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Introduction

Corrosion of reinforcing steel is one of the most important and prevalent mechanisms of deterioration for concrete structures in marine environments. High permeability concrete, poor design detailing, and construction defects, such as inadequate depth of cover, are quality control problems, which allow the ingress of salt and moisture into the concrete. The higher concentrations of salt and moisture can result in accelerated corrosion of the reinforcing steel and significant deterioration to the concrete structure. Conventional repair methods, which include the removal of damaged concrete and repair with cementitious patching materials, have proven to be ineffective in controlling corrosion under these conditions.

Over the last ten years, cathodic protection (CP) has increasingly been used to provide long-term corrosion control for reinforced concrete structures in marine environments. CP is an electrochemical method, which can effectively stop further corrosion of the reinforcing steel regardless of the salt content in the concrete. Systems using both sacrificial (galvanic) and impressed current anodes have been successfully applied to the splash, tidal and atmospheric zones of marine structures.

Concrete 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, bridge substructure elements and retaining wallsare examples of structures in the direct exposure category, whereas, multi-storied condominiums and other buildings 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 can be very different.

Semi-Submerged Structures

Reinforced concrete structures that are partially or fully submerged in seawater are especially prone to reinforcing steel corrosion due to a variety of reasons. These include high chloride concentration levels from the 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: 1) the submerged zone (always below seawater), 2) the splash and tidal zone (intermittently wet and dry), and 3) the atmospheric zone (well above mean high tide and infrequently wetted).

Figure I provides a section view of the various corrosion regions associated with a concrete pile in a marine environment.

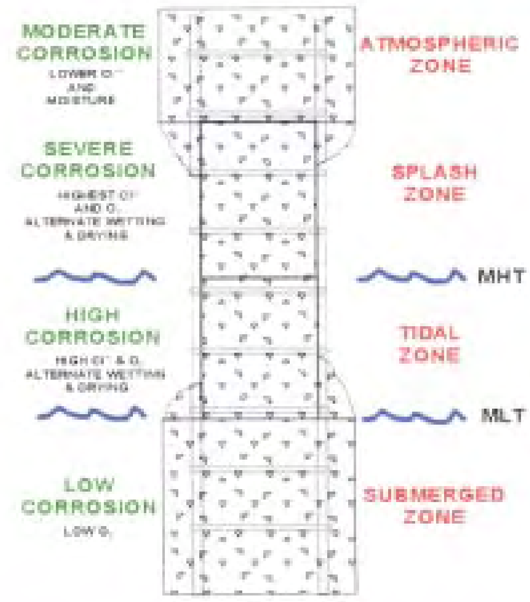

Figure I. Section view showing corrosion regions of a concrete pile in a marine environment.

Each of the above zones has very different corrosion characteristics. For instance, the corrosion rate below water level is limited by low oxygen availability, and 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 macrocell corrosion activity.

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 passivating 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 temperature and resistivity (1).

Conventional Repair

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, with 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. Figure II is an example of a prestressed concrete pile in Florida that was previously repaired with a conventional concrete pile jacket.

Figure II. Previously repaired concrete bridge pile in a marine environment, Florida.

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.

Cathodic Protection in Marine Environments

Both impressed current cathodic protection (ICCP) and sacrificial or 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 oxidize in favor of the steel reinforcement. A rectifier is used to power the system. The rectifier converts alternating current (AC) to direct current (DC). 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 impressed current system. If a contact occurs, 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 conductive coating system in a marine environment could be less than 10 years, where as titanium mesh can readily 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. Due to their low driving voltage, sacrificial anodes are appropriate on structures that have single mats of steel, such as bridge substructure components. Also, since the sacrificial anode is connected directly to the reinforcement, shorting of the anode 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 non-encapsulated 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 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. Table II provides an outline of the various anode types by category.

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. 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.

Impressed Current Systems

Conductive Coating. One of the first anode systems used on concrete structures is the conductive coating or carbon loaded paint. One of the advantages of the conductive coating is its ability to be applied easily to irregular surfaces, such as deck soffits and bridge piers. The paint is sprayed, rolled or brush applied over a platinum niobium wire, at a thickness of approximately 300 microns DFT. The wires are typically spaced at 3-6 m intervals. The conductive coating is black, so a decorative paint is required as an overcoat. Conductive paint systems are particularly subject to short circuits from exposed steel such as rebar chairs that exist on the underside of structural elements. Furthermore long term durability in marine environments is suspect, especially in areas subject to surface wetting.

