Long-term hybrid galvanic corrosion protection of reinforced concrete structures

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Abstract

Hybrid corrosion protection can be used to provide corrosion arrest and prevention in degrading reinforced concrete to increase the service life of the structures. The proprietary technology is a relatively new electrochemical treatment for concrete structures, having been patented in 2005 (Patent GB2426008B).

Due to it being a relatively contemporary technology, accurate and reliable empirical data over the life span of a structure repaired with hybrid galvanic anodes does not yet exist. This paper is the first to present over 10 years of empirical data, recorded every 6 hours from one of the very first installations of the hybrid corrosion protection system, thus providing a rigorous and reliable assessment of the structure's long-term performance. Results demonstrate that hybrid galvanic anodes exhibit a responsive behaviour to maintain the concrete environment and respond to corrosion hazards as also reported by others. Even after prolonged periods of low current output, the anodes respond to changing environmental conditions, providing the higher current output required to afford the necessary polarisation to the reinforcement, and hence protection of the structure. Steel potentials also continued to trend towards more positive values, a generally agreed indication of passive reinforcement. Overall, this study is unique, being the first to present continuous, long-term performance data on hybrid galvanic anodes for the corrosion protection of reinforced concrete structures.

Keywords

Corrosion, maintenance & inspection, concrete structures, service life

1 Introduction

Many reinforced concrete structures suffer from corrosion induced structural deterioration. The two main causes of corrosion in concrete structures are chloride attack and concrete carbonation. These lead to acid build-up, destruction of the local passive oxide layer on the steel and, in the example of chloride, self-catalyse the electrochemical process of corrosion (Glass and Buenfeld 1996). The ionic solution generated by this process creates in turn a current with a local anode at the sight of corrosion. The aim of any concrete protection system is therefore to return the reinforcement and its environment to a passive or negligible corrosion state. Typically, concrete provides a highly alkaline environment for the reinforcement with pH above 13. Under these conditions, the steel remains passive owing to formation of an oxide film, which covers its surface and presents a barrier to further metal dissolution (Glass and Buenfeld, 1996; Page and Treadaway, 1982).

One technology that has been successfully applied to arrest corrosion is a combination of electrochemical treatments termed a hybrid electrochemical treatment (Glass et al. 2008, Christodoulou and Kilgour 2013). A hybrid treatment briefly impresses a current off a galvanic anode using a battery or temporary power supply for a period of about one to two weeks. This arrests active corrosion by re-alkalising the local environment and polarising the steel around the repair by providing a driving potential with an initial large current to kick-start the restoration and passivation of the reinforcement before connecting the anode to the steel to continue delivering galvanic protection (Glass et al 2008).

This paper reviews the performance over time of one of the earliest applications of such a hybrid electrochemical treatment system, which is now over 10 years old. The paper is the first of its kind to present long-term continuous empirical data for this technology.

2. Technical Background

Concrete is normally highly alkaline and steel in this environment is protected by a passive film. Figure 1 shows a section of the potential-pH diagram for iron and its oxides in water. Passive films are not perfect, and some reaction of iron and water does occur. This is usually negligible. However, in the presence of chloride ions, hydrochloric acid is produced and localised pitting corrosion results. The production of acid is considered to be an essential feature leading to significant corrosion damage on passive steel (Figure 1). The local environment at the steel is moved from a region where insoluble oxides are the most stable product to an anodic region of lower potential and lower pH where iron is soluble by the process of corrosion initiation (Glass and Buelfeld 1996, Broomfield 2007, Dodds et al. 2018).

A commonly used repair technique to arrest deterioration due to chloride induced corrosion is the use of Impressed Current Cathodic Protection (ICCP). The technique relies on the continuous passage of a constant electric current through the electrolyte to the corroding metal surface and reverses the direction of the electric current produced by the corrosion reactions. It has a proven track record and it has been used worldwide to protect reinforced concrete structures from both existing and future chloride induced deterioration (Broomfield 2004, Christodoulou et al. 2013, Concrete Society 2011). One of the issues with ICCP is the maintenance and running cost over the life of the system, for example, the need for a permanent and consistent power supply.

