The Performance and Assessment of Galvanic Anodes In Concrete Structures

C. Stone, G. Glass and D. Bewley, Concrete Preservation Technologies Ltd.

INSTITUTE OF CORROSION

Meet the Authors

Christian Stone

Gareth Glass

David Bewley

Christian Stone

Christian Stone, M.S., M.Phys., is a corrosion scientist and technical expert at Concrete Preservation Technologies who specialises in the development of next-generation corrosion management systems, supports the use of cathodic protection worldwide, and is a leading expert in corrosion in RAAC concrete. Christian sits on a number of professional organisations, is a member of the Loughborough University RAAC Research Team, and is currently undertaking further research on RAAC with Loughborough University.

Gareth Glass

Gareth Glass is a Director at Concrete Preservation Technologies, a position he has held since the inception of the company in 2005. He has extensive experience in materials technology, durability and rehabilitation of structures with over 100 publications to his name in the area of corrosion protection. He obtained his PhD from the Corrosion and Protection Centre, University of Manchester.

David Bewley

David Bewley is the Commercial Manager at Concrete Preservation Technologies, a position he has held since 2015. He is an Associate of the Chartered Institute of Building and has worked in the construction industry for 38 years. He is responsible for developing sales globally and supporting the distributor network.

Introduction

This work discusses the development of galvanic corrosion control for reinforced concrete structures and considers system performance and assessment through the lens of three case studies. Also referenced is the current UK National Highways Manual of Contract Documents for Highway Works, which includes a galvanic anode specification and guidance on the use and performance assessment of galvanic anodes for patch repair protection.

Many reinforced concrete structures are exhibiting premature corrosion damage within their design life, commonly due to the absence or breakdown of effective barriers to the ingress of aggressive agents. Adequate concrete cover, the use of high-performance concrete, and the application of coatings and sealants can all play a part in protecting the embedded steel reinforcement, but where such barriers are missing or have been compromised, an appropriate corrosion control system may be required to keep the structure safe and functional.

Galvanic anode technology has substantially advanced over the past 25 years, along with an increasing understanding of how the systems behave within reinforced concrete.

Galvanic Technology

Galvanic anodes are electrochemically active metals, often zinc, that are connected to and corrode in preference to steel. When two metals are connected in an ionically conductive environment (bi-metal couple), the more noble metal will act as the cathode and the more active metal will act as the anode. Current will flow driven by the potential difference between the metals, corroding the anode and protecting the cathode. When zinc corrodes and provides a protective current to the steel in reinforced concrete, the passivity of the natural steel potential will increase, making the natural steel potential less negative, and corrosion of the steel will be inhibited.

Galvanic anodes are voltage-limited devices. The protection current output is dependent on both the available voltage and the impedance of the environment. Generally, concrete has a high resistivity, so initially, galvanic anodes were only considered suitable to protect warm, wet concrete environments where the resistance was lower [1]. It was suggested that in more resistive concrete, the limited power of the anodes would inhibit any effect they might have on corrosion. However, subsequent field experience has demonstrated that galvanic anodes are a lot more effective than originally thought.

Early methods of galvanic anode assessment involved the use of potential mapping to evaluate the zone of influence of an anode, that is, the distribution of beneficial effects [2]. In 2004, the responsive nature of galvanic anodes was noted (see figure 1). Galvanic anode protection current was shown to respond to changes in environmental resistivity, just as reinforcement corrosion responds to changes in resistivity [3]. More galvanic current was delivered during times of higher corrosion risk.

