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Selection Guidelines For Using Cathodic Protection Systems On Reinforced And Prestressed Concrete Structures

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SELECTION GUIDELINES FOR USING CATHODIC PROTECTION SYSTEMS ON REINFORCED AND PRESTRESSED CONCRETE STRUCTURES

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ABSTRACT

When cathodic protection is selected as a rehabilitation method for a concrete structure, there are many choices that can influence the type, effectiveness, durability and cost of the system. If the structure is complex in design and exposed to a dynamic environment, proper selection of the system components is important to suitable performance and longevity of the system. In particular, the cathodic protection system should be selected keeping in mind the owner's long term interests and maintenance capabilities. The purpose of this paper is to provide a general guideline to owners and design engineers for proper selection of cathodic protection systems to overcome corrosion problems on reinforced and prestressed concrete structures.

Keywords: impressed current cathodic protection, galvanic cathodic protection, reinforced concrete, cathodic protection system design, cathodic current density, anode current density, maintenance

INTRODUCTION

Cathodic protection (CP) has been used since the early 1800s to protect ship hulls from corrosion. During the early 1920's, the use of CP spread to oil and gas pipelines and underground steel storage tanks. Today, federal regulations in the USA require that all underground steel pipelines and underground storage tanks containing and/or transporting hazardous liquids or gases must be cathodically protected to prevent corrosion. It has been more than 30 years since the first CP system was installed on a reinforced concrete bridge deck in 1973 near Sly Park, California.[1] Today it is estimated that over 2 million m^2 of concrete structures are cathodically protected world wide.

It is well known that CP is a powerful method for controlling corrosion of reinforcing steel in chloride contaminated concrete. The Federal Highway Administration stated that cathodic protection is the only rehabilitation technique that has proven to stop corrosion in salt-contaminated concrete bridge decks regardless of the chloride content of the concrete.[2] However, in the 1980's and early 1990's, several obstacles were encountered, which resulted in substandard performance of many systems. These obstacles were directly related to problems associated with insufficient track record, product durability and ambiguous technical specifications. Now after 30-years of practical experience, design professionals have a better understanding of how cathodic protection works and how it can be used to effectively control corrosion of reinforcing steel in chloride contaminated concrete.

The purpose of this paper is to provide a general guideline to owners and CP design engineers regarding the selection of impressed current and galvanic cathodic protection systems for reinforced and prestressed concrete structures. Using the insight that has been provided by the track record from existing systems, as well as detailed knowledge of structure and environmental conditions, cost-effective and durable CP systems can now be designed and installed. It is not the intent of this paper to make recommendations regarding the various types of CP systems, but to provide engineers and owners with guidelines regarding material properties, system performance and standards before undertaking a CP system design and installation.

FACTORS THAT INFLUENCE DECISION TO USE CP

The intent of cathodic protection is to provide a long-term corrosion control system that is technically acceptable and cost effective to the owner. The owner is probably the most important decision-maker in the CP system selection process. Factors, which may influence an owner's decision to use CP, include:

- Remaining life of concrete structure
- Design life of CP system
- Maintenance and monitoring requirements for the system
- Initial CP installation cost
- Life cycle cost of CP system rehabilitation
- Long term durability of the system (based on existing track record)
- Appearance of structure after completion (aesthetics)

In addition, a design engineer may be influenced by other factors, such as:

- Type of construction (i.e., prestressed, post tensioned or conventionally reinforced concrete)
- Cathodic protection design current density (i.e., mA/m^2 of steel surface)
- Maximum anode current density (i.e., mA/m^2 of anode surface)
- Proper zoning and distribution of protective current
- Installation methods and feasibility of incorporating the system into the repair scheme

- Electrical continuity of embedded steel
- Availability of AC power
- Type of transformer rectifier, including control mode, enclosure and accessories
- Remote monitoring system for rectifier
- Other costs associated with the installation (i.e., traffic control, enclosures, scaffolding, etc.)

