TECHNICAL ARTICLE

Total Corrosion Management – State of the Art Report

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BUILDING TRUST

TABLE OF CONTENTS

1 Abstract 3

2 Background 3

2.1.1 Carbonation induced corrosion 3

2.1.2 Chloride induced corrosion 3

3 Corrosion Management Systems 4

3.1 Concrete Repair Mortars 4

3.2 Corrosion Inhibitors 5

3.3 Hydrophobic Impregnations 7

3.4 Protective coatings 8

3.5 Concrete re-alkalinisation and chloride extraction 8

3.6 Cathodic Protection 9

3.6.1 Induced Current Cathodic Protection 9

3.6.2 Galvanic Protection 9

4 References 14

5 Legal Note 14

6 Key Words 14

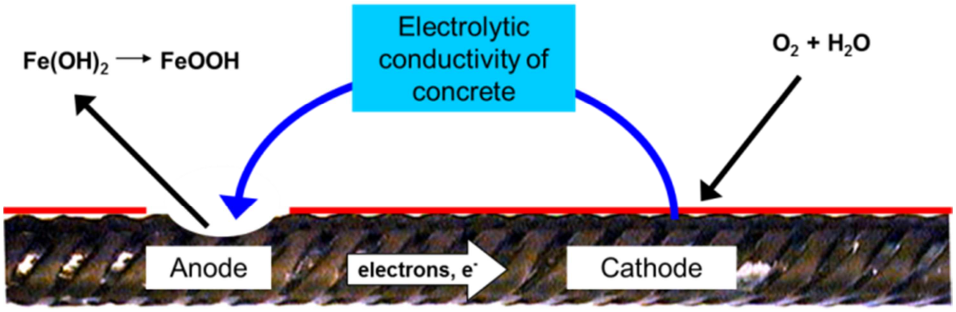
1 ABSTRACT

2 BACKGROUND

Reinforced concrete structures such as buildings, bridges, etc. are designed to last a long time – it is not uncommon for bridge structures to have a design life of 100 years.

By having the designed cover and appropriate mix design, concrete itself provides generally the relevant protection for the reinforcement steel bars.

During hydration, cement generates hydrated lime that is responsible for a high alkaline environment. Reinforcing steels are then placed in a passive condition as a stable iron oxide is formed.



However, either due to the carbonation process where the concrete is losing its high alkaline level or due to chloride breakdown, reinforcing steels are no longer in passive conditions and start to corrode.

The above happens when for example, the cover is below than specified, lack of compaction or curing.

Corrosion of steel in concrete behaves in the same way as corrosion of a metal in electrolytes solutions. The corrosion occurs always at the anodes.

Conditions required for corrosion:

- Loss of passivity (due to carbonation process or the presence of chloride).
- Humidity in the pores (electrolytes).
- Presence of Oxygen near the reinforcing bars.

All three criteria must exist for the corrosion to occur.

2.1.1 CARBONATION INDUCED CORROSION

When carbon dioxide comes in contact with the hydrated lime that is present in the non-carbonated concrete, a carbonation reaction occurs. The highly alkaline (pH ~13) lime is being transformed into low alkaline (pH ~9) calcium carbonate

$Ca(OH)_2 + CO_2 \rightarrow CaCO_3$

Corrosion originated from carbonation is rather slow (2/100 to 2/10 mm reduction of rebar per year), typically affects large areas of reinforcement and results in concrete spalling before loss or reinforcement cross section becomes critical for the structural safety.

Carbonation induced corrosion typically occurred often in structures having a low concrete cover (Figure1).

Figure 1: Carbonation induced corrosion with low concrete cover

2.1.2 CHLORIDE INDUCED CORROSION

Even in high alkaline condition (non-carbonated concrete), when chlorides reach the reinforcement level, they generate localised acid generation that yield to pitting corrosion.

Figure 2: Typical pitting chloride induced corrosion

Speed of chloride induced corrosion is fast (1 to 10 mm a year), very local and produces no externally visible signs until the concrete cover delaminates. Sudden collapse of structures due to local loss of reinforcement cross section without prior signs may happen(Figure2).