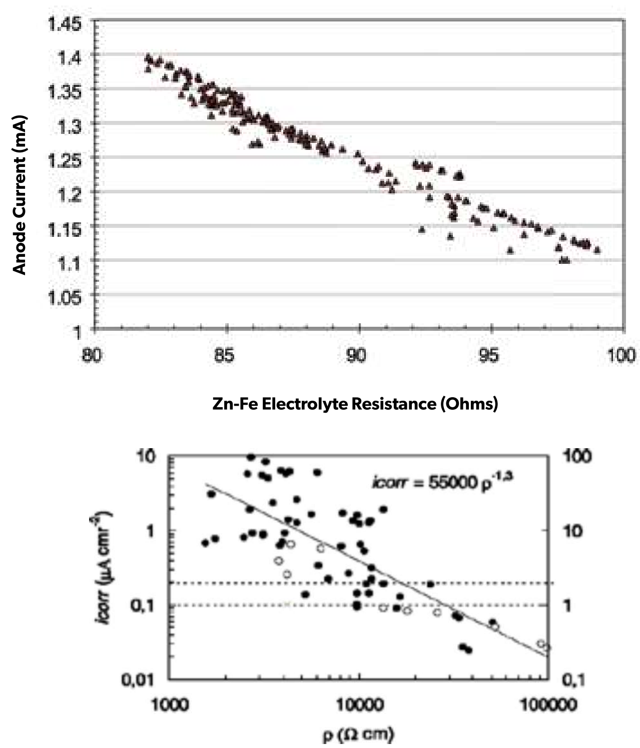

Figure 1: Effect of Resistivity on Anode Current Output [3] and Steel Corrosion Rate [4].

continues on page 26

Studies confirmed that galvanic anodes were unlikely to deliver large polarisations in high resistivity environments but observed under laboratory conditions, using similarly activated and positioned zinc and steel anodes, that a zinc anode responds to environmental events such as moisture ingress and temperature changes more rapidly than a steel anode, so the protective current being passed to the steel increases more rapidly than the increased corrosion risk [5].

In the 1990s, proponents of galvanic anode technology suggested it could be used to address the incipient anode effect, a commonly observed phenomenon whereby accelerated corrosion occurs immediately outside the patch repair boundary [2, 6]. Several possible mechanisms arising from the process of repairing the concrete may trigger the incipient anode effect [7].

Early galvanic patch repair anodes were pre-encased in a highly conductive mortar shell and tied directly to the steel close to the patch edge, embedded within the patch repair material. They were marketed as 'no monitoring and maintenance' products with a life of at least 10 years. Subsequently, new arrangements were developed to promote the flow of current to the at-risk steel outside of the patch repair [8].

Images and data in this paper relate to galvanic anodes, which are installed into a putty in drilled holes in the host concrete to optimise current distribution and are not embedded in the patch repair material. Current distribution is critical, as the commercial justification for the use of galvanic patch repair anodes arises from the protection they deliver just outside the area of repair. This effectively means the repair covers a larger area, as illustrated in Figure 2 below.

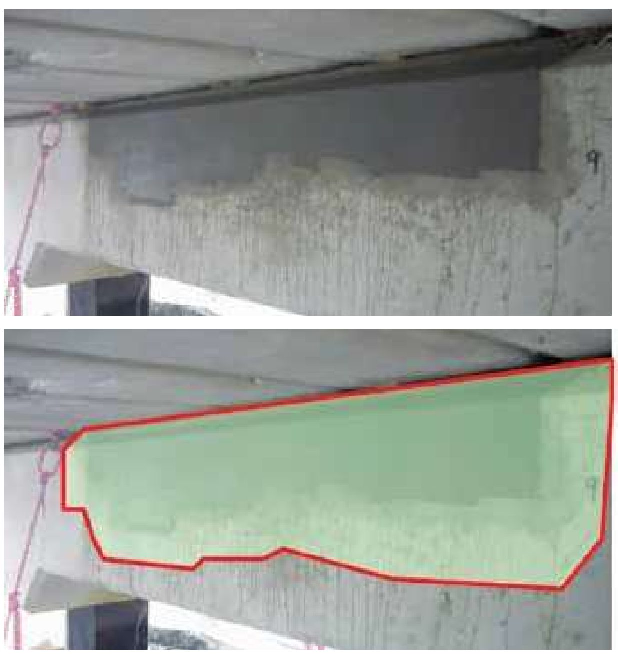

Figure 2: Effect of Patch Repair Without Galvanic Anodes (Above) and with Galvanic Anodes (Below).

UK National Highways published an updated Manual of Contract Documents for Highway Works in 2020 which, for the first time, included a standard specification for patch repair galvanic anodes along with guidance notes [9,10].

