Applications for Galvanic Anodes in Prestressed Concrete

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Abstract

Protection techniques that incorporate galvanic anodes are providing new possibilities for extending the life of prestressed concrete structures. By corroding sacrificially, galvanic anodes provide corrosion protection to embedded reinforcing steel. For existing structures, galvanic anodes can provide localized corrosion protection to extend the life of patch repairs, or can provide global protection for structures with chloride contaminated but sound concrete. Embedded galvanic anodes can also be used in new construction to provide an extra built in defense against future corrosion problems.

Introduction

During recent years, the mechanisms of corrosion of embedded metals in reinforced concrete structures have become generally understood. Recent advancements in concrete technology have provided many tools for the structural engineer to utilize when designing new structures subject to corrosive environments. Increased concrete cover, lower permeability concrete, corrosion inhibiting chemical admixtures, pozzolanic mineral admixtures and various reinforcing systems with enhanced resistance to corrosion activity are just a few examples of the numerous options that may be considered when designing new structures with enhanced durability.

Photo 1 Precast/prestressed double T beams ends suffering from chloride-induced corrosion.

This understanding of materials combined with the quality-controlled manufacturing environment and the reduced likelihood of cracking due to drying shrinkage allows today's precast/prestressed concrete to be a particularly durable building material. While it is generally agreed that properly designed and constructed precast/prestressed concrete structures provide adequate durability for their expected service life, there are still a substantial number of older existing structures that are in need of rehabilitation due to on-going corrosion activity.

The rehabilitation of existing prestressed concrete structures presents special challenges to the practicing engineer. Unlike new construction, the number of suitable corrosion protection options is generally limited. And to complicate matters, the corrosion of high tensile strength steel under load in precast/prestressed concrete can be particularly damaging and presents special considerations to both the rehabilitation process and the selection of corrosion protection systems.

Corrosion Fundamentals

The corrosion of reinforcing steel in concrete is an electrochemical reaction that is influenced by various factors including chloride-ion content, pH level, concrete permeability, and availability of moisture to conduct ions within the concrete. Five elements are required to complete the corrosion cell: an anode, a cathode, an ionic path, a metallic path between the anode and cathode, and the availability of oxygen.

The anodic site becomes the site of visible oxidation (corrosion) and the cathode is the location of the reduction reaction which is driven by the activity at the anode. In precast/prestressed concrete, the metallic path can be provided by the embedded prestressing stands and/or the mild steel reinforcing. The ionic path is provided by the concrete matrix with sufficient moisture for conductivity and oxygen is generally available from the atmosphere due to the permeability of concrete to the diffusion of gases.

Due to the high alkalinity of the concrete pore water solution, a thin passivating oxide layer is formed and maintained on the surface of the embedded steel thus protecting it from corrosion activity. Until this passive film is destroyed by the intrusion of aggressive elements or a reduction in the alkalinity of the concrete, the reinforcement will remain in a very passive non-corroding state.

For the corrosion process to be initiated, 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. Chloride-induced corrosion is most commonly observed in structures exposed to roadway de-icing salts or a marine environment though direct exposure to salt water or wind-borne sea spray. Chlorides can also be introduced to the concrete during the original construction by the use of contaminated aggregates or chloride-containing admixtures.

