MATEC Web of Conferences **361**, 02001 (2022) https://doi.org/10.1051/matecconf/202236102001
Concrete Solutions 2022

A review of developments in cathodic protection systems for reinforced concrete structures

Rene Brueckner[1,*], *Ryan* Cobbs[1], and *Chris* Atkins[2]

[1]Mott MacDonald, Materials and Corrosion Technology, Bristol, UK
[2]Mott MacDonald, Materials and Corrosion Technology, Altrincham, UK

Abstract. Cathodic protection is a corrosion management strategy for deteriorating reinforced concrete structures or it can be used as preventative measure in situations where corrosion may be expected during the service life as a result of the environmental exposure conditions. The technology has advanced over time. There are now a number of different systems that can conveniently be considered in three categories, including impressed current cathodic protection (ICCP), hybrid cathodic protection (HCP), and galvanic cathodic protection (GCP). Asset owners need to choose which option to use possibly without understanding the different sustainability, environmental, health and safety, construction, technical, operational, and monitoring aspects. Generally, it is agreed among corrosion engineers that ICCP is the most powerful and robust solution for corrosion management in structures with widespread deterioration. HCP and GCP can also be viable options, even in the most aggressive environments with future maintenance intervention. The advantages and disadvantages of each system are discussed in detail. This paper also explains why the commonly accepted life expectancy of ICCP systems is 50 to 75 years compared to HCP and GCP, which are typically limited to 15-30 years. The details of the likely maintenance requirements, associated timescales, and whole-life costs for a 100-year design life are analysed with references to sustainability. That includes a discussion about the corrosion management system that presents the lowest embodied carbon option for different environments.

1 Introduction

Steel embedded in concrete normally does not corrode despite being in a moist environment within a porous material. When concrete hydrates it produces a highly alkaline solution with a pH in excess of 13. Under alkaline conditions a stable oxide film forms over the surface of the steel that protects it from corrosion. However, the protective nature of this passive film can be compromised due to two commonly encountered mechanisms of chloride ion attack and carbonation.

Chloride ion attack is considered the most significant cause of concrete deterioration. When chlorides reach the steel in sufficient quantities, they disrupt the passive film and form localised areas of intense corrosion. Chlorides usually derive from external sources such as de-icing salt or chloride containing spray and sometimes internal admixtures and aggregates. In the past, calcium chloride was added to concrete to accelerate hydration, and marine dredged aggregates were widely used in coastal areas. The latter two internal sources may be encountered in structures constructed up to the mid-1970s in the UK.

Corrosion of steel in concrete due to carbonation is a result of the reduction of alkalinity that protects the steel surface. The atmosphere contains a small proportion of carbon dioxide which can dissolve in moisture to form a mild acid. The carbonic acid produced reacts with the alkalinity in the concrete and can reduce it to a level where corrosion can occur.

The rate of those two types of attack depends on the moisture content and porosity of the concrete matrix. Concrete is a material with a large pore system that is governed by the concrete mix design parameters and in particular by the water-cement ratio. Common mixes used in the construction industry have a w/c-ratio in excess of 0.38 which enables a connected capillary pore system to form. This pore system allows aggressive media to penetrate the concrete matrix enabling the reaction of carbon dioxide dissolved in the pore water with the calcium hydroxide forming calcium carbonate what is known as carbonation. Chloride ions penetrate the concrete through the pore water by diffusion.

2 Corrosion Management Strategies

Corrosion on the steel surface is initiated when the passive oxide layer is disrupted by either carbonation or chloride ingress in the presence of water and oxygen. When chlorides reach the steel in sufficient quantities, which threshold is typically specified as 0.4% chlorides by mass of cement but may practically be around 0.6%

* Corresponding author: rene.brueckner@mottmac.com

or higher, they disrupt the passive film and form localised areas of intense corrosion.