Arc Sprayed Zinc (ICCP). The technique of zinc metallizing as used in cathodic protection of reinforced concrete was first developed by the California Department of Transportation in 1983 (3). The Oregon Department of Transportation now use arc sprayed zinc ICCP to control corrosion on historic arch bridges along the Pacific coastal highway. The process of metallizing involves the melting of a metal or alloy in the form of wire, typically by a high amperage arc, and spraying the molten metal onto the concrete with compressed air. The zinc coating is typically applied to a dry film thickness of 300-400 microns. The system works similar to a conductive coating, except the platinized niobium wire is replaced with a metal pad. Testing arc sprayed zinc systems through electrochemical aging has shown that bond strengths actually increase with time due to secondary mineralization of the zinc reaction products (4). As with conductive coatings, arc sprayed zinc ICCP systems are also subject to short circuits from exposed steel at the concrete surface.

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 or shotcrete (Figure III). 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 these anodes 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.

Figure III. Titanium anode mesh encapsulation with shotcrete, Hong Kong container berth.

Titanium Anode Mesh Integral Pile Jacket System. Another system known as the integral pile jacket 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 bridge 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 (5). Since the 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 IV is an example of a titanium mesh integral pile jacket system on a bridge in Florida.

Figure IV. Integral pile jacket system on bridge piles in Florida.

Titanium Ribbon Mesh Slotted System. This system involves the use of a catalyzed titanium ribbon and a non-shrink cementitious grout as the slot backfill. Ribbon mesh sizes are typically 13-mm and 19-mm wide. Slot spacing is dependent on steel density, but is typically 200-400 mm on center. A typical concrete slot is 10-mm wide by 25-mm deep for the 13-mm wide anode and 32-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. 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 overlay for mesh encapsulation is a concern. Sufficient cover over the rebar must be present, or the steel must be located with a pachometer so the slots can be installed between the bars. Figures V and VI show two slotted system installations using titanium ribbon mesh.

Figure V. Slotted system installation on the top side of a condominium balcony in Florida.

Figure VI. Slotted system installation on the underside of a wharf terminal in Australia.

Discrete Anode System. The discrete anode system is one of the most cost-effective systems for beams, piles and columns. The anodes are relatively easy to install and do not require extensive saw cutting or use of concrete overlays. The discrete anodes are typically inserted into drilled holes that are 20-25 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. Several systems are available. These include a discrete titanium ribbon mesh system, ceramic anodes and platinized titanium wire with a carbon rich backfill. Current densities at the anode-concrete interface should be limited to 220 mA/m^2; otherwise degradation of the cement paste at the anode-concrete interface may result.

Thermally Sprayed Titanium. Thermally sprayed titanium anodes for cathodic protection of reinforced concrete have been applied to several structures in the field on a trial basis. The first installation was in 1994 on the Depoe Bay Bridge in Oregon. The results of the field trials to date indicate that the systems are operating at relatively low output levels and are achieving criteria for cathodic protection of steel in concrete. Arc sprayed titanium is somewhat more difficult to apply than arc sprayed zinc, due to the hardness of the wire and subsequent wear of the spray tips. Titanium, however, is relatively inert in the environment and there are no known environmental impacts using this type of system. In theory, the anode has very long life expectancy (i.e., >100 years) and it is possible that the liquid catalyst may be reapplied to the titanium surface in the future, if needed.

Cast iron and MMO titanium anodes. Impressed current systems using cast iron and mixed metal oxide (MMO) titanium anodes have been used to cathodically protect the immersed section of concrete structures below mean low water and portions of the tidal zone. Both tubular and rod type anodes have been use. The anodes are installed individually in the mud or in specially constructed sleds to distribute current through the water to the concrete reinforcement. Heavy cables are fed from the anodes, through the mud to the rectifier.