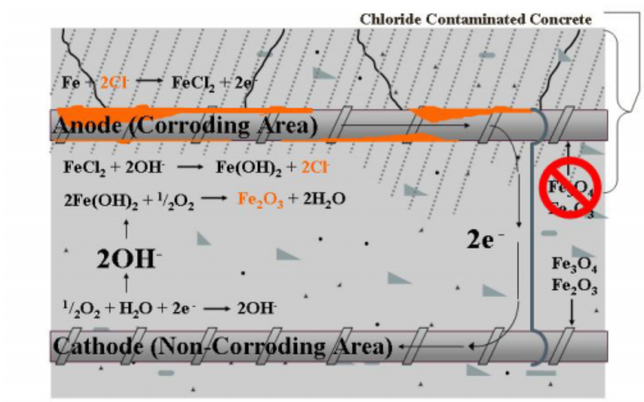

Figure 1 Chloride ion induced corrosion cell in concrete

The passive condition of the reinforcing can also be disrupted by the loss of alkalinity in the concrete matrix surrounding the reinforcing steel. It is generally accepted that a pH greater than 10 is sufficient to provide corrosion protection in chloride ion free concrete. The reduction in alkalinity is generally caused by carbonation, a reaction between atmospheric carbon dioxide and calcium hydroxide in the cement paste in the presence of water. The result is a reversion of the calcium hydroxide to calcium carbonate which has insufficient alkalinity to maintain the passive oxide layer. The amount of time for the zone of carbonated concrete to reach the level of the reinforcing is a function of the amount of concrete cover, presence and extent of cracks, concrete porosity, humidity levels, and the level of exposure to carbon dioxide gas. Carbonation-induced corrosion can be observed in structures situated in industrial environments where airborne pollutants are more commonplace or structures with a high degree of concrete porosity or low concrete cover over the reinforcement.

Over time, concrete spalling and delaminations result from the expansive pressures of the steel corrosion by-products which can create tremendous tensile stresses in the concrete matrix. If corrosion activity is left unchecked, significant section loss of the reinforcing can occur and structural repair or replacement may eventually be required.

When corrosion-induced delaminations are repaired, typical procedures include marking the area of delaminated or loose concrete, mechanically removing concrete around the complete circumference of the steel until no corrosion by-product is evident, cleaning the remaining contaminated concrete and rust from the exposed steel, and filling the open cavity with new concrete or mortar (ICRI, 1995).

Unless all of the chloride contaminated concrete is removed, the concrete surrounding the reinforcing steel will likely contain abrupt differences in chloride levels between the patch and the existing concrete substrate. The difference in chloride levels results in differences in the corrosion potentials between the two concrete environments and is the driving force for new corrosion activity to commence in the adjacent chloride contaminated concrete.

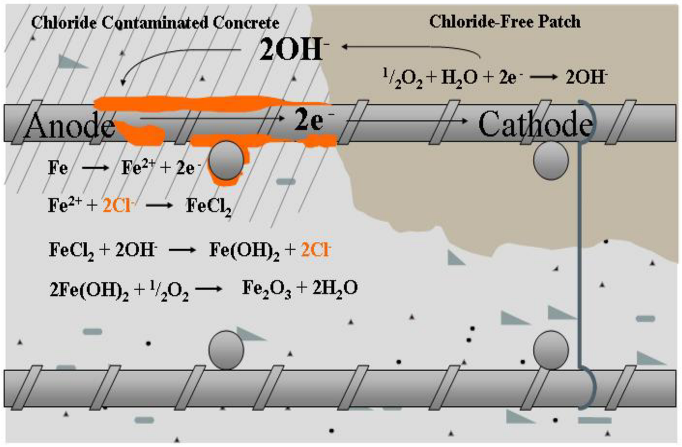

Figure 2 Patch Accelerated Corrosion in Concrete

This phenomenon is commonly referred to as "ring anode corrosion", "halo effect" or "incipient anode formation." The evidence of this activity can be the formation of new concrete delaminations adjacent to previously completed repairs. The new corrosion activity eventually causes additional damage in as little as a few years. The time between repair programs will be influenced mainly by the amount of chloride present and the conductivity of the concrete.

Despite the corrosion concerns, the repair of delaminated concrete is necessary for structure serviceability. Therefore, an understanding of the corrosion issues is important when developing a rehabilitation strategy for a given structure. In many cases, longer-term corrosion solutions may be considered in lieu of on-going "chip and patch" maintenance.