Different systems are available to address the issue of controlling steel reinforcement corrosion:

- Concrete repair mortars (hand applied, sprayed and flowable systems)
- Corrosion inhibitors
- Hydrophobic Impregnations
- Protection coatings
- Concrete re-alkalisation
- Concrete chloride extraction
- Impressed Current Cathodic Protection
- Galvanic Protection (Embedded galvanic anodes)

3 CORROSION MANAGEMENT SYSTEMS

3.1 CONCRETE REPAIR MORTARS

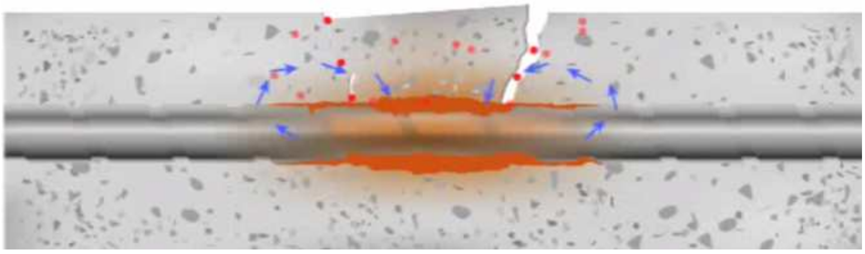


Figure 3: Spalling due to chloride corrosion

Repair mortars are used generally used to reinstate the spalling concrete due to steel reinforcement Corrosion (Figure 3). The corrosion of steel reinforcement affects many reinforced concrete structures. Patching with hand placed repairs is a common repair technique that involves the removal of physically deteriorated concrete (by hydro demolition or jack hammer), cleaning the steel reinforcement within the patch and finally restoring the concrete profile with a proprietary repair mortar. This process renders the steel within the repair area passive[1].

In many cases corrosion-induced deterioration has subsequently been observed in the parent concrete in the immediate area around the patch repairs, sometimes within a few months following completion of the repair process[2]. This phenomenon is known as incipient or ring anode formation or the halo effect[3].

The concept that macrocell activity (the formation of spatially separated anodes and cathodes) causes the incipient anode effect was first introduced by Page and Treadaway[4] in 1982. They suggested that the redistribution of anodic and cathodic sites following concrete repair affects future corrosion risk (Figure 4).

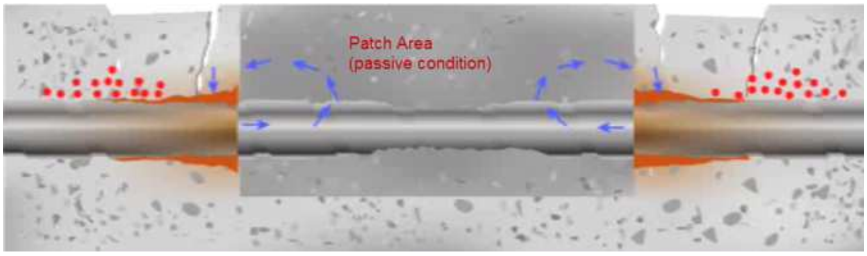


Figure 4: Spalling at the adjacent zones due to the incipient anodes corrosion

Figure 5: Successive patch repairs due to incipient anode corrosion in car park deck

C Christodoulou[5] shows that a widely held view is that the cause of incipient anodes is the loss of the natural cathodic protection provided by the corroding steel to the steel in the parent concrete adjacent to the patch repair (Figure 5).

We could summarize the incipient anode process as follow:

- Spalling due to reinforcing steel chloride induced corrosion occurs in the anodic zones.
- Removal of the concrete is done in these affected areas.
- Repair is carried out with proprietary cement based repair material that is highly alkaline.
- The freshly repaired zone is now turning to a cathodic zone (due to the high alkalinity of the repair mortar).
- The cathodic zones that were surrounding the anodic zones (spalled areas) are now turning to anodic zone as they are less alkaline than the freshly applied repair mortar and most likely contain already some chlorides.
- The reinforcing steel that was previously in the protected cathodic zones is now no longer in passive environment as this zone has turned as anode.
- Acceleration of the corrosion occurs then in the newly formed anodic zones (surrounding the patch areas) – refer to figures 5 & 6.