One of the effects of an electrochemical treatment like ICCP is also to produce hydroxyl ions on the steel raising the pH. The local environment at the steel is then moved from a region where iron is soluble to a region where insoluble oxides are the most stable product. This has been proven to provide sustained protective effects to the steel reinforcement even when the protective current has been interrupted and chloride contamination remains (Christodoulou 2010, Christodoulou 2012, Polder et al. 2011). This re-alkalisation process is also illustrated in Figure 1 and would lead to a restoration in steel passivity. It is termed pit re-alkalisation when localised pitting corrosion is arrested. Such an effect may halt corrosion or delay its onset in concrete that is contaminated with chloride even when the protective current has been removed and there is no cathodic polarisation at all.

Galvanic corrosion protection on the other hand, is based on the principle of dissimilar metal corrosion. When two dissimilar metals are connected together, one will tend to act as an anode and will corrode, while the other will form the cathode. A natural potential difference between the different metals drives the current from the anode to the cathode (Christodoulou et al. 2009, Christodoulou et al. 2014, Dugaerte and Sagues 2009). The main metal used to protect steel in concrete is zinc, which provide a constant potential and is slowly consumed in the generation of the protection current. No external power supply is required. Because each element of anode surface acts as its own power supply the hybrid anode system offers a flexible solution as it is relatively easy to target any area of need.

Hybrid corrosion protection combines the advantages of both ICCP and galvanic anode technology into one system. Like standard galvanic systems, it comprises a discrete zinc anode system which is installed into pre-drilled cavities within the reinforced parent concrete (Figure 2). Compared to ICCP and galvanic protection, hybrid is a relatively new development in electrochemical protection treatments, being patented for the first time in the UK in 2005 (GB2426008B).

The hybrid anodes are manufactured using 18 mm diameter zinc cylinders, ranging from 25 to 220 mm in length, with an integrated titanium connector wire. A coating is applied to the surface of the anode in order to keep the anode active throughout its design life.

Initially, the system is connected to a temporary, constant 9 V DC power supply, typically for a period of at least 1 week, depending on the type of reinforcement (e.g. mild steel or prestressed), to deliver a charge to the reinforcing steel. This initial impressed treatment phase re-passivates the reinforcement by means of generating a reservoir of alkali at the steel – concrete interface (Christodoulou and Kilgour 2013, Glass et al. 2012, Holmes et al. 2011a).

During this initial impressed current phase, a charge will be delivered to the reinforcement which is responsible for generating hydroxide at the steel interface and restoring passivity. The exact amount

of charge varies depending on concrete mix design, bulk resistivity, chloride contamination from de-icing salts and the steel-concrete interfacial condition. Studies by Glass et al. (2008), Polder et al. (2011), Holmes et al. (2013) and Dodds et al. (2016) have shown that based on to the aforementioned parameters, the charge required to achieve passivation varies between 50 kC/m² and 250 kC/m². For design purposes, a value of 50 kC/m² is generally used in accordance to the manufacturer's recommendations and thus this paper evaluates the effectiveness of the installed hybrid corrosion protection system against this design value.

Following completion of the initial energisation phase, the hybrid anode is then disconnected from the temporary DC power supply and connected directly to the steel reinforcement, creating a galvanic cell, similar to a battery. This latter treatment phase continues for the remainder of the anodes' working life and under dry, cool, low corrosion risk conditions, provides a relatively low maintenance current to the steel reinforcement to maintain the natural alkaline environment and steel passivity without the need for ongoing inspection or maintenance.

3. Methodology

This section provides a brief description of the structure itself, the hybrid system design and the empirical data recording and monitoring.

3.1. Structure

Whiteadder Bridge is a 90 m long structure that forms part of the B6461 carrying traffic over the Whiteadder Water at Canty, near Paxton, UK. It opened in 1973 and is constructed from four steel girders supported on bearings directly above reinforced concrete piers (Figures 3 and 4). A historical drawing of the reinforcement detailing of the piers is shown in Figure 5.

