# Corrosion Mitigation Systems for Concrete Structures

By J. Christopher Ball and David W. Whitmore

According to a recently completed study by the U.S. Federal Highway Administration, the annual direct cost of corrosion to the U.S. economy is estimated at $276 billion, or 3.1% of the U.S. Gross Domestic Product (GDP). If indirect costs such as loss of productivity are included, the annual cost is conservatively estimated at $552 billion, or over 6% of the GDP.

While these statistics are related to the overall cost of corrosion, all anecdotal information indicates that the annual cost for corrosion-related repair or replacement of concrete structures is considerable. Over the long term, owners of both public and private structures are faced with rising costs to maintain their structures. Forward-looking owners recognize the significant incentive to protect their investments and consider systems that can economically extend the life of today's concrete structures.

## Corrosion Basics

Prior to the consideration of corrosion mitigation systems, it is useful to gain a general understanding of the basics of corrosion of reinforcing steel in concrete. A brief overview is presented as follows:

### General Corrosion

The corrosion of reinforcing steel in concrete is an electrochemical reaction that is influenced by various factors, including chloride-ion content, pH levels, concrete permeability, and availability of moisture to conduct electricity. Five elements are required to complete the corrosion cell: an anode, a cathode, an ionic path, a metallic connection between the anode and cathode, and the availability of oxygen. In practical terms, the anode is the site of rust formation on the reinforcing steel, the cathode being another area of the rebar protected by the corrosion of the anode, the metallic connection is provided by the network of reinforcing steel, and the ionic path is through the concrete matrix with sufficient moisture for conductivity.

When mild steel is used as reinforcement in concrete, a protective oxide layer is initially formed on the surface of the rebar due to the alkalinity of the concrete. As long as this film is maintained, the reinforcement will indefinitely remain in a very passive state.

For corrosion to occur in concrete, the passive oxide film on the reinforcing steel must be destroyed. In most cases, this is due to the presence of sufficient chloride-ions at the level of the steel (generally thought to be 1.0 to 1.4 lb of water-soluble Cl- per yd$^2$ [0.6 to 0.8 kg/m$^2$]). Chloride-induced corrosion can be commonly found in structures exposed to deicing salts or a marine environment. Chlorides can also be introduced to the concrete during the original construction by the use of contaminated aggregates or chloride-containing admixtures.

The passive oxide film can also be destroyed by the loss of alkalinity in the concrete matrix surrounding the reinforcing steel. The reduction in alkalinity is generally caused by carbonation—a reaction of atmospheric carbon dioxide with calcium hydroxide (in the cement paste) in the presence of water. The result is a reversion of the calcium hydroxide to calcium carbonate (limestone), which has insufficient alkalinity to support the passive oxide layer. The amount of time for the carbonated zone to reach the level of the reinforcement is a function of the amount of concrete cover, concrete porosity, humidity levels, and the level of exposure to carbon dioxide gas. Once the carbonation reaches this steel, the passive layer will be destroyed, and the corrosion process may commence.

Over time, concrete delaminations result from the expansive pressures of the corrosion by-products. If corrosion activity is not arrested, section loss of the reinforcment can occur and significant structure repair or replacement may eventually be required.

### Patch-Accelerated Corrosion

When concrete delaminations are repaired using typical "chip and patch" procedures, abrupt changes in the concrete chemistry surrounding the reinforcing steel are created. Typical repair procedures call for removal of the contaminated concrete around the full circumference of the reinforcing steel within the repair area, cleaning of bond-inhibiting corrosion by-products from the steel, and refilling the cavity with new chloride-free, high-pH concrete (ICRI Technical

Guideline No. 03730). In the case of chloride-induced corrosion, this procedure creates adjacent chloride-contaminated and chloride-free zones with significantly different corrosion potentials. This difference in corrosion potential (voltage) is the driving force for new corrosion sites to form in the surrounding chloride-contaminated concrete.