COMPLEXITIES THAT INFLUENCE CP SYSTEM PERFORMANCE

It is important for the design engineer to understand the principles of cathodic protection and have a general knowledge of electricity and electrochemical theory. This is especially true for impressed current cathodic protection (ICCP) systems. The knowledge obtained from actual field experience with cathodic protection systems is probably the most important attribute for a design engineer. Field structures offer many complexities for CP system design including:

Exposure to a Dynamic Environment

When the concrete is exposed to a wet and dry environment, the circuit resistance between the anode and the reinforcing steel changes constantly. Even though the zoning may be properly defined for an impressed current system, localised wet conditions may influence the current output from the anode. This will affect concrete resistivity and as a result unbalanced current distribution in the zone may occur. Cracking in the concrete to the surface of the anode may also have the same effect on current distribution. In addition, some types of CP anodes can be readily damaged when excessive current discharge occurs in localised areas of the anode. Therefore, the CP design engineer must consider these conditions.

Variations in Concrete Cover

Although the depth of cover over the rebar may be specified in the construction documents, the actual depth of cover may vary from location to location. When an ICCP system is energized, localized high current discharge may occur in the areas where the anode and reinforcing steel is extremely close. If the distance between the anode and reinforcing steel is less than 5 mm, an electrolytic or near short may develop. This condition may result in the discharge of a highly concentrated current density at the point and in the case of impressed current systems, lead to acidification of the cementitious material around the anode. Furthermore, uneven current distribution to the reinforcing steel may result. These conditions must be considered in the CP system design.

Variations in Chloride Contamination

Since the majority of cathodically protected structures are situated in marine or de-icing salt environments, the level of chloride contamination may vary considerably from one location to another. When the reinforcing steel is exposed to higher chloride concentrations, a higher current density is required for protection. Bennett and Broomfield have suggested various levels of polarization and current density that are required for concrete structures as a function of chloride concentration at the steel surface.[3] These conditions must be considered in the CP system design so that all the reinforcing steel receives sufficient protective current.

Variations in Reinforcing Steel Density

Marine structures such as concrete jetties, piers and intake structures may have complex reinforcing steel densities due to their structural design. This may result in shielding and uneven current distribution to the reinforcing steel. When the CP system is designed for these structures, the design engineer must consider the variations in steel density so that uniform current distribution is provided to all the reinforcing under consideration. To incorporate these conditions into a CP system design, extensive field experience with theoretical background in current distribution modelling is required.

Variations in Concrete Resistivity

Repairs made during previous construction projects may contain concrete that is extremely high in electrical resistivity. High resistivity concrete “shields” current from reaching the reinforcing steel. During the preliminary design phase, previous concrete repairs should be tested for resistance using a plate and sponge and compared to the native “unrepaired” concrete. This is accomplished by measuring the AC resistance between the plate and the rebar over the repaired area and then moving the assembly to an adjacent unrepaired area and repeating the measurement. To ensure proper current distribution, the concrete repair material should not be more than 5 times the electrical resistance of the native concrete.

Electrical Continuity

In order for the reinforcing steel to be adequately protected it must be electrically continuous. Any reinforcing steel that is “floating” in the concrete will not be in the electrical circuit and therefore will not receive protective current. Isolated steel may also receive corrosion interference current from the CP system. This is especially true with impressed current systems. During the repair phase of the project, all exposed reinforcing bars should be checked for electrical continuity and any deficiencies should be corrected. If repairs are minimal, five bars per 100 m^2 should be checked for continuity by drilling and exposing the bar for testing.

IMPRESSED CURRENT VS. GALVANIC ANODE PROTECTION

Cathodic protection for reinforced concrete structures may utilise either impressed or galvanic current. The main difference between the two systems is that ICCP systems require a rectifier to power the anode and the rectifier must be monitored and maintained. Each type of system has advantages and disadvantages. The following are favorable conditions (not requirements) for impressed current and galvanic systems:

Favorable Conditions for Impressed Current Cathodic Protection (ICCP):

- Remaining structure service life is relatively long (> 30 years).
- AC power is available.
- High level of CP current density is required due to high chloride concentration (> 1500 ppm) and/or high rebar density.
- Owner's ability to monitor and maintain rectifiers or willingness to contract the maintenance responsibility to an outside source.
- Concrete structure is exposed to cyclical wet and dry conditions.
- Concrete structure is not subject to occasional wetting.