To prevent the onset of corrosion or protect the steel against ongoing corrosion electrochemical techniques can be used. The most common electrochemical solution is cathodic protection (CP). However, other techniques such as corrosion inhibitors, realkalisation, chloride extraction, and electro-osmotic methods can mitigate the risk of ongoing corrosion in reinforced concrete structures decreasing the rate of corrosion to a tolerable level. CP can be a particularly effective repair technique for chloride contaminated concrete and is generally installed as a retrofit solution. It is used less commonly for carbonated concrete. CP can also be utilised as a cathodic prevention system for installation during construction.

On the principle that corrosion occurs due to the formation of anodic sites where metal is lost and cathodic sites which are unaffected, CP works by polarizing the steel reinforcement in an electrical circuit, making the steel entirely cathodic to a system of installed anodes (see Figure 1). These can be self-powered galvanic anodes (GCP) or inert anodes powered by a low voltage DC supply, commonly referred to as impressed current cathodic protection (ICCP). In more recent years hybrid cathodic protection (HCP) systems have been developed based on the advantages of the GCP and ICCP systems.

ICCP systems generally use inert long-life anodes such as mixed metal oxide coated titanium or titania (titanium oxide ceramic). The steel is polarised using an external DC power source. Galvanic systems use less noble metal anodes, commonly zinc, aluminium, or magnesium, which corrode preferentially to the steel and provide the required protection. Hybrid cathodic protection systems use galvanic anodes and initially connect them to a temporary external DC power source to re-passivate the steel reinforcement before switching to self-powered galvanic protection.

CP systems must be carefully designed, and many different factors must be taken into account, such as the aggressiveness of the environment, the area of steel to be protected, the type of anode used, and the sensitivity of the concrete to other deterioration mechanisms. This assessment will determine the most effective and robust system to be used to treat any particular structure.

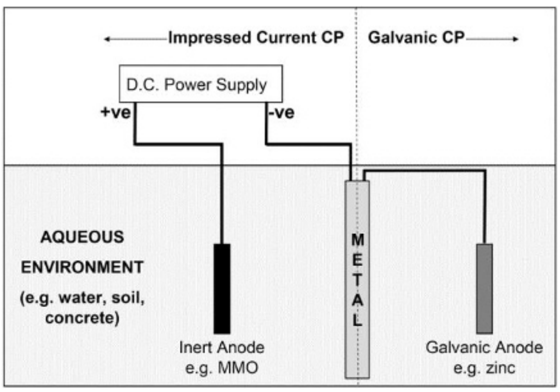

Fig. 1. Schematic of Impressed and Galvanic Cathodic Protection, Lambert (2009)

2.1 Galvanic Cathodic Protection

GCP is usually used as a medium-term solution with a design life of 15 years. The types of galvanic anodes can be divided into surface applied and embedded discrete systems. These systems work on the principles of potential difference, whereby a small current flow of between 0.2-2.0 mA/m^2 from the anodes to the steel is sufficient to reduce corrosion to an insignificant amount.

Discrete galvanic anodes are commonly installed within concrete patch repairs to mitigate incipient anode effects which moves corrosion to the edges of the repair resulting in premature failures. Discrete galvanic anodes may also be installed in non-repaired concrete in pre-drilled cavities and entire elements may be protected from corrosion. Surface applied anodes are generally used when large areas require protection as an alternative for simpler installation than discrete anodes.

The main advantage of the GCP system is that it does not require a permanent power supply, and as a result, they are more straightforward to install as less electrical wiring is involved. This is also a disadvantage as the system is self-powering; it has a limited protection current, similar to a battery. The low driving voltage of GCP systems is particularly advantageous when overprotection must be avoided, such as in the case of prestressed elements.

2.2 Impressed Current Cathodic Protection

CP systems based on impressed current are usually installed on larger structures to protect large areas affected by corrosion. These systems can provide effective reinforcement corrosion prevention in excess of 25 years and potentially up to 50 and 75 years. Protection of the reinforcement is achieved by polarization using an external DC power source. ICCP systems use inert long-life electrodes such as mixed metal oxide coated titanium which do not get consumed. The reference electrodes and power units largely govern the system's design life but can be replaced. Annual monitoring is essential to detect any faults due to the risk of power failure. However, it should be noted that failure of the power supply does not lead to an immediate loss of protection, and the necessary maintenance work can be carefully planned.

