Galvanic Cathodic Protection System Complying With Code Based Protection Criteria

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Synopsis: Impressed current cathodic protection of reinforcement in concrete structures is a technique developed over the last 40 years and today is a well accepted method for repair and prevention of corrosion. More recently galvanic anodes systems have been used to provide a similar method of corrosion control but with the benefits of limited wiring. Such systems have the potential for wide spread use on smaller areas or elements where the complexities of impressed current systems make them unwieldy. Issues when using zinc galvanic anodes in or on concrete are assurance that corrosion protection criteria are achieved, prevention of the zinc passivation and use of a universal design life assessment method.

The paper describes a review of anode systems used on concrete. Limitations of the systems are discussed in relation to ease of application, assurance of corrosion protection and durability of the systems. A method of assessing the design life is also provided. Particular attention is given to three new types of galvanic anode systems. Zinc layer anodes are zinc sheet bonded to the concrete surface. A proven method of combining adhesive and passivation protection is described. Zinc roll anodes are rolls of zinc foil embedded in an activator paste in drilled holes. The performances of systems using activator pastes are described. Zinc lump anodes are blocks of zinc coated with an activator layer and embedded in new concrete (cathodic prevention) or repair concrete (cathodic protection). Installation of galvanic anode systems are discussed in relation to typical areas of use, ease of application, monitoring of cathode protection criteria and durability including design life assessment.

Keywords: Concrete, durability, chloride, carbonation, cathodic protection, repair, galvanic anode

1. Introduction

Impressed Current Cathodic Protection (ICCP) systems are not without their problems but over the last 50 years they have been found to be suitable for a wide range of concrete structures. In the USA over 500 bridges have had ICCP applied. Chirgwin 2009 reports that *"RTA has eight ICCP systems in operation However due to the relatively high cost of ICCP and the high demand on internal resources the number of ICCP systems that can be commissioned is limited … Delay in implementing ICCP leads to an increase in the level of concrete deterioration .. Apart from the structural implications … increases the cost of ICCP installations due to a greater volume of concrete patching."* Because of the economic issues with ICCP RTA are considering the use of lower cost galvanic anode systems for holding repairs. In this paper the development of various galvanic anode CP systems are considered with the objective of providing a better understanding of the systems available and developing design requirements for galvanic systems.

2. Development of Galvanic Anode Cathodic Protection for Concrete

The wide spread acceptance of ICCP systems serves to show that use of CP systems for concrete are eminently practical. However, impressed current systems are not practical for protection in many areas, e.g.:

- where resources are not available for ICCP system (e.g. RTA situation)
- where ICCP systems are very expensive (e.g. for small projects or projects with many isolated areas)
- on projects where electrical systems are not suitable (e.g. hazardous area)
- in areas where wiring is not practical (e.g. many mine site areas)
- where localized protection is required (e.g. at corners, joints or areas of localized low cover)
- where incipient anodes may commence active corrosion

For steel structure sacrificial zinc anode are used extensively and they form a logical extension for corrosion protection on reinforced concrete structures. In this paper the development and current status of galvanic anodes is discussed. In particular criterion for assuring protection is achieved and a method of designing galvanic systems are outlined.

3. Scientific Basis for Cathodic Prevention and Cathodic Protection

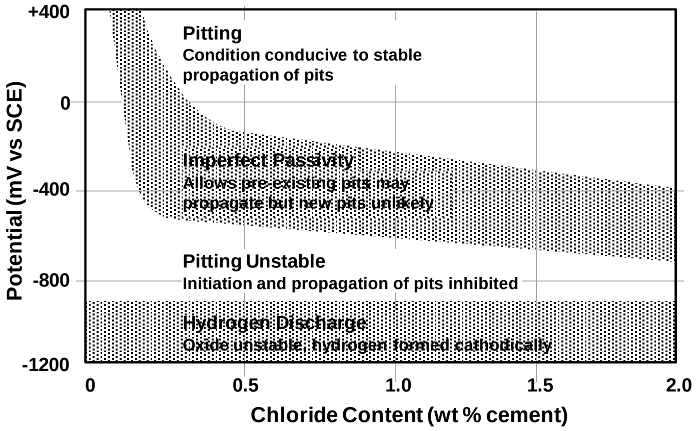
Page describes cathodic protection in relation to his simplification of Betolini et al's domains of electrochemical behavior of steel in concrete (Figure 1). Using Figure 1 three types of protection can be derived:

a) Cathodic Protection: For repair of structures corroding due to chloride ingress the reinforcement the reinforcement is polarized from 'Pitting' to 'Pitting Unstable' to provides protection but even movement to 'Imperfect Passivity' reduces the corrosion rate.

b) Cathodic Prevention: In new structures where chlorides have not caused corrosion activation only a small polarization is required to put the reinforcement in the 'Imperfect Passivity' domain. Then, even as chloride levels increase, pits will not form.

c) Incipient Anode Prevention: The area around a repair is likely to have some chloride but pitting will not have commenced as reinforcement in the repaired area previously acted as the anode so pitting corrosion has not commenced. Such areas can still be protected by a small shift in potential to the Imperfect Passivity Zone.

Figure 1 : Domains of Electrochemical Behaviour of Steel in Concrete



This basic understanding of corrosion protection given by Figure 1 is useful when considering the objectives of different galvanic anode systems. Key aspects are:

1) A major benefit of using galvanic anodes such as zinc is that they cannot polarize the steel sufficiently to take it to the hydrogen discharge range.

2) In cathodic prevention systems only a small polarisation is required to insure the steel stays protected while in a corrosion protection higher polarisation is required. A system that is suited to cathodic prevention may not be suitable for cathodic protection. Anode surface area is less critical as relatively small anode : cathode surface areas ratios can provide the current necessary to provide the small polarisation.

Other factors in galvanic anode system design are:

3) Current drawn, and hence rate of use of anode, to protect steel in concrete depends on the potential drop, i.e. polarization achieved (current = potential drop x resistance). Hence polarisation achievable depend on the current output from the anode system which is a function of the anode area and current density at the anode.

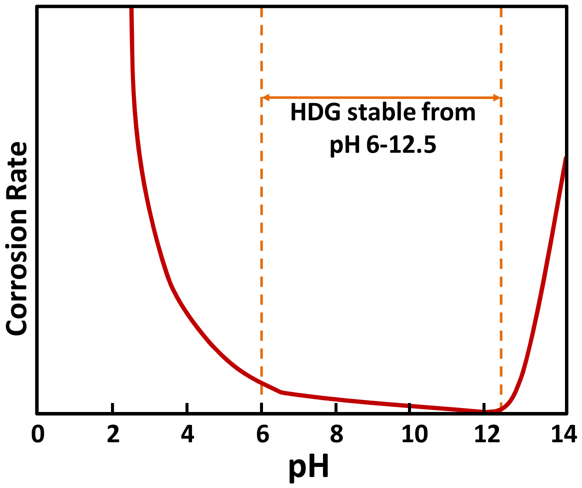
4) Resistivity if the protection current delivered is proportional to the resistance of the circuit clearly the resistivity of the electrolyte must be considered. In a corrosion cell the spread of the potential field, and hence current can be estimated from the geometry of the anode and cathode, the potential difference and the resistance of the electrolyte at the anode and cathode. Sagues[7]models the 'throw that can be expected from point anodes with time. The model shows that as the steel density and anode spacing increases the throw decreases dramatically. For a depolarization of 150mV, anodes at 0.5m spacing and heavy reinforcement densities the throw would reduce from 200mm to 80mm only

after a year and would drop significantly with time after that. With a depolarization of 100mv and light reinforcement the throw would reduce from 400mm to 300mm after one year.

