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EVALUATION OF GALVANIC TECHNOLOGIES AVAILABLE FOR BRIDGE STRUCTURES*

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ABSTRACT

The use of sacrificial anode technologies to treat corrosion damaged concrete is an option that can be considered in specific cases. This is a rapidly growing field with many new innovations appearing in the market. The sacrificial anode technologies currently available are generally less powerful than impressed current cathodic protection but they are much less complex to apply. The technology requires no installed power supply and the installation of electrical cables is mainly limited to non-critical monitoring. Uncontrolled anode-steel shorts present no problems to system function and stray current corrosion of discontinuous steel is limited. In many cases the technology can be targeted to areas of need. In general, the output of a sacrificial anode system cannot be adjusted to manage a corrosion risk. However, some sacrificial anode systems have been used in both an impressed current and a sacrificial role and future corrosion risk may be addressed by turning the system into an impressed current system, or by applying a brief impressed current treatment to arrest the corrosion process.

INTRODUCTION

Corrosion of steel reinforcement in concrete structures is a major problem on bridge substructures. Causes include de-icing salt ingress, cast in chlorides and carbonation (Page and Tradeaway 1982). The corrosion products are expansive and cracks, delamination and spalling may result. Corrosion damage to bridge structures generally arises from chloride contamination of the concrete cover.

Cathodic protection (CP) has been one of the essential components of the repair and maintenance strategy on bridge structures. Since the original adoption of this technology, there have been a number of advances. One of these is sacrificial cathodic protection. The use of sacrificial anode technology to prevent and arrest corrosion is an attractive alternative to impressed current cathodic protection because of its simplicity. It requires no power supply and the installation of electrical cables is mainly limited to non-critical monitoring. Uncontrolled anode-steel shorts present no problems to system function and stray current corrosion of discontinuous steel is limited. While the technology is perceived to be less powerful than impressed current cathodic protection, when it comes to arresting intense corrosion activity, new products from a variety of independent suppliers have been appearing on the market and developments have been made to improve the technology.

This study was undertaken to identify sacrificial anode technologies available and to assess the potential impact of these technologies on the repair of corrosion damaged bridge structures on UK Highways

* This paper has been adapted from a report produced for the UK Highways Agency for Area 9, Sacrificial anodes in concrete repair, Document reference 9-410414-F-RP-0001. August 2006

Agency's Maintenance Area 9. Information on sacrificial cathodic protection/prevention systems was collated and analysed to assess performance, identify factors affecting protective effects, identify where such technology might be advantageously used and to assess monitoring methodology.

ELECTROCHEMICAL TREATMENTS

Electrochemical treatments for corrosion damage involve passing a current through the concrete to the steel from an installed anode system (Drewett 2005). In impressed current electrochemical treatment, the anode is connected to the positive terminal and the steel is connected to the negative terminal of a source of DC power. In sacrificial electrochemical treatment, the protection current is provided by corroding sacrificial anodes that are directly connected to the steel. In both cases the steel becomes the cathode of the electrochemical cell that is formed.

CP is the most widely used electrochemical treatment and is normally applied using an impressed current. An example is shown in Figure 1. In CP a permanently installed anode delivers a small current (typically less than 10 mA per square metre of steel surface) for a long period of time to the steel reinforcement. Cathodic prevention is a limited form of CP that is designed to prevent corrosion initiation on passive steel. Both prevention and protection are addressed in BS EN 12696:2000 (the British and European cathodic protection standard) and typical steel protection current densities range between 2 to 20 mA/m² for cathodic protection and between 0.2 and 2 mA/m² for cathodic prevention.

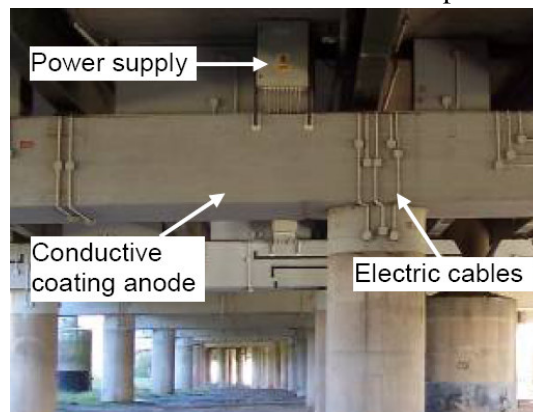


Figure 1: Typical impressed current cathodic protection installation on motorway substructure.