The new corrosion activity is commonly referred to as "ring anode corrosion," "halo effect," or "incipient anode formation." Once again, from a practical standpoint, the evidence of this activity can be new concrete spalls adjacent to the previously completed patches. The time between repair programs will be influenced mainly by the amount of chloride present and the conductivity of the concrete. It is not uncommon, however, to find additional repairs required in 2 to 5 years.

Despite the corrosion concerns, the repair of delaminated concrete is necessary for structure serviceability, but having an awareness of these corrosion issues is important. Developing a corrosion management strategy will depend on many factors, including the amount of existing damage, level of contamination, environmental exposure, and the owner's requirements and budget. In many cases, longer-term corrosion solutions may be considered.

## Corrosion Mitigation Strategies

### Removal and Replacement

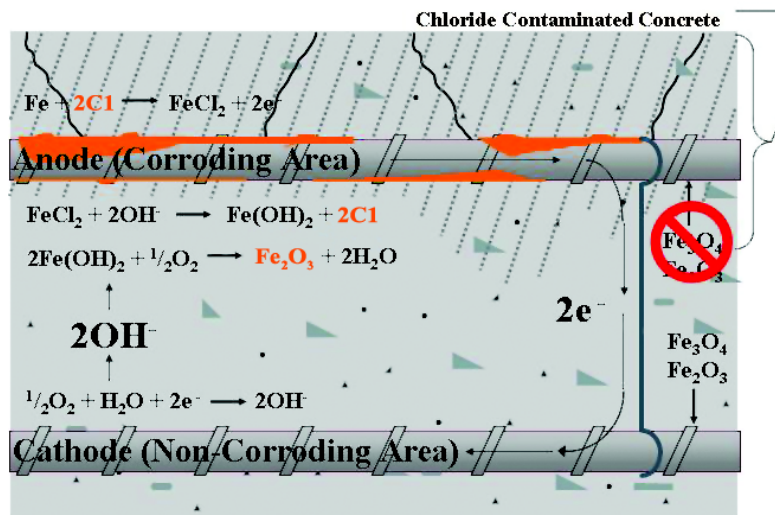Widespread removal of chloride-contaminated or carbonated concrete is a long-term solution