Particularly in case of chloride induced reinforcement corrosion, concrete repair mortar alone might not provide desired long term efficiency of the repair.

They have to be combined with suitable corrosion control systems in order to avoid formation of incipient anodes.

3.2 CORROSION INHIBITORS

An inhibitor is a substance that either delays or retards the rate of a chemical reaction. A corrosion inhibitor is then defined as a substance that delays the onset of corrosion or reduced the existing corrosion rate of steel.

Corrosion inhibitors for reinforced concrete, are available as admixture mixed together with the repair mortar or concrete or as surface applied product; the second case being the most common for concrete repair.

3 types of corrosion inhibitor exist in the market:

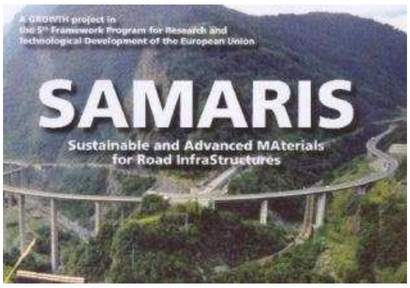
- Anodic inhibitors that suppresses the anodic reaction – typical product is nitrite based inhibitor. They are considered as dangerous if the concentration is not high enough, accelerated corrosion may occur.
- Cathodic inhibitors either slow the cathodic reaction itself or selectively precipitate on cathodic areas to increase the surface impedance and limit the diffusion of reducible species to these areas – Typical products are zinc compound (precipitation of oxide forming a protective film on the rebar) or sodium sulphite acting as oxygen scavenger. They are considered as safe but they are less efficient than anodic inhibitors
- Ambiodic (mixed) inhibitor that acts simultaneously on both anodic and cathodic zones. This class of inhibitor has a synergy effect, combining the benefits of both anodic and cathodic types even at low dosage. They are safe as if a low dosage is used, no corrosion acceleration has been found but only a lower effect.

Surface applied and admixed Sika FerroGard are based on ambiodic inhibitor technology.

Surface applied corrosion inhibitor (Sika FerroGard 903) was launched in 1997.

This product is based on mixed amino alcohol. Amino alcohols are very small and very volatile particles. They do not react with the cement and they are available to migrate freely within the cement matrix[6].

In summary Sika FerroGard-903:



- Penetrates the concrete in liquid & vapour phase
- Displaces hydroxides on the steel surface in carbonated concrete
- Displaces chlorides on the steel surface
- Forms an adsorbed chemical layer 100-1000 angstrom thick on the surfaces of the steel reinforcement
- Reduces iron dissolution at the anode
- Reduces oxygen access at the cathode

However, in many countries surface applied corrosion inhibitor technology only found limited acceptance. There are still significant limitations with regards to their uses:

- The first limitation is their ability to migrate in quantity enough to be effective. Effectively, if the concrete is of high quality and/or the cover relatively thick, the likelihood for the inhibitor molecules to migrate deep enough in sufficient quantity to reach the reinforcement bars, is low. This situation arises often in the case of civil engineering structures.
- The second major limitation is the presence of chloride in the concrete. By experience and following intensive researches such as the **SAMARIS**[7] project, the inhibitors are not effective if certain quantity of chlorides is already present near the reinforcing bars.

In summary, for the marine or civil engineering structures exposed to de-icing salts, corrosion inhibitor is not the optimum solution to mitigate existing corrosion.

This being said, we nevertheless have some positive return on the use of FerroGard-903 in chloride induced corrosion – the SAMARIS project presents one of them – Fleet Flood Bridge where the inhibitor was used successfully to address the issue of incipient anode corrosion.

On the other hand, this technology works at its best in carbonation induced corrosion for three main reasons. This was shown by Heiyandtuduwa[8] (Figure 6) and Taché[9].

- Carbonation induced corrosion is often associated with low concrete cover. Hence it is easier for the inhibitor to reach the reinforcement steel
- Carbonation mainly occurs in concrete of lower quality – hence lower density, respectively better penetration of the inhibitor.
- Corrosion speed associated to carbonation is rather slow so it is easier for the inhibitor to be effective.