Sacrificial (Galvanic) Systems

Arc Sprayed Zinc (Galvanic). Nearly half of the sacrificial zinc systems have been applied in the hot marine environments of southern Florida. FDOT have used the thermally sprayed zinc as a sacrificial anode on marine structures in the splash and atmospheric zones (6). The zinc is applied directly to cleaned steel in areas where damaged concrete was removed and to the adjacent concrete surfaces. It has been shown, however, in field trials and laboratory studies that the performance of pure zinc as a sacrificial anode is greatly influenced by the presence of moisture at the anode-concrete interface (7). In areas above the splash zone where the concrete is relatively dry, the current output of zinc will greatly decrease with time due to the passivating effects of the zinc oxide layer. This condition can result in insufficient current for cathodic protection of the reinforcing steel.

Arc Sprayed Aluminum-Zinc-Indium. Under a 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 - similar to zinc. Test results from field trials and laboratory studies are very encouraging and show a significant increase in current output as compared to pure zinc (8). The improved performance of the Al-Zn-In alloy is attributed to an indium activating agent, which tends to reduce the passivating effect of the anode. The anode is now produced in cored wire form. The outer jacket is aluminum, and the inner core is filled with a zinc/indium powder. Figure VII shows the sacrificial Al-Zn-In alloy applied to a bridge pier along the gulf coast of Texas.

Figure VII. Arc spray application of galvanic Al-Zn-In to a bridge pier in Texas.

Zinc Adhesive Anode. This material consists of a 0.25-mm thick zinc sheet with hydrogel backing (ionically conductive adhesive). No special equipment or engineering skills is required for installation of this anode. A liner is simply removed from the backing and the laminate is pressed onto the concrete surface. The surface of the concrete should be relatively smooth and clean for this application. The edges should be sealed with silicon caulking to prevent moisture ingress. The system has been installed on several bridge substructure projects and condominium balconies along the coast of Florida (Figure VIII) .

Figure VIII. Zinc adhesive anode being applied to a bridge pier in Florida.

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.

Cast Zinc and Aluminum Anodes. Bulk zinc and aluminum anodes have been used successfully to cathodically protect portions of reinforced concrete structures below mean low water and portions of the tidal zone. The anodes consist of cast zinc and aluminum that are submerged adjacent to the concrete pilings.

Applications

To properly select a cathodic protection system for a concrete structure in a marine environment, owners and consulting engineers must understand the difference between the anode types and where and when to use them. It is important to consider installation methods, performance, design require- ments, environmental issues, tidal variations, monitoring, maintenance and aesthetic appearance.

Certain systems perform well in direct exposure environments, while others are more suited for indirect exposure environments. For example, conductive coatings may have problems bonding to concrete in the splash and tidal zones of concrete piles and therefore are not recommended for these applications. Slotted systems may have limitations with respect to concrete cover, but do not have threshold limitations. Titanium mesh systems with concrete overlays require proper surface preparation to ensure bonding of the overlay. Titanium anodes are suitable for higher current density applications and where longer life is required. As previously stated impressed current systems can be adjusted to suit the current requirements for a particular structure, where as galvanic systems cannot be adjusted.

Zinc in sufficient quantities is known to be toxic to aquatic life, therefore thermally sprayed zinc systems may require enclosures to contain zinc dust and rebound. Surface preparation, concrete dryness and applicator experience, are important factors to consider for bonding of thermally sprayed coatings. Also, surface applied systems are easier to apply to vertical and overhead surfaces as compared to encapsulated systems. However surface applied systems typically have shorter life expectancy. All of these issues need to be addressed when selecting a particular system in a marine environment.

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	Impressed Current System	**Sacrificial (Galvanic) System**
Merits	• longer anode life • current can be controlled • 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	• requires monitoring and maintenance • electrical isolation required between anode and steel • conduit & wiring required • detailed monitoring & control for prestressed concrete	• shorter anode life • anode current delivery is dependent on anode chemistry and surrounding environment • current cannot be adjusted or controlled

Table I. Comparison of Cathodic Protection Systems

	Surface Applied	**Encapsulated**	**Immersed**
Impressed Current	• conductive coating • arc sprayed zinc • thermally sprayed titanium	• titanium anode mesh encapsulation • titanium ribbon mesh slotted system • discrete anode system • titanium anode mesh integral pile jacket	• cast iron or MMO titanium anodes
Sacrificial (Galvanic)	• arc sprayed zinc • arc sprayed Al-Zn-In • zinc adhesive anode	• zinc mesh integral pile jacket	• cast zinc or aluminum anodes

Table II. Anode Types by Category