EXTENDING THE LIFE OF CONCRETE STRUCTURES – THE LATEST TRENDS AND DEVELOPMENTS IN ELECTROCHEMICAL REPAIR TECHNIQUES

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INTRODUCTION

Impressed Current Cathodic Protection (ICCP) was first applied to control steel reinforcing corrosion in concrete structures during the late 1980’s in Australia and New Zealand.

Sacrificial CP systems, development of different anode materials and types, and advances in remote control systems over the last 20 years have resulted in more efficient installations and cost-effective solutions. Other electrochemical rehabilitation techniques such as chloride extraction and re-alkalisation have also been introduced. ICCP installations in NZ and Australia have performed very well and the long term cost benefits of electrochemical repair techniques are well proven but still, very few structures in NZ have been treated by electrochemical methods.

Recent developments including Cathodic Prevention and installation of permanent monitoring probes to detect the onset of reinforcing steel corrosion from the time of construction have been recently installed to some important structures in Asia and Australia. These same techniques are perfectly suited to the types of structures that exist in New Zealand and the aggressive service environment they are exposed to.

The life of reinforced concrete structures can be extended by the application of appropriate electrochemical techniques and the long-term benefits in relation to service life, cost and environment warrant serious consideration in the pursuit of working towards a more sustainable future in our buildings and other structures.

BACKGROUND

It is unrealistic to expect a 50 or 100 year service life from any concrete or steel civil structure without a maintenance strategy. Regular condition assessment, monitoring, programmed maintenance, or preventative maintenance measures should be part of routine asset management.

Chloride induced corrosion of steel reinforcement is the most common cause of deterioration of concrete structures in Australasian and Pacific Rim countries. Many of our cities and civil structures are situated in or near coastal locations. Bridges, wharves, buildings and industrial plants in this region commonly suffer from chloride contamination.

Chloride contamination of concrete and the resulting reinforcing steel corrosion is a well-known and documented problem. In its simplest form, a rusting steel bar embedded in chloride saturated concrete is an electrochemical reaction. The chloride contaminated concrete becomes the electrolyte and the steel bar forms anodic (corroding) and cathodic (protected) zones. This is in effect a form of natural cathodic protection where the rusting steel is protecting the unrusted section of steel bar.

The traditional approach to treating concrete deterioration has been to repair spall damage as it occurs. This involves breaking out of defective concrete, the cleaning of reinforcing steel and then reinstating the concrete, using hand applied, sprayed or formed and poured repair materials. Unless the chloride contaminated concrete is entirely removed from the vicinity of the reinforcing steel, such repairs will seldom provide an extended life of more than period of 5–10 years.

Incipient anode formation is often the effect of patch repairs and continued corrosion of adjacent rebar. Frequent repeat repair cycles are the all too common end result.

In some structures, repairing problems as they emerge can be accommodated and often suits a clients budget and this will continue to be the approach adopted in a lot of cases.

However, there are many structures that cannot be left to deteriorate to this point. The first signs of spalling concrete are usually an indicator of a more deep seated problem. The old saying that what you can see ‘…is just the tip of the iceberg…’ is particularly apt in regard to concrete deterioration.

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The concrete repair industry is littered with contracts where scheduled quantities have ballooned once repair work starts. There are many examples where the final cost to the client has increased so much that the scope has to be reduced. In fact there are known cases where traditional repair has been abandoned early in a contract in order to install the more cost-effective option of Cathodic Protection.

Electrochemical repair techniques offer major advantages over traditional concrete repair as they require far less concrete removal and treat all reinforcing steel, not just those bars rusting and causing spalling concrete. Repeat repair cycles are avoided.

We are also seeing more frequently the early deterioration of pre-tensioned concrete elements in bridge and wharf structures constructed during the 1970’s and 80’s in NZ. Highly stressed prestressing strand suffers from a particularly localised aggressive and severe corrosion in chloride contaminated concrete. By the time the deterioration reaches a point where it is visible, the structural integrity is usually seriously compromised. Repair options at this point are not good, and strengthening solutions usually need to be incorporated before the damage becomes too severe. In the worst cases demolition has even been seriously considered. A 30 year life expectancy for such civil structures is clearly unacceptable.

It is the authors’ opinion that we will see increasing numbers of pre-tensioned concrete structures showing premature deterioration and failure in the near future.