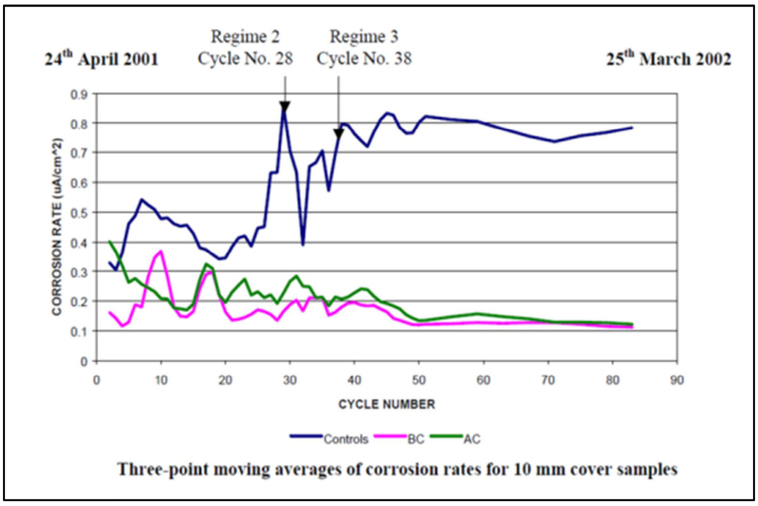


Figure 6: Carbonated concrete - inhibitor effect (applied before and after carbonation)

When effective, inhibitor technology is a very cost effective technique.

Typically, corrosion inhibitors will be more effective for carbonation induced corrosion on buildings and low to moderate levels of chlorides rather than to mitigate chloride induced corrosion on civil engineering or marine structures with high or very high levels of chlorides.

3.3 HYDROPHOBIC IMPREGNATIONS

Hydrophobic impregnations can be divided in two types.

Products designed for civil engineering structures typically silanes with high solid content and products for other substrates then concrete (e.g. brick buildings) typically siloxanes with low solid content. This report address only issues related to products for civil engineering structures.

Silane type hydrophobic impregnations are effective solutions to reduce water penetration on a structure and numerous field reports attest their long term performances. Christodoulou[10] has shown that "Treatment as old as 20 years can still be present and offer a residual protective effect".

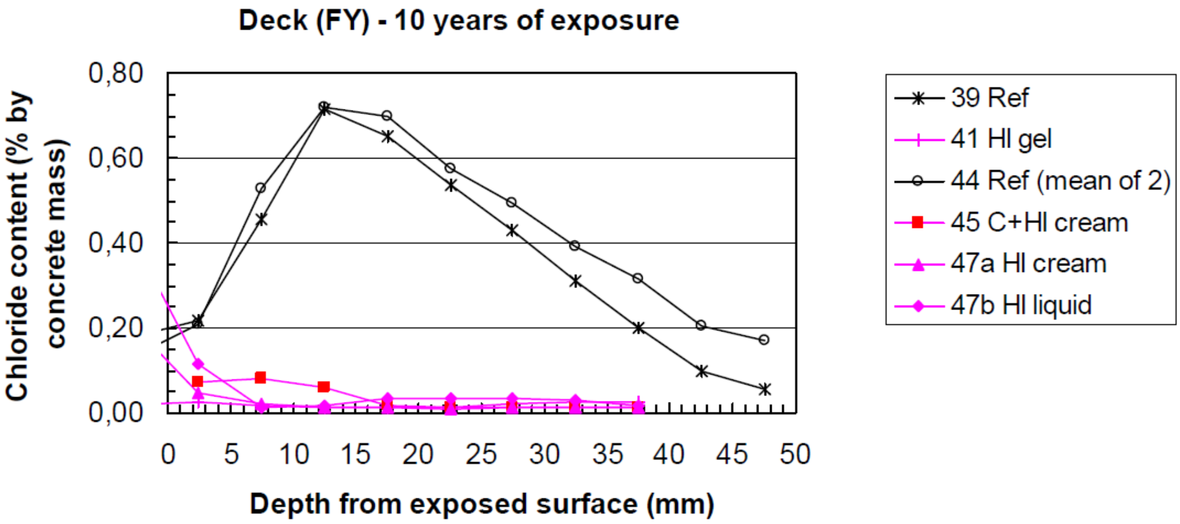


Figure 7: Chloride profiles Norway structure

They are very efficient to prevent chloride migration in concrete. Eva Rodum[11] has carried out tests on existing structure and show that the hydrophobic impregnation used are very effective in preventing the chloride to migrate even 10 years after application – (Figure 7).

