USING CATHODIC PROTECTION TO CONTROL CORROSION OF CONCRETE INFRASTRUCTURE IN MARINE ENVIRONMENTS

FUNAHASHI, Miki PE
MUI International
www.mui-int.com

Abstract

In coastal marine environments corrosion of the reinforcing steel is one of the most prevalent mechanisms of concrete deterioration. Concrete structures that are partially or fully submerged in seawater are especially prone to reinforcing steel corrosion. High chloride concentrations, availability of moisture and wet/dry cycling of the concrete are the primary factors that contribute to the ongoing corrosion process.

Traditional methods of repair, such as removing deteriorated concrete and replacing with concrete repair mortar, may not be sufficient to slow down the corrosion process to a point where the deterioration rate of concrete is insignificant. Structures in marine environments that are repaired with conventional methods may develop concrete damage in a short time frame due to the aggressive nature of the ongoing corrosion process.

Over the last fifteen years, cathodic protection has increasingly been used to provide cost-effective corrosion control for reinforced concrete structures in marine environments. Both galvanic and impressed current cathodic protection systems have been used for this purpose. This paper reviews the corrosion process in marine environments and the types of systems that are available to control corrosion in the atmospheric, splash, tidal and submerged zones. Cases histories are given. The advantages and disadvantages of each system are discussed.

1. Introduction

Structures in marine environments can be divided into two categories of exposure; direct and indirect. The direct exposure category includes structures that are partially or fully submerged, and the indirect category includes structures along the coastline, which do not come into direct contact with seawater. Jetties, wharves, piers, bridge substructure elements and retaining walls are examples of structures in the direct exposure category, whereas, buildings, bridges and other structures along the coast are examples of structures in the indirect exposure category. Although the results of the corrosion process are similar for all reinforced concrete structures, the process by which corrosion occurs, the corrosion rate and the appropriate repair method are very different.

1.1 Direct Exposed Structures

Reinforced concrete structures that are partially submerged in seawater are especially subject to reinforcing steel corrosion due to a combination of reasons. These include high chloride concentration levels from seawater, wet/dry cycling of the concrete, high moisture content and oxygen availability. Three areas on concrete structures in marine environments can be distinguished regarding corrosion:

- the splash and tidal zone (intermittently wet and dry)
- the atmospheric zone (well above mean high tide and infrequently wetted)

Corrosion of the reinforcement in the immersed zone and lower portion of the tidal zone is generally considered negligible, even though the concrete may contain high levels of chloride ions. This lower rate of corrosion is partially due to the fact that oxygen cannot readily diffuse into the water saturated concrete through the water filled concrete pores.

Conversely, lower chloride and moisture content limit the corrosion rate above high tide. Corrosion is most severe within the splash and tidal zones where alternate wetting and drying result in high chloride and oxygen content. High moisture content in this region also contributes to high electrical conductivity of the concrete. Electro-chemical coupling of this zone with other regions of the structure will allow development of macro-cell corrosion activity.

1.2 Atmospherically Exposed Structures

Structures in the indirect exposure category are subject to corrosion from air born salts and moisture from the atmosphere. The quality of the concrete and depth of cover play a major roll in the ingress of chloride ions and time to corrosion. Carbonation, the process by which carbon dioxide from the atmosphere diffuses through the porous concrete and neutralizes the alkalinity, helps destroy the passive film on the reinforcing steel and contributes to the onset of chloride induced corrosion. Concrete structures in hot tropical marine environments are especially prone to concrete deterioration, since corrosion rates are greatly influenced by electrolyte resistivity, temperature and relative humidity [1].

1.3 Conventional Repair

As stated above, conventional rehabilitation techniques, which consist of removing delaminated areas of concrete, cleaning affected steel and patching with Portland cement mortar, have proven to be ineffective for marine structures. Repairs are often repeated every several years, which each successive repair being increasingly greater in magnitude. The presence of high levels of chloride ions remaining in the parent concrete will allow the corrosion process to continue unabated. The repair material also proves to be a problem since corrosion cells are inadvertently created between steel embedded in the chloride-free repair material and the steel embedded in the existing chloride contaminated concrete. This results in corrosion damage along the periphery of the patch and eventually complete failure will occur within the surrounding material and the repair itself.

The significance of this problem has forced the Florida Department of Transportation (FDOT) to study ways of mitigating corrosion of reinforcing steel in concrete marine structures. FDOT is responsible for approximately 3,000 bridges that are situated along 2,000 km of coastline. Field and laboratory results have led FDOT to implement cathodic protection as a means of controlling corrosion of reinforced concrete members in the splash and tidal zone [2]. However dealing with tidal movement provides additional complexity, in that the design of the cathodic protection system must take into account the reinforcing steel above and below the water level.