The installation method of the ICCP systems mainly depends on the characteristics of each structure. Mesh and overlay systems are very robust and can provide protection of 50-75 years. The mesh is installed on the surface of the structure, which will have undergone conventional concrete repair, and is then embedded in a cementitious overlay, which is typically over 25mm thick. This may be a dry-mix gunite or wet-mix gunite when dust and noise disruptions are required to be minimised. The main disadvantages of the mesh and overlay system are that an additional dead load is added to the structure, head room may be lost and that it is not suitable for vibrating structures.

Discrete anodes are used when the dimensions of the structure cannot be altered due to restrictions to the headroom or sides, for example in the case of railway bridge abutments and piers or car parks. Discrete anodes are resilient against vandalism and can provide protection for more than 25 years. Such systems can protect reinforcement beyond 100mm depth and remote from accessible faces in contrast to a mesh and overlay system. The main disadvantages are that it is limited to thicker elements, and a series of bore holes may be required for the installation. This increases the risk of short-circuits, damaging the steel and is a serious health and safety concern due to hand-arm vibration (white finger) issue.

Discrete anode systems are designed for bridge pier crossheads and half-joints where the access to the upper reinforcement is limited. The accessible faces of the elements are protected with a mesh and overlay, but the remaining reinforcement requires protection by discrete anodes. Figure 2 shows a pier crosshead where the deck joint is located immediately above and penetration of chloride contaminated water has caused severe deterioration.

Fig. 2. Deteriorated Bridge Crosshead

Bridge structures can also be protected using a cassette system provided that sufficient humidity is present. The cassette system consists of an anode in a glass fibre filled FRP tray which can be mounted on a concrete surface. The glass fibre foam is impregnated with a hydroscopic chemical enabling the foam to remain moist simply by being in contact with the atmosphere, Brueckner et al. (2011).

Other impressed systems on the market are conductive coatings which can provide a design life in excess of 15 years. Their main disadvantage is the reduced life which is comparable with the design life of galvanic zinc layer anodes. Conductive coatings are surface applied with a minimum addition of dead load to the structure and do not affect any limitations on headroom and other dimensions. Such systems may be ideal in car parking structures or where minimum access between elements is present.

2.3 Hybrid Cathodic Protection

Hybrid cathodic protection is a two-phase system combing both an impressed and galvanic system into one. The principle behind the system is that an initial impressed current is powerful enough to arrest ongoing corrosion, followed by galvanic action to prevent future initiation. In practice, the design parameters for one commercially available system are generally as follows:

- Impressed current charge: 50 to 500kC/m2 of steel
- Galvanic current output: 0.2 to 2mA/m2 of steel
- Design life: 25-30 years

To date, hybrid systems for reinforced concrete comprise discrete zinc-based anodes installed in pre-drilled cavities. This is much like GCP systems utilising embedded anodes. The main difference with hybrid systems is the requirement for impressed current to deliver a charge and arrest corrosion. It is reported that a minimum charge of 50-60 kC/m^2 is sufficient in moderately aggressive environments Glass et al (2006), Polder et al (2009), which correlates to a chloride (Cl) content by mass of cement in the range of 0.4 to 1% (medium risk) CS TR 60, (2004). There are no published practical examples where greater charges than 50 kC/m^2 have been adopted. In a laboratory study 100 kC/m^2 of charge delivered was sufficient to achieve cathodic protection by way of achieving the 100mV decay criteria with 3% Cl (high risk) at the depth of steel Glass et al (2008). The time taken to deliver the charge varies, anodes with integrated power in some examples are reported to take to between 45 and 100 days Krishnanetal et al (2020). While anodes powered using an external power supply, 7 to 14 days is said to be typical Glass et al (2008) Christodoulou et al (2020).

