# Data analysis of the long-term residual effect of cathodic protection on reinforced concrete structures

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**Abstract.** The application of impressed current cathodic protection (CP) is a well-established technology for the corrosion protection of reinforced concrete structures situated in marine environments. While the protective benefits of cathodic protection are well known, the lasting effects following the discontinuation of CP current are not entirely understood.

This paper presents research findings on the residual protective effect which is known to occur following long durations of impressed current cathodic protection. The residual effect was replicated in university laboratories using reinforced concrete test blocks and accelerated CP testing methods. The experimental results depicted a clear improvement in the electrochemical state of the reinforcing steel with a shift of 150 to 300 mV to more positive values following CP application.

The research also involved analysis of monitoring data from six in-service cathodic protection systems which were operating in Australia for nearly two decades. The behaviour of the steel potential readings was analysed and the results of the combined research confirmed that the protection provided by cathodic protection systems does not actually cease when the CP current is switched off. Rather, the embedded steel undergoes a significant and sustained shift to more positive values and this phenomenon is documented and discussed in this paper.

## 1. Introduction

The application of impressed current cathodic protection (CP) is a well-established technology for the corrosion protection of reinforced concrete structures. Cathodic protection is typically applied to structures situated in marine environments, and in Australia, the technology has become widely accepted as an effective and resolute method for arresting corrosion in concrete bridges, wharves and jetties [1].

Following long-term periods of CP application to reinforced concrete structures, previous studies by other researchers [2,3,4,5] have observed and documented the existence of residual protection following the long-term application of cathodic protection.

The hypothesis is that the long-term application of impressed current cathodic protection makes the reinforcing steel passivated, and once the cathodic protection current is interrupted, the steel remains passivated for an extended period of time, and there is a persistent protective effect which arrests the initiation of corrosion in concrete. Experimental work [6] has found that design current densities can achieve the intended polarisation effect for the steel reinforcement with relatively low current densities.

Laboratory research work [7] has demonstrated the hypothesis that chloride ions are repelled from the steel over time with the application of cathodic protection current, and that concrete alkalinity increases, and this re-establishes a passive iron oxide layer on the embedded steel. The research work concluded that the longer cathodic protection current was applied, and the higher the current density, the longer the residual effect [7].

The hypothesis for this phenomenon has been described by other researchers. A study [8] found a relationship between an increase in concrete alkalinity, especially near the interface of the concrete and steel, which is generated by cathodic protection, and the repulsion of chloride ions away from the reinforcing steel as an effect of the cathodic protection current. The author explained how shifts in polarisation caused the steel to become more negative to a level where thermodynamically, corrosion of steel cannot occur [8].

This shift or 'residual effect' can be assessed by comparing the potential of reinforcing steel before CP application with its potential after CP application and allowing sufficient time for depolarisation. The theory is that the depolarised potential of steel, after being subject to cathodic protection current for an extended period of time, should be more positive than its natural potential (the original potential before CP application). The difference in potential demonstrates a potential lasting effect (ie. the 'residual effect') which can occur after the interruption of cathodic protection current.

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It remains unknown for how long the residual effect following cathodic protection persists. A paper [9] noted that following chloride extraction from a concrete element, the survey engineers performed potential mapping testing on the element and found that there was a positive shift in potential of about 80 – 100 mV and this indicated that the oxide layer was intact or was forming around the steel reinforcement. The study indicated that the chloride ions repelled away by the electrochemical process resulted in increased passivity around the embedded reinforcement.

## 2. Experimental Methods

To better understand the residual protective effect which is known to occur following the discontinuation of current after long periods of impressed current cathodic protection, the following two experimental methods were applied:

a) Laboratory testing of concrete specimens using accelerated CP testing methods, and
b) Analysis of data taken from six operational CP installations in Australia.

### 2.1 Laboratory Testing

A total of six concrete and steel specimens (test blocks) were constructed for the laboratory testing. The test blocks were designed to basic specifications to produce steel and concrete elements with measured levels of chloride contamination.

The principles for cathodic protection design and application were based on the guidelines in Australian Standard AS 2832.5–2008 *Cathodic protection of metals, Part 5 Steel in concrete structures.*

The laboratory testing setup allowed for the use of power supply units, a computer, data logger and a fume hood for the duration of the accelerated CP treatment.