Special Considerations for Precast/Prestressed Concrete

Corrosion activity in precast/prestressed concrete is generally localized in nature and can usually be attributed to design, construction, and maintenance issues. Examples of these deficiencies may be improper drainage, leaking cold joints, failed concrete overlays and membranes, or leaking expansion joints allowing chloride containing water to saturate prestressed concrete not designed for severe exposure conditions. These deficiencies should be addressed to extend the overall service life of the prestressed concrete structure, especially if the cost and disruption of member replacement is large.

Corrosion in concrete elements with prestressed reinforcing potentially has greater consequences than conventionally reinforced concrete. While the corrosion of non-prestressed reinforcing is generally considered to be more of an issue of concrete durability and aesthetics than structural performance, the corrosion of prestressed steel and the subsequent loss of section have greater ramifications. Since the applied stress level is typically between 55-65% of ultimate, loss of cross section and an increase in stress on the remaining cross section could possibly lead to a point of yielding or fracture. Secondly, when compared to reinforcing bar, prestressed tendons are made up of smaller diameter wires that lose cross sectional area more rapidly at the same corrosion rate (ACI 222.2R-01).

Because of unique issues surrounding the corrosion of prestressing steel, the American Concrete Institute specifies lower acceptable chloride thresholds when using prestressed reinforcing in new construction.

Table 1 Chloride Limits for New Construction (ACI 222R)
(% by weight of cement)

Type of Test	Acid Soluble	Water Soluble	Water Soluble
Test Method	ASTM C1152	ASTM C1218	Soxhlet
Prestressed Concrete	0.08%	0.06%	0.06%
Reinforced Wet	0.10%	0.08%	0.08%
Reinforced Dry	0.20%	0.15%	0.15%

As noted earlier, industry recognized corrosion-damage repair procedures for conventionally reinforced structures include removal of concrete and the complete exposure of embedded metals. For prestressed concrete, this procedure would release the stored energy of the prestressing strand and significantly reduce the applied prestressing force. This is of particular concern if the corrosion damage is located in load bearing areas as is typically the case if prestressed concrete beam ends under leaking expansion joints are corroded.

Photo 2 Precast/prestressed beam repair. Delaminated concrete cover removed but strands remain partially embedded in chloride-contaminated concrete.

Because of this concern, the repair of precast/prestressed concrete members in practice may only include the removal of the delaminated concrete cover to keep the steel partially bonded in an attempt to prevent the loss of additional prestress force. Following these repair procedures, patch accelerated corrosion can be more severe since new corrosion activity can take place throughout the base of the repair (where the steel is in contact with both chloride contaminated and fresh concrete) instead of just around the patch edges.

High tensile strength prestressing steel also has a greater susceptibility to stress corrosion cracking and hydrogen embrittlement. Stress corrosion cracking is a special type of corrosion that only occurs when steel is under tensile stress and is subject to a corrosive environment. Hydrogen embrittlement is caused by the adsorption of atomic hydrogen into the metal. These issues can be of particular concern to structural elements since they cause a loss of ductility of the reinforcement and potential brittle failure.

Corrosion Protection Systems for Existing Precast/Prestressed Structures

Barrier Systems

The use of surface applied barrier systems such as sealers and coatings are often considered for mitigating future corrosion activity. Barrier systems primarily function by preventing the ingress of chloride ions, moisture and/or carbon dioxide into the structure. Depending upon the environment and the material selected, an increase in service life can be achieved when the proper system is applied to a new structure or to a structure without significant chloride contamination at the level of the reinforcing steel. If the structure is exhibiting corrosion distress, the benefit of barrier systems will be limited if the structure is already contaminated and sufficient amounts of oxygen and moisture or humidity are available to enable corrosion activity.

Cathodic Protection

One corrosion mitigation technique which is sometimes used is cathodic protection. Cathodic protection mitigates corrosion activity by supplying sufficient electrical current from an external source to overcome the on-going corrosion current in the structure. In general, cathodic protection can be provided by impressed current systems which utilize current from an external power source or galvanic systems which generate current using the principle of dissimilar metal corrosion.