Other electrochemical treatments designed to arrest reinforcement corrosion include temporary treatments such as chloride extraction and re-alkalisation. In these systems a temporarily installed anode system is used in conjunction with a temporary DC power supply to deliver a large current of the order of 1000 mA/m² for a short period (typically less than 3 months) to the steel reinforcement.

Anode systems for concrete structures may be divided into surface applied systems and embedded discrete systems. The anode-steel surface area ratio is an important feature that affects the performance required from anode systems and is normally taken into account in the design of cathodic protection anode systems. The anode surface area tends to be smaller than the steel surface area particularly for discrete anodes and the current density off the anode tends to be higher than that delivered to the steel cathode.

Inert anodes resist anode consumption, while sacrificial anodes are consumed in the process of delivering the protection current. Both surface applied and embedded discrete sacrificial anodes have been used in the application of sacrificial CP and cathodic prevention. The life of sacrificial anodes may be relatively short and anode replacement is an issue affecting their use.

SACRIFICIAL ANODE SYSTEMS

Principles of Operation

Sacrificial cathodic protection, or galvanic protection as it is often referred to, 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 dissimilar metals drives the current from the anode to the cathode. The main sacrificial metals used to protect steel in concrete, are aluminium alloys and zinc (Broomfield 2008). These metals are sacrificed in the generation of the protection current. No external power supply is required. A schematic illustration of sacrificial cathodic protection system is provided in Figure 2. Because each element of anode surface acts as its own power supply the anode system does not need to be installed in zones and it is relatively easy to target the system to an area of need.

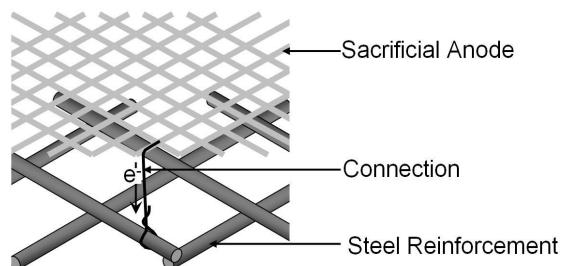
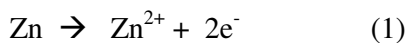
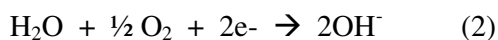


Figure 2: A sacrificial anode in the form of a mesh connected to the steel reinforcement which becomes the cathode of the galvanic cell that is formed.

A typical material used is zinc. Such an anode has about 0.5 to 1.0V available to drive the current to the steel. The dissolution of the zinc anode can be expressed by equation 1.



This action triggers a beneficial cathodic reaction on the steel surface which releases hydroxyl ions that neutralise the effect of chlorides (equation 2)



The current generated from a sacrificial anode is directly related to the resistance of the environment in which it is placed and the chemistry of the anode material. The current output is approximately inversely proportional to this resistance (Glass and Buenfeld 1997). This is convenient because this resistance also tends to be inversely proportional to the aggressive nature of the environment.

Figure 3 shows a published relationship between the steel corrosion rate and the resistivity of concrete (Morris et al. 2002). It appears to confirm a common perception that concrete resistivities above 20 k Ω cm represent a small corrosion risk (Broomfield 1997). However much higher steel corrosion rates occur at lower concrete resistivities and this may be countered by a higher current output from the sacrificial anode system. Sacrificial anode systems are, therefore, most suited to concrete environments where steel corrosion is only significant at low concrete resistivities. Traditional sacrificial cathodic protection in soil environments has been applied at resistivities up to 20 k Ω cm using magnesium anodes and a protection criterion that is much more onerous than the more pragmatic criterion adopted for concrete (US Army Engineers 2004). In the less common instances where corrosion occurs at high concrete resistivities, sacrificial anode technologies may struggle to deliver protection.

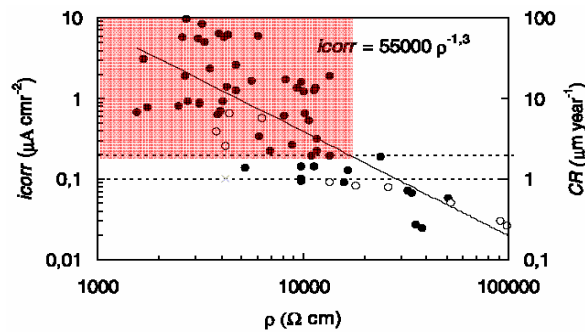


Figure 3: Corrosion rate plotted as a function of concrete resistivity (Morris et al. 2002).