Once the charge is complete, the hybrid anodes are switched to the galvanic phase. Generally, the anodes will act galvanically for the remainder of their intended design life with relatively low maintenance requirements. The minimum current output from the anode for corrosion prevention is between 0.2 to 2 mA/m^2 BS EN 12696 (2017). However, galvanic action is reported to be only responsive to corrosion risk so in benign environments less charge current is delivered Holmes (2009). This is also a topical point regarding the life expectancy of hybrid and galvanic anodes as any retained energy in theory means they could have the capacity to last longer. Another view is the anode condition will govern which is likely to worsen overtime and build an inherent resistance to current flow. Sergi et al (2020) shows examples of galvanic anode installations which are performing over 20 years so it credible that hybrid system would achieve 30 years in service performance.

When considering whether to chose a hybrid system, it must be taken into consideration that the requirement for future replacement is a distinct possibility due to self-consumption of the anodes. Essentially, this means full repeat works could be necessary after 25 years.

In general, discrete anodes are suited where targeted protection is needed. Widespread applications do not necessarily prevent the use of discrete anodes but have added health safety risk associated with hand arm vibration and dust etc from drilling. If there are congested areas of steel reinforcement creating pre-drilled cavities could be problematic due to clashes with the steel.

3 Option Selection

The selection of the corrosion management strategy to be adopted for a particular structure is recommended by the consulting engineer and the recommendation is often based on the engineer's experience and preference for a specific cathodic protection system. To improve the understanding of the advantages and disadvantages of each system, including the whole life cost and to reduce the influence of the engineer's preference, in the UK a Structures Management Options Report (SMOR) may be requested by the Technical Approval Authority (TAA) in accordance with CS 462 if there is more than one BS EN 1504-9 option for the repairing or managing the structure.

The SMOR should consider all viable BS EN 1504-9 repair and management options, e.g. the various cathodic protection systems, associated health and safety risks, estimated whole life costs for each option, impact of repairs on the road network, the future management strategy, environmental aspects and overall sustainability.

3.1 Basic Assumptions

The three cathodic protection system options discussed above have different design life, budget cost and monitoring frequency assumptions that need to be considered in SMORs. The following table summarises assumptions based on CPA Technical Note 12, 2019, and the experience currently adopted in the UK.

The main difference between the three systems is the design life. GCP systems can be expected to provide corrosion protection of 15 to 20 years but would require anode replacement at the end of life if the required structure's service life is greater. A similar requirement applies to HCP systems where the system's design life is 25 to 30 years. The main advantage of ICCP systems is the design life of the anodes used can be assumed to be 75+ years, but the main disadvantage is the disproportionate service life of the electrical power and monitoring equipment which is 25 years.

Table 1. Design Assumptions

CP System	GCP	HCP	ICCP
Design Life:			
Anode system	15-20 years	25-30 years	75+ years
Electrical equipment	-	-	25 years
Estimated Cost / Unit:			
Design and installation	£300/m^2	£400-£555/m^2	£480-540/m^2
Anode removal	£150/m^2	£150/m^2	-
Electrical equipment and replacement/ installation	-	-	£3,500-£6,000 EA plus Traffic management
Monitoring	Required annually by ISO 12696 but often undertaken as part of General (every 2 years) and Principal Inspections (every 6 years)	Required annually by ISO 12696 but often undertaken as part of General (every 2 years) and Principal Inspections (every 6 years);Initial first year monitoring (ISO 12696): £3,000-£6,000;Annual monitoring: £1,000-£2,000/year {£1,500-£5,000 [CPA (2019)]}	Required annually by ISO 12696; Initial first year monitoring (ISO 12696):£3,000-£6,000; Annual monitoring: £1,500-£2,000/year {£1,500-£5,000 [CPA (2019)]}
Operation and Maintenance	Replacement of anodes / monitoring equipment at 15-20 year intervals or earlier depending on monitoring (costs see design / installation)	Replacement of anodes / monitoring equipment at 25+ year intervals or earlier depending on monitoring (costs see design / installation)	Replacement of electrical power supply and monitoring systems at 25+ year intervals; Potentially remote monitoring equipment: £500 to £1000 [CPA (2019)]; Electricity costs: approx. £30/year

This may require replacement of the accessible electrical equipment which requires major maintenance every 25 years and possibly some acceptance that the operating parameter stabilise over time, and so the benefits of replacing embedded probes can be risk assessed. The extent of intervention required is less than full replacement of a GCP or HCP system if the specified structure's service life extension is significantly greater than the system's life.