Favorable Conditions for Galvanic Cathodic Protection:

- Lower current density is required due to low chloride content (< 1,500 ppm) and/or low rebar density.
- AC power is not economically available.
- Structure is subject to moisture or occasional wetting.
- Protection of only one mat of reinforcing steel is required.
- The owner does not have the capability or desire to maintain the rectifier.
- Structure does not have adequate depth of concrete cover (< 10 mm) or steel is exposed in many areas on the concrete surface

ANODE SELECTION

The anode is one of the most critical components of the CP system. It is usually the most expensive component and several options may exist. In theory, given that all other parameters are defined, the anode is the primary electrode that is used to discharge current into the electrolyte and achieve cathodic protection of the reinforcing steel. In reality, however, different anode systems are more suitable for certain applications.

Installation methods may also play a major roll in anode selection. Where a large amount of concrete repair is required, an anode directly attached to the exposed reinforcing steel and installed in the repair or overlay area may be preferable. Where access to the lower surface of a structural component is limited, such as the soffit of a beam or pile cap in a marine jetty, a discrete anode system installed in drilled holes may be more appropriate.

The selection of the anode system must also be considered when a particular maintenance requirement exists. For example, in industrial plants where frequent shutdowns occur, access to the work area is critical and therefore the anode system must be robust enough to withstand periodic maintenance activities that may occur. The selection of the anode type is also dependent on the remaining life of the structure. Requirements for excessive life of the CP system components may sometimes be required for no reason other than a longer life is perceived to be more desirable. Design life should therefore reflect the remaining service life of the structure.

ICCP Systems

Inert Anodes. When the remaining life of a structure is considered long (i.e., > 30 years), an impressed current system using an inert anode is generally recommended, since these anodes do not require replacement during the remaining life of the structure. To determine an embedded anode's expected life expectancy NACE Test Standard TM0294-94 “Testing of Embeddable Anodes for Use in Cathodic Protection of Atmospherically Exposed Steel Reinforced Concrete” is used. Activated titanium anode mesh (Figure 1), titanium ribbon mesh (Figures 2 & 3) and discrete titanium or conductive ceramic anodes are available (Figure 4). Life expectancy may vary between 25 and 100 years depending on the type of anode and catalytic coating that is used. Each anode type has specific advantages and disadvantages, which include:

Titanium Anode Mesh Advantages:

- Uniform current distribution
- Excellent redundancy
- Longest track record

Titanium Anode Mesh Disadvantages:

- Requires a cementitious overlay or thin set if tile is used.
- Concrete overlays may provide added dead load problems.
- Anode must cover all concrete surfaces that require protection

Titanium Ribbon Mesh Advantages:

- No requirement for concrete overlay.
- Long track record.
- Can be installed in slots or attached directly to exposed reinforcing steel using plastic clips.
- Suitable for new concrete structures.
- Typically less expensive than titanium anode mesh.

Titanium Ribbon Mesh Disadvantages:

- Current distribution is less uniform compared to mesh systems.
- Requires sufficient concrete cover (> 5 mm) over the reinforcing steel.
- If the cementitious grout in the slots is not sealed from the outside environment, saltwater penetration into the slots may cause local high current discharge and acidification of the surrounding grout.
- Depending on the reinforcing steel density and anticipated current distribution, ribbon mesh anodes may have to be installed on all concrete surfaces that require protection.

Discrete Anode Advantages:

- No requirement for concrete overlay.
- Anodes can typically be installed from one side of the structure.
- Anode installation does not require extensive saw cutting.
- Good current distribution when anodes are positioned sufficiently remote from the rebar.
- Since discrete anodes are installed deep in the concrete where chloride concentrations are low, the anodes may be operated at higher current densities.