When inspected in 2006, the bridge exhibited areas of substantial spalling and delamination to the piers, due to chloride ingress from leaking of the deck joints. The presence of chlorides was confirmed through testing of dust samples from depth increments (0-25mm, 25-50mm, 50-75mm, 75-100mm) at particular locations. The highest chloride ion content was recorded in Pier B (West river pier) with

1.68% by weight of cement measured in two locations at the depth of reinforcement, indicating a high risk of chloride-induced corrosion. The extent of corrosion was confirmed through half-cell potential mapping of the piers, which highlighted local, corroding anodic locations within the structure. A typical example of the material sampling on the piers is shown in Figure 6.

Following the structural inspection and material testing, AECOM (previously Faber Maunsell) developed a design for structural repairs and corrosion protection to prevent further deterioration which would have had adverse impact on the load carrying capacity of the bridge. A summary of the works, which were executed in 2006 is as follows:

- Concrete repairs to abutments, piers and parapet coping;
- Installation of a hybrid corrosion protection system;
- Localised repairs to structural steelwork;
- Installation of parapet coping plates;
- Spray applied waterproofing to piers, including bearing shelves;

Hybrid anodes were installed across the entire face of the four reinforced-concrete piers at horizontal and vertical centres between 400 mm and 500 mm, to achieve a design life of 30 years. Reference electrodes were installed in an upper and lower zone on Pier C (East river pier) to monitor the change in steel potential readings at 12 locations. The upper zone is typically dry as the river water does not reach that high in tidal or flood situations. The lower zone is typically much wetter. Approximately 50 hybrid anodes are installed within the monitoring zone across 10 rows.

Data logging equipment was installed within a junction box on the bridge which can be remotely accessed using a modem link to a desktop PC using the appropriate software. The data logger battery is recharged through daylight hours by means of a solar panel.

A sprayed waterproofing membrane was also applied to the entire surface of the piers following the concrete repairs.

3.2. Monitoring

A number of tests were undertaken to assess the passivity of the steel reinforcement, including:

- a) potential measurements,
- b) current output measurements, and
- c) corrosion potential measurements by means of polarisation resistance.

Measuring steel potentials against a standard reference electrode is a well-established technique. In general, measurements more positive than approximately -200 mV against Cu/CuSO₄ (copper/copper sulphate) are considered statistically to be in the area of “low corrosion risk”, and measurements more negative than -350 mV against Cu/CuSO₄ are considered to be in the area of “high risk” of ongoing corrosion (Concrete Society 2004, Elsener 2003). Steel potentials can give a good approximation of the corrosion risk of steel, but they are affected by various other factors, such as temperature, humidity, oxygen availability etc.

3.3. Performance assessment

The structure was inspected visually in March 2014, 7 years after the repair works were completed. The inspection found no visible defects to the reinforced-concrete piers which are protected by the hybrid corrosion protection which is an indication of successful system performance, as the parent concrete still had high levels of residual chlorides following the structural repairs and yet there have been no further concrete spalls. Water and rust staining were observed from the primary steel girders due to water ingress through the deck joints.

Electrochemical systems for atmospherically exposed structures are assessed in accordance to ISO BS EN ISO 12696 (BSI 2016). The criteria for achieving cathodic protection are reproduced in Table 1. The standard also highlights that these are not necessarily supported by theoretical considerations, but are a non-exhaustive, practical series of criteria to indicate adequate polarisation which will lead to the maintenance or re-establishment of protective conditions for the steel within the concrete. Furthermore, it is also stated that the data collected shall be reviewed and interpreted in respect of the following criteria as modified by the particular requirements of the structure, its environment or developing expertise in respect of the criteria of protection for reinforced concrete.

Constant current systems such as ICCP aim to provide protection via polarisation. Constant potential systems, like galvanic anode systems, aim to restore and maintain the steel's environment so it may meet polarisation criteria only when the protection is needed.

