was provided with two coats of phenolic resin-based coating. Though phenolic resin-based coating has excellent resistance against water and many chemicals, the polymer is susceptible to decay when exposed to ultra-violet ray. As a solution, dry coarse sand was sprayed on the second coat of same phenolic resin based coating on the exterior faces of girders. All the types of treatment, when tested under a water head of 20 m, were found to have zero permeability. Many concrete bridges of East Coast Railways and other organizations were provided with acrylic coatings.

15.0 Conclusion

Concrete bridges, roadways and other structures of recent times, compared to such structures of earlier periods, have suffered early damages due to the use of inappropriate materials (both cement and reinforcing bars) and due to a lack of adequate curing.

Many of the problems, associated with the use of high strength rebars with surface deformations, OPC with high specific surface, high C_3S/C_2S ratios, blended cement, cement with excessive contents of water soluble alkalis and inadequate curing, can be alleviated if all exposed surfaces of concrete will be protected with waterproofing treatments.

The Indian code for concrete structures has mandated the provision of surface protection systems for the prevention of the ingress of water as one of the ways to make concrete structures durable. Several bridge authorities have adopted specifications for the surface protection of concrete bridges as a part of their schedules of rates. Many concrete bridges all over the country have been protected with the provision of surface coatings and other treatments in recognition of the fact that if left unprotected, as in the past, today's concrete structures, unlike concrete structures of earlier decades, will fail to be durable.

Multiple protection strategies may be cost effective for long-term corrosion protection. One such strategy is the use of epoxy-coated rebar in combination with a durable concrete containing corrosion inhibitors, having a low permeability, and adequate concrete cover. Silica fume and fly ash can be added to the concrete to reduce permeability and provide additional corrosion control. However, there is a need to balance the costs of the additional control measures against how much additional service life can be expected as a result of the added control measures. The additional costs can usually be justified based on a life-cycle costs analysis. Some factors to be considered when choosing a corrosion-control measure include:

- Reliability and effectiveness of the measure.
- Risk of unintended side effects.
- Possibility of future installation of other control measures.

Cathodic Protection of Reinforced Concrete Structures

[Extracted from "Understanding Corrosion and Cathodic Protection of Reinforced Concrete Structures", by Steven F. Daily, Corrpro Companies, Inc. USA]

1.0 Fundamentals

There are many ways to slow down the corrosion process, however cathodic protection (CP) is the only technology that has proven to stop corrosion in existing reinforced concrete structures, regardless of the chloride content in the concrete. What is CP? Quite simply CP is a widely used and effective method of corrosion control. In theory it is defined as the reduction or elimination of corrosion by making the metal a cathode via an impressed direct current (DC), or by connecting it to a sacrificial or galvanic anode. Cathodic areas in an electrochemical cell do not corrode. By definition, if all the anode sites were forced to function as current-receiving cathodes, then the entire metallic structure would be a cathode and corrosion would be eliminated.

For decades, CP has been successfully used to protect underground pipelines, ship hulls, offshore oil platforms, underground storage tanks, and many other structures exposed to corrosive environments. The first application of CP to a concrete structure was a bridge deck in 1973. This system continues to function with no physical delamination of the concrete. CP of steel in concrete is quite simply a means of fighting fire with fire, or in this case, electricity with electricity. The corrosion process generates electric currents. CP supplies a source of external current to counteract the corrosion current. Hence, corrosion can be eliminated.

As indicated above, there are two types of CP systems – impressed current and galvanic. An impressed current CP system for concrete structures may require the following basic components:

- DC power supply (rectifier).
- Inert anode material, such as catalyzed titanium anode mesh.
- Wiring and conduit.
- Instrumentation, such as embedded silver/silver-chloride reference electrodes.

A schematic of an impressed current CP system using catalyzed titanium anode mesh is shown in Fig. 1.

A rectifier is used to convert alternating current (AC) to direct current. A rectifier works on the same principle as an AC adapter for a computer or a battery charger. In an impressed current CP system, the rectifier provides the power (i.e. low voltage direct current) and controls the amount of power to each zone. Rectifiers are available in many types and operating outputs. Mainly, they are designed to provide either constant current or constant voltage to the anode system.

