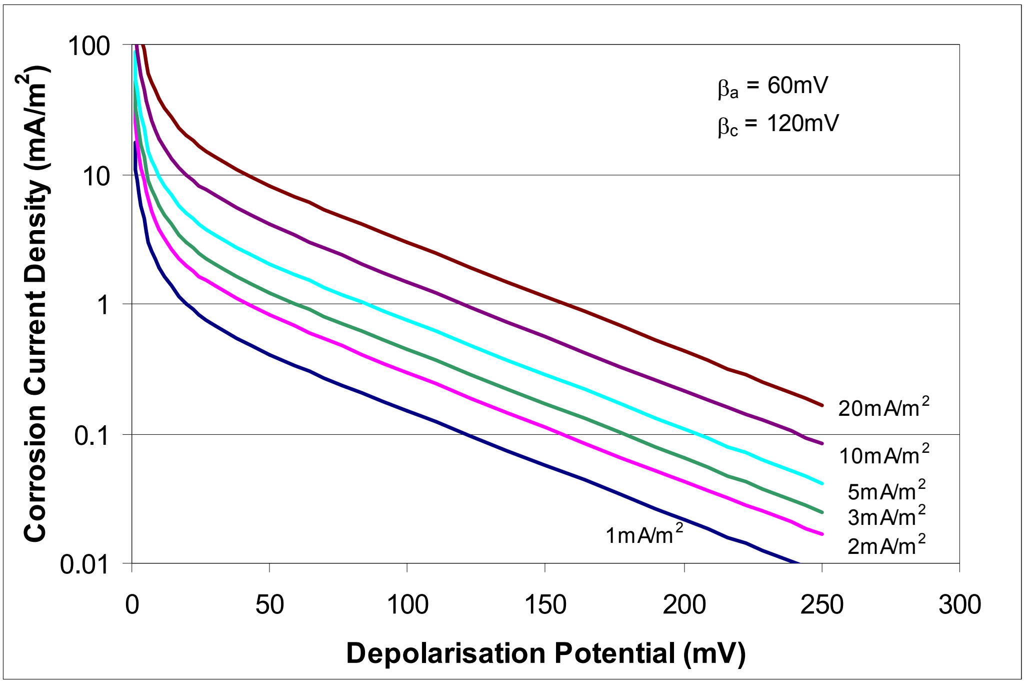


Figure 11 Observed potential shift for open circuit corrosion rates at increasing applied currents (from Glass et. al, NACE Corrosion, 55 (1999), 286)

Knowledge gained from these and the other trials**Error! Bookmark not defined.** enhanced by additional research has enabled the further development of galvanic anodes. Single anodes with modified geometry and encasing mortar composition have been developed with double and four times the current output capability for use in more severe conditions. Some of these have now been installed at the Leicester Bridge as a new field study (Photo 4). The new repaired area contains three ‘double-output’ anodes and seven ‘quadruple-output’ anodes at a maximum spacing of 300mm. Chloride levels in the adjacent undamaged concrete was found to be in the range 1.0-2.6% chloride by weight of cement. Ideally, this highly contaminated concrete should have been removed but it provides an opportunity to test the capability of the improved anodes. Monitoring is at its infancy but very early results show a mean ‘instant-on’ current of 1450μA per ‘double-output’ anode and 2620μA per ‘quadruple-output’ anode, both considerably higher than the current of the original anodes at the equivalent time.

Photo 4 Part of the repaired area of the east face of the west pier at Column 2, showing location of ‘double-output’ and ‘quadruple-output’ anodes.

DISTRIBUTED CURRENT ANODES

Other configurations of galvanic anodes have also been developed for more global corrosion control methodologies. One such configuration is the system installed at a bridge abutment in Sidney, Ohio (Photo 5). The abutment had been contaminated with chlorides causing localised corrosion of the reinforcing steel.