Due to the limitations of the above, the standard also permits the use of the alternative performance verification criteria, in case the ones presented in Table 1 cannot be met. These alternative performance verification criteria are presented in Table 2. There is no requirement in ISO 12696 to meet more than one of the Table 1 or Table 2 criteria.

4. Results

Figure 7 demonstrates the current output of the anodes as a function of time over a period of 11 years. It can be observed that initially, there is a higher current output which gradually reduces into a steady state of current output needed to maintain the steel polarisation once the local concrete pH and chloride concentrations are restored. The differences in current output between the lower and upper zones is due to the differences in environmental conditions – the lower zone is closer to the river and contains a higher moisture content.

It is further noted that occasionally the current output of the anodes spikes before settling back again into a steady current output. This behaviour has been associated with the occasional flooding of the river that Witteadder Bridge is crossing, lowering the concrete resistivity and increasing ionic mobility. This has been termed “Responsive Behaviour” (Dodds 2016, Holmes 2011b).

Overall, figure 7 confirms the viewpoint that anodes will typically have a higher current output early in their service life. This is associated with the fact that they are more electrochemically active in the early phase of their service life, responding to the moisture in the mortar, building up the hydroxide reservoir, slowly migrating chloride ions towards the anodes and restoring the steel environment (Glass et al. 2008). The current will continue to drop until the steel has reached a point of electrical

current demand equilibrium and passivity. Once the latter is reached, it is evident that the current demand and associated output from the anodes becomes nearly constant.

A cyclical swell in current can also be observed on figure 7 every year. This is the result of temperature variations – normally expected in an outdoor environment – increasing the ionic mobility; the current then responds and reacts to this increased risk. Furthermore, the average annual current output for each zone is illustrated on Table 3. As it can be observed, the current output has decreased over time and as observed by the graphs, it responds to environmental conditions.

Figures 8a and 8b illustrate the steel potentials for both the upper and lower zones over a period of over 11 years. It can be observed that the steel potentials have moved towards more positive values and generally remained stable and thereafter they are only influenced by topical and short-lived environmental exposure variations, such as the ones induced by the occasional flooding of the river. As discussed in Section 3.3, this trend is regarded as an indication of steel passivity (BSI 2016). The instances where the potentials dipped towards more negative values coincide with the periods of river flooding causing a responsive behaviour from the anodes, increasing the current output to restore the steel's polarisation potential.

Figure 9 illustrates a closer up look at the behaviour of the steel potentials following a flooding event of the river and the responsive behaviour of the anodes. By comparing Figures 7 and 9, it can be observed that the steel responds immediately to the increased current supplied by the anodes as a result of the substantially lower concrete resistivity following the river flood.

Plotting the steel potentials against the current output of the anodes provides useful information on the relationship between the two measurements. As can be observed from Figure 10, with the continuous move of steel potentials towards more positive values (as also seen in Figures 8a and 8b) the current demand of the anodes is also significantly reduced. This further supports the findings of

Holmes et al. (2011b) which suggests that when steel in a passive and benign condition, it does not require significant amounts of current to achieve and maintain protection.

An electrode is polarized when its potential is forced away from its value at open circuit or corrosion potential. Polarization of an electrode causes current to flow due to electrochemical reactions it induces at the electrode surface. Polarization resistance, behaves like a resistor and can be calculated by taking the inverse of the slope of the current potential curve at open circuit or corrosion potential. Figure 11 demonstrates the typical polarisation resistance exhibited by the reinforcement.

Further detail in the responsive behaviour of the anodes is shown in Figure 12. It can be observed that as soon as the steel potentials get depressed to more negative values, the current output of the anodes increases. Subsequently, as the potentials rise to more positive values the current output of the anodes decreases. This self-regulation increases the lifetime of the system. The zinc is sacrificed via the current expenditure only when needed to restore the local steel environment and to maintain the potential.

A further polarisation resistance relationship between current output of the anodes and steel potential after 8.5 years is shown in Figure 13.

5. Discussion

This paper presents the first ever set of published empirical data on the long-term performance and anode output from a hybrid anode corrosion protection system.