Discrete Anode Disadvantages:

- Detection of shallow steel in drilled holes may be difficult.
- If the anodes are spaced at too great a distance, areas of surrounding steel may be under protected.
- Discrete anodes that are operated at high current densities may require plastic tubing for gas ventilation.

Carbon Based Anodes. Carbon based anodes include conductive polymers, a carbon based paste that is used as a backfill around discrete anodes, surface applied conductive coatings and carbon fibers that are dispersed in a cementitious overlay. Although the initial cost of carbon-based anodes may be less than titanium or ceramic anodes, durability and performance problems may develop over time. These may include:

- When a carbon-based anode (not an inert material) discharges CP current, the anodic reaction involves oxidation of the carbon. As a result, the conductivity of the anode material may decrease with time, resulting in failure of the anode.

- Carbon-based anodes are generally more subject to chlorine gas evolution at lower levels of current than titanium or ceramic based anodes. Acid may develop may develop in sufficient quantity to dissolve the cementitious paste around the carbon-based anode, resulting in disbondment of the anode.

- Surface applied impressed current anodes, such as carbon-based conductive coatings, are particularly subject to electrical short circuits at the concrete surface. The short circuits are due to exposed or partially embedded rebar chairs and wire ties that come in contact with the anode.

- Carbon-based conductive coatings may disbond from the concrete surface if exposed to excessive moisture (i.e., splashing water or leaking expansion joints) due to high anodic current discharge in the effected area. Also, in dry concrete conditions the anode may “dry-out” with time resulting in increased circuit resistance and high driving voltage at the rectifier. According to the European Standard CEN 12696, conductive coatings vary in performance but have a range of anticipated lifetime of 5 to 15 years.

Consumable ICCP Anodes. Thermally sprayed zinc is sometimes used as a consumable (non-inert) impressed current anode for cathodic protection of reinforcing steel in concrete. Sprayed zinc anodes have been used extensively by the Oregon Department of Transportation for cathodic protection of coastal bridges.[4] When a consumable anode material such as sprayed zinc is used, the zinc will be consumed while discharging CP current. If the zinc is exposed to wet conditions, the consumption of the zinc is accelerated not only by consumption at the zinc-concrete interface, but also by atmospheric corrosion at the exposed outer surface. To reduce this effect, a protective topcoat for the zinc anode is usually required. Spayed zinc, when used as an impressed current anode, is also subject to problems with electrical short circuits, similar to the carbon-based conductive coating system, as described above. In general, the life expectancy for this type of anode is less than 20 years.

Galvanic Anode Systems

When a galvanic anode system is selected, the life is generally expected to be shorter than an ICCP system because the anode must consume to produce the protective current. Therefore, if a concrete structure has a relatively long life remaining, the galvanic anode may need replacement during the remaining life of the structure. In general, the life expectancy of a sacrificial anode may be 5-20 years (or longer), and is dependent on the type of material used and the environment that it is exposed to.

The primary benefit of a galvanic anode is its simplicity and the fact that minimal or no maintenance is required. Since galvanic anodes normally operate below the threshold for hydrogen embrittlement, they are considered safe for cathodic protection of prestressed and post tensioned concrete. The amount of current that is generated by a galvanic anode is greatly influenced by environmental factors, such as moisture and temperature. Galvanic anodes, such as thermally sprayed Zinc and Aluminum-Zinc-Indium, have recognized advantages over impressed current systems, such as ease of application to vertical and overhead surfaces and minimal or no maintenance. Galvanic anodes are considered to be self-regulating, and anode current and protection levels will vary with time.