The specification covers acceptance criteria and testing by electrical potential survey. A maintenance- free service life of at least 10 years is specified, and evidence is required of similar structures where the proposed galvanic anode has performed satisfactorily for at least 5 years without evidence of incipient anode-induced corrosion damage up to 300 mm from the repair boundary, i.e., the at-risk zone. Evidence might be provided by visual assessment and/or hammer tapping. The specification does not require evidence of anode current output, as this can be misleading. For example, an anode may produce current, but, depending on the anode design and location, the current could be largely discharged to the immediate steel to which it is attached and not the at-risk steel outside the patch. A similar philosophy underpins the requirement for half-cell potential measurements to be recorded around the patch perimeter pre and post anode installation; the most significant factor is the condition of the steel around the patch and the degree to which protection is provided. Initial steel polarisation is evidence of the galvanic anode giving measurable protection to at-risk steel. Subsequent measurements can provide evidence of the on-going condition of the steel.

An example of before and after steel potentials recorded around a patch repair to a National Highways structure in 2023 is provided in Figure 3.

Figure 3: Steel Potentials were Recorded Before (Yellow) and After (Pink) Connection of The Galvanic Anodes.

Potential measurements may be used as a form of commissioning. The data can show that the anodes are connected and are providing protection outside representative patch repairs when they are installed. For National Highways, the use of the technology does not place any additional monitoring or maintenance requirements on the repaired structure beyond that required by the standard two yearly General, and six yearly Principal, Inspections.

The use of galvanic cathodic protection in concrete structures has evolved beyond patch repair protection, as demonstrated by two of the three case studies on the next page.

Grosvenor Car Park

Grosvenor car park was constructed around 1975. By 2010 it had suffered extensive corrosion damage to the decks due to chloride contamination from de-icing salts (Figure 4).

Figure 4: Examples of Corrosion Damage Observed During the Repair of the Car Park in 2010 and 2011.

The solution for the Grosvenor car park included the use of galvanic anodes installed in drilled holes at the edge of the concrete repair. The anodes were connected to the steel exposed in the repair using a connector of the anode assembly (Figure 5). The application of a high-quality repair mortar completed the repair process [11]. To reduce complexity, there was no facility to disconnect the anodes or measure current output. The commissioning process for galvanic anodes was in its early stages of evolution at this point in time.

Figure 5: Installation of Anode in Parent Concrete at Repair Edge and its Connection to the Steel In 2010.

Performance assessment was conducted by mapping the potential on the surface of the concrete adjacent to the repaired area relative to a stationary electrode. This was used to determine the extent of protection provided by the anodes and check the anode spacing. An example of the data is provided in Figure 6. It shows the potential gradient caused by the effect of the anodes in the vicinity of the patch repair as a function of the distance from the edge of the repair.

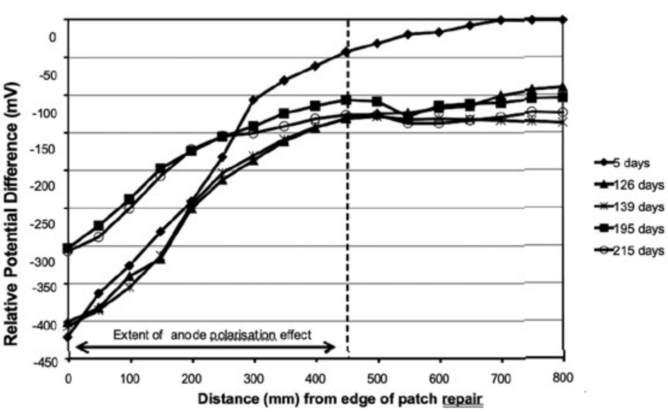

Figure 6: Anode Polarisation Effect as a Function of Distance From the Repair Edge.

The polarisation effect was monitored for 215 days at various locations throughout the car park. The distance of the effect ranged between 500 and 750 mm from the edge of the repairs [11]. After this time the deck was coated with a trafficable waterproofing membrane and was no longer accessible for potential mapping (Figure 7).

Figure 7: Coating or Membrane Applied to the Decks of The Grosvenor Car Park in 2011.

In 2023, more than 12 years after the installation of the anodes, a visual inspection of the car park was undertaken. There was substantial evidence of ponding water and some evidence of coating wear, but no evidence of further corrosion-induced damage was visible. Examples showing the condition of the car park are provided in Figures 8.

Figure 8: Evidence of Poor Drainage (Left), Membrane Wear (Right) Observed in 2023.