5.1. Responsive Behaviour

As it was observed in Figure 7, there are isolated and distinct events during which the current output of the anodes increased by approximately 5 fold. By closer examination of these occurrences, it was

established that these events took place at the same time as when the local river burst its banks causing flooding, wetting the piers. This is also supported further by the lower zone having a substantially greater response than the upper zone. This is due to the fact that local wetness of the concrete caused a reduction in overall concrete resistivity which as a result increased the current demand and output of the anodes.

In addition to the above, it can also be observed that the current output of the anodes over time is decreasing. This is associated to the fact that the concrete has re-alkalised - chloride ions have slowly migrated towards the anodes away from the reinforcement and the steel requires little protective current as the corrosion risk is low due to the resistance of the concrete. In this state, little current is required to adequately protect the steel from corrosion.

Overall, it can be observed that the anodes respond to environment-related requirements for protective current systems. Current output from the anodes appears to respond to changes in the nature of the environment the concrete is exposed to, passing a higher current when required to address an increase in the overall steel corrosion risk (signified by increased steel anode current) and low current when there is a lower steel corrosion risk. This observation is supported further from the results shown in Figure 10.

5.2. Polarisation

Typically, steel in concrete is considered to be protected from corrosion when the criteria of either cathodic prevention or cathodic protection in accordance to ISO 12696 (BSI 2016) are satisfied. Cathodic prevention is considered to be applied on new structures from the start of their life and with no prior corrosion, whereas cathodic protection applies to the rehabilitation of corroding ageing concrete structures.

In particular, the design standard recognises two scenarios of cathodic protection, namely:

- *cathodic protection* restoring passivity, and
- *cathodic protection* reducing corrosion rate

The performance criteria used to assess whether there is sufficient polarisation of the reinforcement, thus satisfying cathodic protection are given in Tables 1 and 2 respectively (BSI 2016). As discussed by Holmes et al. (2011b), this perceived need for polarisation inhibits the use of responsive behaviour, as demonstrated in the data of this work and also that of others (Holmes et al. 2011b, Dodds et al. 2016).

Current controlled power-supplies like the ones used predominantly in Impressed Current Cathodic Protection applications, suppress current fluctuations in order to maintain consistent polarisation levels (Holmes et al. 2011b). This is in contrast to responsive galvanic systems where a constant potential is applied to vary the current flow, restoring passivity at times of risk or maintaining the environment to reduce corrosion. This is a feature of the product which consequentially results in difficulties for the system in complying with the typical test criteria of restoring passivity.

Based on all of the above, and the provisions within ISO 12696 (BSI 2016) for galvanic anode systems where the non-exhaustive and non-theoretically considered criteria shown in Table 1 may not be achieved, performance of the hybrid corrosion protection system has been undertaken by means of a corrosion risk assessment. In doing so, the alternative criteria shown in Table 2 were utilised.

In particular, Figures 8a, 8b and 9 demonstrate that steel potentials have moved towards more positive values and generally remained stable. The isolated events where potentials have spiked towards more negative values have been discussed previously and they all relate to the responsive behaviour of the anodes in response to the environmental changes; namely the local flooding of the river banks and associated wetting of the concrete piers.

The above is reinforced further from the data shown in Figure 12 which combines steel potentials and current output. As it can be observed, steel potentials trend towards more positive values while the current demand from the anodes is decreasing. This is also supported by Holmes et al. (2011b) and also Dodds et al. (2016).

Furthermore, Figures 14a and 14b demonstrate one such responsive behaviour of the hybrid corrosion protection anodes and also an analysis of the potential-current relationship.

The decaying potential at each reference cell, following the current surge is plotted against the logarithm of the zone current. The data also provide a good indication of the prevailing conditions before the surge occurred and it can be observed that generally there was a state of equilibrium.