The responsive behaviour discussed above is an ideal behaviour for sacrificial anode systems. Factors that change concrete resistivity include temperature, chloride content and moisture. Sacrificial anode systems are likely to respond positively to all the factors that induce a change in concrete resistance. However variations in the environment at the anode may differ from variations in the environment at the steel. Sacrificial anodes may be located on the concrete surface, within a patch repair material or embedded in purpose formed cavities in the parent concrete. It is preferable to arrange the anodes such that they can respond to more aggressive environmental conditions at the same time or before these conditions affect the steel in the concrete.

Sacrificial Anode Types

The application of sacrificial anode CP systems to concrete is relatively new compared to their use in protecting steel in soils and sea water. Issues affecting sacrificial anode systems for concrete structures include maintaining the activity of the sacrificial metal, expansive products of metal dissolution and attachment to the reinforced concrete structure. The natural alkalinity and density of concrete may cause some sacrificial metals to passivate or prevent the dissipation of the corrosion product and concrete does not tolerate expansive corrosion products in the same way that sea water and soils do.

A number of systems have been developed that address these issues and an increasing range of sacrificial anodes is being offered by suppliers. The known sacrificial anode products may be divided into the following types:

- Metal coatings applied directly to the concrete surface
- Sheet anodes attached to the concrete surface.
- Distributed anodes embedded in a cementitious overlay.
- Discrete anodes embedded in cavities in the concrete.

Experience of sacrificial anode systems on reinforced concrete structures is more limited than impressed current systems. Early known galvanic systems installed on bridge structures were the trials installed in the USA on bridge decks between 1976 and 1980 using zinc and aluminium metal sheets in a cementitious overlay containing chloride ions (Sagues and Powers 1994). Zinc, thermally applied as a coating to concrete is probably the most widely used galvanic system in the world. These systems are not proprietary products and are not promoted by any particular company.

In the 1990's various surface applied proprietary systems were developed, and from 1999 discrete anode systems embedded in cavities in the concrete were introduced to the market. The most widely used systems in the UK are discrete sacrificial anodes that are embedded in holes formed for this purpose and in repair areas in the concrete.

Sacrificial anode products currently known to be available in the UK include thermally sprayed zinc and aluminium, jacketed zinc mesh with a cementitious overlay, adhesive lined zinc sheeting and discrete anodes for embedment in areas of concrete patch repair, discrete anodes for use in cavities formed for the purpose of installing anodes and sacrificial anodes that can be used as both impressed current and sacrificial anodes. Most of these anode systems are proprietary products. Non-proprietary products include thermally sprayed zinc and zinc or aluminium mesh in a porous overlay that may be achieved using an air entrained cementitious material that usually contains some chloride as an activating agent (Broomfield 1992).

Examples of these systems are shown in Figure 4. This is probably one of the most rapidly developing areas in the field of reinforcement corrosion in concrete and new products are regularly emerging into this new market (Pianca and Schell 2004).



Figure 4: Sacrificial anode examples including a thermally applied metal coating (top left), adhesive zinc sheets (top right), discrete anodes in drilled holes (bottom left), discrete anodes installed in patch repair (bottom right) (Dugarte et al. 2007).

SYSTEM PERFORMANCE

Factors Affecting Performance

There are a number of factors affecting the performance of a sacrificial anode system. These are summarised in the Table 1.

Factor	Effect
Charge capacity / current output	The maximum theoretical life cannot exceed a period determined by the anode charge capacity and anode current output.
Anode activity / surface area	Determines protection current output and discrete anodes in particular need a method of anode activation. For alkali activated systems, anode activation is dependent on the quantity of alkali in the assembly.
Anode delamination / adhesion to concrete	Sacrificial anode systems applied to concrete surfaces in particular are at risk of suffering from delamination and loss of contact with the concrete.
Current distribution	Discrete anodes distribute current poorly compared to surface applied anodes but protection can be targeted to the area of need.
Continuing corrosion	Products designed for use in a preventative role may fail when trying to arrest an active corrosion process.
Concrete Resistivity	An increase in concrete resistivity reduces the protection current output of a sacrificial anode which limits the protection delivered.

Table 1: Factors affecting the performance of sacrificial anode systems applied to reinforced concrete structures.

Protection Delivered

The protection delivered by a sacrificial anode system is largely determined by the current output of the anode system and its distribution to the protected steel (Dugarte et al. 2008).