Thermally Sprayed Zinc. Sprayed zinc anodes have been used extensively by the Florida Department of Transportation for galvanic protection of reinforced concrete bridges in marine environments.[5] However when zinc is used as a sacrificial anode, the zinc may passivate before it is consumed completely especially when it is exposed to drier concrete conditions. When passivation occurs, a thin protective film is formed on the anode surface, which prevents it from discharging sufficient CP current. Figure 5 shows the effect of pH on the corrosion rate of zinc.[6] The time to passivation is dependent on the environment and the pH of the concrete. To enhance the zinc anode performance in drier concrete conditions, a liquid humectant may be applied over the anode. The intent of the huemectant is to hold moisture at the anode interface, so that the reduction of current caused by the passivation effect is minimized. However reapplication of the humectant may be required within in a short period of time (i.e., 3 years).[7]

Thermally Sprayed Aluminium-Zinc-Indium. This alloy was developed during the laboratory-testing portion of a Federal Highway Administration research contract and consists of 80 percent Aluminum, 20 percent Zinc, and 0.2 percent Indium (Al-20Zn-0.2In).[8,9] Several installations have been completed in marine and northern de-icing salt environments (Figure 6). The anode has demonstrated in both field and laboratory testing to provide a degree of cathodic protection that is superior to thermally sprayed zinc.[4] Based on predicted consumption rates and test data, this anode can be expected to provide a reasonable life expectancy of 10-15 years in a sub-tropical marine environments and possibly 15-20 years in northern de-icing salt environments.

Mortar Enhanced Zinc Anodes. Small zinc anodes in chemically enhanced mortar have been used extensively to control the macro cell corrosion, which is formed around the perimeter of concrete patch repairs (Figure 7). These anodes are wire tied to the exposed steel rebar around the perimeter of the repair at intervals specified by the manufacturer. However, testing has shown that the current produced by these anodes is usually insufficient to meet criteria for cathodic protection for the steel in the chloride-contaminated concrete. Ip and Pianca have reported that the effective current delivery of these anodes is small and the reinforcing steel away from the anode will likely receive only a small amount of current from the anode.[10] Small cylindrical zinc anodes encased in an enhanced cementitious mortar have also been installed in drilled holes for corrosion control in chloride contaminated concrete. The spacing between these anodes should be based on the reinforcing steel density, concrete resistivity and chloride concentration of the concrete at the rebar. Since the current throwing power of the zinc anode is relatively low, proper spacing is critical to ensure adequate protection and even current distribution.

Zinc Adhesive Anode. The zinc adhesive anode consists of a zinc sheet that is laminated to an ionically conductive hydrogel, which acts as an adhesive. These anodes have the benefit of simplicity and easy installation. Initial current density is reported to be high, however long term durability issues are a concern especially in wet conditions where adhesion of the hydrogel can be effected. To overcome this problem sealing of the joint areas and perimeter of the sheeting is recommended to prevent moisture ingress.

CATHODE PROTECTION CURRENT DENSITY

Cathode current density can be defined by applicable standards or left to the design engineer based on their practical experience. When performance criteria are defined, the permanent nature of many anode installations means that it is often prudent to specify a minimum cathode current density. Many standards and specifications exist for this purpose, as shown in Table 1. If no minimum cathode current density is defined, the design could result in failure of the system to meet performance criteria.

It is important to note that structure type and environment will determine the effective cathode current density. Proposals for reduced current density should therefore reference very similar structures in very similar environments. For example, a current density used on a bridge in North America may not be relevant to an intake structure in the Middle East, where higher ambient temperatures and chloride concentrations exist. Where performance criteria are to be used, then it should be clarified that any cathode current density specified is the minimum requirement and does not exempt the designer from producing an operational design that meets the performance criteria.

ANODE CURRENT DENSITY

Anode current density is one of the major factors in determining the cost of the CP system for concrete structures. It is also the property most misunderstood, specifically in its importance to concrete chemistry and durability. In order to understand this importance a brief description of the significance as it relates to concrete is given below.