2. Cathodic Protection in Marine Environments

Both impressed current cathodic protection (ICCP) and sacrificial (galvanic) anodes have been used for corrosion control of concrete structures in marine environments. Impressed current systems utilize an inert anode material, such as titanium mesh, which is forced to slowly corrode (oxidize) in favor of the steel reinforcement. A rectifier is used to power the system and converts alternating current to direct current. One of the main benefits from the ICCP system is the ability of the rectifier to adjust and control the current. In marine environments, corrosion rates can vary significantly between the atmospheric, splash and tidal zones. Variations in steel density can also affect current distribution. Therefore independent zoning and control of the anode system is an important design consideration.

Electrical isolation between the anode and reinforcing steel is critical to ensure proper operation of an ICCP system. If a contact occurs between the anode and steel, the short circuit could make the anode zone partially or totally ineffective. Depending on which anode is used, the life expectancy of ICCP anodes is typically much greater than sacrificial anodes. For instance the life of a carbon based conductive coating system in a marine environment could be less than 10 years, where as the life expectancy of a iridium based catalyzed titanium mesh may exceed 75 years.

Sacrificial or galvanic cathodic protection is based on the principle of dissimilar metal corrosion and the relative position of specific metals in the galvanic series. Sacrificial CP systems have the advantage of no auxiliary power supply, and the advantage of being used for prestressed or post tensioned concrete without the risk of elevated potential levels which can lead to hydrogen embrittlement of the steel. The current generated from a sacrificial anode is directly related to the environment that it is placed. Anodes in wet/humid environments will typically produce higher levels of current than anodes in drier less humid environments. Due to their low driving voltage, sacrificial anodes are appropriate for prestressed concrete structures and structures that have single mats of steel, such as bridge piers and columns. Also, since the sacrificial anode is connected directly to the reinforcement, shorting of the system is not a concern.

To properly select and design a system for concrete structures in marine environments, owners and consulting engineers must understand the overall differences between impressed current and sacrificial (galvanic) anode systems. Table I provides a comparison of the merits and demerits for both of these systems.

Cathodic protection systems for concrete structures in marine environments fall into three categories: surface-applied, encapsulated and immersed. The surface applied systems may involve the application of the anode material over the entire surface or to selected areas where cathodic protection is most needed. A condition survey of the structure will assist in determining the extent of reinforcing steel corrosion and cathodic protection required. The encapsulated system may involve a concrete encasement, spray applied shotcrete, concrete overlays, saw cutting for ribbon mesh in slots, or drilling to insert discrete anodes. Immersed anodes usually consist of sacrificial bulk zinc or aluminum anodes or impressed current anodes such as mixed metal oxide tubular anodes or high silicon cast iron anodes.

It is particularly difficult to apply cathodic protection to the splash and tidal zones of concrete structures because of the constant wetting and drying, marine growth, and possible abrasion and impact from floating debris. Furthermore, any anode installed in the splash and tidal zone will experience high levels of current discharge if allowed to directly contact the seawater. This phenomenon occurs because of the tendency of the anode to “leak” high levels of current into the seawater due to the path of least resistance to the steel in portions of the structure below water. Many corrosion engineers have recognized this effect, and designers have developed methods to deal with the problem [3]. Current leakage may be reduced by using an electrical insulator over the anode, or by applying a supplemental current from a cathodic protection system installed below the water line.

3. Impressed Current Systems

3.1 Titanium Anode Mesh Encapsulation

Catalyzed titanium mesh anodes consist of expanded titanium mesh with a mixed metal oxide catalyst applied to the surface. The mesh is typically fastened to the patched and prepared concrete surface using nonmetallic fasteners and then overlaid or otherwise encased in Portland cement concrete. These systems are normally designed and installed such that the average anode current density does not exceed 110 mA/m^2. As reported above, the life expectancy of ELGARD™ anodes (iridium based coated anode) can readily exceed 75 years. Power is delivered to the mesh via lead wires and titanium current distributor bars. Such systems perform well because the precious metal oxide coating is the active anode, which slowly oxidizes with time. Under normal anodic conditions, the titanium substrate will passivate and is not consumed. The anode is therefore considered dimensionally stable.

When this type of system is used, the bonding of the overlay concrete is critical to provide a durable system. Before the titanium mesh is applied on the top of a deck structure, the concrete surface must be scarified to provide good bonding to the overlay concrete. However, application of shotcrete to sound concrete surfaces (vertical and overhead) has not been successful due to problems with bonding.