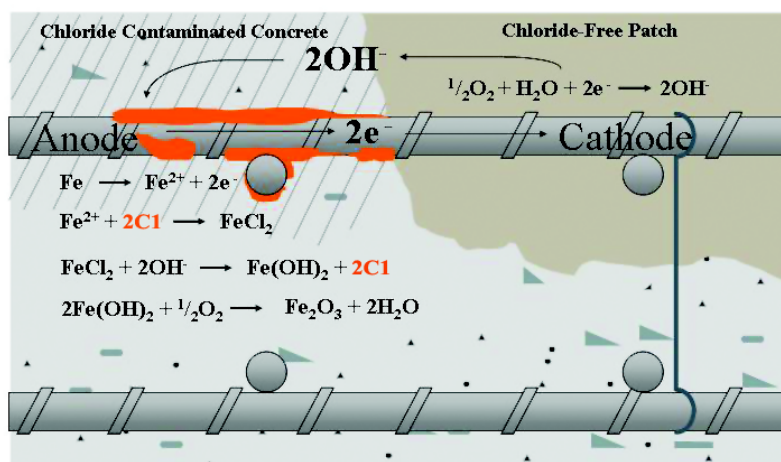

*Figure 1: Corrosion cell in concrete*



*Figure 2: Patch-accelerated corrosion in concrete*



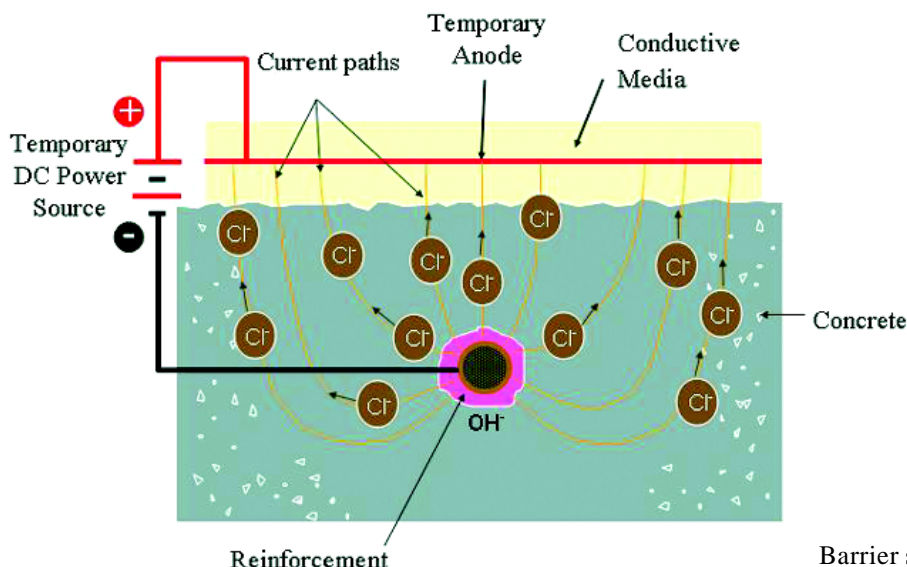*Figure 3: Removal of chloride-contaminated concrete*

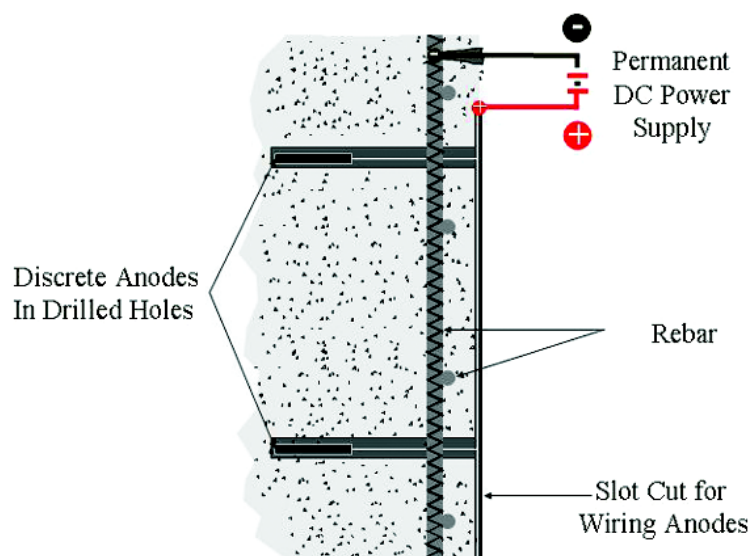*Figure 4: Electrochemical chloride extraction process*



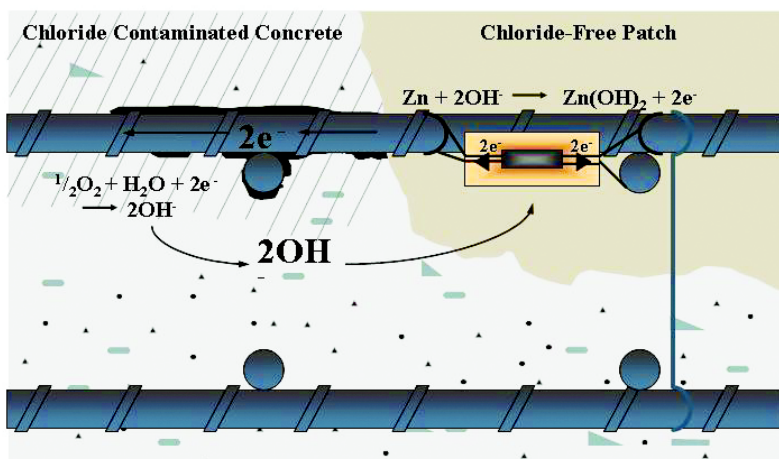*Figure 5: Impressed current cathodic protection*



*Figure 6: Embedded galvanic anode installed in patch repair for protection against patch-accelerated corrosion initiation*

because this method removes the source of the corrosion problem. This approach lends itself to structures with severe corrosion problems as evidenced by a large percentage of the surface area being delaminated. This option, however, is generally cost-prohibitive or impractical in many situations. Removal and replacement can also create structural concerns during the repair execution that can result in shoring requirements and increased costs.