4. Use of Zinc as the Galvanic Anode

Anodes protect the steel reinforcement as they have a lower natural potential than the steel and hence a potential difference is set up between the anode and steel such that the anodes corrodes rather than the steel. Zinc is often used as the anode as it has a small manageable corrosion expansion and an ideal potential that is sufficient to polarize the steel but not so great that it can cause hydrogen evolution. However zinc anodes passivated at the normal pH of concrete (Figure 2) and this made early attempts in the 80's to use perforated zinc sheet in concrete unsuccessful. Since then various methods of maintaining the zinc activity have been developed. These include use of lithium nitrate based mortars to keep the pH above 13.5 and chloride and sulphate low pH based pastes.

Figure 2 : Stability of Zinc In an Alkaline Mortar



Passivation of the anode doesn't only occur due to the environment. Metal impurities in the zinc led to the formation of a dense, tightly adherent iron oxide film on the zinc surface. Hence the iron content of the zinc has to be limited to a level where the iron oxide layer does not form and this is dependent on the overall chemistry of the zinc.

A principle question with zinc anodes is whether they produce the protection potential for cathodic protection and if they do what the life of the anode will be based on its consumption rate. Impressed current systems can operate successfully at current densities in excess of 20mA/m2 (ref Page) and it can be calculated that some zinc systems would last only around 5 years at that density (ref Page). It is important to recognize that systems successfully used for Cathodic Prevention, where current densities of 1-2 mA/m^2, may give very short lives where a high driving force is required.

5. Types of Zinc Anode

Zinc being the obvious sacrificial material means that many companies have developed sacrificial anode systems. These developments are discussed below as they give a good guide to the key aspects of a galvanic anode CP system

Distributed Anodes

In the mid 90's galvanic anodes for embedment in concrete suitable for cathodic prevention of incipient anodes were developed Bartholomew patent of 1994). These used a small puck of zinc embedded in a Lithium based mortar. The lithium gives a pH in excess of 13.5 and at that pH the zinc remains active and corrodes sacrificially to the reinforcement. By placing the anodes around the edge of repairs (i.e. close to the incipient anode areas) and because only low current was required to give the small polarisation required the protective current developed was sufficient. The manufacturers recognised that the system was not suitable for cathodic protection due to the current output limitations stemming from the high

The original system has been used extensively and the later systems with higher anode areas and masses have had many trials. There is limited information on the anodes themselves and the systems are used based on the manufacturers guide of the number of anodes required. This lack of a formal design method prevents assessment of the rate of consumption of anodes. For example Brown undertook a study for the Virginia Department of Transport and reports that even in a low current density cathode prevention system anode consumption was around 5% in 130 days. Even though currents decrease over time the high consumption at low current densities indicate a relatively short life. Considering repairs are often only expected to last 15-20 years this may not always be an issue but if lives unexpectedly slip to 10 years or less then the maintenance cost could be unacceptably higher, particularly given that these anodes are embedded and not simple to replace.

Another issue is the ability of the anodes to sufficiently polarize corroding reinforcement in a full cathodic protection arrangement. Sagues[7] undertook laboratory and field trials and found that *".. point anodes of this size and at the placement density used, and for the amount of steel in the slabs, are not likely to provide substantial levels of cathodic protection of an already corroding bar assembly.".* He did note that once the corroding bars were switched out of the circuit the anodes did provide 100mmv depolarization values on the passive steel.

There are various types of distributed anodes available and their performance is dependent on surface area, zinc mass and activation system. The issue of throw is a significant consideration and a model such as Sagues would be a useful design tool if manufacturers were compelled to give accurate product information.

Thermally Sprayed Zinc Anode

Another system developed in the mid 90's was arc sprayed zinc. In this system zinc is sprayed onto the concrete surface to act as a sacrificial anode. The issue of passivation of the zinc in contact with the concrete is an obvious potential problem. Gawedzinski[3] reports on trial systems installed on bridges and notes *".. potential surveys indicate the systems are not protecting the steel. It appears the anodes do not develop enough current ..".*

Since then the sprayed zinc systems have been developed further, Considerations has been given to achieving high initial bond, breakdown of bond due to acidification of the interface, quality assurance of application and how the zinc stays in contact with the concrete as the surface corrodes. It has been found that the systems can work with relativity long design lives particularly in a cathodic protection mode (Covino[6]) where currents are low. In Cathodic Protection situations the system could give high current outputs (>10mA/m^2).