Prince Bishop Car Park

Prince Bishop car park was built in the late 1990s and is located in the heart of Durham City. In 2019 an interconnected galvanic anode system was installed into the decks above supporting beam lines, where movement induced cracking had provided routes for chloride-contaminated water ingress, resulting in widespread corrosion damage.

Thirty reference zones were installed across the 5 decks. The locations were chosen as a representative sample of the protected area and included many of the most negative potentials found during the potential mapping of the structure prior to repair. A sample of the potential map can be seen in Figure 9, with the red colour indicating the highest corrosion risk zones along beam lines [12].

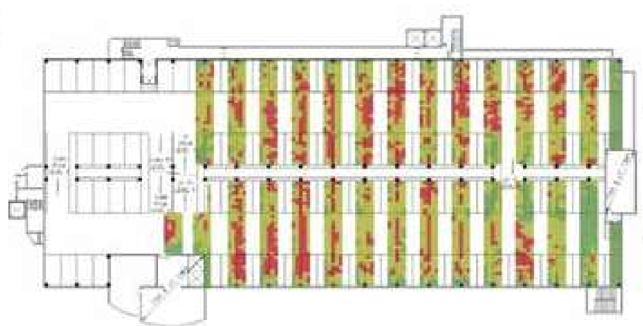

Figure 9: Pre-Installation Steel Potential Survey with ASTM C876 Colour Coded Corrosion Risk Bands.

continues on page 28

During the initial installation, the effect of the anode on the local steel potential was measured at 50 mm intervals away from an installed anode as shown in Figure 10. The mixed potential of the anode and the steel indicated the ability of a single anode, installed in a drilled hole away from the steel, to protect reinforcement at a distance of around 600 mm from the anode. Galvanic anodes are often installed in a grid configuration, in which case the steel within the grid will typically be polarized by the overlapping effect of four anodes, not just one, significantly increasing the degree of protection.

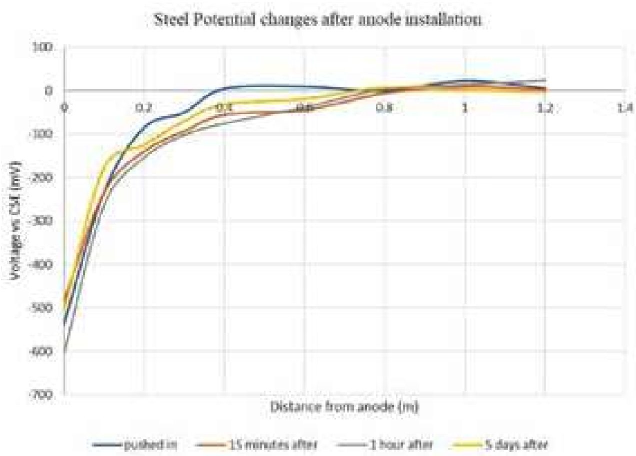

Figure 10: Relative Steel Potential Data Taken From a Single Anode Installed on the Car Park Deck Over a 5 Day Period.

The anodes at Prince Bishop car park were installed in 4 staggered rows across the deck, 2 rows directly above the beams and 1 row on either side of the beam as seen in Figure 11. All four of these rows formed one zone, connected by insulated titanium wires to two steel connections in the deck or via a junction box mounted in discrete locations. Data was accessible in the zones where reference electrodes were connected to the junction boxes. After anode installation, the deck was coated with a trafficable protective membrane to prevent further water ingress.

Figure 11: Car Park Deck Photo Taken After Installation of Anodes Before the Application of Deck Coatings.

During the installation and commissioning routine inspection de-polarisation tests were performed in order to calculate the local corrosion rates of the steel reinforcement and to measure the natural (depolarized) steel potentials. Steel potentials indicate the passivity of the steel and can be tracked over time.

During the first 4 years of service, the natural steel potentials were found to have trended much more positively in all test zones by an average of 76.6 mV, indicating the steel is becoming more passive, as shown in Figure 12 (below). Corrosion rates in June 2023, calculated using the Butler- Volmer Equation, were found to be between 0.03 and 0.86 mA/m^2; significantly below the 2 mA/m^2 threshold for negligible corrosion, and a visual inspection indicated no visible signs of corrosion.