## Barrier Systems

The use of sealers, coatings, and overlays are often considered for mitigating future corrosion activity. Barrier systems operate by preventing the ingress of chloride ions, moisture, and/or carbon dioxide into the structure. A significant increase in life expectancy can be achieved when the proper system is applied to a new structure or to a structure without significant contamination at the level of the reinforcing steel. If the structure is already contaminated and showing signs of corrosion distress, the use of barrier systems will generally have a limited impact on the service life of the structure.

## Electrochemical Treatments

An alternative approach to achieve long-term corrosion protection is to address the underlying cause of corrosion without the widespread removal of contaminated but sound concrete. For many projects, electrochemical treatments are a cost-effective strategy for providing corrosion protection over large areas.

Electrochemical chloride extraction (ECE) is a short-term process where an electric field is applied between the reinforcement in the concrete and an externally mounted mesh. The mesh is embedded in a conductive media, generally a sprayed-on mixture of potable water and cellulose fiber for vertical and overhead surfaces. During treatment, negatively charged chloride ions are transported away from the rebar and toward the positively charged external electrode mesh by means of ion migration, where they are trapped and removed in the fibrous electrolyte mixture.

For structures subject to carbonation-induced corrosion, a variation of the ECE process can be utilized to re-alkalize (increase the pH of) the concrete. The primary differences between ECE and re-alkalization are the choice of electrolyte, the duration of treatment, and the procedures to verify a successful application.

## Impressed Current Cathodic Protection

Another option to consider is the installation of an impressed current cathodic protection (ICCP)

system. ICCP systems start with the installation of permanent anode(s) into the structure. An external DC power source is applied with the anode being connected to the positive (+) terminal and the reinforcing steel connected to the negative (-) terminal. Properly designed, installed, and maintained, ICCP systems can provide long-term protection to the reinforcing steel. According to industry standards, an ICCP system is considered to be 100% effective when the system polarizes the reinforcing steel sufficiently to result in a 100mV depolarization after the system is turned off.

Additionally, ICCP systems can be cost-effective when used to protect large areas, and the initial costs are spread over a long period of time. Periodic inspection and maintenance of the system is required. If an ongoing monitoring and maintenance program is unlikely, other corrosion mitigation strategies should be considered.



*Figure 7: Florida condominium with distributed galvanic protection system*

## Galvanic Protection

Galvanic protection is achieved when two dissimilar metals are connected. The metal with the higher potential for corrosion (generally a zinc-based system in concrete applications) will corrode in preference to the more noble metal. As the sacrificial metal corrodes, it generates electrical current to protect the reinforcing steel.

Potential applications for galvanic systems include balconies, walkways, bridge and parking decks, and precast/prestressed concrete. Two types of galvanic protection systems are used for these applications: distributed systems for global corrosion protection and discrete anodes for localized protection.

Distributed systems consist of galvanic anode(s) that are placed onto the surface of the concrete or embedded in a concrete overlay. Discreet systems utilize embedded galvanic anodes (EGAs) tied to the steel which is exposed in the area to be repaired. EGAs can also be used to protect the remaining chloride-contaminated or carbonated concrete by installing into drilled holes on a grid pattern.

To address patch-accelerated corrosion, palm-sized EGAs are used in conjunction with traditional concrete repair by tying the anodes onto the reinforcing steel at the perimeter of concrete patches. Once the concrete is placed, the zinc anodes provide localized galvanic protection to prevent corrosion initiation of the adjacent reinforcing steel. EGAs can be used to provide corrosion prevention at the interface of new concrete and existing contaminated concrete such as partial- or full-depth concrete repairs, expansion joint replacements, and bridge widening projects.