Figure 5 shows the zinc current density delivered off a proprietary discrete anode system over a 4 year period (Glass 2004). The anode current density is approximately 50 times the steel protection current density. Figure 6 shows the current output of a non-proprietary thermally applied zinc anode system on an inland bridge structure over a 2 year period (Brousseau 1997). In both cases the anodes deliver sufficient current to act in a preventative role (1 to 2 mA/m² protection current to the steel on average). The anodes appear to be effective in delivering cathodic prevention current densities.

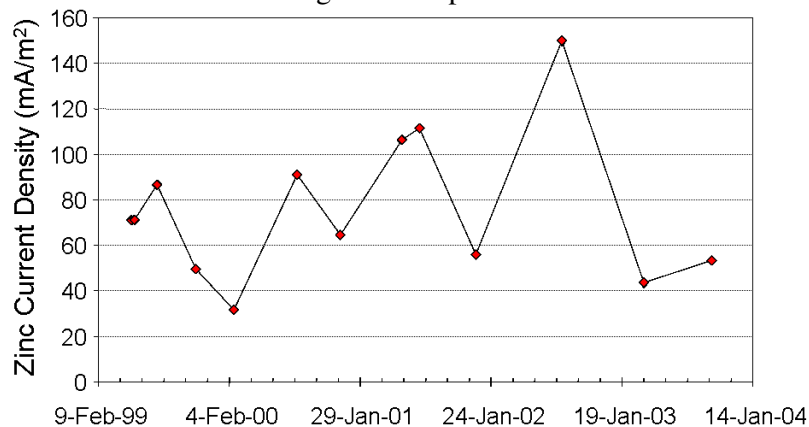


Figure 5: Anode current density output as a function of time over a 4 year period (Glass et al. 2004).

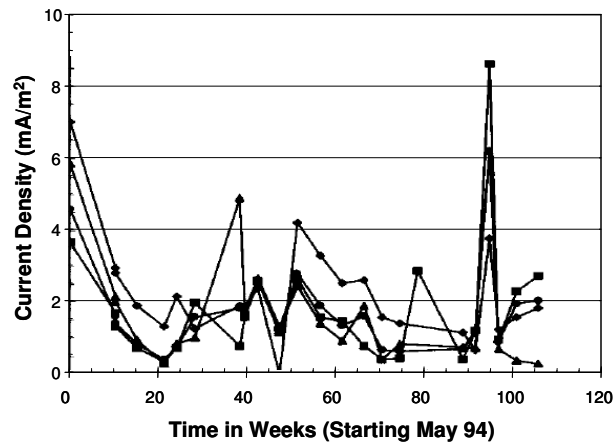


Figure 6: Current output of a thermally applied zinc anode on a bridge column in Montreal, Canada recorded at four representative anode segments (Brousseau et al. 1997).

Long term current output data on sacrificial anode systems is limited. The cyclic behaviour is evident and is usually attributed to the responsive behaviour of the anode to changing environment conditions. The principal environmental factor affecting the performance in terms of the protection current delivered to the steel by a sacrificial anode is resistivity which is a function of moisture content, chloride content and temperature. Figure 7 shows the daily variations in anode current output which is a function of the daily temperature cycles (Glass et al. 2007).

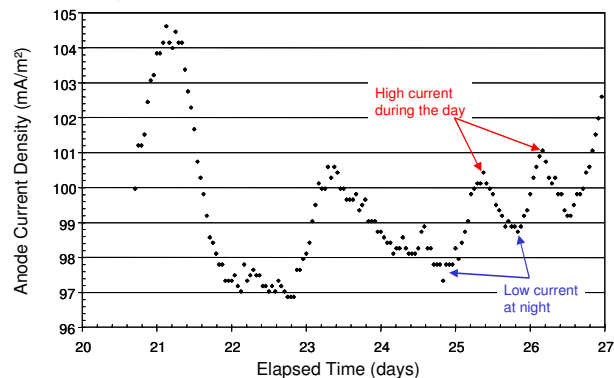


Figure 7: Daily variations in anode current output (Glass et al. 2007).

The protection delivered is also a function of current distribution (Sagüés et al. 2005). This affects discrete sacrificial anode assemblies more than distributed surface applied anode assemblies and is discussed in greater detail below.