#### *2.1.1 Concrete blocks*

The mix design for the control blocks was intended to replicate the condition of chloride contaminated concrete cover typically seen in marine structures. While certain structures, particularly infrastructure assets situated in coastal or river environments, may have some corrosion prevention considerations in the concrete mix design, for the purpose of this experimental work, the concrete blocks had no chemical admixtures or supplementary cementitious materials added to the design mix.

#### *2.1.2 Chloride in the concrete mix*

To simulate moderate to heavily chloride contaminated concrete, sodium chloride (NaCl) was dissolved in the concrete mix water (to ensure an even distribution in the concrete mix) and thus the bulk of the embedded steel in the concrete test specimens was situated in chloride contaminated concrete. This method had previously been applied as a way to produce various concrete specimens with measured levels of chloride concentration equally distributed throughout the concrete specimen [10].

Another objective of the research was to assess whether any residual protective effect could be variable to the extent of chloride concentration in the concrete test blocks. To this end, two different levels of chloride concentration were selected for both the control and test blocks. The chloride concentration levels selected for the experimental work were 35 grams and 70 grams of NaCl per litre of mix water for the concrete mix (the variations in NaCl content in the mix water resulted in concrete with chloride % W/W of cement of 1.36 and 1.91).

After casting and curing of the concrete blocks, dust samples from each block were extracted by drilling. These samples were submitted to a laboratory for chloride content analysis. The purpose of this testing was to establish a baseline chloride content in the test blocks and subsequently allow for measurement of any changes following the accelerated application of cathodic protection current.

#### *2.1.3 Anodes*

Three ribbon anode strips were embedded in the concrete test blocks during construction. The anodes were Mixed Metal Oxide (MMO) titanium coated ribbon anode strips, with a design current rating of 5.3 mA/lineal meter.

#### *2.1.4 Reference electrodes*

During construction of the test blocks, a reference electrode was positioned in a pre-determined location in each test block. The electrode was positioned between the MMO ribbon anode and the embedded rebar, and its position was fixed by plastic chairs to ensure that the reference electrode was parallel to and not touching the embedded steel. The design for the test blocks is shown in Figure 1.

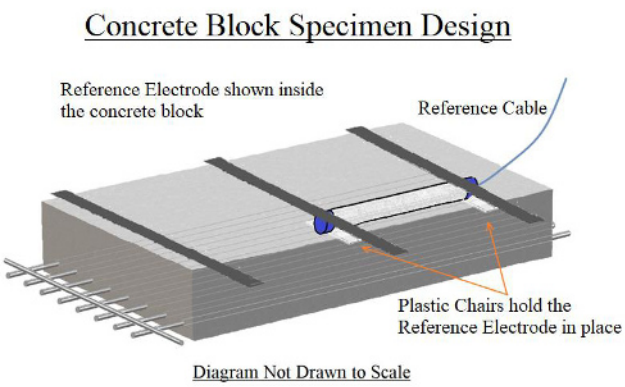


**Figure 1.** Concrete test block design showing the rebar, anode strips and the position of reference electrode situated on the two plastic chairs.

### *2.1.5 Measurement of steel potential*

The potential of the steel bars was measured against embedded Silver/Silver Chloride (Ag/AgCl) reference electrodes, and an external calibrated Copper/Copper Sulphate ($Cu/CuSO_4$) reference electrode.

The 'natural' or base potential of the embedded bars was determined following the establishment of electrical continuity between the bars by an additional bar and wire ties. The electrical continuity of all the steel rebars in each block was tested and verified. Following confirmation of steel continuity, the potential readings were recorded and these constituted the 'natural' potential for the concrete specimens prior to the application of cathodic protection current.

The depolarisation data from the test blocks was measured by embedded Silver/Silver Chloride reference electrodes connected to data logging equipment to record steel depolarisation following interruption of the CP current.

### *2.1.6 Accelerated testing*

The principle of accelerated testing has previously been applied in related research work [7] in which the application of substantially higher current density over time was used as the method to simulate the effects of long-term cathodic protection application.

The accelerated testing methods allowed the concrete specimens to receive the current density which would have been impressed over a number of years of routine operation.

The number of Amp hours of current being applied to each block was calculated in equivalent years based on an assumed typical impressed current cathodic protection operation (10 mA/m² of steel surface area).

The longer time duration was expected to reproduce the conditions where a residual protective effect, in the form of more positive steel potential values than the natural potential could be demonstrated by analysis of the depolarisation data.

The cathodic protection systems were connected to power supply units and energised over periods of 57 and 131 days. The total impressed current to each test block was measured in Amp-hours and a factor for the accelerated CP application was calculated.