In the case of a limited life extension of plus 5 to 10 years of the GCP or HCP's design life a replacement of the system may not be required as residual protection, or a coating system, can fulfil the requirements or minor deterioration can be accepted during that time.

3.2 Maintenance Requirements

ISO 12696 does not differentiate between the frequency of inspection for any of the CP options. All require the ability to measure depolarisation of the system, to confirm protection, and all require quarterly performance assessments and an annual system review that should incorporate a visual inspection. In addition, where AC power is required this may be subject to local regulations regarding the frequency of inspection and monitoring.

The visual inspection element is not defined in the same level of detail as a bridge inspection. Where a bridge inspection would require full access for an engineer within touching distance, i.e. Principal Inspection at 6 year intervals, this is not often provided for cathodic protection systems after the first year. There is limited visual information gathered and the concept of an annual road closure on a major highway is not considered acceptable. The first 12 months of operation can often include a delamination survey, but after that, inspections usually are undertaken when data suggests there is a problem or when there is visible degradation identified from visual viewing points around the structure.

When an impressed CP system rectified power supply or monitoring equipment fails or becomes obsolete, it may not be necessary to replace it with a similar system. Once significant data has been collected a view can be taken as to the levels of monitoring and control that are actually required. The operating output generally stabilises over time and so it may be possible to utilise a simple constant voltage DC power supply, which typically comes with a significantly reduced cost. With regards to embedded probes, again a view can be taken. If historical potential decays are acceptable, the replacement of probes can be considered on a case by case basis.

Table 2. Practical Considerations

CP System	GCP	HCP	ICCP
Network disruptions / installation time	Initial: Less than HCP and ICCP but depending on area to be protected; Maintenance: Reoccurrence of network disruptions during system replacement. More frequently than HCP system; Overall: Highest network disruption during whole-life cycle of a structure.	Initial: More than GCP but less than ICCP but depending on area to be protected.; Maintenance: Reoccurrence of network disruptions during system replacement; Overall: More network disruption during the whole-life cycle than ICCP but less than GCP due to slightly longer design life.	Initial: Longer than GCP and HCP but depending on area to be protected and the system used; Maintenance: Minimal disruption during replacement of power supply and monitoring systems; Overall: Less network disruption during whole-life cycle.
Practical Considerations	The holes for galvanic or hybrid anodes are typically larger diameter than for drilled in impressed current anodes; The reinstatement with new anodes at the end of the design life may not be a practical option; Replacement of the wiring and associated connections, data logging equipment and reference electrodes.	Close reinforcement may cause an electrical 'short' and/or lead to concentrated current distribution to the steel in the anode hole. Additional drill holes are often required; The holes for hybrid or galvanic anodes are typically larger diameter than for drilled in impressed current anodes; The reinstatement of existing with new anodes may not be a practical option; Replacement of the wiring and associated connections, data logging equipment and reference electrodes; Full encasement of anodes is required but difficult to verify in practice. A systematic decrease in performance may occur where voids are present. This risk is dependent on the type of anode used, i.e. whether already encased in cementitious mortar or not.	Short-circuits between anode and reinforcement causes faults. This needs to be checked and prevented; The system requires power and needs to be switched on to work; The control unit needs to be positioned in a place that considers the risk of vandalism, damage from flooding and accessibility for monitoring; SIM cards used for remote monitoring require regular replacement, i.e. every 2 years; More complex wiring may create faults

3.3 Practical Considerations

Practical considerations and the time required to install or replace a cathodic protection system will also need to be considered when recommending a CP system. The time to install galvanic or hybrid CP systems can be significantly less than an impressed system but this depends on the surface area to be protected. Depending on the structure's specified lifetime extension the number of future interventions may be significant, requiring additional network disruptions and associated expenditure. These include costs from disruptions to the local community and road users and impacts on the environment.