From the potential against logarithm of current density plot (Figure 14b) it is also possible to calculate the cathodic Tafel slope (β_c). From Figure 14b, the calculated Tafel slopes are generally lower than the typical value of 120 mV used for corrosion current density calculations (Christodoulou et al. 2010, Christodoulou et al. 2012, Concrete Society 2004, British Standards Institution 2016) which suggests that generally, calculation of corrosion current density tends to be overestimated. Lifetime or anodic corrosion loss calculations are therefore likely to be conservative by nature.

5.3. Current density

A general industry concern in the use of galvanic and hybrid anodes is passivation of the anode material, which is typically zinc. Furthermore, typical galvanic anode systems do not have permanent monitoring systems to capture continuous performance data, but rather measurements being taken at distinct time points.

The data presented as part of this work are unique as they are the first of their kind to provide both continuous and long-term data on the current output of the anodes and the associated response of the steel potentials.

The data observed across Figures 7 and 12 demonstrate that after approximately 0.5 years of operation (e.g. 6 months), the current output from the anodes has stabilised. The annual average currents and the overall average current outputs are shown on Table 3. It can be observed that year-on-year the current outputs have been reducing. This should not though be mistaken for passivation of the zinc anodes.

In fact, there are 6 distinct events where the anodes have responded to changes in the prevailing environmental conditions and in fact current output increased by up to 10 orders of magnitude. This demonstrates that the anodes are still electrochemically active, and have the capacity to respond to environmental changes and current demand from the steel reinforcement.

Furthermore, having over 10 years' worth of continuous data (taken at 6-hourly intervals) of current output, it is possible to verify the performance of the anodes against the design current density. Galvanic anode systems are typically designed on the basis of cathodic prevention using a design current density of no more than 2mA/m^2 (British Standards Institution 2016).

As it can be observed from both the annual average current outputs and also from the 10-year term average current output (Table 3), the demand from the anodes has at all times been substantially less than the design current density of 2mA/m^2 . Generally, the average current anode output from the lower zone anodes has been higher than that of the upper zone anodes. However, this is explained by the fact that the lower zone is subject to a much more varying and changeable environment, including occasional wetting.

352

353 Overall, the data provide confidence that the actual current density of the anodes is in practice and
354 over a period greater than 10 years lower than the assumed design current density, suggesting that
355 the recommendations of ISO 12696 are appropriate and valid. As shown in this case, this will result in
356 a lower utilisation of the anodes and as such will have positive effects in extending the service life of
357 the hybrid corrosion protection system.

358

359 **6. Conclusions**

360 This work presents unique and original data on the long-term performance of hybrid galvanic anodes
361 for the corrosion protection of reinforced concrete structures. In particular, the following items are
362 concluded:

- 363 • The structure was inspected visually in March 2014, 7 years after the repair works were
364 completed and found no visible defects to the reinforced-concrete piers which are protected by
365 the hybrid corrosion protection which is an indication of successful system performance, as the
366 parent concrete still had high levels of residual chlorides following the structural repairs and yet
367 there have been no further concrete spalls.
- 368 • Hybrid galvanic anodes exhibit a responsive behaviour, as previously reported by Holmes et al
369 (2011b). It has been observed that even after prolonged periods of low current output (1 year+),
370 the anodes will respond and react to changing environmental conditions, providing higher current
371 output to afford the necessary polarisation to the reinforcement, and hence protection.
- 372 • Steel potentials continued to trend towards more positive values over several years, a generally
373 agreed indication of passive (and hence protected) reinforcement.
- 374 • The data provide confidence that the actual current density of the anodes is in practice and over a
375 period greater than 10 years lower than the assumed design current density, suggesting that the
376 recommendations of ISO 12696 are appropriate and valid. As shown in this case, this will result in
377 a lower utilisation of the anodes and as such will have positive effects in extending the service life
378 of the hybrid corrosion protection system

- The calculated Tafel slopes (β_c) are less than the usually applied value of 120 mV (British Standards Institution 2016) which suggests that generally, calculated corrosion current densities are over-calculated.

On balance, the data presented as part of this work provides a robust understanding on the performance characteristics of hybrid galvanic anode systems based on long-term empirical site data which demonstrates the ability of such an electrochemical system to provide sustainable and resilient protection to reinforced concrete elements against chloride induced deterioration.