The accelerated testing calculations are provided in Table 1. The total charge passed over time, measured in Amp-hours (A h), formed the basis of the accelerated testing calculations.

**Table 1.** In laboratory conditions, three of the test blocks were subjected to accelerated cathodic protection application for the equivalent of 3.89 years, 8.86 years and 9.72 years.

| Accelerated Cathodic Protection Testing | | | |
|---|---|---|---|
| Test Blocks: | **Block 3** | **Block 4** | **Block 6** |
| Chloride level | Low Chloride | High Chloride | High Chloride |
| Amp-hours | 39.1 | 89.0 | 97.7 |
| Duration of energising (days) | 57 | 57 | 131 |
| Factor of accelerated CP (based on 10 mA/m$^2$ of steel surface) | 24.9 x | 56.7 x | 62.3 x |
| Years equivalent of CP (at 10 mA/m$^2$ of steel surface) | 3.89 yrs | 8.86 yrs | 9.72 yrs |

For the three test blocks, the accelerated testing is summarized as follows:

- Test block 3 had a total charge of 39.1 Amp-hours applied, which was the equivalent of 1419 days or 3.89 years of theoretical cathodic protection application in concrete at a current density of 10 mA/m$^2$ of steel surface area.
- Test block 4 had a total charge of 89.0 Amp-hours applied, which was the equivalent of 3235 days or 8.86 years of theoretical cathodic protection application at the same current density of 10 mA/m$^2$ of steel surface area.
- Test block 6 had a total charge of 97.7 A-h applied. This was the equivalent of 9.72 years of theoretical cathodic protection application at the same current density of 10 mA/m$^2$ of steel surface area.

## 2.2 Analysis of Test Data from Operating CP Systems

The secondary component of the research was a study of monitoring data from six (6) in-service cathodic protection systems which had been operational for a number of years (3 to 16 years) and had their CP current interrupted or temporarily discontinued for a period of time. The 6 structures were all situated in marine environments and had varying degrees of exposure to saltwater and tidal fluctuations.

The availability of real-world operating data, especially over long durations of time such as the case with cathodic protection, is quite scarce and its analysis provides a valuable insight into the lasting effects of steel polarisation from cathodic protection application.

The use of real monitoring data, did however, present some limitations. The types of structures relevant to this study are reinforced concrete structures situated in saltwater environments. This mainly includes multi-span concrete bridges, harbour jetties and wharf structures. Other marine structures, such as culverts, dolphins, tunnels and seawalls are relevant to this field of research but are not represented in this study.

The data was originally used by engineers and technicians for the purpose of CP system testing and adjustment. The collection of data was not intended for future research purposes, and therefore information such as the tidal conditions at the time of testing were not recorded. In addition, there are no meaningful chloride concentration results available for the 6 structures. So, while the data provides many valuable insights into long-term cathodic protection, its usefulness is limited.