Thermally sprayed zinc systems can be effective but they require specialist application skills, a strong underatanding of the key success factors and a high level of quality assurance. Although significantly less resource hungry than ICCP they still demand significant resource and are not really suited to use on small areas due to issue with stop/start application.

Early Hydrogel Zinc Sheet Anode

In the late a zinc sheet cathodic protection system that could be bonded to the concrete surface and remained active due to the hydrogel was introduced. The galvanic protection worked very well due to the high surface area and maintenance of zinc activation. The system was tested on three sites by the Illinois Department of Transport. They concluded (Gawedzinski) that *".. the system did conform to the NACE specification of a 100mV depolarization over 4 hours."*

Unfortunately the system had three problems and it seems only one product batch was made before the system was discontinued.

- production difficulties as the gel jambs the production plant
- the high pH of the hydrogel necessary to maintain the zinc activation led to the formation of a zinc oxide layer that passivated the anode under certain conditions.
- some failures due to the hydrogel in locations of water leakage. Gawedzinski notes that in the Illinois trials *"…where the anode was placed on the outside of the fascia beams in areas exposed to leaking joints, it was beginning to separate from the face..".*

Modern Zinc Sheet Anode

After the system early zinc sheet was discontinued a 2 year R&D project was undertaken by an alternative manufacturer. Working in conjunction with a specialist zinc sheet manufacturer the issues were resolved by 2002 and applications of the zinc layer anode system commenced in Europe and USA. The system has recently been introduced into Australia. Solutions to the production and pH issue remain confidential. However it is known that a low pH chloride base is used but other factors account for the high output. The issue with water contamination was resolved by incorporating suitable waterproofing systems into the system design.

6. Codes

AS 2832.5 governs the use of cathodic protection of steel in concrete. It recognizes the European standard EN 12696 on the same topic. Both codes give the same alternative protection criteria, i.e.:

- 'instant off' potential more negative than -720 to -1100mv (-770 to -900mv if prestressed) with respect to a Ag/AgCl/0.5M KCl electrode.
- a 24hr potential decay of 100mV min.
- a long term potential decay of 150mv min.

These are proven values for cathodic protection and although some manufacturers suggest that they are too onerous, less onerous values have not been proven. Hence these values should be observed for cathodic protection systems using galvanic anodes. Alternative protection requirements may be suitable for galvanic prevention (e.g. depolarization of 50mV).

7. Research Results

Zinc galvanic anodes have been used for cathodic prevention in concrete for the last 15 years and for cathodic protection (higher reinforcement current density required) for the last 10 years and the following research is of value in assessing the current densities required to give protection:

Sergi(1) provides data on 13 structures where zinc anodes in a lithium nitrate based mortar were embedded in concrete and used for corrosion prevention and cathodic protection. Small anodes were a plane zinc disc in an alkaline mortar with no attempt to increase the zinc surface area. The larger anodes had a series of thinner zinc discs in an alkaline mortar. The anode model is given for the cathodic prevention and the surface area of the zinc is around 3400mm^2 for a zinc weight of 0.06kg i.e. 60,000mm^2/gm. Some of Sergi's results were manipulated assuming that the anode for cathodic protection had a surface area around 13700mm^2 for a weight of 0.18kg to give the data in Table 1.