Many of our concrete structures built in the 1950’s and 60’s have given good service to date but are approaching the stage where preserving and maintaining their condition is becoming an issue.

Difficulties associated with access, operational disruption, and structural support associated with traditional breakout and repair are simply too troublesome or costly to consider for some civil structures and electrochemical repair techniques offer reliable and cost-effective long-term solutions.

TRADITIONAL CORROSION PREVENTION MEASURES

Various techniques have been employed over the years to improve the durability and service life of reinforced concrete structures with varying degrees of success such as:

a) Concrete mix design
A low water/cement ratio reduces permeability and conductivity of the concrete. In addition, cement type and the addition of admixtures such as silica fume, fly ash and slag play a significant role in reducing the corrosion rate of reinforcement in concrete.

Corrosion inhibitors are chemicals that can be added to the concrete to decrease the corrosion rate. There remains several questions related to the long-term experience with corrosion inhibitors; the effect on concrete properties, the acceleration of corrosion when the corrosion inhibitors are used with inadequate dosage, and other issues related to the leaching out and evaporation of the inhibitors from the concrete. It appears that if inhibitors are used in suitable concentration they may delay the initiation of corrosion, however there is no established evidence that the commercial inhibitors available at present are able to reduce the corrosion rate after the initiation of corrosion.

b) Reinforcement protection

Epoxied coated reinforcement was introduced in the 1980’s and there is now a major controversy regarding the use of it in new structures to improve the corrosion resistance of reinforcement.

Galvanised reinforcement - for marine structures, where the primary problem is chloride induced corrosion, the increase in service life could be too short to justify the extra cost. Rapid corrosion will occur when galvanised and black steel is used in the same structure and is electrically connected in chloride-contaminated structures.

Stainless steel reinforcement has been used in various countries in structures situated in aggressive environments. Stainless steel has been used in construction joints or critical gaps between columns and decks. There is no extensive performance data available from long-term use of stainless steel as reinforcement in concrete. Because of the very high cost, it is not likely that the entire reinforcement for a large marine structure would be made from stainless steel. A more likely use of stainless steel would be for the outer rebar layer in the tidal splash zone. The possibility of galvanic corrosion in this case between stainless steel and carbon steel needs to be considered.

c) Protective coatings

Coating of the external concrete surfaces may under some circumstances assist in delaying the onset of reinforcement corrosion. In a marine environment, especially in the tidal and splash areas, it is unlikely that such a measure will be effective in preventing reinforcement corrosion.
In addition, Australian and New Zealand Codes have been revised in recent times to include additional measures for increased durability such as additional cover to reinforcing steel for different categories of exposure.

Despite these techniques and advances in workability and placement techniques, examples of deterioration continue to show up on a regular basis.

New Zealand infrastructure asset management systems are not as well developed as in European countries for instance and two significant challenges we face are:

1. Preserving and maintaining the condition of existing structures, and
2. Ensuring that new structures provide an acceptable life expectancy.

**ELECTROCHEMICAL CORROSION PREVENTION**

The key to ensuring an acceptable service life is to identify susceptible structures and apply preventative measures before the deterioration becomes too severe.

Electrochemical techniques are developing a reputation internationally of providing the best options for long term reinforcing steel corrosion control.

Of the various types of electrochemical repair, the two most predominant are:

1. **Cathodic Protection (CP)** – impressed current CP usually applied to existing structures to arrest reinforcing steel corrosion once it has started and protect it from ongoing corrosion.

2. **Cathodic Prevention (CPrev)** - installed at or near the time of construction and prevents the initiation of reinforcing steel corrosion.

In this paper we refer to Cathodic Protection or CP as meaning “Impressed Current Cathodic Protection”. Sacrificial CP systems are not included in subject of this paper.

Other electrochemical repair techniques have been used with success mostly in Australia and include Chloride Extraction and Realkalisation. These techniques are less suited to marine structures.

**CATHODIC PROTECTION**

Impressed Current Cathodic Protection, is regarded internationally as the most effective method of treating chloride induced reinforcing steel corrosion. CP has been used extensively throughout the world since the early 1980’s and throughout Australasia since the late 1980’s and has been the subject of many international papers and journals. It is not the intention of this paper to describe CP in detail other than the brief description below.