Unlike impressed current cathodic protection systems, the galvanic system voltage is fixed (similar to a battery) and the amount of current generated is a function of the surrounding environment. Galvanic anodes will generate higher current output when in a more corrosive or conductive environment. For example, current output will likely exhibit a daily and seasonal variation based on moisture and temperature changes.

Due to the limitation in driving voltage, in some situations, galvanic systems may not achieve the accepted 100 mV depolarization criteria for complete cathodic protection. Previous studies indicate, however, that current density in the order of 0.4 mA/m$^2$ of steel surface area has prevented the initiation of steel corrosion in concrete with chloride levels as high as 2% by weight of cement (10 times the chloride threshold to initiate corrosion activity).

This range of current density has been shown to provide "cathodic prevention." When combined with the low system maintenance, the lack of external power supply required, and the general compatibility with prestressed and post-tensioned steel, EGAs provide an attractive choice for corrosion protection for many applications.
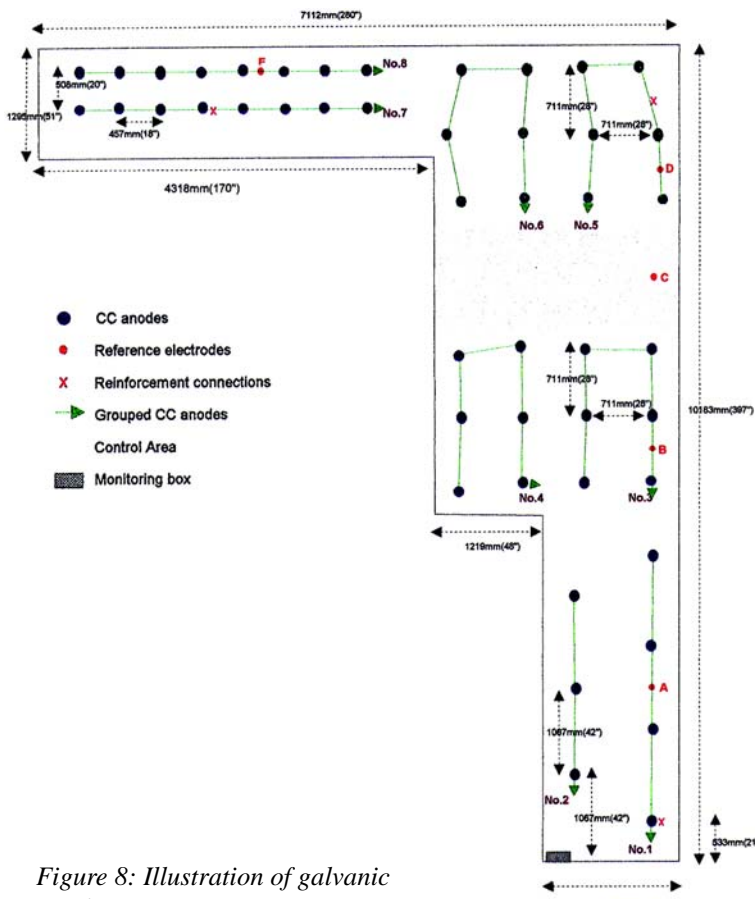
*Figure 8: Illustration of galvanic anode spacing*



*Figure 9: Galvanic anodes installed prior to deck coating*

## Embedded Galvanic Anodes
## Case Study

The Florida coast provides one of the most corrosive environments in the world and is an excellent test area for corrosion mitigation systems. Elevated chloride levels from sea spray combined with high temperatures and humid conditions provide a very corrosive environment. In this type of situation, typical "chip and patch" repair programs can show signs of patch-accelerated corrosion in as little as 2 to 3 years.

In June of 2000, a condominium on the east coast of Florida exhibiting concrete spalling from patch-accelerated corrosion was selected for the application of an EGA system. The purpose of the installation was to reduce the level of corrosion activity and to cost-effectively increase the service life of the chloride-contaminated balconies and walkways.