Anode Life

Anode life is primarily determined by anode current output, anode charge capacity, anode utilisation and anode efficiency and may be calculated using Faraday's laws (Clapham et al. 2006). In simple terms anode life is given by the useful mA-hours (charge capacity) of the sacrificial metal divided by the average output in mA. A current of 1 mA delivered for 50 years is equivalent to a charge of 440 Amp hrs (1 Amp hr = 3.6 kC). The useful charge capacity of an anode system is determined by the anode efficiency and utilisation. Longer lives may generally be achieved by using more anodes or anodes with high charge capacities that deliver low current densities. These parameters may be requested from the anode suppliers or obtained from independent tests.

Various factors may affect utilisation of an anode system. These include loss of sacrificial anode activity and loss of adhesion of the anode system to the concrete. Loss of adhesion is mainly associated with anode systems applied to concrete surfaces and is discussed further below.

The level of anode activity is particularly important on small surface area embeddable discrete anodes which are required to deliver a high anode current density (Dugarte et al. 2007). For alkali activated anodes, the activating agent is also consumed in the process of anode dissolution and this can affect anode life. When soluble activating agents are applied to anodes on concrete surfaces, the application of the agents may be required at regular intervals to achieve a long term benefit. Loss of anode activity may also arise in a benign environment that is dry or cold which does not represent a failure if the anode re-activates sufficiently rapidly to maintain protection when the environment becomes more aggressive.

Current Distribution versus Adhesion to Concrete

Surface applied anode systems achieve good current distribution to the embedded reinforcement but adequate adhesion can be difficult to achieve on a variable material like concrete. The anode corrodes producing corrosion products at the concrete surface and the anode has different thermal expansion properties to the concrete substrate (Broomfield 1992). One system has effectively been withdrawn from the US market following a number of adhesion failures. However partial anode delamination does not always mean loss of function and current may continue to be delivered off a partially delaminated anode system.

Discrete anode systems are embedded within the concrete cover quite often within cavities formed for this purpose and, therefore, adhesion does not present a problem. However, these anode systems can suffer from poor current distribution. Anode-steel geometry strongly influences current distribution and when bare steel passes close to the anode it is difficult for the anode to protect steel at any substantial distance from the anode. In a recent academic study wherein sacrificial anodes were installed in patch repairs it was observed that average levels of polarisation fell to less than 30 mV at a distance of 150 mm from the patch and less than 20 mV at a distance of 300 mm from the patch after 90 days (Dugarte et al. 2007).

Some discrete anode systems are only recommended for use in a preventative role. Failure to stop corrosion may occur when the anode system is not sufficiently well distributed, when the anode is located in a resistive patch repair material, and when the anode system is not powerful enough. This is a proven risk and needs to be considered in the selection of these systems (Brown and Sharp 2008).

MONITORING

The most common criterion for cathodic protection requires 100mV of potential decay on interrupting the protection current. In sacrificial cathodic protection, the anode current output cannot be adjusted to ensure that this criterion is always met. Alternative criteria must therefore be considered.

An estimate of open circuit steel corrosion rate may be obtained by associating the potential decay with the applied current density. The open circuit corrosion rate as a function of steel potential shift and applied current density is given in Figure 8 (Glass 1999). If an applied current density of 2 mA/m² achieves a potential shift of 50mV, the open circuit corrosion rate is probably in the range associated with passive steel. However, if the applied current density is 20mA/m², then a potential shift of 50 mV would indicate that the steel is still corroding. Measured open circuit steel corrosion rates should preferably be below 1 mA/m².

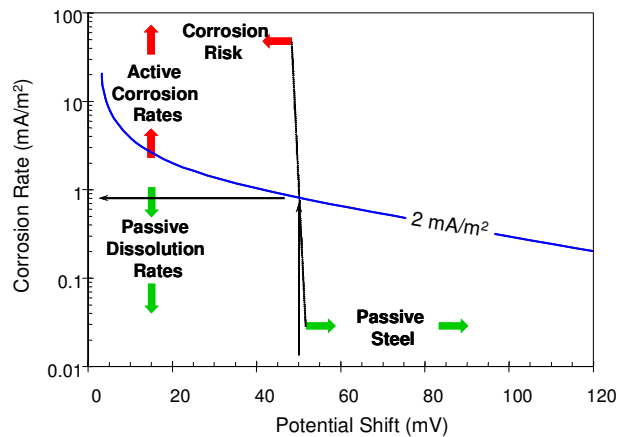


Figure 8: Open circuit steel corrosion rate as a function of potential shift and applied current density.