As part of the rehabilitation, which also included enlargement and strengthening of the abutment, the cracked and spalled concrete was removed, long lengths of the anode were fixed onto the surface of the abutment wall along the existing steel reinforcement, and supplementary epoxy-coated steel reinforcement was installed to accommodate the additional thickness of concrete that was placed along the whole face of the abutment wall. The purpose of the anode network was to protect the existing steel from chloride-induced corrosion allowing un-cracked chloride-contaminated concrete to remain in place and thus reduce concrete breakout. The cross sectional configuration of the repaired abutment wall and adjoining structural elements are shown in Figure 12.

Photo 5 A distributed current-type anode system used for corrosion control of the enlarged abutment at a bridge in Sidney, Ohio.

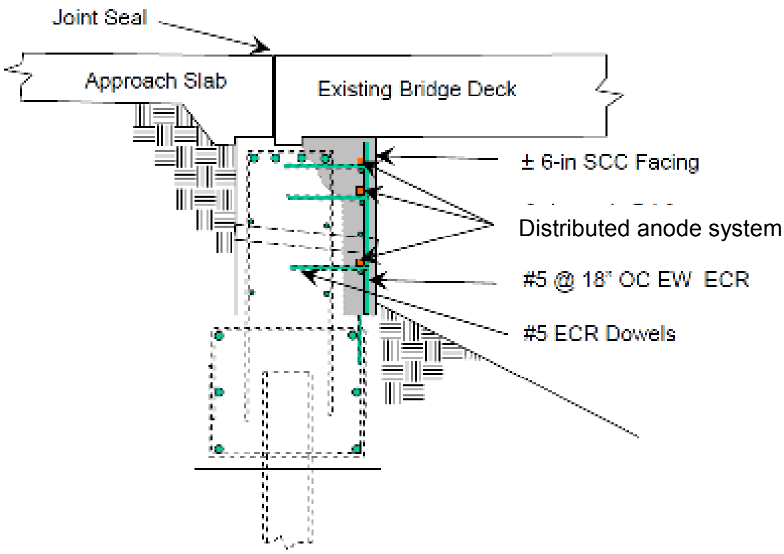


Figure 12 Cross sectional detail of the abutment rehabilitation system

The current output, shown in Figure 13, is seen to be strongly related to temperature. Its magnitude varied considerably on an annual basis with temperature but the mean current density has been gradually reducing year by year. After an initial level of over 35 mA/m^2 of steel area in the first few days, it averaged over 8 mA/m^2 during the first year lowering gradually to around 5 mA/m^2 in the fourth year. These levels of current density are within the design limits of 2-20 mA/m^2 of steel area as specified in EN 12696:2000.[7] Current densities in impressed current cathodic protection systems are also normally reduced with age as the steel becomes easier to polarise. Depolarisation levels were measured to be well in excess of 100mV as specified in the same standard, suggesting that the galvanic system was deemed to satisfy the criteria for cathodic protection of steel reinforcement. Apart from the high current output achieved, the better distribution of the current to the steel owing to the positioning of the anodes is thought to have contributed to the much higher depolarisation potentials recorded.

