The Electrochemical Desalination of a Coastal Road Bridge

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ABSTRACT

A significant number of Australia's road bridges are located in coastal regions and hence subject to aggressive environmental conditions through direct contact with salt water and indirectly through wind borne salts. This paper describes the electrochemical desalination of a road bridge substructure affected only by wind borne salt attack. This structure is located within 100 metres of the coastal dunes and displayed very high chloride ion concentrations in the reinforced concrete piers and headstocks. Additional comment is supplied on the reasons for choosing the remedial technique combined with a protective coating strategy and its effectiveness on this structure.

1. INTRODUCTION

Orealla Crescent overpass bridge is located on the David Low Highway just south of the popular tourist township of Noosa. This structure is situated within 100 metres of the coastal sand dunes and subject to severe and constant offshore wind attack. The nature of the topography due to the depressed underpass results in a wind tunnel effect which has significantly increased the chloride ion concentrations at Pier 2. This structure consists of three spans of prestressed beams 6.1m/12.2m/6.1m supported by reinforced concrete headstocks and columns. It was constructed in 1971 as part of a land development scheme by private enterprise. Subsequently the Queensland Main Roads Department inherited the asset management of this structure. The following sections describe the initial investigation of the condition of this structure and the subsequent remediation techniques.

2. CONDITION SURVEY

2.1 Initial survey

An initial condition survey was undertaken in December 1995 when the bridge was approximately 24 years old. This survey was initiated due to the observation of significant spalling from the piers and prestressed beams and vertical cracking in the piers. Table 1 contains a summary of the visual classification of the structure prior to coring. The visual condition rating reported in Table 1 was based on the level of observed spalling, cracking and delamination. Significant vertical cracking was observed in the Eastern face of both piers. Pier 2 displayed a large delaminated zone on its Northern face. The soffit of the prestressed beams in Span 3 were showing significant spalling and underlying corrosion due to the penetration of chloride ions.

Table 1 – Visual Condition of Structure

Item	Condition
Pier 1	Poor
Pier 2	Very Poor
Span 1	Fair
Span 2	Fair
Span 3	Very Poor

This structure represents the first example of chloride induced corrosion in prestressed concrete members detected by Main Roads. A sample of concrete spalls collected on the first inspection in December 1995 were analysed for average total chloride ion content and the results are reported in Table 2.

Table 2 – Chloride ion content of spalls

Location	Chloride Ion Content (kg/m3)	Carbonation Depth (mm)
Pier 2 East	6.3	3 - 10
Pier 2 North	4.8	14
Span 3 Beam	12.7	10 - 15

The data in Table 2 indicates the prestressed concrete beams have higher chloride ion contents and similar carbonation depths to the reinforced concrete piers. This indicates the prestressed concrete used in this structure is of a lower quality than normally encountered. In general it would be expected that the prestressed concrete components would out perform the associated reinforced elements regarding durability performance in a similar environment.

2.2 Analysis of cores

A series of cores were extracted from each Pier and a sample of prestressed beam soffits. Table 3 summarises the density, compressive strength and carbonation depth information and Table 4 the chloride ion content data obtained from the cores.

Table 3 – Strength of cores

Element	Density (kg/m3)	Strength (Mpa)	Carbonation (mm)
Pier 1 Stem	2253	39.5	10
Pier 1 Head	2300	76.3	3
Pier 2 Stem	2263	37.4	10
Pier 2 Head	2280	64	8
Span 1 Beam	2400	66	7
Span 2 Beam	2400	37	8
Span 3 Beam	2340	51	5

From the results detailed in Table 3 it can be seen that the pier headstocks yielded higher compressive strengths than their associated stems. The compacted density of the pier stems was also lower than the headstock concrete. This information obtained from the cores was consistent with the visual condition of the piers indicating significant distress in the pier stems and no visible distress in the pier headstocks.

The results in Table 4 indicate the penetration of chloride ions has been most significant in the Pier 1 Stem, Pier 2 Headstock and stem and the Span 3 Prestressed Beams. The orientation of this bridge in relation to the prevailing southeasterly breeze has induced a higher penetration of chloride ions in Pier 2 Stem and Headstock and Span 3 Beam soffits. The spill through abutment at Span 3 captures the sea breeze and funnels it Westward under the Span 3 Beams. This environmental effect has produced a concentration of chloride ions in the region of Span 3 as noted in Table 4 and reflected in the visual damage ratings in Table 1.