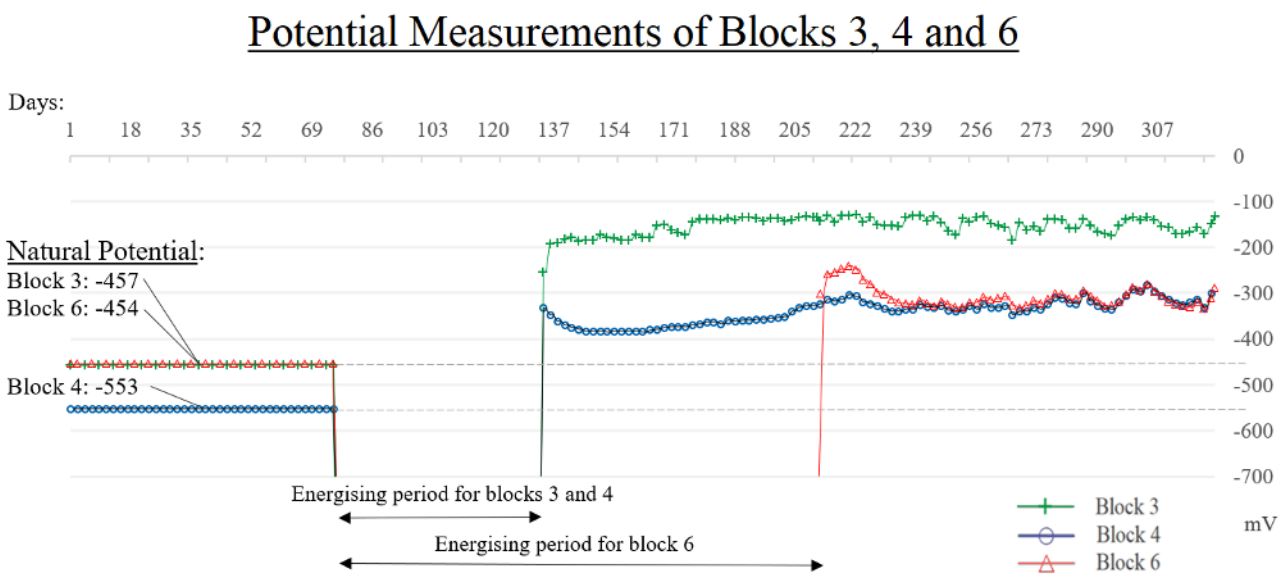


**Figure 2**. Potential Measurements for blocks 3, 4 and 6

## 3. Results and Discussion

### 3.1 Depolarisation of test blocks

Following the accelerated testing and the discontinuation of cathodic protection current, the depolarisation of the test blocks was recorded by data logging equipment for 190 days for blocks 3 and 4, and, 112 days for block 6.

The test results indicated all three test blocks had a marked shift in steel potential to less negative values following the application of CP current. The depolarising potentials are displayed in Figure 2 (above), and are shown against assumed stable natural potentials over the testing period.

The depolarisation readings (average of the last 20 days of testing) for the concrete blocks following the accelerated cathodic protection testing were as follows:

- Block 3 (low chloride) – Average depolarised potential -156 mV. This represents a shift from the natural potential of 301 mV to more positive values.
- Block 4 (high chloride) – Average depolarised potential -311 mV. This represents a shift from the natural potential of 242 mV to more positive values.
- Block 6 (high chloride) – Average depolarised potential -314 mV. This represents a shift from the natural potential of 140 mV to more positive values.

The results validate the hypothesis that electrochemical treatment can shift the steel potential, after the discontinuation of current, which is known as the 'residual protection' or 'residual effect' and can be replicated and measured for some period of time.

### 3.2 Chloride testing results

The chloride ion concentration in the concrete was tested before and after the accelerated cathodic protection testing. The objective was to demonstrate that one of the causes of improved passivity of the embedded steel was the migration of chloride ions away from the embedded steel. Less chloride ions in the vicinity of the steel surface means that fewer chloride ions can react with the protective oxide layer on the steel. Consequently, the regeneration of chloride ions and attack on the protective oxide layer is reduced.

Dust Samples 1 (DS1): The primary chloride samples taken from all 6 blocks. The results were used to establish indicative base levels of chloride concentration in the test samples.

Dust Samples 2 (DS2): Secondary chloride samples were taken from 3 test blocks at predetermined locations. The pre-determined locations were positioned directly above the rebar, and below the anode strips.

Dust Samples 3 (DS3): Tertiary chloride samples were taken from 3 test blocks at predetermined locations. The pre-determined locations where directly above the rebar, and positioned below (in line) with the anode strips.

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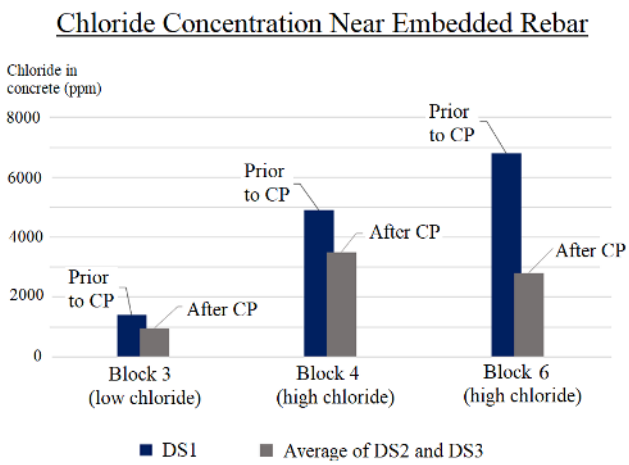


**Figure 3.** Chloride concentration in test locations in the vicinity of embedded rebar

Figure 3 shows the test results of DS1, and the average test results of DS2 and DS3 following the accelerated CP testing. The averaged amounts are intended to be more representative of the concrete condition and the concentrations of chloride following the accelerated testing. While the result samples vary slightly, all samples from DS2 and DS3 showed a marked reduction in chloride concentration compared to DS1. This substantiates the understanding that chloride ions are repelled from the steel location and move towards the anode inside the concrete during the application of high current densities.