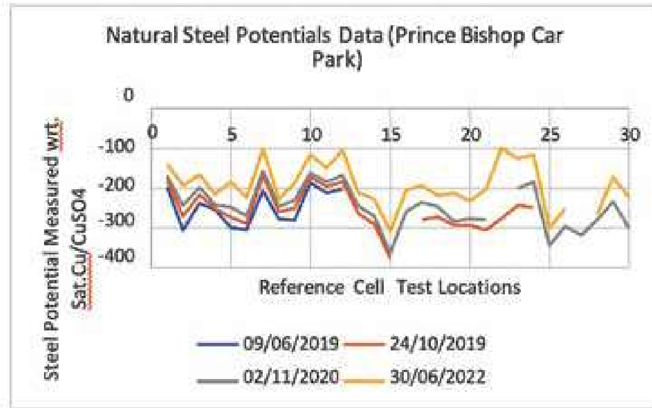

Figure 12: Steel Potentials Measured Over a 4 Year Period After installation of a Purely Galvanic Corrosion Management System.

Whiteadder Bridge

By February 2007, the piers of Whiteadder Bridge, near Berwick-upon-Tweed in Northumberland, had suffered extensive visible cracking and delamination of the concrete cover. Chloride contamination was high at up to 1.68% by weight of cement, and the piers were subject to extreme wet-dry cycling due to frequent flooding of the River Tweed. The damage is illustrated in Figure 13.

Figure 13. Example of the Damage (Left) and Repair Using Anodes (Right) on the Bridge Piers in 2007.

A hybrid galvanic corrosion protection system was installed on the piers as part of the solution. This installation was not a purely galvanic system. Using the hybrid anodes, an initial period of impressed current was applied for approximately one week to arrest the ongoing corrosion. Following the short phase of impressed current, and for the past 16 years, the system has operated in purely galvanic mode to maintain steel passivity. This has become a commonly used technique for structures subject to aggressive conditions. Embedded reference electrodes were installed into the protected zones, and steel potentials and anode currents have been continuously monitored since installation using data loggers, which, to date, have recorded over 10 million datapoints, revealing patterns that would otherwise be undetected by periodic spot readings. The average steel potential for both zones following the 2007 repair is plotted as a function of time in Figure 14. The trend is towards more positive or passive steel potentials. The temporary negative shifts in steel potential are associated with increased anode current output during flood events [13].

Both current and potential shifts have been used to determine corrosion rates, and in both lower and upper zones, the corrosion rates are indicative of passive steel [14,15].

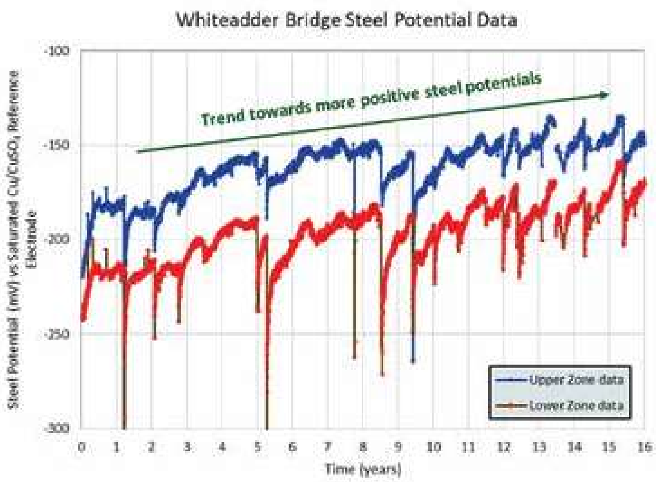

Figure 14: Steel Potentials as a Function of Time Since 2007 in the Upper and Lower Zones on the Piers.

Though the initial current from the anodes was high, in part a design feature of the anode type used, the long-term data shows the anodes achieving a steady state. The trend in current is provided on a logarithmic scale from years 7 to 16 in Figure 15 below. The current trend has not substantially changed over this period, with the average current responsive but relatively stable over the 9-year period. The biggest effect on current is the flood events, which give rise to an order of magnitude increase, peaking at over 6 mA/m^2 of current density. Smaller increases are observed cyclically due to temperature fluctuations.

Figure 15: Trend in Current Output Over the Last 9 Years.