Table 4 – Chloride ion levels of cores (kg/m3)

Element	Surface Value	At Level of Reinforcement
Pier 1 Stem	2.0 – 4.8	1.6 – 2.9
Pier 1 Head	3.6	1.1
Pier 2 stem	2.3 – 5.0	0.9 – 6.0
Pier 2 Head	6.3 – 6.9	5.7
Span 1 Beam	1.5 – 2.0	1.4 – 1.9
Span 2 Beam	1.9 – 4.6	1.5 – 3.2
Span 3 Beam	3.9 - 10.3	2.7 – 4.7

2.3 Summary of condition analysis

As a result of the above condition analysis it was decided by the owner to repair this structure by electrochemical desalination of the Pier 1 Stem and Pier 2 Stem and Headstock. The Beams were to be treated by repair of damaged areas and silane coating of all exposed soffit areas. They could not be treated by the electrical repair system due to concerns with hydrogen embrittlement of the prestressing strands. In addition all the substructure elements treated by desalination were to be coated with a multi layer protective coating system.

The desalination technique was chosen as it would provide the least interruption to local traffic and pedestrians and limit the amount of dust and noise to local residents. The following sections describe the technique and results obtained on this structure.

3. DESALINATION

3.1 Introduction

Steel in sound concrete is protected by an oxide film that forms on steel surfaces in highly alkaline environments. This film is stable at pH values higher than about 9.5. In a chloride-contaminated environment the film is penetrated and the steel is subject to corrosion. The corrosion of reinforcement will take place when the following conditions are satisfied:

- presence of moisture and oxygen
- sufficient electrical conductivity
- presence of sufficient % of chloride ions

Desalination is a non-destructive electrochemical treatment, which halt ongoing corrosion in chloride contaminated concrete by reducing the number of chloride ions and reinstating the passive oxide layer on the reinforcement.

3.2 The process

Desalination is performed by applying an electric field between an anode system temporarily placed on the concrete surface and the reinforcement in the concrete.

On polarising the system, the chloride ions are transported from the rebar surface toward the anode and are hence removed from the concrete.

In addition to the removal of the chloride ions from around the reinforcing steel, hydroxyl ions are produced on the steel surface, which increases the pH level in the concrete surrounding the reinforcement.

3.3 Fundamentals

Similarly to cathodic protection (CP), a direct current is applied between the reinforcement and an external anode. In the case of CP, this current is between 2-20 mA/m^2 of steel surface. For desalination this current is between 1-2 A/m^2 of concrete surface.

On energising the system i.e. connecting the reinforcement to the negative terminal, and the external anode to the positive terminal of a source of DC current, the negatively charged chloride ions will migrate towards the positive electrode, and are hence removed from the concrete. In addition to this, there is production of hydroxide ions on the cathode leading to an increase of the pH near the rebar.

The disadvantages of the treatment are related to the evolvement of hydrogen at the cathode, which may be absorbed into prestressing steel, causing embrittlement, and the possible increased risk of alkali-aggregate reaction (when reactive aggregates are present in concrete) resulting from higher sodium and potassium concentrations in the concrete. These reactions are likely to occur at very high voltage.

4. FIELDWORK

4.1 Condition Survey

As a part of the desalination treatment, and in addition to the previous testing, a survey of the structure was performed. The aim of this survey was to assess:

(a) Corrosion activity of reinforcement by potential and resistance mapping
(b) Rebar continuity
(c) Position of rebars
(d) Concrete cover
(e) Visual damage
(f) Delamination of concrete
(g) Chloride profiles in selected locations

As a result of this survey all areas to be repaired were identified and repair and desalination specifications were prepared.

4.2 Repair work

The repair work carried out for the structure was minimal, with only delaminated and spalled concrete areas being removed. Therefore no problems were created in relation to noise, dust and debris.

4.3 Extraction systems

Three extraction systems were used in this installation. The purpose in using three systems was to gain information in relation to the practicality and efficiency of each. The systems used were as follows:

Steel mesh sprayed with cellulose fibre
Wooden battens were attached to the concrete surface. The steel mesh was fixed to the wooden battens, which act as spacers between the concrete and the steel. The cellulose fibre and electrolyte were sprayed on and applied to a thickness sufficient to encapsulate the steel mesh. The fibre was encapsulated with plastic sheets and was kept wet during the treatment.

Titanium anode with industrial felt
The felt cloth was rolled onto the concrete surface in two layers, with titanium mesh anode placed between them. The materials were kept wet during the treatment.

Reservoir panel system
Reservoir panels filled with electrolytes and with built in titanium anode mesh were bolted to the pier surface. Throughout the process, the electrolyte was drained

from the reservoir and replaced on a weekly basis in order to maintain the rate of extraction.

4.4 Installation

The elements to be desalinated were divided into 16 separate electrical zones, based on the corrosion activity of reinforcement, the capacity of the power supply units used, and the anode system.

Steel and anode contacts were made for each of the 16 zones and the four transformer rectifier units. The capacity of each transformer unit was 40 amps/30V.