CP is a method of forcing the corrosion reaction away from the reinforcing steel to an external anode by the use of an applied DC current. A small DC power supply is connected (+ve) to the anode and (-ve) to the reinforcing steel. The steel is forced into a cathodic state where it cannot corrode, hence the term “Cathodic Protection”. The production of electrons is by way of the external power supply. The circuit is completed with the concrete forming the electrolyte and the corrosion reaction takes place harmlessly away from the reinforcing steel at the external anode.

The electrical ‘potential’ of the reinforcing steel is lowered to the point where corrosion does not occur and can be measured by the use of reference electrodes embedded into the concrete adjacent to a steel bar. This measurement of potential is the basis by which the performance of CP systems is assessed.

CP is a ‘live’ system that can be regularly monitored and adjusted to ensure the steel is adequately protected. Provided a system is properly designed, installed and monitored, it will run for many years with minimal maintenance. Life expectancy of a CP system can be in the order of 20 to 30 years or more, far longer than the life expectancy of traditional concrete repair methods.

Computerised remote monitoring and control systems such as the Savcor RECON have greatly improved the installation and monitoring costs and reliability of CP systems.

A large number of reinforced concrete structures have been protected by impressed current CP throughout Australasia, including the following:

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>Westminster Court Apartments, Auckland</td>
<td>CP to north face of 8 storey building</td>
</tr>
<tr>
<td>1996</td>
<td>Sydney Opera House</td>
<td>CP &amp; CPrev to 1,400 m² of concrete broadwalk structure</td>
</tr>
<tr>
<td>1997</td>
<td>Trident Building, Manly</td>
<td>CP to 4,000 m²</td>
</tr>
<tr>
<td>1998</td>
<td>Fisherman Islands Wharf, Berths 4 &amp; 5, Port of Brisbane</td>
<td>CP to 8,500 m² of concrete wharf underside</td>
</tr>
<tr>
<td>1999</td>
<td>Carillon War Memorial, Wellington</td>
<td>CP to an historic National War Memorial structure</td>
</tr>
<tr>
<td>1999</td>
<td>Axis Fergusson Container Wharf, Auckland</td>
<td>CP to a critical section of cast-insitu beams</td>
</tr>
<tr>
<td>2000</td>
<td>Seaview Wharf, Wellington</td>
<td>CP to 2,000 m² of the wharf underside.</td>
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2005 Thorndon Wharf, Wellington
CP to transverse beams and other elements ongoing.

2007 Calliope Wharf, RNZ Naval Base, Devonport
CP to 28 No pretensioned girders

2006 Swanson Dock East, Port Melbourne
CP to 160 beams plus piles and other elements underway – Australia’s largest CP project to date. 2 year project currently in progress.

Other structures treated by CP include:
- Grassy Island Wharf, Tasmania
- Morell Bridge, Melbourne
- Windang Bridge, NSW
- Nerang Bridge, Queensland
- South Trees Bridge, Queensland
- Fairton Pelt Works, Ashburton
- Deep Creek Bridge, Pacific Highway, NSW
- Missingham Bridge, Ballina
- Ephraim Island Bridge, Gold Coast

The oldest Cathodic Protection installation in NZ continues to provide protection from reinforcing steel corrosion after 17 years service. We have no reason to expect anything less than 30 years service from this CP system.

An important point worth mentioning is the fact CP was applied to most of these structures after a history of failed conventional concrete repairs.

The introduction of Australian Standard AS 2832.5 – 2002 Cathodic Protection of Metals, Part 5: Steel in Concrete Structures (based on British and European Standards) has enabled owners of structures and their engineers to specify CP to internationally accepted design principles and performance standards.

CATHODIC PREVENTION

Cathodic Prevention (CPrev) is used to increase the durability and service life of concrete structures in severe marine environments. It can be used with other compatible advances in concrete technology such as high performance concrete mixes.

CPrev is similar to impressed current CP but is usually installed and commissioned at the time of construction to protect reinforcing steel from corrosion before it starts.

CPrev is an electrochemical technique that involves the application of a small electrical current using anodes that have been embedded in the concrete during construction. This system can be applied to an entire structure or to selected elements of a structure with the aim of preventing reinforcement corrosion when chloride penetration from the environment takes place during the service life of the structure.

The technique is based on the principle that the critical chloride threshold increases as the potential of steel decreases. The decrease of reinforced steel potential is obtained through the application of a direct current, which flows through the concrete from an anode applied on the concrete surface to the reinforcement.