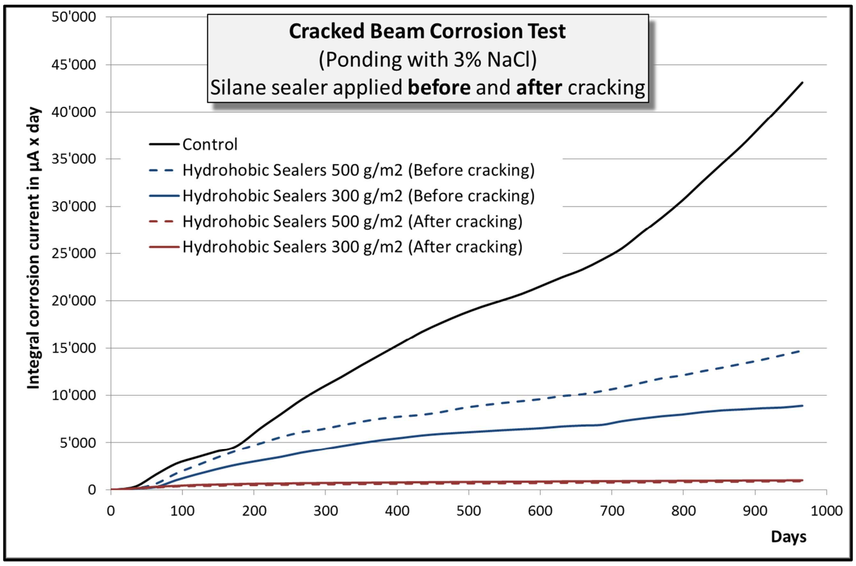


Figure 8: Preventive effect of Silane to prevent chloride induced corrosion

Internal tests have shown that Silane treatments are effective method to prevent corrosion by stopping the ingress of chlorides – (Figure 8).

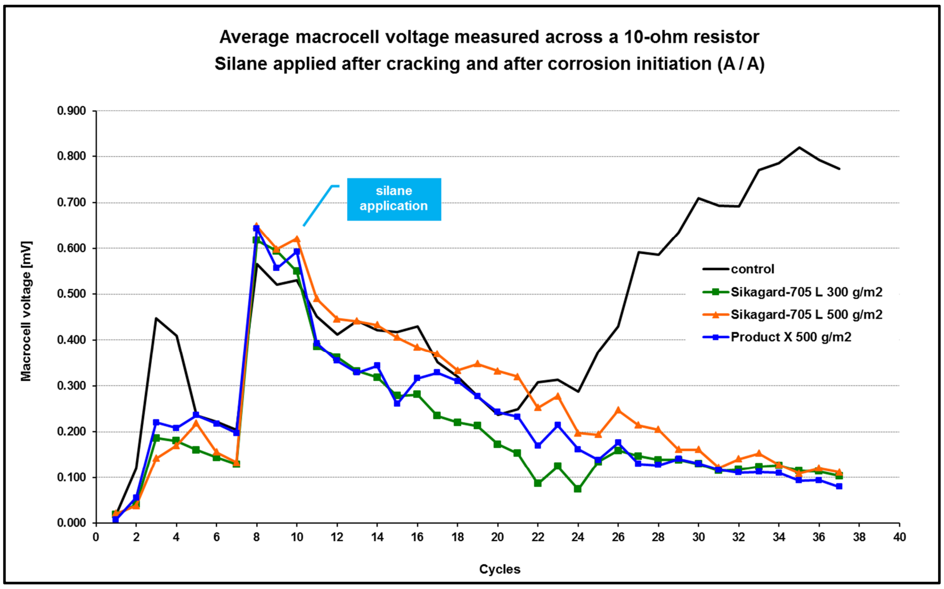


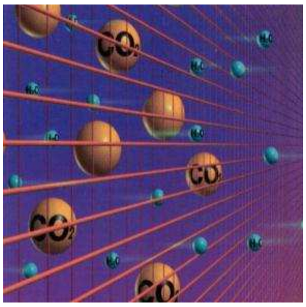
Figure 9: Some effect of Silane to halt chloride induced corrosion

However these same internal tests, carried out to see if this technique can be effective to halt corrosion when this one is already advanced, show some limitation – (Figure 9).

