Cathodic Protection of Reinforced Concrete Structures – A Practical Method of Arresting Rebar Corrosion

Alan R Bird Bsc CPEng MIEAust RPEQ

INTRODUCTION

The major factors leading to the deterioration of reinforced concrete are poor construction practice and the environment. These factors are interrelated, for example: inadequate depth of cover to rebars, or excessively porous concrete, may allow penetration of atmospheric contaminants such as carbon dioxide or chlorides to reach the steel. In the presence of oxygen and moisture, this will cause it to corrode. Sooner or later, cracking and spalling of the concrete cover will occur as the expanding rust products build up bursting stresses around the rebars.

It is therefore of great importance in aggressive environments to provide a sufficient cover of high quality concrete to all embedded steel. This is particularly so in coastal and marine structures, where chloride contamination from wind-borne salt spray can be severe.

It remains doubtful, however, whether concrete conforming to AS 3600 and placed by the best practices will, in such severe environments, avoid significant deterioration during the lifespan typically required of such structures.

There are three primary methods commonly used to treat concrete which is suffering, or threatened by, corrosion damage to embedded steel:

- Patch repairs or partial rebuild
- Protective coatings
- Cathodic protection

There are other methods, such as chloride extraction, which are not yet proven commercially in Australia.

In the case of a chloride-contaminated structure, patch repairs are likely to provide only a limited cure to the problem because new corrosion sites are often formed adjacent to the repair. Coatings will restrict the ingress of chlorides or moisture into the concrete and thus reduce the development and rate of corrosion in mildly contaminated structures, but they are unable to arrest active rusting as a result of severe contamination. It is also necessary to replace the coatings at regular intervals to give continuing protection.

Cathodic protection is designed to halt all the active corrosion and prevent new sites from developing. Although it has been used for immersed and buried structures for well over 100 years, Cathodic Protection of reinforced concrete by means of an impressed current has been widely used only since the early 1980s. The relatively high electrical resistivity of concrete, compared with soil or water, and the difficulty in obtaining a uniform current spread to all the embedded steel components, have required the development of special materials and procedures.

Cathodic Protection is an economical alternative to patch repairs in chloride-damaged structures, not only because it provides a long-term solution but also because it obviates the need for massive removal and replacement of contaminated concrete. It is also cost-effective in severely carbonated structures. It is now used extensively as a means of corrosion control in concrete and has been applied to a wide variety of structures in coastal regions in Australia.

Cathodic Protection is an economical alternative to patch repairs in chloride-damaged structures, not only because it provides a long-term solution but also because it obviates the need for massive removal and replacement of contaminated concrete.

THE PROCESS OF CORROSION OF STEEL REINFORCEMENT IN CONCRETE

Reinforcing steel in concrete initially protected from corrosion by the high alkalinity provided by the cement, which stabilises the passive oxide layer on the surface of the steel. The passive layer can be destroyed by a reduction in alkalinity to below about pH 10, such as may be caused by carbonation from the atmosphere or by the presence of aggressive chloride ions. These ions may be present as a result of chloride contamination of the concrete materials at the time of placing, or by ingress from external sources such as a marine environment or de-icing salts. The mechanism by which chloride ions disrupt the passive layer is unclear but empirical testing has allowed a threshold contamination level to be defined with a high degree of confidence. It may be represented approximately as 0.4% of total (acid soluble) chlorides by weight of cement in a standard OPC concrete sample.

Once the passive layer on the steel has been disrupted, an electrochemical cell can be formed in the presence of oxygen and moisture. The concrete provides the electrolyte in the cell, with the steel rebar completing the circuit and transmitting electrons from anode to cathode.

The moisture content of the concrete has a significant impact on the efficiency of the cell, since it affects both the electrical resistance to the circuit and the chemical reactions.

While oxygen is consumed at the cathode to release hydroxyl ions and thus to increase the local alkalinity, rust (iron oxides) and acid are formed at the anodic site. Rust occupies a far greater volume

than its parent metal and the process leads to a gradual buildup of bursting stresses within the cover concrete and, eventually, to spalling of parts of the concrete surface.

It is important to note the potentials set up by the corrosion process. These are typically of the order of – 500 mV at the anodes, compared with – 100 mV at the cathodes. If the concrete at the most actively corroding anodes is removed and replaced with a high quality repair mortar, ie by traditional patch repair methods, the induced protection will be removed from the untreated cathodes and the formation of new anodic sites will be encouraged. These incipient anodes will grow and repeat the cycle of corrosion damage, sometimes in a very short time if the environment is sufficiently aggressive.

CATHODIC PROTECTION OF STEEL REINFORCEMENT IN CONCRETE

Cathodic protection involves the establishment of a small DC current from an external anode, through the concrete to the rebar. The current charges the steel negatively and it becomes cathodic, ie not corroding. By passing this very small current from a supplemental anode to embedded reinforcement, corrosion can be halted for an indefinite period.

The supplemental anode transmits electrons which are consumed at the reinforcing steel. Other benefits of this process include the production of hydroxyl ions at the steel surface (thus reverting the pore water in the concrete to an alkaline state) and the gradual migration of the negatively charged chloride ions towards the new anode and away from the steel.