In the case that the required service life extension is greater than the design life of a galvanic or hybrid CP system, the system will need to be replaced, whereas the replacement of ICCP anodes is less likely. Galvanic and hybrid CP anodes are cemented in place and replacement by drilling them out could cause additional damage to the structure which will need to be repaired.

Table 2 summarizes the main practical considerations that will need to be considered for each system.

3.4 Advantages and Disadvantages

The main decision as to which system is suitable is typically down to life, availability of AC power and future exposure conditions. The physical cost of the materials is often not significant when compared with the installation costs, and indeed in some cases quoted costs for installation have been known to be similar. From a client's viewpoint the decision becomes a choice of the required life, and most clients will choose the longest life possible. Given the monitoring requirements in ISO 12696 are similar for all cathodic protection systems, there is no notional advantage or disadvantage for any of the options. Most impressed current systems are powered using mains electricity, and so this could be a fundamental requirement, but since concrete cathodic protection can be left off for a period of time, it could be possible to use a more intermittent source such as solar, or even the switched supply for street lighting. The main issue to consider then becomes simplifying the installation to increase the efficiency of the installation element. It is important for all parties to work together to produce the most effective system.

Additional secondary details that may determine the suitability of a system is the risk of hydrogen embrittlement to post tensioned steel and potentially the experience of the contractor installing such systems. With regards to robustness some HCP anodes have been found to be susceptible to damages to the clamp style connection between anodes and interlinking wire which are checked before installation but may be damaged during placement. Furthermore, due to the limited availability of long-term field data compared to GCP and ICCP systems the initial energisation requirement could not be verified yet for all exposure conditions. Table 3 presents the main advantages and disadvantages of the three systems.

3.5 Sustainability

A common measure of sustainability is the embodied carbon equivalent value of the materials used, measured in kg/CO_2e. In producing a reinforced concrete structure, a large amount of embodied carbon has already been invested in the manufacture of the cement and reinforcement. The main gain in sustainability is to prevent corrosion from taking place in the first instance and wasting this energy. Atkins and Lambert (2022) concluded that if there was a risk of carbonation-induced corrosion, coating and recoating the concrete wastes less embodied carbon than allowing the corrosion to take place and then undertaking concrete repair. If chloride-induced corrosion has taken place, impressed current CP wastes less embodied carbon than concrete replacement. If there is a risk of chloride-induced corrosion, coating the concrete wastes less embodied carbon than allowing the corrosion to take place. The inclusion of an impressed current CP system at the time of construction wastes the smallest amount of embodied carbon.

If an overlay is required this will add embodied carbon, when compared with embedded anodes, reflecting 25mm of concrete, which reflects approximately 8kgCO_2e/ m^2, which can be avoided. If a typical amount of anode is assumed, Atkins and Lambert (2022) suggested 3kgCO_2e/m^2 reflected the embodied carbon in the anode, plus operating energy that adds approximately 0.1kgCO_2e/ annum. A typical galvanic installation would be between 4 and 9 No 65g anodes per m^2 of concrete, giving 260 to 585g/m^2 of zinc (ignoring the encapsulation mortar). One kg of zinc has embodied carbon equivalent figures of 3.09kgCO_2e/kg Circular Ecology (2019) so the galvanic option is between 0.8 to 1.8kgCO_2e/kg, suggesting the galvanic option may have a lower embodied carbon, until the life required means repeated anode installation.

In the case of structures where network disruptions are required to install the CP system qualitative / non-measurable sustainability aspects will need to be considered which include traffic delays and restrictions. These can affect the CO_2e by the length of road diversion, additional fuel consumptions in traffic congestions and associated environmental pollution. Environmental pollution as a result of the time spent on site and frequency of major works during the life of a structure become more important aspects to be considered. The Welsh Government National Application Annex to CS 462 proposes a weighting of 60% for sustainability (30%), environment (10%) and health, safety and wellbeing (20%) compared to 40% for costs and technical applicability [WG NAA CS 462].