The Norcure RD2 units, which have been developed especially for realkalisation and desalination, were used in this installation.

Monitoring of the treatment and adjustment of current/voltage was carried out via a PC connected to the transformer/rectifier units.

4.5 Results

Chloride sampling was carried out prior to treatment and at regular intervals during the extraction process. Monitoring the performance of the system and recording the test results was carried out on a regular basis.

The chloride test results are presented in Table 5 below. On treatment completion, all chloride levels were below 0.4% w/w of cement in all locations at steel depths of 25 - 50mm, with the exception of one location where the chloride level was 0.63% w/w of cement.

The chloride extraction treatment was terminated after nearly 10 weeks of operation, at which time the criteria of the system had been reached.

Table 5 – Chloride Test Analysis

No.	**$Cl^{-\%}$ w/w cement before desalination**	**$Cl^{-\%}$ w/w cement after desalination**	**Reduction of $Cl^{-\%}$**
1	**0.44**	**0.25**	**42%**
2	**1.06**	**0.20**	**81%**
3	**0.44**	**0.19**	**57%**
4	**0.97**	**0.30**	**69%**
5	**0.73**	**0.11**	**85%**
6	**0.85**	**0.18**	**79%**
7	**0.65**	**0.12**	**82%**
8	**1.25**	**0.63**	**49%**
9	**0.75**	**0.20**	**74%**

5. GENERAL COMMENTS

The performance of the three systems was identical in relation to the chloride extraction process. No evidence from the data obtained suggested any major advantages for any of the three systems. However, from practical point of view, some of the comments regarding the systems are as follows:

Steel mesh sprayed with cellulose fibre

After the completion of the treatment, a large percentage of the steel mesh used as anode material with the cellulose fibre was reduced to rust, which has stained the concrete surface during treatment. The staining was removed by sandblasting as a part of the surface preparation for the protective coating.

The cost of steel mesh is much lower than titanium mesh and the installation of steel mesh is much easier than installing the standard titanium mesh from a practical point of view due to the ease of handling thicker mesh.

Sprayed cellulose fibre has the advantage of being able to conform to any concrete shape and is self-adherent. Some of the disadvantages of using fibre are the clean up and disposal of the material after the completion of the job.

Titanium anode with industrial felt

The felt system is difficult to install in vertical surface and like cellulose fibre must be maintained wet during the treatment. This system is usually used on horizontal surfaces such as decks.

Reservoir panel system

The reservoir panel system must be built to fit a given structure but the initial cost is high. From our limited experience with the system, our opinion is that it can be considered appropriate for large applications where the panels could be re-used many times. The maintenance of the tanks is required on daily basis and they can be subject to vandalism if left unattended.

Generally, the selection of the extraction system should be considered based on each particular case. Where staining of the concrete is not considered a major issue due to the need of sandblasting prior to coating application, we consider that the steel mesh sprayed with cellulose fibre system is the preferred system from practical point of view.

6. ADDITIONAL PROTECTIVE COATINGS

On completion of the desalination process a range of protective coatings were applied to protect and enhance the treated bridge piers. A summary of these coatings is given in Table 6.

Table 6 – Summary of Treatments

Treatment No.	Time from Removal of CE	Type
1	3.5 weeks	Silane
2	8 weeks	Acrylic Copolymer
3	10 weeks	Aliphatic Urethane

Treatment No.1 was applied approximately 3.5 weeks after removal of the CE system. The delay was due to the time required to :

(a) Remove the system
(b) Water blast the treated areas
(c) Allow some drying time for the concrete surfaces to create an anchor for the silane
(d) Await suitable weather conditions

The silane treatment was tested for effectiveness of penetration by coring and physical examination. The depth of penetration varied from 1 to 10 mm.

Treatment No. 2 consisted of two coats of pigmented acrylic copolymer spaced 5 days apart. This treatment acted as a textured filler for the coarse surface finish produced by the chloride extraction process and as additional surface protection.

Treatment No. 3 was a permanent ant-graffiti protective coating which was applied twice. Before applying this treatment a bridging layer of acrylic polyurethane was applied and allowed to cure for 24 hours.

7. CONCLUSIONS

The efficiency of the chloride removal process, the ease of operation, the time required to complete the process and the cost depend on the pre-installation investigation, the skill of the operators, the design of the system and the proper selection of the main extraction system components (anode, electrolyte and wetting system).

The extraction process for this structure was completed very satisfactorily by reducing the level of chloride in nearly all test locations to values where corrosion of reinforcement caused by chloride contamination of concrete is unlikely. Additional long term monitoring of the total system will be undertaken by the owner over the next 5 years to assess the long term effectiveness of this type of repair process.

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