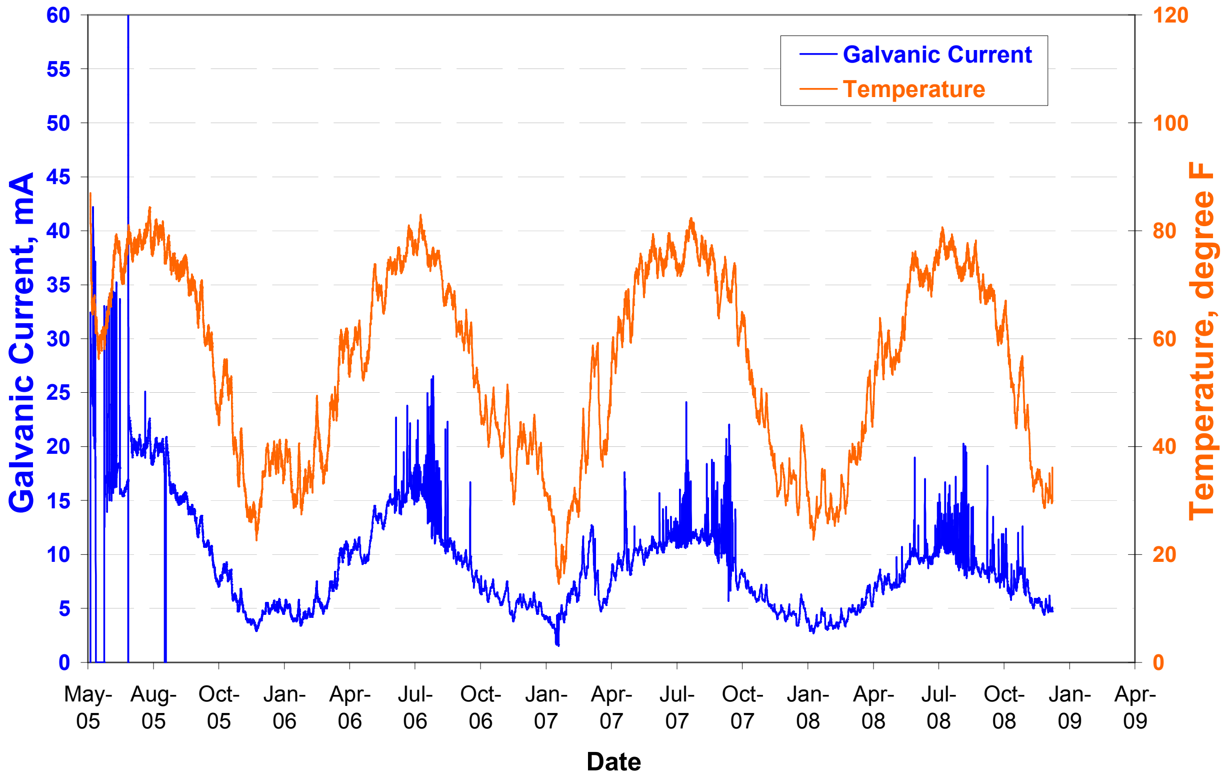


Figure 13 Current output of anode system and its relationship to temperature

CONCLUSIONS

1. Puck-like 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 ten 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. Similar cylindrical anodes positioned in a grid configuration showed equally good performance over the 5 year trial period.
2. Depolarisation levels of the steel reinforcement after disconnection of the anodes for periods of either 4 hours or 24 hours showed a dependence on the current density delivered by the system achieving values averaging around 100mV in the corrosion control mode. The depolarisation was also seen to be related to the corrosiveness of the concrete to the steel, increasing as the current increased.
3. In the case of the puck-like anodes used in cathodic prevention mode in patch repairs, depolarisation potentials rarely exceeded 50mV around the periphery of the repair over the first 112 days, but then increased to over 100mV after 9 years. The 100mV depolarisation criterion, which applies to cathodic protection systems, is unlikely therefore to apply for cathodic prevention systems of this type. An alternative more realistic criterion should be developed. It is suggested that the change in the rest potential of the steel, following periods of depolarisation over a constant time (4 or 24 hours), be considered as a criterion for establishing the performance of the system. In this particular case, it was seen that the steel rest potential gradually moved in a positive direction signifying improved passivity of the steel.

4. Although the current output of the puck-like anodes followed an overall decreasing trend, the driving power of each anode did not show any evidence of diminishing. To the contrary, the current output at switch-on, following a period of depolarisation, was seen to increase with time, possibly because the potential of the steel gradually moved in the positive direction thus increasing the 'drive voltage' between the anode and the steel.
5. Lessons learned from the field studies and from further research have enabled the production of enhanced performance anodes using a better surface area to volume ratio and improved chemical composition of the encasing mortar. Anodes with double or quadruple the current output capability have been used in a new field study. Early results confirm their higher capacity.
6. The technology was shown to be very flexible and by utilising a distributed current-type anode set-up consisting of long anodes affixed along the steel reinforcement, it was possible to achieve current densities compatible to conventional cathodic protection systems and depolarisation levels exceeding 100mV.

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