It is highly significant that the long-term data shows the trend in current stabilising after the initial period of operation. A predictive model extrapolating short term data from the initial period of operation could lead to a false conclusion that current would continue to fall and that the system would become ineffective within 10 years [16,17]. However, in reality, the anodes are continuing to deliver protection in response to corrosion risk, and the structure is showing no signs of corrosion distress as shown in Figure 16.

Figure 16. Whiteadder Bridge in March 2023.

Conclusion

In the UK and beyond, there are numerous examples of galvanic anode systems that have been successfully providing protection to steel in concrete for well over 10 years. Following installation and commissioning, these systems require no maintenance. Galvanic anodes are voltage-limited devices, and, therefore, their current output is primarily driven by the resistivity between the anode and the steel. They respond in a positive way to changes in the aggressive nature of the concrete environment, which give rise to changes in concrete resistivity.

For patch repair protection, the position of the anode and the nature of the anode assembly are highly significant, as protection is required outside of the patch, not inside the patch.Evidence of anode influence outside of the patch is a requirement of the current UK National Highways specification for galvanic anodes, which requires 300 mm protection beyond the repair boundary. Within this standard, steel potential measurements and visual assessment are preferred to anode current measurements, which, when taken in isolation, are not sufficiently indicative of the protection delivered to the at-risk steel.

The Grosvenor and Prince Bishop Car Park case studies illustrate how half-cell potential measurements can be used to demonstrate the distribution of beneficial effects from a galvanic anode. The long-term Whiteadder data shows an on-going trend towards passive steel potentials and anode current reaching a steady state while remaining extremely responsive to environmental changes. For a structure subject to variable exposure conditions, this characteristic may significantly extend anode life, as very little anode material will be consumed at times of low corrosion risk.

References

1. BS EN 12696:2000, Cathodic protection of steel in concrete, British Standards Institute, 2000.
2. C. L. Page and G. Sergi, Journal of Materials in Civil Engineering, Vol. 12, No. 1, (2000), pp.8 – 15.
3. G. K. Glass and N. Davison, “Long term performance of galvanic anodes in concrete” (Invited Presentation), TRB technical committee meeting on Concrete Durability, Transport Research Board, Washington, January 2004.
4. W.Morris, A.Vico, M.Vazquez and S.R.de Sanchez, Corrosion Science., Vol. 44 No.1, (2002), pp.81-99.
5. S.P.Holmes, G.D. Wilcox, P.J Robins, G.K. Glass and A.C. Roberts, Corrosion Science, Vol 53 No.10, (2011). pp3450-3454.
6. J. J. Bartholomew, J. E. Bennett, B. L. Martin and T. A. Mitchell, Method and Apparatus for Cathodically Protecting Reinforced Concrete Structures, US Patent Application No. 892913, June 1992.
7. Christodoulou C, Goodier C, Austin S, Webb J and Glass GK, Corrosion Science, 69 (4) (2013) pp. 123-129.
8. C. Christodoulou, C. I. Goodier and S. A. Austin, “Site performance of galvanic anodes in concrete repairs”.in: Grantham, M, et al (eds). Concrete Solutions 2014. Proceedings of Concrete Solutions, the 5th International Conference on Concrete Repair, 1st-3rd September 2014, Belfast, Boca Raton, Fl: CRC Press, pp. 167-172.
9. https://www.standardsforhighways.co.uk/search/b3f60365-847a-4fd4-abdb-747568a1c726.
10. https://www.standardsforhighways.co.uk/search/55e1b2ae-296b-42fe-9370-893972ae3a0f.
11. C. Christodoulou, C. I. Goodier, S. A. Austin, G. K. Glass and J. Webb, Construction and building materials, Vol.50 (2014), pp.300-307.
12. ASTM C876-22b (2022).
13. D. Bewley and C. Stone, Concrete, Vol.57 No.5 (June 2023) pp.43-45.
14. W. Dodds, C. Christodoulou and C. Goodier, Proceedings of the Institution of Civil Engineers - Construction Materials, Vol171 No.4 (2018) pp.149-160.
15. G. K. Glass, N. Davison and A. C. Roberts, Materials and Corrosion, Vol.70 No.3 (2019) pp.503-510.
16. D Whitmore, ICRI Webinar: Design Considerations for Galvanic Anodes, 6 December 2022.
17. D Whitmore and G Sergi, NACE Corrosion 2021, AMPP, Paper no. 16712 (2021).