In summary, hydrophobic impregnations are very effective over long period of time to prevent chloride induced corrosion.

Their effect to mitigate existing corrosion is more debatable and may depend on the level of corrosion.

3.4 PROTECTIVE COATINGS



The primary function of concrete protective coating is to halt the progress of the carbonation front in the concrete.

They can be also formulated to be able to bridge cracks even at very low temperature (down to -20°C).

Sika has good track field reports on the durability of our protective coatings – typically 10 -15 years for flexible coating such as Sikagard-550 W or 15-20 years for products like Sikagard-680 S.

After repair is carried out, they can be used to further stop the ingress of deleterious elements (chlorides, CO_2) and to provide a homogeneous aspect of the substrate by hiding the difference in colour due to the patch works.

Protective coating will work as corrosion mitigation in the same way as hydrophobic impregnation by preventing further ingress of deleterious agents (e.g. Cl, CO_2) and by drying out the concrete.

3.5 CONCRETE RE-ALKALINISATION AND CHLORIDE EXTRACTION

Although different techniques these two systems work by inducing a current during a limited period of time.

For the re-alkalisation technique, the current generates hydroxides which increase the alkalinity of the concrete pore solution.

For the chloride extraction, the system generates a current that draws the chlorides toward an anode placed provisionally at the concrete surface.

These two systems can be quite effective but there is some risk associated to them:

Some negative impacts on the concrete surface that somehow might be affected were reported. Also they cannot be used on prestressed concrete due to the very high current output that is being used during a rather long period. This current output might generate hydrogen embrittlement

Re-alkalinisation and chloride extraction can be efficient but they are labour intensive and very costly. Once the reinforcement steel bars are back to passive conditions, protective coatings need to be used to prevent either the carbonation front or the chlorides to reach them again. There is also known risks (deterioration of concrete surface) and limitation (prestressed structure).

3.6 CATHODIC PROTECTION

Cathodic protection of reinforced concrete structures falls under an EN ISO 12696 standard which has been recently revised.

The standard is valid for both impressed current cathodic protection and galvanic protection.

3.6.1 IMPRESSED CURRENT CATHODIC PROTECTION

The corrosion protection is provided by placing an anode made for example of Titanium mesh at the surface of the concrete and connected to the reinforcement network – (Figure 10). A current is then drawn in the system that maintains the rebar in the cathodic zones meaning no corrosion can then occurred in this areas even in presence of high chloride.

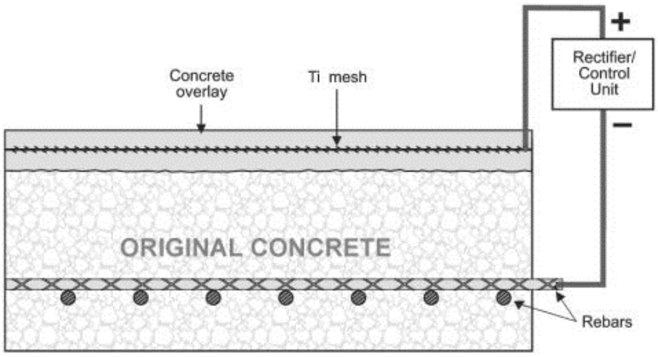


Figure 10: Induced current cathodic protection

When installed properly, this is the only system available that arrests completely corrosion activity. However, it requires high skill to design and install the system. It also requires alimentation of current and continuous monitoring through the entire service life to ensure the system is running properly. Lack of service might eventually result in destructive effect of induced current to the structure protected.