3.2 Titanium Anode Mesh Integral Pile Jacket System

Another system known as the integral pile jacket ELGARD™ CP system has been used on over 800 concrete bridge pilings in Florida. This system uses a prefabricated fiberglass jacket, which is supplied with the mesh anode attached to the inside of the jacket using special offsets. The jacket system is mounted to the piles using compression bands and the void between the jacket and concrete surface is filled with a cementitious grout. The systems installed with pile jackets have been successful in controlling corrosion on piles in the splash and tidal zones. The jackets have the additional benefit of acting as electrical insulators, thus preventing the flow of current through seawater to submerged steel [4]. Since the iridium based catalyzed titanium anodes have extremely low consumption rates and long life expectancy (i.e. > 75 years), life cycle costs are generally favorable regarding their use. Figure 1 is an example of a titanium mesh integral pile jacket system on a bridge in Florida.

3.3 Titanium Ribbon Mesh Slotted System

This system involves the use of a ELGARD™ catalyzed titanium ribbon and a non-shrink cementitious grout as the slot backfill. Ribbon mesh sizes are typically 13-mm and 19-mm wide and 1.3-mm thick. Slot spacing is dependent on steel density, but is typically 200-400 mm on center. A typical concrete slot is 8-mm wide by 25-mm deep for the 13-mm wide anode and 30-mm deep for the 19-mm wide anode. In areas of spalled and delaminated concrete, the ribbon can be attached to exposed rebar with plastic clips, and covered with shotcrete. This method has been proven to be cost-effective for the installation. Titanium current distributor bars provide continuity between the strips and are spot-welded to the ribbon mesh in the transverse direction.

This system has been especially useful for concrete structures that cannot tolerate the additional dead load of a concrete overlay or where bonding of the concrete overlay for mesh encapsulation is a concern. Sufficient cover over the rebar must be present, or the steel must be located with a rebar locator, so that the slots can be installed between the bars. This type of design has proven to provide more uniform cathodic protection current to the reinforcing steel. Figures 2 and 3 show the installation of a slotted system using titanium ribbon mesh on the underside of a deck in Japan and Australia, respectively.

3.4 Discrete Anode System

The discrete anode system is one of the most cost-effective systems for beams, piles and columns. In addition, discrete anodes can be utilized to protect the pile cap soffit in areas where it is not accessible from the surface.

ELGARD™ Discrete anodes are relatively easy to install and do not require extensive saw cutting or the use of concrete overlays. The anodes are typically inserted into drilled holes that are 20-30 mm in diameter and backfilled with a non-shrink cementitious grout. The length and spacing of the anode is dependent on the steel density and protection requirements for cathodic protection. Typically, 500 to 600 mm spacing is used. Several types of anodes are available. These include a discrete titanium ribbon mesh, titanium tubular mesh, ceramic anodes and platinized titanium wire with a carbon rich backfill. The titanium tubular mesh and ceramic anodes are designed to produce higher anode current output.

When a structure component contains significantly high rebar density, the use of a discrete anode system may not be applicable. Congested areas of reinforcing steel may preclude drilling of holes for discrete anodes and could provide short circuit or near short circuit conditions. Also, in areas of high steel density the CP current from the discrete anodes will be shielded by the inside rebar cage and a limited amount of CP current will reach the outer rebar cage where CP is most needed.

Figures 4 and 5 show the installation of a discrete anode system using titanium mesh tubular anodes and ribbon mesh anodes to protect the lower portion of a pile cap and pile cap soffit on a pier in Hong Kong and the substructure of a bridge in Australia..

4. Sacrificial (Galvanic) Systems

4.1 CORRSPRAY™ Arc Sprayed Aluminum-Zinc-Indium

Under a US Federal Highway Administration research contract, a new alloy has been developed as a sacrificial anode for cathodic protection of concrete. The anode consists of an Aluminum-Zinc-Indium (Al-Zn-In) wire, which is thermally sprayed onto concrete. The superior performance of the Al-Zn-In alloy compared with other types of sacrificial anodes is attributed to an indium activating agent, which tends to reduce the passivating effect of the anode [5, 6]. Figure 6 shows the sacrificial Al-Zn-In alloy applied to a bridge pier along the gulf coast of Texas.

4.2 Zinc Mesh Integral Pile Jacket.

The zinc mesh integral pile jacket system is designed to protect the tidal and splash zones of bridge pilings. The system consists of snap-together fiberglass jackets with expanded zinc mesh fastened to the inside face of the jacket assembly. The annular space between the jacket and the pile is then filled with a cementitious grout. Since the system is pre-assembled, installation is quite simple.

4.3 Cast Zinc Anodes.

Bulk zinc or aluminum anodes have been used successfully to cathodically protect portions of reinforced concrete structures below mean low water and portions of the tidal zone.