Impressed Current

Impressed current systems are widely recognized as an effective method of corrosion control. However, impressed current systems are a potential source of hydrogen generation if the polarization is sufficiently high. If this occurs, some of the hydrogen generated enters the steel network while most of it combines as harmless molecular hydrogen. Some research has indicated that potentials more negative than -977 mV_{cse} (copper sulfate electrode) can cause hydrogen embrittlement (Hartt, Kumria, and Kessler 1993). Due to this concern, the use of impressed current cathodic protection on prestressed concrete elements has been limited, especially in North America.

Galvanic Protection

An alternate approach to achieve long-term corrosion protection is to utilize galvanic protection systems. Galvanic protection can be used alone or in combination with barrier systems for multilevel 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.

Table 2 Galvanic Series

Metal	Volts*
Magnesium	-1.75
Zinc	-1.10
Aluminum alloy (5% Zn)	-1.05
Steel in concrete	-0.2 to -0.35

* Typical potentials measured with respect to copper sulfate electrode

Unlike impressed current cathodic protection systems, the galvanic system voltage is fixed and the amount of current generated is a function of the surrounding environment. Galvanic anodes will generate higher current output when the environment is more corrosive or conductive. For example, current output will likely exhibit a daily and seasonal variation based on moisture and temperature changes. Some have referred to this type of sacrificial system as a "limited form of intermittent cathodic protection" (Glass et al, 2003).

As noted above, when placed on prestressed steel, the polarized potentials of cathodic protection systems should remain less negative than -977 mV_{cse} to prevent the generation of hydrogen. The potential for actively corroding zinc is -1,100 mV compared to passive steel in concrete at -200 mV_{cse} and actively corroding steel at -350 mV_{cse}. Connecting actively corroding zinc to steel inside the concrete will provide a source of electrons to the steel and will shift the potential of the steel in a negative direction. Since the maximum driving potential of the zinc is limited to -1,100 mV_{cse} and there will be voltage drops due to the resistance of the concrete and polarization of the zinc itself, it is very unlikely that the potential of the steel will be driven to be more negative than -977 mV_{cse}. As a result, it is unlikely that a zinc based galvanic system will be responsible for the generation of atomic hydrogen and thus will not increase the likelihood of hydrogen embrittlement.

Due to the limitation in driving voltage, galvanic systems in some situations may not achieve the industry accepted 100 mV depolarization criteria for complete cathodic protection. However, previous studies indicate that current densities as low as 0.4 mA/m^2 of steel surface area have prevented the initiation of steel corrosion in concrete containing chloride content as high as 2% by weight of cement or 10 times the threshold to initiate corrosion activity (Bertolini et al, 1998). This range of current density has been shown to provide "cathodic prevention". Current densities of 1 to 7 mA/m^2 have been shown to reduce corrosion and extend the service life of actively corroding steel (Glass, Hassanein and Buenfeld, 2001).

Considering the low system maintenance, the lack of external power supply required, and the general compatibility with prestressed and post-tensioned steel, embedded galvanic anodes provide an attractive choice for corrosion protection for many applications. Galvanic protection systems are used for two types of applications: distributed systems for global corrosion protection and discrete anodes for localized protection.

Distributed systems consist of galvanic anode(s) that are placed on the surface of the concrete or embedded in a concrete overlay. Discrete systems utilize embedded galvanic anodes tied to the steel which is exposed in the repairs, or installed into the existing concrete by drilling or coring holes on a grid pattern.   Discrete embedded galvanic anodes in particular have been used to protect chloride-contaminated prestressed beams previously exposed to leaking joints or poor drainage.