Because the removal of spalled concrete was to be performed in accordance with the ICRI guidelines, which state that concrete removal be continued until clean steel is encountered, the actively corroding areas were being addressed by the concrete repairs. The primary concern of the owners was to delay corrosion initiation within the sound but chloride-contaminated areas that remained.

To evaluate the performance of the EGA system, 47 anodes were installed into drilled holes on two separate balconies. The anodes were installed in a grid pattern at three different spacings—18, 28, and 42 in. (45, 71, and 107 cm) on center.

A remote monitoring system was installed to measure current output of the anodes and to conduct depolarization testing of the system. Results indicate that all areas achieved sufficient overall current output for cathodic prevention. As mentioned previously, cathodic prevention occurs when sufficient current is generated (greater than 0.4 mA/m$^2$ of steel surface area) to provide corrosion mitigation. Assuming that the conditions do not change, the amount of current required to provide cathodic prevention decreases over time as hydroxyl ions are generated at the steel (thus increasing pH), chloride ions migrate away from the steel, and passivity develops over time.

Readings taken 5 months after anode installation indicated that the polarization of the steel was less than 100 mV. Although this is considered to be less-than-complete cathodic protection, a significant level of corrosion protection is nevertheless provided to the steel. Subsequent readings have indicated increasing polarization over time.

*Table 1: Test results from Florida Condominium Test Balcony A (5 months after installation)*

| Balcony A | Ref Cell A | Ref Cell B | Ref Cell C | Ref Cell D | Ref Cell E |
|---|---|---|---|---|---|
| Subzone<br>Anode spacing | 1<br>42 in. (107 cm) | 3<br>28 in. (71 cm) | Control<br>N/A | 5<br>28 in. (71 cm) | 8<br>18 in. (46 cm) |
| Dist. from anode | 21 in. (53 cm) | 14 in. (36 cm) | 30 in. (76 cm) | 14 in. (36 cm) | 9 in. (23 cm) |
| 24 h depolarization (mV) | 87 | 46 | 46 | 53 | 82 |
| Current density (mA/m$^2$) | 1.7 | 2.2 | N/A | 1.0 | 1.8 |

*Table 2: Test results from Florida Condominium Test Balcony B (5 months after installation)*

| Balcony B | Ref Cell A | Ref Cell B | Ref Cell C | Ref Cell D | Ref Cell E |
|---|---|---|---|---|---|
| Subzone<br>Anode spacing | 1<br>42 in. (107 cm) | 3<br>28 in. (71 cm) | Control<br>N/A | 5<br>28 in. (71 cm) | 8<br>18 in. (46 cm) |
| Dist. from anode | 21 in. (53 cm) | 14 in. (36 cm) | 30 in. (76 cm) | 14 in. (36 cm) | 9 in. (23 cm) |
| 24 h depolarization (mV) | 21 | 73 | 4 | 35 | 67 |
| Current density (mA/m$^2$) | 1.5 | 2.5 | N/A | 1.1 | 0.8 |

After successfully demonstrating the system performance, EGAs were used to reduce the corrosion activity and delay the initiation of corrosion in new areas on the remaining 15,000 ft$^2$ of balconies and walkways.

## Understanding Technologies

As detailed previously, there is a wide range of corrosion mitigation systems available for concrete structures, each with its advantages and limitations. Developing a basic understanding of the mechanism of corrosion and available corrosion mitigation technologies provides a strong foundation for developing long-term corrosion management strategies that increase the service life of concrete structures while meeting the owner's requirements and budget.

## References

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*As Vice President of Vector Corrosion Technologies, David W. Whitmore is actively involved with professional organizations such as ICRI, the National Association of Corrosion Engineers (NACE), and ACI International, where he is involved in repair and corrosion committees that focus on the development of specifications and standards for technologies to rehabilitate and protect concrete structures.*