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References

- B. Elsener, Half cell potential measurements–potential mapping on reinforced concrete structures, RILEM TC 154-EMC: electrochemical techniques for measuring metallic corrosion, Mater. Struct. 36 (2003) 461–471.
- Broomfield J (2004) A case history of cathodic protection of a highway structure in the UK. Proceedings of Corrosion 2004. Annual Conference and Exhibition, New Orleans, LA, USA, paper 04344.
- Broomfield J (2007) Corrosion of Steel in Concrete: Understanding, Investigation and Repair, 2nd edn. Taylor & Francis, Abingdon, UK
- BSI (2016) BS EN ISO 12696:2016: Cathodic protection of steel in concrete. BSI, London, UK.
- Christodoulou C and Kilgour R (2013) The world's first hybrid corrosion protection systems for prestressed concrete bridges. Proceedings of Corrosion & Prevention 2013, Australasian Corrosion Association, Brisbane, Australia, paper 076.
- Christodoulou C, Glass G and Webb J, Corrosion management of concrete structures [technical note]. Structural Engineer, 87 (23-24), pp. 20 – 22
- Christodoulou C, Glass G, Webb J, Austin S and Goodier C, Assessing the long term benefits of Impressed Current Cathodic Protection, Corrosion Science, 52 (2010), pp. 2671 – 2679 DOI information: 10.1016/j.corsci.2010.04.018
- Christodoulou C, Goodier C, Austin S, Glass G and Webb J, On-site transient analysis for the corrosion assessment of reinforced concrete, Corrosion Science, 62 (2012), pp. 176 – 183 DOI information: 10.1016/j.corsci.2012.05.014
- Christodoulou C, Goodier C, Austin S, Webb J, Glass G, A new arrangement of galvanic anodes for the repair of reinforced concrete structures, Construction and Building Materials, 50 (2014), pp. 300 – 307, DOI information: 10.1016/j.conbuildmat.2013.09.062

415 Christodoulou C, Sharifi A, Das S, Goodier C, Cathodic Protection on the UK's Midland Links
 416 motorway viaducts, Proceedings of the Institution of Civil Engineers: Bridge Engineering, (2013), DOI
 417 information: 10.1680/bren.12.00015

418 Concrete Society (2011) Technical Report 73, Cathodic Protection of Steel in Concrete. The Concrete
 419 Society, Croydon, Camberley, Surrey, UK.

420 Concrete Society, Technical Report 60, Electrochemical Tests for Reinforcement Corrosion, Surrey,
 421 UK, 2004.

422 Dodds W, Christodoulou C, Goodier C, Hybrid anode concrete corrosion protection – independent
 423 study, Proceedings of the Institution of Civil Engineers: Construction Materials,
 424 <http://dx.doi.org/10.1680/jcoma.16.00024>.

425 Dugarte M., Sagüés A.A., Galvanic point anodes for extending the service life of patched areas upon
 426 reinforced concrete bridge members. Contract No. BD544- 09. Final report to Florida Department of
 427 Transportation, Tampa, Florida; USA: September 2009.

428 Glass G, Christodoulou C and Holmes S (2012) Protection of steel in concrete using galvanic and
 429 hybrid electrochemical treatments. In Concrete Repair, Rehabilitation and Retrofitting III: Proceedings
 430 of 3rd International Conference on Concrete Repair, Rehabilitation and Retrofitting, ICCRRR-3, Cape
 431 Town, South Africa (Alexander MG, Beushausen HD, Dehn F and Moyo P (eds)). pp. 523–526. CRC
 432 Press, Taylor and Francis Group.

433 Glass GK and Buenfeld NR (1996) Reinforced concrete – its principles of deterioration and repair. In
 434 Modern Matters – Principles and Practice in Conserving Recent Architecture (Macdonald S (ed.)).
 435 Donhead Publishing, Shaftesbury, UK, pp. 101–112.