When a cathodic system is energized, the rebars are polarised to the 'protection potential', which is the electrochemical potential at which the corrosion rate becomes negligible. This requires a negative potential shift, from the natural (as found) potential, of the order of 100-300 mV and it is generally defined as that which will give a potential decay of at least 100 mV in the 4 to 24 hours

following complete disruption of the DC current.

Before designing a Cathodic Protection system for a reinforced concrete structure, various parameters need to be established, mainly by non-destructive testing. The electrical continuity of the reinforcement must be established, to ensure that all bars will be protected. The electrical resistivity of the concrete is measured in order to determine operating voltages. The location and extent of the corrosion damage (anodic areas) are determined by means of a half-cell potential survey. The applied current densities are calculated on the basis of steel surface area and extent of corrosion damage.

Typical initial Cathodic Protection current densities in chloride contaminated stucutres are in the range of 1 to 20 mA/m^2 of steel surface.

During the operation of the Cathodic Protection system, the initial current density can be reduced as chloride migration away from the rebar proceeds and the pH level increases.

Reactions at the anode surface in a Cathodic Protection system generate acidity and the anode current density must therefore be kept within certain limits in order to prevent excessive production of acidity. A maximum anodic current density of 110 mA/m^2 is recommended by NACE. It is also necessary to ensure that no steel is polarized to a more negative potential than – 1150 mV versus a copper/copper sulphate reference electrode (CSE) to avoid the possibility of hydrogen embrittlement of the steel surface.

The most recent development in cathodic protection of concrete structures is the internal anode system, where probe anodes, usually made from titanium mesh ribbon, are placed in drilled holes in the concrete surface and embedded in grout.

OPERATING A CATHODIC PROTECTION SYSTEM

Cathodic Protection systems are generally powered by mains electricity converted to DC at the required voltage by a transformer/rectifier. The positive terminal is connected to the anode and the negative to the reinforcing steel. Solar power can be used at remote sites.

Various criteria have been proposed to establish the effectiveness of a Cathodic Protection system once it has been energised. These included parameters such as:

- potential shift;
- potential decay;
- operating potential; and
- current-potential relationship.

The criterion generally accepted today is that the system is performing effectively if the 100mV potential decay has been achieved.

After commissioning, this performance is monitored by means of reference cells embedded in the concrete close to the reinforcement. The half cells may be composed of silver/silver chloride, activated titanium, zinc or other materials, the primary requirements being stability, accuracy and longevity. The operating voltage and current are also monitored and adjusted as necessary; this can be done manually at the control cabinet, through a local computer or by modem connection to a remote computer.

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.

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:

High silicon cast iron anodes within a conductive asphalt layer 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.

Conductive polymer 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.

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.

SOME EARLY APPLICATIONS OF CATHODIC PROTECTION

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:

A floor slab in a Sydney apartment building 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 its energising in 1989.

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

A bridge abutment at Frankston, Victoria, 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.

A housing estate in Copenhagen, Denmark, comprising 1943 apartments in 17 blocks, 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.

A wharf at King Island, Tasmania, was contaminated with chlorides to the extent that much of the cast insitu beams and precast deck soffit was cracked or delaminated. A titanium mesh system encased in gunite was chosen for 1300 m2 of concrete requiring treatment; the installation was completed and energised in mid 1992.

A road and rail bridge at Weipa, Queensland, across 1.1 km of trial estuary, was found to have significant chloride contamination in its precast concrete piles and insitu concrete headstocks. 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.

Cathodic protection has become accepted and widely used as a means of halting corrosion of steel in deteriorating reinforced and prestressed concrete structures.

CONCLUSION

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.

It is also recognized as a means of prevention of corrosion damage in new structures, where for a small percentage of the capital cost the design life expectations can be met without repeated and expensive repairs.

BIBLIOGRAPHY

Cathodic Protection of Reinforced Concrete – State of the Art and Case Studies, 1992, Remedial Concrete Engineering Pty Ltd, Melbourne.

'Cathodic Protection of Reinforced Concrete Structures', in *NACE Technical Report No. 36,* 1989, The Concrete Society, London.

Mussinelli, G L, Tettamanti, M, Irwin, R W and Lawson, M J 1988, *Corrosion of Reinforcing Steel in Concrete and its Prevention by Cathodic Protection,* Pacific Concrete Conference, Auckland.

Irwin, R W 1990, *Cathodic Protection of Chloride Saturated Concrete Structures,* Construction Techniques Group Ltd, Auckland.

Gronvold, F O and Nielsen-Dharmarante, K 1991, *Internal Anodes in Concrete Structures,* NACE Corrosion '91 Conference, Cincinnati.

Tettamanti, M, Irwin, R W and Smith, C V 1992, *Cathodic Protection of Reinforced Concrete Buildings: Two Years of Experience at Westminster Court Apartment Building,* NACE Conference.

Gaggin, I A Booth, G L, Kirby, T A and Collins, F G 1991, Grassy Wharf – *a Case Study in Concrete Deterioration,* Austroads Conference, Brisbane.