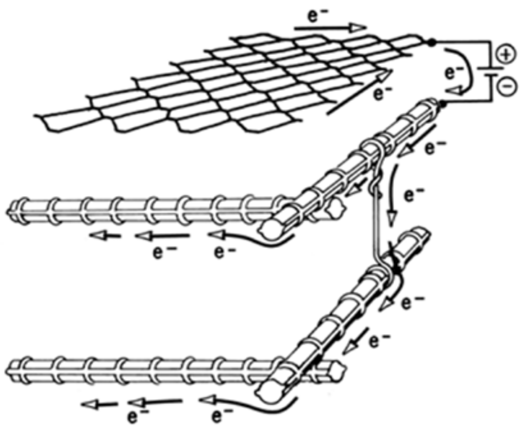

Fig.1: Schematic diagram of impressed current CP system

The anode is one of the most critical components for a cathodic protection system. It is used to distribute protective current to the reinforcing steel and provides locations for anodic reactions to take place in lieu of the reinforcing steel. By using relatively inert materials, such as catalyzed titanium, anode consumption is minimized. One of the main benefits of catalyzed titanium is that its life expectancy can be determined through accelerated life testing. N.A.C.E. Standard TM0294-94, "Testing of Embeddable Anodes for Use in Cathodic Protection of Atmospherically Exposed Steel-Reinforced Concrete" gives procedures for accelerated life testing of these anodes. Based on test results using this method, it has been found that the life of catalyzed titanium anodes can readily exceed 40 years for existing structures, and over 100 years for new reinforced concrete structures (i.e. cathodic prevention). Fig. 2 shows the application of titanium anode mesh to a bridge deck. The mesh is subsequently covered with a concrete overlay.

Fig. 2: Anode Mesh installation on a bridge deck

A sacrificial or galvanic anode system for reinforced concrete uses a more reactive metal (anode) such as zinc or aluminum-zinc-indium (Al-Zn-In), to create a current flow (Fig.3). Sacrificial anode systems are based on the principle of dissimilar metal corrosion and the relative position of different metals in the galvanic series.

Fig. 3: Arc-spray application of sacrificial Aluminum-Zinc-Indium

The direct current is generated by the potential difference between the anode and reinforcing steel when connected. The sacrificial anode will corrode during the process and is consumed. Current will flow from the anode, through the concrete, to the corroding reinforcing steel. Galvanic anodes may be installed as cast anodes (Fig. 4) or thermally sprayed onto atmospherically exposed concrete to form a sacrificial coating. Fig. 4 shows the arc-spray application of an Al-Zn-In coating to a reinforced concrete bridge pier.

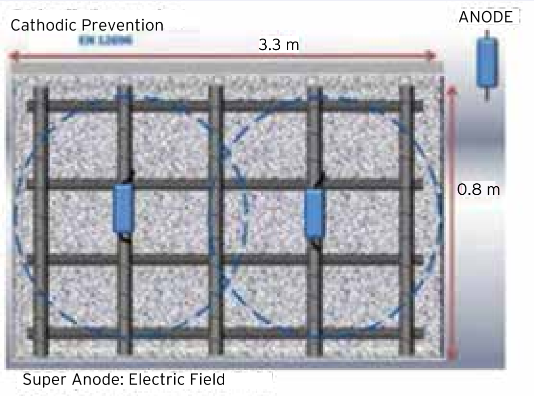

Fig. 4: Schematic diagram showing installation of Sacrificial Galvanic anode

Galvanic CP systems have the benefit of no auxiliary power supply and the advantage of being used for pre-stressed or post tensioned concrete without the risk of elevated potential levels, which can lead to hydrogen embrittlement of the steel. The anode life, however, may be relatively short as compared to the inert anodes, which are used with impressed current systems. Also, the current that is produced by a galvanic anode is a function of its environment, i.e. moisture and temperature conditions, and the output cannot be easily adjusted or controlled as with the impressed current method.