To understand how Cathodic Prevention works it is important to consider the corrosion and protection conditions, shown in Figure 1. If environmental conditions belong to zone (A), pitting corrosion is possible. In order to gain protection the potential must be brought to zone (B) where pitting does not initiate but can propagate or to zone (C) to stop even active pits.

![Figure 1 – Evolution path of cathodic prevention](image)

In the same Figure 1 the typical evolution path in terms of potential and chloride content of Cathodic Prevention is shown. Lowering the potential of new passive steel allows passivity to be maintained even when chloride content becomes higher than the critical content for non-polarised structures.

Such polarisation leads to conditions of imperfect passivity where pitting corrosion, although it cannot initiate, can propagate. It should therefore be emphasised that cathodic prevention has to be applied before corrosion initiates and must be maintained throughout the entire service life of the structure. If pitting corrosion has already initiated, then the higher cathodic protection current is required.

The basic philosophy of Cathodic Prevention is that a much smaller current is required to prevent corrosion initiation compared to that used in Cathodic Protection to suppress ongoing corrosion (3-5 mA/m² of steel area for CPrev compared to 10-20 mA/m² for CP).

The design, monitoring and operation of Cathodic Prevention is similar to Cathodic Protection.

The main difference is related to lower current density requirement and ease of installation during construction. The installation cost for Cathodic Prevention is substantially lower than a retrofitted Cathodic Protection system.
CATHODIC PREVENTION PROJECT 
EXAMPLES

Measures such as using high performance concrete, increasing the cover to reinforcement, application of protective coating, the use of corrosion resistant reinforcement and the use of corrosion inhibitors can minimise corrosion resistance of steel reinforcement.

However for some important structures or elements located in harsh marine environments, these measures alone are sometimes not considered adequate to increase the design life of the structures for 100 years. On such structures, closure and major maintenance works in the future may be prohibitive if not impossible to execute. Additional preventive corrosion measures must be used to guarantee service life of even a few decades.

Cathodic Prevention was applied for the first time in Italy in 1989 as “a method of preventive maintenance of new structures that are expected to become affected by chloride contamination in the future”.

Since then a number of significant structures in Australia and Asia have been treated by Cathodic Prevention. The details set out below are provided as a brief overview of the projects only and are each the subject of separate technical papers.

In the Cathodic Prevention projects set out below, the CPrev systems use LIDA® Grid anode. The mesh ribbon anode is fixed to, but held off the reinforcing steel cage with a cementitious spacer before the concrete is poured. Reinforcing steel is made electrically continuous before pouring.

Reference electrodes are also embedded into the concrete near the reinforcing steel and the proprietary Savcor RECON remote control and monitoring have been installed to monitor the CPrev systems.

CPrev projects detailed below have been designed and installed by Savcor ART Pty.

Sydney Opera House Broadwalk Structure commissioned in 1996

During a major rehabilitation of the Sydney Opera House structure in 1995-6, a CPrev system was installed to the reinforced concrete pre-cast elements of the Western Underbroadwalk structure. These elements had suffered a long history of excessive deterioration problems and a decision was made to replace them and incorporate a CPrev system.

A total of 18 A-frames, 17 midspan ties, and 17 pre-cast walkway sections have been constructed with CPrev incorporated.

Figure 2: Sydney Opera House Underbroadwalk structure showing elements where CPrev was applied.

This system continues to perform as designed and has prevented corrosion of the reinforcing steel.

Lawrence Hargrave Drive commissioned in 2005

A section of Lawrence Hargrave Drive between Clifton and Coalcliff, north of Wollongong, was closed for repair in July 2004 due to geological instability of the area. The A$49 million, 665 metre Sea Cliff Bridge was constructed to bypass this section of road. The bridge was opened in December 2005 and is located offshore, curving about 45 metres to the east of the cliff face. The bridge is 41 metres above sea-level at its highest point.

During the construction of the bridge, a CPrev system was incorporated into the pile caps and columns of GD2 and GD3, in order to prevent corrosion of the embedded steel. These elements of the structure were considered to have the highest future risk of chloride induced corrosion. Total concrete surface area protected is 4,890 m².

Figure 3: Sea Cliff Bridge – Aerial View (with GD2 on left and GD3 on right)
Hangzhou Bay Bridge, China - 2006

At 36 kilometres, the world’s longest sea bridge, will cut the length of a road trip from Shanghai to Ningbo from 400 km to just 80 km. Construction of the US 1.42 billion dollar six-lane bridge began in November 2003 and is due for completion in 2008.