5. Conclusions

Reinforcing steel corrosion is the primary cause of deterioration for concrete structures in marine environments. In partially or semi-submerged structures the high chloride concentrations, wet/dry cycling, high moisture content and oxygen availability play a major roll in the corrosion process. Conventional repair methods, which include the removal of deteriorated concrete and repair with cementitious patching materials, have proven to be ineffective in controlling corrosion. Cathodic protection using both impressed current and sacrificial (galvanic) systems has proven to be effective in providing long-term corrosion control for concrete structures in marine environments.

In marine environments, corrosion rates can vary significantly from the atmospheric to the splash and tidal zones. Variations in steel density can also affect CP current distribution. One of the primary benefits of the impressed current system is the ability of the rectifier to adjust and control the current, so that adequate cathodic protection is provided to the structure. Independent zoning and control of the system is therefore an important design consideration. ELGARD™ titanium mesh and ribbon mesh anode systems can be used for a variety of applications and have significant design life (i.e., >75 years).

Newly developed sacrificial anodes, such as thermally sprayed Aluminum-Zinc-Indium (CORRSPRAY™) shows great promise for galvanic cathodic protection of reinforced and prestressed concrete structures. These systems are safe for cathodic protection of high strength steel in prestressed concrete structures, and requires minimal monitoring and maintenance.

Appendix

	Impressed Current System	Sacrificial (Galvanic) System
Merits	• longer anode life • current can be controlled to provide higher current density • extensive track record	• inherently simple • no monitoring & maintenance • no requirement for electrical isolation • risk of hydrogen embrittlement on high strength steel is minimal • saw cutting & concrete encapsulation for anodes is not required
Demerits	• more complex in design and installation • rectifier requires monitoring and maintenance • electrical isolation is required between anode and steel • conduit & wiring is required • typically not used for prestressed concrete	• shorter anode life • anode life is dependent on surrounding environment (i.e., moisture and temperature conditions) • current cannot be controlled

Table I. Comparison of CP Systems

Figure 1. Pile jacket system installed on the prestressed concrete piles in Florida, USA.

Figure 2. Titanium ribbon mesh anode slotted system installed on the deck soffit in Japan.

Figure 3. Ribbon mesh anodes are attached to exposed rebars on pile capos in Australia.

Figure 4. Titanium discrete tubular mesh anode installed in the pile cap in Hong Kong.

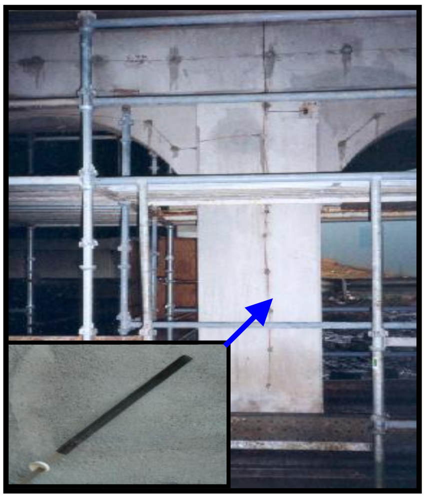

Figure 5. Discrete titanium ribbon mesh anode installed in bridge substructure in Melbourne, Australia.

Figure 6. Thermally sprayed aluminum alloy galvanic anode installing on the prestressed beams and pile caps in Galveston, Texas.

REFERENCES

1. Andrade, C., Alonso, C., Sarria, J., Influence of Relative Humidity and Temperature on the On-Site Corrosion Rates, Fourth CANMET/ACI International Conference on Durability of Concrete, Sydney, Australia, 1997: p17-22.

2. Kessler, R.J. and Powers, R.G., Use of Marine Substructure Cathodic Protection in Florida, Past and Present, Paper No. 910727, Transportation Research Board, 70th Annual Meeting, Washington, 1994

3. Clear, K.C., Cathodic Protection of Reinforced Concrete in Contact with Conductive Liquid, US Patent No. 4,692,066, 1987

4. Martin, B.L., Arase, K. and Kawamata, K., Cathodic Protection of Structures Containing Prestressed Steel in USA, Japan Concrete Institute, Tokyo. 1994

5. Funahashi, M. and Young, W.T., Development of New Sacrificial Anode Reinforced and Prestressed Concrete Structures, Second CANMET/ACI International Symposium on Advances in Concrete Technology, Las Vegas. 1995

6. Funahashi, M., Young, W.T., Field Evaluation of a New Aluminum Alloy as a Sacrificial Anode for Steel Embedded in Concrete, US Department of Transportation, Federal Highway Administration, Publication No. FHWA-RD-98-058, 1998