Reference electrodes are used to evaluate cathodic protection levels. They may be portable devices or permanently embedded probes in the concrete structure. The most commonly used embedded reference electrodes are silver/silver chloride (Ag/AgCl). Reference electrodes should have a separate ground connection to the reinforcing steel. CP systems also require a negative connection to the reinforcing steel (return path for electric current).

With CP, chloride ions will slowly migrate away from the reinforcing steel and toward the anode. Furthermore, the production of hydroxide ions at the steel surface will cause the concrete to revert back to an alkaline state. These factors when taken together will quickly arrest the corrosion process when current is applied, and allow the passivating film to reform on the surface of the reinforcing steel. It is important to realize that with cathodic protection corroded reinforcing steel cannot be restored to its original native state, but corrosion of steel in concrete can be effectively stopped through the application of cathodic protection.

When evaluating a structure as a candidate for cathodic protection, several parameters should be considered. These may include:

- Remaining service life should be > 10 years.
- Delaminations and spalls should be < 50% of structure area.
- Chloride content should be > 0.026% by weight of concrete.
- Half-cell potentials should be > - 200 mV, indicating a breakdown of the passivating film.
- The candidate structure should be structurally sound.
- The majority of reinforcing steel bars should be electrically continuous.
- AC power should be available.

The process of cathodic protection for reinforced concrete structures surprisingly takes little power. Data has shown that typical CP operating current densities range between 0.2 and 2.0 mA/m^2 for cathodic prevention of new reinforced concrete structures, as compared with 2 to 20 mA/m^2 for CP of existing salt contaminated structures. This will result in power consumption ranging from 1-3 watts per 1,000 m^2 of concrete for new construction, and 3-15 watts per 1,000 m^2 for existing structures.

Once the CP system has been installed it is necessary to provide routine monitoring and maintenance. For impressed current systems, this involves visual inspection of the system and periodic checks at the power supply to ensure proper operation. As a minimum, the periodic checks should entail measurement of the voltage and current for each anode zone. Ensuring the supply of direct current from the rectifier to the structure in accordance with the operation and maintenance manual is the most important operating parameter. Remote monitoring systems may also be incorporated to help facilitate monitoring of the rectifier. As indicated above, galvanic anode systems have no power supply and therefore they require minimal monitoring and maintenance.

2.0 Development of Anode Systems

The high resistivity of concrete as an electrolyte has been an obstacle to the use of cathodic protection of reinforcement until recent years. Developments in anode technology since the 1980's have seen the emergence of a wide variety of anode systems for various applications:

2.1 High Silicon Cast Iron Anodes within a Conductive Asphalt Layer

These were one of the first developments for flat slabs, particularly bridge decks. The additional weight of the asphalt and its short lifespan were disadvantages which led to the development of alternative systems such as slotted anodes, where the conductive string anode was placed in a sawcut in the surface of the concrete. Various anode types were tried, platinum-clad niobium wire proving quite successful, but the high current density required gave rise to excessive generation of acidity at the anode. Conductive coatings, using carbon-laden acrylic paint as the conductive anode, have also proved popular in situations where additional weight must be minimized, but there lifespan is limited. Flame sprayed zinc is a new development of this approach.

2.2 Conductive Polymer Wire

This wire was popular in the early 80s but was superseded by the introduction of expanded titanium mesh anodes. These systems comprise an activated titanium mesh coated with mixed metal oxides, encased in a conductive cementitious overlay, often of gunite. The mesh configuration minimizes and spreads the current distribution over each protection zone of the concrete surface and thus reduces the risk of acid generation at the anode. This method remains widely used because of its effectiveness with very small current densities and the longevity of titanium. It is particularly suited to large concrete surfaces such as slabs and beams.

2.3 Installation of Titanium mesh

A more recent development in cathodic protection of concrete structures is the internal anode system, where probe anodes of activated titanium mesh are placed in drilled holes in the concrete surface and embedded in cementitious grout. This method has the advantages of negligible added weight, relative cheapness and the ability to protect distant rebars. It is particularly suited to massive elements such as beams and columns but not to thin slabs.