Regardless of what anodes are commercially available, anode current density is defined only for inert materials such as catalyzed titanium and conductive ceramic anodes. NACE Standard TM0294-94 “Testing Of Embeddable Anodes For Use In Cathodic Protection Of Atmospherically Exposed Steel Reinforced Concrete” provides detailed procedures for accelerated life testing of these anodes. Based on this standard, anodes shall survive a minimum total charge density of 38,500 A-hr/m^2 of actual anode surface at 107.6 mA/m^2 (10 mA/ft^2) of the anode current density for 40 years of operating life. For example, if a CP design engineer specifies 215 mA/m^2 (20 mA/ft^2) for the anode current density, then the total charge density for the test would be twice the above or 77,000 A-hr/m^2 to last 40 years.

It should be noted that the ability of the anode to operate at high current densities is not related to the performance of the anode in concrete where potential damage to the concrete is usually the governing factor rather than consumption of the anode itself. It is not uncommon for mixed metal oxide coated titanium anodes to be rated at 600A/m^2 for 20 years in seawater, whereas the anode current density in concrete is much lower than this (as high as 0.215 A/m^2 or 215 mA/m^2).

When any anode is operated at a high current density with chloride ions in the concrete electrolyte, the anodic reactions involve chlorine gas evolution. The chlorine gas reacts with the concrete pore water solution and forms hydrochloric acid at the anode-concrete interface. The amount of acid generated is related to the current density at the anode surface. At low concentrations, these acids are absorbed or buffered by the concrete with no detrimental effects. However, above certain concentrations, acid build up can lead to damage at the anode/concrete interface. Eventually the interface becomes sufficiently deteriorated such that contact between the anode and concrete is reduced leading to increased localised resistance. This in turn can result in increased current flow to other parts of the anode circuit, thus raising the current density in these areas. This ‘knock on’ effect can result in whole parts of the anode circuit becoming inoperative and, in extreme cases, can cause significant damage to the concrete.

Due to the possible detrimental effects of acid generation, much research has been conducted on the safe operating current densities for anodes in concrete. The ability of concrete to withstand the acids produced at the anode was monitored in terms of anode current density in field trials. Based on practical experience, it is not recommended that any anode be operated at a current density greater than or equal to 107.6 mA/m^2 (10 mA/ft^2) in highly chloride-contaminated concrete for inert anode materials. When the anodes are embedded in chloride free or very low chloride contaminated concrete, the system could be operated as high as 215 mA/m^2 (20 mA/ft^2). It has to be noted that since an impressed current anode is positively charged during the system operation, it attracts negatively charged chloride ions. Therefore, the chloride concentration at the anode-concrete interface may increase with time, depending on the location of the anode.

For a given cathode current density, the anode current density is a function of the amount of steel being protected per unit area of anode. It is therefore important to accurately calculate the steel surface area to be protected in order to validate other properties that are specified.

ANODE ZONING

A cathodic protection zone is defined as an area which can be independently controlled. A sub zone is separate within the concrete but can be combined with other sub zones externally to form the zone. Zones can be specified in terms of size and/or environment. It is important that areas in different environments can be controlled separately. This could be due to differing current demands or variations in resistivity.

If an area below water, were connected with an area that is dry, then current would flow to the wet, low resistance area in preference to the higher resistivity region. It is therefore important to specify that allowances for environmental changes across a structure are included in the zone layout. The degree to which this is defined also depends on the structure type.

Zone size is another parameter that may be included in the specification. This can be defined in terms of surface area or current requirement and the definition can also extend to include such features as construction joints and/or geometric characteristics.

Zones are often used as the basis for defining other items such as the degree of permanent monitoring, so it should therefore be carefully considered. Effort in monitoring and maintaining a system is related to the number of zones. Very large zones may be undesirable from a control point of view, but too many small zones would require a greater effort in monitoring and adjusting the system and the potential requirement of an unacceptable high voltage rectifier output.

SUMMARY

In summary, anode selection is a subject in itself and where installation, operational or maintenance constraints exist, then the various anode systems available should be carefully considered prior to design. However, if the anode configuration or installation method is not important and other parameters, such as anode life, protection current densities, zoning, current distribution and maintenance have to be considered.