Table 1 : Corrosion Current Using Embedded Zinc Anodes

	Corrosion Prevention			Cathodic Protection		
	Anode current density (mA/m^2)			Anode current density (mA/m^2)		
	Yr 1	Yr 2	Yr 3	Yr 1	Yr 2	Yr 3
Mean	33	22	10	45	27	14
+95% CI	132	92	31	106	51	26
Max	131	94	26	87	40	18

The anode current density does not change markedly and any increased performance arises from the increase anode to cathode ratio. Hence the data provides some guidance on current densities that can be used for design. Given the low cost of increasing protection relative to the high cost (actual cost plus public cost) of failure it is reasonable to require a very low likelihood of premature failure. This likelihood is difficult to assess as the distribution is not normal and the data is limited. Hence anode densities for design could be based on those shown in Table 2.

Table 2 : Anode Current Densities (mA/m^2)

Year	Discrete Galvanic Anodes	Surface Layer Anodes
1	50	20
2	30	5
Remainder	10	5

For surface anodes the current will become controlled by oxygen diffusion to the cathode and the higher anode surface area will lead to lower anode current densities. The authors have found that values given in Table 2 are appropriate.

For a given puck size the surface area of zinc can be increased by around 2.5 times by sculpting the zinc block within practical limits. This enables a high zinc surface area per kilogram of zinc which, assuming the current density on the zinc that is the limiting factor in the emf, produces a higher current /kg of zinc. Whilst this is positive for economic polarization of the reinforcement (the same effect can be achieved without sculpting by simply increasing the number of anodes) care has to be taken in design to ensure there is sufficient zinc to maintain protection over the design life. Sculpted anodes have a surface density of around 90,000 mm^2/kg zinc compared to 550,000 mm^2/kg zinc for zinc sheet. This high surface area of zinc minimises the limitation of anode current density in providing sufficient current to polarize the reinforcement.

Sergi states that increasing the anode area in each anode and the number of anodes led to the increase in current produced. Unfortunately the area of zinc in the anodes is not given and this cannot be confirmed. Certainly the current density on the reinforcement was increased by a factor of 5 when the cathode:anode increased.

8. Design Life Calculation Methods For Galvanic Anodes

Loss of Zinc mass

The life of a zinc anode is defined by the rate of consumption of the zinc and can be calculated using Farday's law as shown in equation 1

$$m = Mit/zf \qquad -1$$

where

m = mass of zinc in grams (g)
M = molecular weight of zinc (mass of 1 mole of zinc atoms) = 65.4 g
i = current in Amps (A)
t = time in seconds (s)
z = valency of zinc = 2
F = Faraday's constant = 96500

For a given anode the only unknown is the current.

9. Secondary Effects

a) Alkali silica reaction

The potential field set up by cathodic protection means that sodium and potassium ions are drawn to the rebar and the concentration effect was considered a risk for alkali silica reactions. However the risk has been found to be insignificant if the current is uniform and less than 20mA/m^2 (Sergi & Page). Where there is a risk of ASR exiting then a lithium treatment can be applied to the concrete as part of the repir process.

b) Chloride removal

The potential field also leads to chloride ions being drawn to the anode. This reduces the chloride at the reinforcing leading to a lower polarization and current draw. For surface anode systems chlorides arriving at the surface may become apparent as salts or chlorine gas. This can be an issue if the surface anode has not been designed to absorb or discharge these products.

c) Hydrogen Evolution

If the prestressing steel is polarized to far then hydrogen is evolved and this can lead to hydrogen embrittlement. Limiting the instant off prevents this. Galvanic systems can not polarize the steel sufficiently for this to arise which makes them 'safe' for prestressed structures.

10. Conclusions

There are models for assessing the current throw and anode consumption rate for galvanic anode systems. A standardized approach would enable users to select the anodes to use based on a scientific and economic basis rather than the manufacturer recomended method currently available.

Galvanic anodes provide a useful means of providing corrosion protection. Small discrete anodes are suited to cathodic prevention while anodes with a larger anode:cathode ratio can be used for cathodic protection. Depending on the polarisation achieved and the zinc mass it is quite possible to obtain design lives of galvanic anode systems of 20+years.

11. References

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