3.0 Case Studies of Cathodic Protection Systems

Both the titanium mesh and internal anode systems are becoming widely used on concrete structures around the world. Some early examples of remedial projects are:

3.1 A floor slab in a Sydney apartment building

It was found to have suffered extensive corrosion of top mat reinforcement arising from the use of a chloride-rich magnesite topping. Conventional patch repairs would have required the removal of all the top 100 mm of concrete and would have promoted corrosion of the bottom mat steel; cathodic protection was therefore considered the only practical method of rehabilitation. A titanium mesh system was installed within a 25 mm concrete topping and the protection levels have been found to be satisfactory since it's energising in 1989.

3.2 An eight-storey apartment building in Auckland, New Zealand

It had been seriously damaged by wind-blown chloride contamination and carbonation in its structural concrete frame, since construction 56 years ago. Conventional patch repairs had been attempted during a major renovation in 1982 and had subsequently failed. A titanium mesh anode system in four zones was placed on all external beams and columns in 1990, and successful polarization of external face steel was achieved within three months. Over two years of operation, protection has developed gradually in the internal-face reinforcing steel as far as 800 mm from the anode mesh.

3.3 A bridge abutment at Frankston, Victoria

It was found to be severely contaminated by water-borne chlorides. Corrosion levels were highest in the tidal zone at the base of the abutment and lowest in the atmospheric zone. A titanium mesh anode divided into three horizontal zones was installed and encased in a layer of gunite in 1991. Protection levels were achieved in each zone with markedly different current densities.

3.4 A housing estate in Copenhagen, Denmark

It comprises 1943 apartments in 17 blocks and was found to have extensive corrosion of reinforcement in most of the beams and columns in the access balconies. Each beam/column set required 13 internal anodes and approximately 40,000 in total were installed between 1990 and 1992. All elements were connected to a central personal computer which monitors and controls the system and each anode.

3.5 A wharf at King Island, Tasmani

It was contaminated with chlorides to the extent that much of the cast in-situ beams and precast deck soffit was cracked or delaminated. A titanium mesh system encased in gunite was chosen for 1300 m^2 of concrete requiring treatment; the installation was completed and energised in mid 1992.

3.6 A road and rail bridge at Weipa, Queensland

It was found to have significant chloride contamination in its precast concrete piles and in-situ concrete headstocks across 1.1 km of trial estuary. Trials of different Cathodic Protection systems were undertaken on four piers. On the tidal and splash zones of the piles, mesh anodes were installed in modular foam-lined FRP shells, cement-grouted FRP shells and fabric-formed concrete jackets. Underwater, titanium rod anodes were installed at each pier. In the atmospheric zone of the piles and headstocks, internal anodes were used. The final design chosen was for internal anodes on headstocks and upper piles, combined with immersed rod anodes for the underwater sections of pile. Installation was completed in 1995.

3.7 Draft CT of HPCL Mumbai Refinery

The mesh ribbon was used as anode in new force draft CT of HPCL Mumbai Refinery with cathodic protection system for corrosion protection in year 2013 (Fig. 5).

Fig. 5: Ribon anodes being used for Cathodic protection

4.0 Conclusion

It is normal for a Cathodic Protection system to be tuned over the first two years or so of operation as potentials stabilize and current demands reduce. Monitoring of protection levels and trends is therefore required at intervals of three or six months in the initial stages and annually thereafter, until the system has balanced and needs only regular checking of its operational status.

Cathodic Protection has become accepted and widely used as a means of halting corrosion of steel in deteriorating reinforced and prestressed concrete structures. The advantages of Cathodic Protection over other rehabilitation methods can be summarized as follows:

- Cathodic Protection has the ability to stop the corrosion process for the extended life of the structure.
- Cathodic Protection is a long-term solution (in excess of 25 years), with minimal maintenance requirements.
- Cathodic Protection exhibits long-term economical advantages when discounted over the design life of the system. In many cases, the first cost may be less than a conventional patch repair, with a life four to five times longer.