It may be noted that this assessment is dependent on the value used for the local current density delivered to the steel. The applied current density will vary throughout the system and it is preferable that this parameter is independently determined by measuring the current delivered by a small section of the sacrificial anode system in a location of the potential shift/decay measurement. To measure and interrupt the current from a local section of the anode system, the current must pass through a current sensor and a switch. Monitored currents may also be used to determine residual anode life.

The use of current sensors and switches introduces complexities into a sacrificial cathodic protection system that are best kept to a minimum. An alternative method of assessment available to discrete sacrificial anode systems uses potential mapping. A potential map obtained on a discrete sacrificial anode system is shown in Figure 9 (Glass et al. 2007). The presence of strong anodes is indicated by strong peaks in the potential map and this indicates that the system is functioning. The absence of smaller peaks between the strong installed anodes indicates that there is negligible corrosion risk.

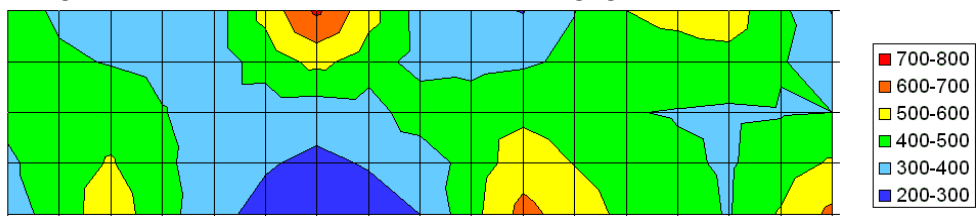


Figure 9: Potential map obtained on a discrete sacrificial anode system on a 50mm grid (Glass et al. 2007).

RISK MANAGEMENT

It is noted above that the output of sacrificial anode CP systems cannot be adjusted to meet specific criteria and are generally less powerful than impressed current systems. The alternative methods of monitoring suggested above assess the condition of the steel rather than an effect of the cathodic protection system. When adverse monitoring data is obtained a need arises to address the risk of corrosion. For sacrificial CP systems, this might, for example, be achieved by installing additional anodes.

Another method of addressing the risk of corrosion is to use a power supply to impress a higher current to an existing anode system to arrest corrosion. Indeed some surface applied anode systems used for sacrificial CP are also routinely installed as impressed current CP systems and it is, therefore, possible to install these as galvanic systems with the option of turning them into impressed current systems if

prompted by the monitoring data. In addition, some anode systems have been designed to allow a high impressed current to be delivered to arrest the corrosion process using a temporary power supply.

CONCLUSIONS

The use of sacrificial anode technologies to treat corrosion damaged concrete is an option that can be considered in specific cases. This is a rapidly growing field with many new innovations appearing in the market. There are currently at least seven proprietary products and two non-proprietary products available in the UK. These include distributed anode systems applied to concrete surfaces and discrete anode systems embedded within the concrete. The technology has been applied to more than 40 bridge structures in the UK to date.

The sacrificial anode technologies currently available are generally less powerful than impressed current cathodic protection but they are much less complex to apply. The available long term performance data for sacrificial anodes indicates that they are generally capable of reducing the risk of corrosion initiation and some sacrificial anode products do only claim to act in a preventative role.

The technology requires no installed power supply and the installation of electrical cables is mainly limited to non-critical monitoring. Uncontrolled anode-steel shorts present no problems to system function and stray current corrosion of discontinuous steel is limited. In many cases the technology can be targeted to areas of need.

However, the design and detailing of such systems needs to consider the risk of failure in current distribution and output to arrest ongoing corrosion. Concrete resistivity is a factor that should be considered. Poor current distribution may arise when discrete anodes are embedded in resistive materials adjacent to chloride contaminated parent concrete and when discrete anodes are spaced too far apart. In addition, distributed sacrificial anode systems applied to concrete surfaces have often suffered from the problem of anode-concrete adhesion failure.

Monitoring is not critical to the function of a sacrificial anode system and may be tailored to match other monitoring requirements of the structure. Potential decay data may be associated with the measured applied current to obtain open circuit steel corrosion rate data. Potential mapping and potential-time data also provide information on the steel corrosion risk.

In general, the output of a sacrificial anode system cannot be adjusted to manage a corrosion risk. However, some sacrificial anode systems have been used in both an impressed current and a sacrificial role and future corrosion risk may be addressed by turning the system into an impressed current system, or by applying a brief impressed current treatment to arrest the corrosion process.

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