Table 3. Advantages and disadvantages

CP System	GCP	HCP	ICCP
Robustness and Performance	Fairly robust within the limits of the system's service life; Long-term track record is available; Performance will be affected if chloride content and moisture in concrete increases.	Long-term field data are limited to maximum 20 years and number of applications is significantly less than ICCP systems; The system is fairly robust but experience has found the clamp style connection of some anodes to the interlinking wire are quite delicate and failure may occur during installation which may go unnoticed; There is limited comprehensive field data to validate the passivation ability of hybrid anodes. A commonly quoted figure required for the initial energisation phase and that is sufficient for passivation is 50 kC/m^2 i.e. of steel surface area. Although, there is not one absolute figure that can be given for a particular set of conditions, e.g. concrete resistivity, chloride content, level of corrosion etc.	Highly robust but system needs to be on and monitored regularly. Long-term data up to 30 years are available; The performance of the system can be monitored and adjusted on site or remotely when identified and required; Ongoing chloride contamination and changes in concrete resistivity can be tolerated and accommodated for by system adjustments; Protection is provided over the entire zone.
Main advantages	No AC connection required; No maintenance required for life extensions within the system's design life; No risk of hydrogen embrittlement in tensioned steel	No AC connection required; No maintenance required for life extensions within the system's design life; No risk of hydrogen embrittlement in tensioned steel	High robustness of system. Electrical equipment that fails can be easily replaced; System output / performance can be adjusted based on monitoring data – high levels of control; Ongoing chloride contamination can be better tolerated than hybrid system.
Main disadvantages	Replacement of whole system including monitoring equipment may be required as zinc is consumed (at approx. 15-20 year intervals but dependent on local moisture and chloride ion content); Consumption of zinc in anodes may vary during expected design life as a result of moisture and chloride ion content in concrete; Not controllable; Increased number of breakouts for rebar connections;	Replacement of whole system including monitoring equipment may be required as zinc is consumed (at approx. 25-30 year intervals but dependent on local moisture and chloride ion content); Consumption of zinc in anodes may vary during expected design life as a result of moisture and chloride ion content in concrete; Limited comprehensive track record of field applications (uncertainty in performance); Not controllable, can theoretically be re energised if protection levels drop; Increased number of breakouts for rebar connections	AC connection required; Replacement of power supply and monitoring equipment at approx. 25-30 year interval or as identified from the monitoring data; Mesh and overlay: additional dead load on structure (25mm thickness); Mesh and overlay: Change in aesthetic appearance due to sprayed concrete surface

3.6 Health, Safety and Wellbeing

The main health and safety risks associated with the installation of CP system is the exposure to cementitious materials and the risk of hand-arm vibration syndrome (HAVS) as a result of drilling. GCP and HCP anodes are installed in drill holes but an ICCP mesh and overlay system also requires drilling to fix the mesh to the surface. Discrete ICCP anodes also require drilling but typically the anode holes are smaller than for GCP and HCP systems, i.e. the exposure time to drilling and therefore the risk of HAVS may be less.

ICCP systems also provide a risk to electrical shock due to the requirement for AC power, and mesh and overlay system pose additional risks of sharp edges and manual handling, see Table 4.

As long as the drilling is undertaken through manpower HAVS will pose the biggest risk to the workforce and ICCP system appear to provide an advantage over GCP and HCP systems on large scales installations.

Table 4. Health and Safety Risks

CP System	GCP	HCP	ICCP
Health and Safety	Hand-arm vibration syndrome (HAVS) – significant number of drill holes can be required both during initial installation and replacement; Anodes are generally larger than discrete ICCP anodes resulting in longer drilling times, i.e. increased risk of HAVS; Working with cementitious materials (COSHH).	Hand-arm vibration syndrome (HAVS) – significant number of drill holes can be required both during initial installation and replacement; Anodes are generally larger than discrete ICCP anodes resulting in longer drilling times, i.e. increased risk of HAVS; Working with cementitious materials (COSHH).	Depending on ICCP system: - Mesh and overlay / surface applied systems: HAVS from mesh fixings and reference electrodes; - Discrete anode system: HAVS similar to hybrid but smaller diameter holes, so typically less drilling; Electrical shock – working AC power; Sharp edges from mesh; Manual handling; Working with cementitious materials (COSHH).