There are many decisions and considerations to be made when a CP system is designed for concrete structures. It is important for design engineers to understand both CP and electrical/electrochemical theories; however, field experience obtained from previous CP projects is significantly more important in the design and installation of a durable and cost-effective system. The complexities addressed by this paper demonstrate the necessity for the use of properly qualified and experienced engineers when approaching this subject.

As the use of cathodic protection for concrete structures becomes more popular, it is important to remember the fundamentals. Obviously, new technologies should be embraced where effective but also the dangers of ignoring fundamentals should be understood. Cathodic protection has proven to be a very effective and powerful means of controlling reinforcement corrosion.

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Table I

Cathodic Protection Current Densities for Existing and New
Reinforced Concrete Structures from various International CP Standards

Standard	Rehabilitation	New Construction
European Standard pr EN 12696-1	2 mA to 20 mA/m^2	0.2 mA to 2 mA/ m^2
Standards Australia AS 2832-5-2002	2 mA to 20 mA/m^2	0.2 mA to 2 mA/ m^2
British Standard BS 7361 – Part 1	5 mA to 20 mA/m^2	N/A
NACE Standard RP0290-2000	N/A	N/A
Japanese JIS	N/A	N/A
Aramco Standard SAES-X-800	20 mA/m^2	N/A
Royal Commission Section 16645	N/A	2 mA / m^2
SABIC Standard B01-E04	20 mA/m^2	5 mA/m^2

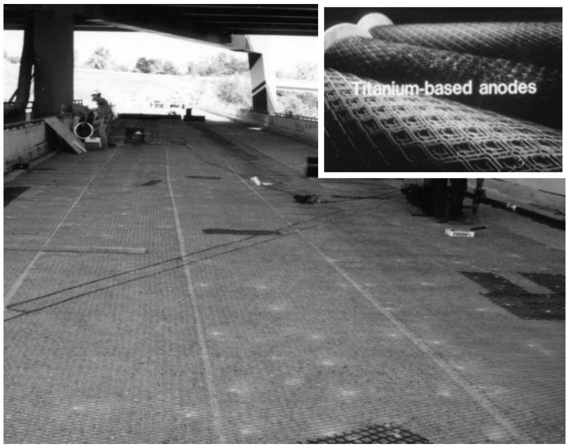

Figure 1. Titanium mesh anode installed on a bridge deck.

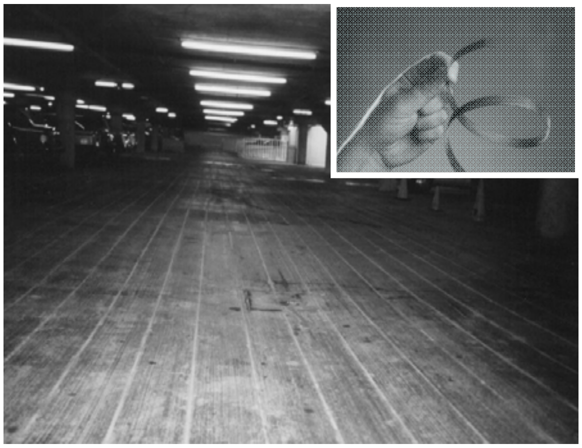

Figure 2. Titanium ribbon mesh installed in concrete saw slots.

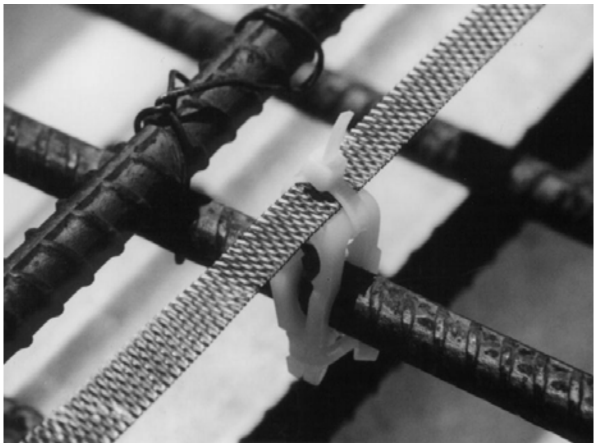

Figure 3. Titanium ribbon mesh anode attached to a rebar using plastic clips.