In summary, impressed current cathodic protection is a very effective system to stop corrosion activity but very complex to design and install, very costly at the installation stage but as well during its life time. Due to its complexity, some failures were reported

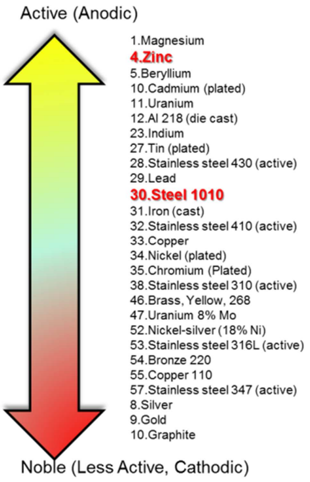
Additionally, this technique cannot be used on prestressed concrete due to the risk of hydrogen embrittlement.

3.6.2 GALVANIC PROTECTION

Galvanic corrosion protection of steel in concrete is based on the formation of a galvanic element (metal) being less noble than steel and is electrically connected to the steel reinforcement bars within the concrete. The steel reinforcement is protected from corrosion as long as sufficient galvanic current flows between the galvanic anode (acting as anode) and the steel reinforcement (acting as cathode). Most commonly, zinc is used as the sacrificial anode material. The galvanic element formed corresponds to a conventional zinc/air battery. First known application of galvanic corrosion protection was on a bridge deck in Illinois in 1977.

The efficiency of galvanic corrosion protection depends on the lasting activity of the zinc anode. Passivation of zinc anode by formation of a passive layer on zinc surface is caused by:

- Deposition of anodic (zinc corrosion) products on zinc surface
- Contact with calcium hydroxide in concrete pore solution



The first generation of galvanic systems applied in reinforced concrete suffered from rapid passivation and therefore lost their protective effect after short time. Passivation has to be addressed by introduction of suitable activation agents – what might result in excessive self-corrosion, consuming up to 70% of the zinc without producing protection current.

Critical reports about mixed results in early applications created resistance in the use of galvanic systems.

Huge research and development effort was invested in the development of galvanic anodes with balanced activation for long lasting effectiveness. There is meanwhile evidence of useful service life of more than 20 years.

Various galvanic protection systems are available:

- Embedded Anodes in patch repair areas
- Embedded anodes outside the patch repair area
- Embedded Hybrid anodes
- Surface applied anodes

Typical advantages of galvanic systems over impressed current cathodic protection are:

- No need for anode wiring (risk of theft of copper wires)
- Simple installation, relatively low cost
- No risk of hydrogen embrittlement in prestressed or post-tensioned tendons
- Self-adjusting current density
- No service or monitoring
- Current density (=level of protection) comparable to impressed current system

Embedded galvanic anodes: (Corrosion Prevention)

These anodes are placed in the repair area adjacent to the existing concrete interface to address the issue of incipient anode corrosion (Figure 11).

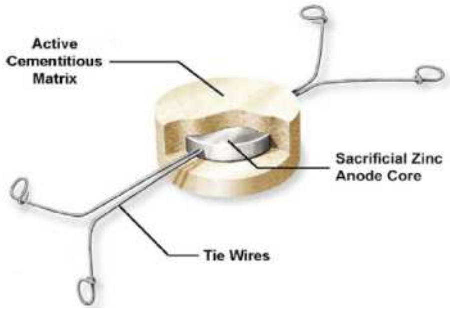


Figure 11: Cut-away of a proprietary anode
To be placed in the patch

The galvanic anode technology for reinforced concrete has been launched for more than 20 years.
Sergi[12] has shown, from several field experiments, the long term durability of these anodes with a good correlation between estimated life span (from anodes consumption) and the measurement after 10 years, the remaining quantity of zinc in the cementitious matrix casing.

This is a simple but effective system to address the issue of incipient anodes even in the presence of high chloride content in the sound concrete.

Figure 12: Typical placing with embedded anodes in bridge deck patch repair

Note the wrong placing of the anodes marked with a red arrow (too far away from the patch edge in the figures 12 & 13)

Figure 13: Typical placing for embedded anodes in bridge column patch repair

Embedded galvanic anodes: (Corrosion Control)

These anodes (Figure 14) are placed in the sound but contaminated concrete and linked together to provide the galvanic current (Figures 15 & 16). They are designed to control ongoing corrosion and to prevent the formation of new corrosion sites.