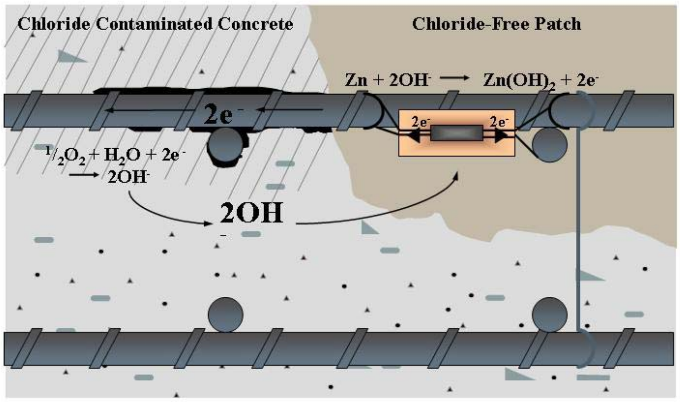

Figure 3 Installation of embedded galvanic anode

To address patch-accelerated corrosion, embedded galvanic anodes are used on concrete rehabilitation projects by tying the anodes to the exposed steel. Once the concrete is placed, the zinc anodes provide localized galvanic protection to the reinforcing steel embedded in the remaining chloride contaminated concrete.

Examples of Galvanic Protection

Example 1 – Embedded Galvanic Anodes in Patch Repair of Prestressed Beam Ends

In 1998, Iowa Department of Transportation was experiencing corrosion problems on the exposed ends of precast/prestressed AASHTO girders due to the leakage of chloride contaminated water at the bridge deck joints. Recognizing that continued corrosion activity in this location may put the structure at risk, the Department utilized embedded galvanic anodes in addition to the required concrete repairs to rehabilitate and provide localized corrosion protection to a total of 84 beam ends.

Photo 3 Prestressed beam end subject to corrosion

Photo 4 Prestressed beam end with galvanic anodes and rebar coating installed prior to concrete replacement.

Loose concrete was removed exposing the outside surface of the corroding prestressed strands and the stirrup steel. Then all strands and rebar were made electrically continuous by connecting at the beam end.

Six embedded galvanic anodes were installed in each beam end with one in the top flange, one in the web section and four in the critical bottom flange. The anodes were tied to the stirrup steel. Per the Iowa DOT specification, an anti-corrosion rebar coating was applied to the exposed steel surfaces taking care not to coat the surface of the anode or the concrete.

Photo 5 Completed prestressed beam end repair with embedded galvanic protection

The repair was completed using an Iowa DOT approved form and pour concrete mix. After sufficient cure time of the repair material, a pigmented sealer was applied to protect from future chloride penetration and to improve the aesthetics of the repaired precast/prestressed beams.

Anode current outputs are significant and vary with the weather. Based on the limited repair area on the end of each beam, the current density to the steel in these areas is significant.

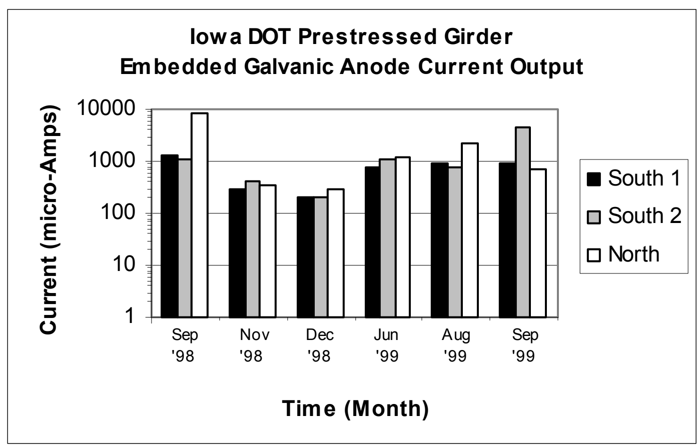

Figure 4 Embedded anode current output for three monitored anodes.