4 Conclusions

The selection of the most suitable repair strategy involving cathodic protections systems is dependent on various factors that include technical applicability, environmental impact, sustainability, health, safety and wellbeing and whole-life costs. The system with the lowest whole-life costs may not be the most sustainable and environmentally friendly solution over the whole life when the weighting of non-technical aspects is increased during such an assessment. In recent years there has been a significant push in the UK from authorities to improve sustainability, reduce the environmental impact and risk to health, safety and wellbeing in addition to mainly assessing construction and operation costs and technical applicability. The Welsh Government National Application Annex to CS 462 proposes a weighting of 60% for sustainability (30%), environment (10%) and health, safety and wellbeing (20%) compared to 40% for costs and technical applicability [WG NAA CS 462].

Authorities are willing to invest more to achieve sustainability goals, reduce impacts on the environment and local economy and society during the specified service life provided that the repair strategy fulfils the technical requirements.

ICCP systems are the most robust with the longest design life and often the most suitable system for long-term service life extensions. GCP systems are more applicable for one-time short-term repairs and HCP systems for medium-term repairs.

References

1. Atkins, C.; & Lambert, P. (2022). Sustainability and corrosion. Proceedings of the Institution of Civil Engineers – Engineering Sustainability, https://doi.org/10.1680/jensu.21.00011
2. Brueckner, R.; Atkins, C.; Foster, A.; Merola, R. & Lambert, P. (2011). Maintenance of Transport Structures using Electro-Chemical Solutions", In: Proceedings of Concrete Solutions, Dresden, Balkema.
3. Circular Ecology (2019). Embodied Carbon - The ICE Database. Circular Ecology, Bristol, UK. See www.circularecology.com/embodied-carbon-footprint-database.html (accessed 19/11/2021)
4. Christodoulou, C.; Cobbs, R.; & Williams, E. (2018). *M4 Malpas Viaduct UK – structural rehabilitation of half-joints*. In: Proceeding of the Institution of Civil Engineers – Bridge Engineering, Volume 173, pp232-247.
5. Concrete Society: *Technical Report 60: Electrochemical tests for reinforcement corrosion.* The Concrete Society, Surrey, UK (2004).
6. Corrosion Prevention Association (CPA), (2019). Technical Note 12: Budget Cost and Anode Performance Information for Impressed Current Cathodic Protection of Reinforced Concrete Highway Bridges, Broomfield, J.
7. Glass, G.K.; Davinson, N.; Roberts, A.C. (2006). *Pit re-alkalisation and its role in electrochemical repair of reinforced concrete*. In: Journal of Corrosion Science and Engineering, Volume 9, pp1-17
8. Glass, G.K.; Roberts, A.C.; Davinson, N. (2008). *Hybrid corrosion protection of chloride-contaminated concrete*. In: Construction Materials, Volume 161, Issue CM4, pp163-172.
9. Lambert, P. 2009. Sustainability of Metals and Alloys in Construction. Sustainability of Construction Materials. Woodhead Publishing: pp 148-170.
10. Krishnan, N.; Zameel, D.v. (2020). *Hybrid anodes for accelerated cathodic protection of corroding concrete structures*. In: Indian Concrete Journal, Volume 92, No. 11, pp101-110.
11. Polder, R.B.; Peelan, W.H.A.; Stoop, B.Th.; Neeft, E.A.C. (2011). *Early stage beneficial effects of*

cathodic protection in concrete structures. In: Materials and Corrosion, Volume 62, Issue 2, pp105-110.

12. Welsh Government National Application Annex (NAA) to CS 462, to be published in 2022