Figure 15: Galvanic anodes linked together for corrosion control in car park deck

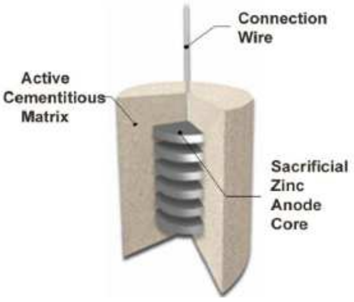


Figure 14: Cut away of a galvanic anode showing zinc core

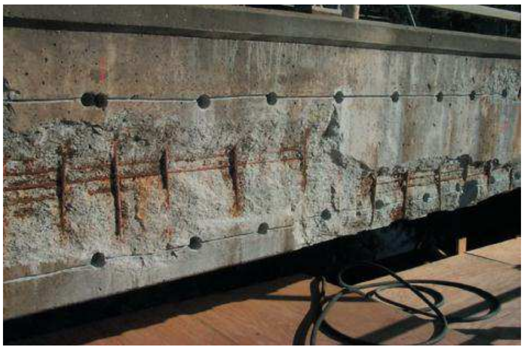


Figure 16: Galvanic anodes linked together in bridge parapet

Some issues [13] have been raised to the efficiency of this system especially in cases of severe existing corrosion. It has been found when running purely in galvanic mode, in the presence of high chloride content, the anode current output is the same as current output of an anode placed in a concrete with no chloride.

Effectiveness of discrete anodes might be limited if used to stop on-going corrosion in areas of severe corrosion.

Surface applied systems

Different systems are available:

- Hot sprayed zinc coating (Figure 17)
- Zinc plates (zinc-hydrogel anode) (Figure 18)
- Jacketing (Figure 19)
- Surface anodes (Figure 20)

Figure 18: Zinc plates

Figure 17: Hot Sprayed zinc coating

Figure 19: Pile jacketing

Figure 20: Surface anodes

Typical limitations are:

Hot spray zinc anode: Require sufficient concrete humidity and high chloride content to operate. Sprayed zinc forms a thin water vapour impermeable layer on concrete. There is high risk of delamination and bubbling on humid concrete.

Zinc plates (Zinc-hydrogel anode): Sufficient concrete humidity required. Hydrogel -pressure sensitive adhesive and electrolyte - is sensitive to exposure to high humidity, risk of delamination and loss of electrical conductivity. There is risk of drying shrinkage and loss of contact in dry conditions.

Jacketing: Complex installation, extremely expensive, sensitive to mechanical damage during installation (grouting) and operation

Equivalent replacement by easier to install systems, typically conventional repair and embedded anode or discrete anodes, is possible.

For example, due to problems with the installation of a pile jacketing system that was originally specified for the Arosa Bridge in Spain (Figure 21), an embedded galvanic anode system was used.

Figure 21: Failed pile jacketing at the Arosa Bridge

Figure 22: Installation of embedded galvanic anodes

Surface applied systems are typically complex, expensive, restricted to specific site conditions and require specialist applicators. Failures are observed quite often due to the complexity of the system.

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5 LEGAL NOTE

The information, and, in particular, the recommendations relating to the application and end-use of Sika products, are given in good faith based on Sika's current knowledge and experience of the products when properly stored, handled and applied under normal conditions in accordance with Sika’s recommendations. in practice, the differences in materials, substrates and actual site conditions are such that no warranty in respect of merchantability or of fitness for a particular purpose, nor any liability arising out of any legal relationship whatsoever, can be inferred either from this information, or from any written recommendations, or from any other advice offered. The user of the product must test the products suitability for the intended application and purpose. Sika reserves the right to change the properties of its products. The proprietary rights of third parties must be observed. All orders are accepted subject to our current terms of sale and delivery. Users must always refer to the most recent issue of the local Product Data Sheet for the product concerned, copies of which will be supplied on request.

6 KEY WORDS

Total Corrosion Management, reinforced concrete, protective coating, corrosion inhibitor, hydrophobic impregnation, cathodic protection, galvanic anodes, ICCP. Impressed Current Cathodic Protection.