For test block 3, after conclusion of the accelerated CP testing, the chloride concentration (ppm) in samples DS2 and DS3 reduced by 31.4%. For block 4, after the accelerated CP testing the chloride concentration reduced by 28.6%, and for block 6, the chloride concentration reduced by 58.8%.

### 3.3 Analysis of test data from operating CP systems

The secondary component of the research involved the compilation and analysis of operational data from in-service cathodic protection systems in Australia. The aim of the research was to assess the potential of embedded steel in concrete following various periods of cathodic protection current application. The hypothesis of the study was that the 'residual effect' after CP application exists and provides a fundamental and significant improvement in the corrosion resistance of embedded steel in chloride contaminated concrete.

Overview of the systems:

- Monitoring data from six (6) CP installations was assessed.
- The structures are all located in coastal locations in Australia.
- In principle, the CP installations were designed to meet the operation and testing requirements detailed in Australian Standard AS 2832.5.
- The author had previously visited the sites of all subject CP installations.
- The design current density for each of the six CP installations was 20 mA/m$^2$ of steel surface.
- The embedded reference electrodes for all six structures are Silver/Silver Chloride (Ag/AgCl) KCl reference electrodes.

These cathodic protection systems are installed on concrete bridges and wharves and have been operational for short to long periods of time (ranging from 3 to 16 years). The cathodic protection current for each of the 6 CP systems was interrupted for different durations and for different reasons such as routine system monitoring, switching the system OFF due to transformer rectifier repairs and due to refurbishment works to the structures which required switching OFF the system for a period of time. The natural potential of the embedded steel (potential before system commissioning) was assessed against the OFF (depolarised) potential readings recorded after current interruption. In addition, the average levels of cathodic protection current required for each system at commissioning, and after years of operation were recorded and compared.

**Years of routine CP application and residual effect**

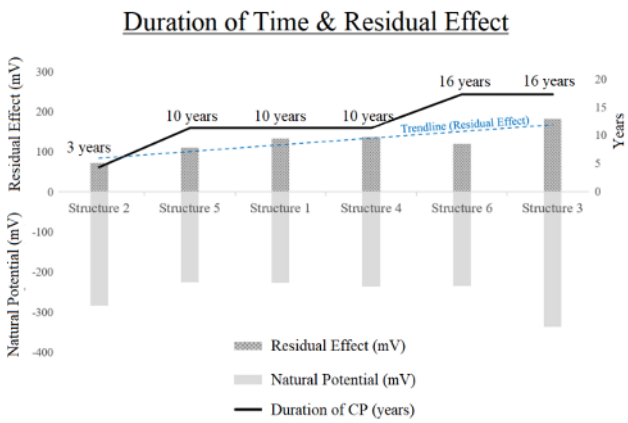


**Figure 4.** Duration of time and residual effect

When observing the number of years of CP protection assessed against the average residual shift in (mV) in each of the 6 in-service structures, a trendline formed which supports the hypothesis that the longer the duration that cathodic protection is applied to a structure, the larger the shift in steel potential that can be expected.

The trend was applicable to all structures in the study with the exception of structure 6. For structure 6, there was a potential shift to less negative values, however the shift occurred for fewer references and was of smaller magnitudes than the other structures. This is because structure 6 is situated in the most aggressive marine environment (defined as high chloride and constant wetting and drying of the concrete) and the high chloride concentrations in the concrete are more easily replenished by the environment. In the scenario of

structure 6, re-passivation of the steel was less effective and this is partially due to the higher concentrations of chloride, oxygen and moisture which are available in the concrete near the surface of the embedded steel.

In the laboratory research, the same occurrence was observed with the high chloride blocks 4 and 6 in comparison to the behaviour of low chloride block 3. For block 3, while being energised with the least current density, the steel potential still shifted to more positive values than with the high chloride blocks. While it was outside the time constraints of the experimental work, it is expected that this shift to more positive values in test block 3 will be sustained for a longer period of time in comparison to the high chloride blocks.

The monitoring data obtained from the in-service CP systems was collected and assessed in accordance to the current applicable standards for cathodic protection in Australia. The collected data, in conjunction with the laboratory experimentation, both indicate a clear net improvement of the corrosion resistance of embedded rebar as a result of the application of cathodic protection current.