Example 2 – Embedded Galvanic Anodes in Chloride-Contaminated Prestressed Box Beam

In 2001, the New York State Department of Transportation had a corrosion problem with the Route 37 Bridge over Little Salmon River in Fort Covington, NY. This structure, built in 1977, consisted of single span precast/prestressed concrete box beams approximately 100 feet in length. The bridge deck sloped to the south fascia and allowed drainage of water down the face of the outside beam. Over time, chloride penetration had caused concrete spalling and delaminations.

Photo 6 Condition of Precast beams prior to rehabilitation program.

Photo 7 Electrical continuity established between the exposed strands

To provide longer-term repair of the affected areas, the NYSDOT specified the installation of cylindrical shaped embedded galvanic anodes. After the loose concrete was removed, individual prestressing strands were made electrically continuous.

Photo 8 Embedded Galvanic Anode Prior to Installation

Three rows of anodes were installed into 2 inch diameter holes approximately 18 inches on center. Two of the rows were on the vertical face and one row was on the bottom near the outside surface. The individual anodes were grouted into the prepared holes using low resitivity mortar and connected to a central wire using sealed button-type connectors. The string of anodes was attached to the strands at the beam ends.

Photo 9 Layout of the galvanic protection system prior to installation.

Photo 10 Layout of the galvanic protection system prior to installation.

After anode installation, concrete replacement was completed by the NYSDOT maintenance crew using the dry spray shotcrete process. Over two years later, the anodes continue to generate current and provide protection to the precast/prestressed concrete.

Embedded Galvanic Anodes – For New Construction, Too

For new precast/prestressed structures, embedded galvanic anodes may provide an additional tool for targeted protection. For example, experience has shown that the most likely location for corrosion damage in prestressed girders is at the beam end under the expansion joint. Embedded galvanic anodes could be added to protect these critical locations to provide economical, long-term, multi-level protection.

Embedded galvanic anodes used in new construction can provide the following benefits:

- Depending upon the environment, the galvanic anodes will continue to provide galvanic protection for approximately 10 to 20 years.
- As the anode corrodes, the cathodic reaction gives the reinforcing steel a net negative charge. While the anode is active, chloride ions (Cl^-) which are negatively charged would be electrically repelled away from the steel.
- The reaction at the cathodic site also generates hydroxyl (OH^-) ions which increase the alkalinity around the reinforcing steel. The residual affect of years of anode activity would be to increase the pH around the steel thus raising the chloride threshold necessary to initiate corrosion (see table below) (Hausmann, 1967).
- Unlike most other protective systems, galvanic anodes can be installed specifically into areas where future corrosion activity is likely.
- Because galvanic anodes can be utilized with this targeted approach, incremental cost is negligible.

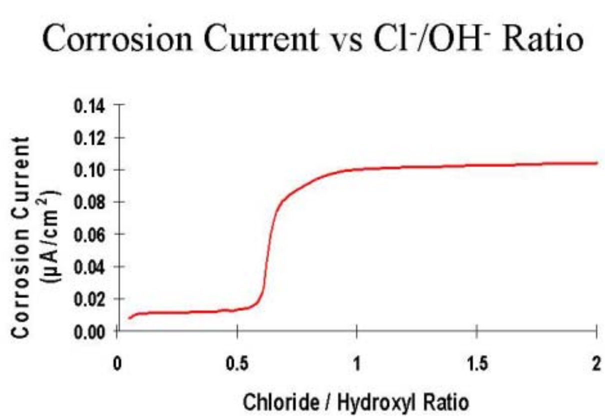

Figure 5 Corrosion activity is a function of chloride content and alkalinity.

Summary

Precast/prestressed concrete is known to be a high quality building material. Recent advances in concrete and admixture technology have allowed the material to be more durable than ever. However, from the standpoint of structural repair and the selection of corrosion mitigation systems, precast/prestressed concrete presents special challenges. Embedded galvanic anodes are a viable option for structure rehabilitation programs and as a proactive strategy to provide targeted protection in new construction.

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