436 Glass GK, Roberts AC and Davison N (2008) Hybrid corrosion protection of chloride-contaminated
 437 concrete. Construction Materials 161(CM4): 163–172, <http://dx.doi.org/10.1680/coma.2008.161.4.163>.

438 Holmes SP, Christodoulou C and Glass GK (2013) Monitoring the passivity of steel subject to
 439 galvanic protection. Proceedings of Corrosion & Prevention 2013, Australasian Corrosion Association,
 440 Brisbane, Australia, paper 133.

441 Holmes SP, Wilcox GD, Robins PJ, Glass GK and Roberts AC (2011a) Long term assessment of a
442 hybrid electrochemical treatment. *Materials and Corrosion* 62(9999): 43–49.

443 Holmes SP, Wilcox GD, Robins PJ, Glass GK and Roberts AC (2011b) Responsive behavior of
444 galvanic anodes in concrete and the basis for its utilisation. *Corrosion Science* 53(10): 3450–3454.

445 Page CL and Treadaway KWJ (1982) Aspects of the electrochemistry of steel in concrete. *Nature*
446 297(5862): 109–115.

447 Polder R, Peelen WHA, Stoop BTJ and Neeft EAC (2011) Early Stage Beneficial Effects of Cathodic
448 Protection in Concrete Structures, *Materials and Corrosion*, V62 No 2.

449

450 **Figure captions List**

451 Figure 1: Model of corrosion initiation and arrest showing the stability of iron and its corrosion
452 products (Glass et al. 2008).

453 Figure 2: Typical hybrid anodes.

454 Figure 3: South elevation of Whiteadder Bridge, UK.

455 Figure 4: Typical structural cross-section of Whiteadder Bridge, UK.

456 Figure 5: Typical reinforcement detailing record of Whiteadder Bridge, UK.

457 Figure 6: Pier elevations of Whiteadder Bridge, UK showing the results of the material testing.

458 Figure 7: Current output of the hybrid anodes over a period of up to 11 years.

459 Figure 8a: Steel potentials (upper zone) over a period of 11 years.

460 Figure 8b: Steel potentials (lower zone) over a period of 11 years.

461 Figure 9: Steel potentials (lower zone) over a period of 3 years.

462 Figure 10: Relationship between steel potentials and current demand from the hybrid anodes.

463 Figure 11: Polarisation resistance relationship between potential and current at 5.25 years.

464 Figure 12: Relationship between current output and steel potential at 8.5 years.

465 Figure 13: Polarisation resistance relationship between potential and current at 8.5 years

Figure 14a: Current surge and potential response recorded at the location of embedded reference electrodes together

Figure 14b: Potential-current analysis.

Table Caption List

Table 1: Primary non-exhaustive performance verification assessment criteria

Criterion	Description
(a)	an “Instantaneous OFF” potential more negative than –720 mV with respect to Ag/AgCl/0,5 M KCl
(b)	a potential decay over a maximum of 24 h of at least 100 mV from “Instantaneous OFF”
(c)	a potential decay over an extended period (typically 24 h or longer) of at least 150 mV from the instant off subject to a continuing decay and the use of reference electrodes (not potential decay probes) for the measurement extended beyond 24 h.

Table 2: Alternative non-exhaustive performance verification assessment criteria

Criterion	Description
(d)	steel/concrete potential in a fully depolarised structure after the cathodic protection system has been switched off for a long period (typically 7 d or longer) less negative than –150 mV with respect to Ag/AgCl/0,5 M KCl.
(e)	further assessment of corrosion risk
(f)	Passive steel is indicated by a corrosion rate of less than 2 mA/m ² and preferably less than 1 mA/m ² .
(g)	A falling trend in corrosion rate combined with a rising trend in corrosion potential is also a sign that protection is being achieved.

Table 3: Annual average current output of anodes.

Year	Average Anode Current Output (mA)	
	Upper Zone	Lower Zone
1	0.5	2.52
2	0.42	2.22
3	0.27	1.8
4	0.17	1.29
5	0.13	0.95
6	0.16	1.39
7	0.12	0.72
8	0.11	0.74
8-year average	0.24	1.45