### 3.4 Reduction in protection current over time

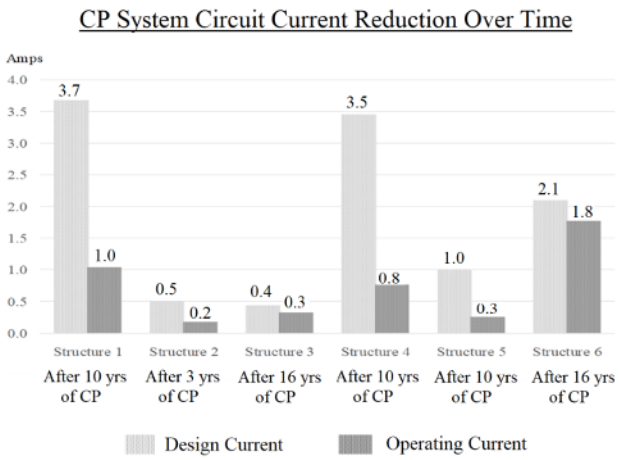


**Figure 5**. CP system circuit current reduction over time

The monitoring data from the 6 cathodic protection installations confirmed that, in all cases, the cathodic protection current required to maintain corrosion protection (as per the applicable standards) reduced over time. The decreases in current over time varied between structures:

Structure 1: The reduction of current over 10 years was measured at 73%.

Structure 2: The reduction of current over 3 years was measured at 60%.

Structure 3: The reduction of current over 16 years was measured at 25%.

Structure 4: The reduction of current over 10 years was measured at 77%.

Structure 5: The reduction of current over 10 years was measured at 70%.

Structure 6: The reduction of current over 16 years was measured at 14%.

For structures 3 and 6, the moderate level of current reduction after 16 years of CP system operation (25% and 14% respectively) is attributed to the harsh environment where these structures are situated and the exposure conditions of most of the protected elements in mostly in tidal and splash zones.

It is important to note that based on the data of the 6 operating systems, for a relatively small percentage of the embedded rebar, there was no evidence of residual effect. This could be related to large variation of chloride content at the steel level between different elements of the structure, initial current density required to maintain protection, and various construction and design issues outside the scope of this research.

### 3.5 Analysis of operating data from CP systems

In general, the data suggests that the longer the duration of CP operation, the greater the resulting residual effect. However, it is important to note that the duration of current interruption for the 6 systems varies from 24 hours to 3 years and full depolarized potential may not be achieved for some systems. In addition, we note that the natural potential and depolarised OFF potentials are affected by tides. While tidal variation was taken into consideration for all measurements, it may still present some level of inaccuracies of data.

Based on the laboratory test results and analysis of data from the 6 operating CP systems, it can generally be concluded that for a large percentage of embedded rebar in a reinforced concrete structure subject to impressed current cathodic protection, the direct result of cathodic protection is not only stopping reinforcement corrosion but improving the corrosion resistance of the embedded rebar. The primary contributing factors for improving the corrosion resistance of embedded rebar are the reduction of chloride concentration at the steel level and the passivation of the embedded rebar as a direct result of hydroxyl ion generation at the rebar by the cathodic protection current.

## 4. Conclusions

- In all three reinforced concrete test blocks, following the accelerated CP testing, a notable shift in steel potential to less negative values occurred. The steel potentials shifted in the range of 150 to 300 mV.
- For test block 3, the average potential shifted from a classification of >95% probability of corrosion to <5% probability of corrosion as per the guidelines in ASTM-C876-80 Standard. Test blocks 4 and 6 improved their potential readings from >95% probability of corrosion to about 50% probability of corrosion. The results ascertain that following sustained cathodic protection treatment, steel

embedded in chloride contaminated concrete can undergo a sustained electrochemical improvement in corrosion resistance (ie. residual protection).

- The analysis of monitoring data from in-service cathodic protection systems showed that for all 6 structures, there was a steel potential shift to more positive values following various extended durations of CP application. Moreover, the longer the duration of CP application, the greater the extent of residual protection that was afforded to the structures.

- Under CP treatment, chloride concentrations can decrease near the vicinity of the steel, with a direct effect on improving the corrosion resistance of the embedded steel.

- The CP current required to maintain protection to embedded rebar (based on the applicable standards) reduced over time as a result of steel passivation. This was demonstrated by the monitoring data from the three experimental test blocks, and the review of in-service structures. The level of reduction varies substantially between different structures and this topic could be subject to further research.

- CP-protected concrete structures situated in harsh marine environments (exposure to constant chloride, oxygen and water in tidal/splash zones), can expect a less pronounced residual effect following cathodic protection application and require higher cathodic protection current to maintain protection in accordance to current applicable standards.

## 5. References

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