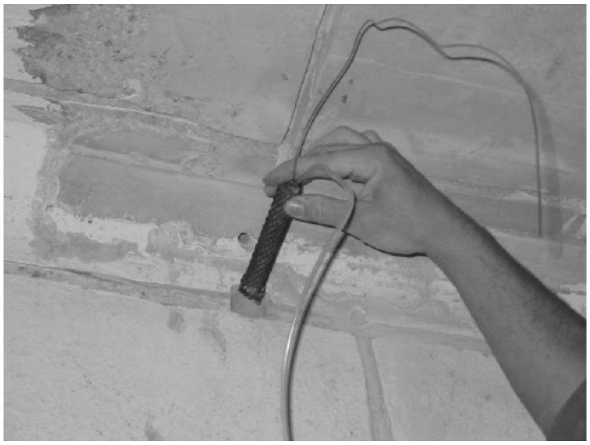

Figure 4. Discrete ceramic anode installation in a drilled hole in a beam.

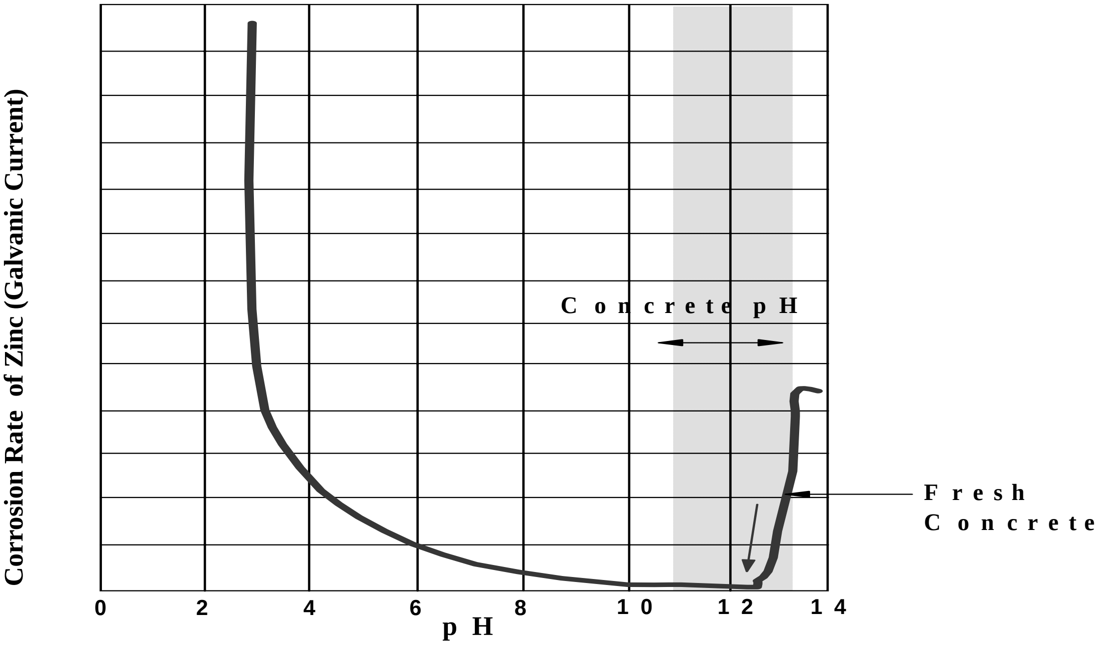

Figure 5. Effect of pH value on the corrosion of Zinc

Figure 8. Thermally sprayed Al-Zn-In anode for galvanic cathodic protection of a concrete bridge.

Figure 9. Installation of mortar enhanced zinc anodes in a concrete repair

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