A CPrev system was installed to protect key sections of the North and South towers of the bridge.

A total of 5,000 m² of concrete surface area has been protected by CPrev.

On such projects as detailed above, the cost of installing CPrev is in the order of 2.5 to 5% as a percentage of the overall project cost.

As can be seen from these case histories, Cathodic Prevention can be installed to selected elements of a structure that are considered to be at a high risk of corrosion during the service life of the structure. CPrev can be combined with other corrosion prevention measures such as the modification of concrete mix design to improve the corrosion resistance of reinforcement and meet the specified durability requirements. Cathodic prevention is an ideal technology for extending the service life and reducing the maintenance costs of reinforced concrete marine structures.

LATEST TRENDS

As previously mentioned in this paper – once the tell-tale signs of concrete deterioration (corroded reinforcing steel and spalling concrete) become apparent, the problem is usually deep seated and quite serious.

Early detection of corrosion of reinforcing steel can assist in planning and implementing appropriate corrosion prevention measures and reduce maintenance costs in the long term.

Monitoring a structure for the onset of corrosion is becoming more common and makes good sense.
Corrosion monitoring is a continually developing field but there already exists reliable means and technology to detect deterioration in its early stages.

Condition assessments of structures to check reinforcing steel cover, concrete quality, chloride content, carbonation penetration measurements and electro-potential corrosion mapping for example have been available for more than 20 years and the techniques are well established. This can be carried out at any time and should be undertaken on a regular basis in any case for any concrete structure.

There are now various types of embedded monitoring and data collection systems available that can:

- Detect chloride ingress into concrete.
- Detect corrosion of reinforcing steel by measuring galvanic current between carbon steel and stainless steel electrodes in the concrete.
- Measure corrosion rate by electrochemical polarisation (linear polarisation resistance LPR/galvanostatic pulse techniques).
- Measure corrosion potential of embedded reinforcement.

These can be installed from new and some can be retro-fitted to existing structures.

Corrosion rate monitoring systems have been installed on a number of Australian structures including Houghton Highway Bridge, Cattle Creek Bridge, Port of Brisbane Wharves 6 & 7, and the Nundah Bypass Bridge in Queensland.

Cathodic Protection of structures containing prestressing steel is now a viable option. Pretensioned structures are particularly suited to corrosion protection by electrochemical techniques if applied at an early stage. Computerised current control and remote monitoring systems are now developed to the point where over-protection and hydrogen embrittlement of the prestressing strand can be avoided. There are already several Australasian structures where CP has been successfully applied to control corrosion – and others where it is being considered. This is in structures of only 30 years age.

With the large number of pretensioned concrete structures we have situated in marine environments, the use of Cathodic Protection to preserve and maintain their condition will increase over the coming years.

CONCLUSIONS

Preserving and maintaining the condition of a concrete structure should be the aim of every asset owner.

Electrochemical techniques offer another very good option to enhance and extend the service life of reinforced concrete structures in marine environments.

There is no doubt that for a new reinforced concrete structure to be built in harsh marine environments with a design life that exceeds 50 years, it is essential that durability strategies are considered and implemented during construction.

For structures where some of their elements will be built in a tidal/splash zone, the application of a Cathodic Prevention system to these zones during construction should be considered. Cathodic Prevention is a sound technique that can maintain the embedded reinforcement of the structure in a corrosion-free environment for its entire design life with minimal maintenance.

Cathodic Prevention can future-proof a concrete structure for a small cost premium upfront, avoiding costly repairs and disruption to the operations further down the track.

Avoiding costly repairs once deterioration has developed and compromised a structure can also be achieved through early detection of reinforcing steel corrosion with the use of permanent monitoring systems either installed from new or fitted to existing structures.

This allows application of Cathodic Protection to existing structures while it is still a practical option. Cathodic Protection is an already well established and economical remedial solution to control reinforcing steel corrosion.

Although New Zealand structures may not rate in terms of size or value to the Lawrence Hargrave or Hangzhou Bridge examples, similar potential maintenance issues exist. In future-proofing some of our more significant exposed marine structures (or at least elements of those structures), Cathodic Prevention should at least be considered for the small cost premium involved.

The case for a modest investment in corrosion monitoring or preventative maintenance early in the life of a structure should not be more easy to justify than it is today when one considers resource consent issues, and the cost and time involved in demolition and reconstruction of civil structures.
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