DURABILITY ISSUES ASSOCIATED WITH THE DESIGN OF REINFORCED CONCRETE STRUCTURES IN MARINE ENVIRONMENTS

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Abstract

In recent years, durability requirements are often specified for new reinforced concrete structures especially for structures to be built in marine environments. It is evident today that the use of high performance concrete, good concrete cover, corrosion inhibitors and protective coating is not sufficient to provide corrosion prevention for reinforced concrete structures in harsh marine environments. Various corrosion prevention measures such as the use of corrosion resistant reinforcement and cathodic prevention have been used in the past 20 years to improve the corrosion resistance of reinforcement for new reinforced concrete structures in marine environments. This paper will provide a brief review of these measures and highlight their applicability under various circumstances.

INTRODUCTION

Reinforced concrete is a composite material that relies on the high compressive strength of concrete and the high tensile strength of steel for its mechanical performance. Steel has poor corrosion resistance and concrete has good anti-corrosion properties. The hydration process of concrete leads to the formation of hydroxides which raises the pH level of the cement to around 12.5 and provides a stable oxide layer on the steel surface, which prevents the anodic dissolution of the steel. Reinforced concrete failure is caused by the corrosion of the steel reinforcing bars as a result of the destabilisation of the oxide layer. When the passivity of the steel partly or completely breaks down, either as result of carbonation or chlorides, the corrosion will start. This means that the electrochemical potential of the steel locally becomes more negative and forms anodic areas, while the other portions of the steel which have the passive layer intact will act as catchment areas for oxygen and will form cathodic areas. In spite of the development of high performance concrete from the early 1970s until today, it is evident that the application of high performance concrete in conjunction with measures such as protective coating, thick concrete cover and corrosion inhibitors is not necessarily good enough for ensuring high durability of concrete structures in marine environments. For this reason, various corrosion prevention measures have been used and specified for new reinforced concrete structures to be built in marine environments. This paper will provide an overall review of these measures and will present a case study for a corrosion prevention measure applied to a structure with a 100 year design life requirement.

CORROSION PREVENTION MEASURES

Corrosion prevention measures include: modifying the concrete mix design to decrease concrete permeability and provide an adequate cover to reinforcement; coating application to limit chloride ingress into the concrete; use of corrosion-resistant reinforcement; addition of inhibitors to the fresh concrete; and cathodic prevention by impressed current.

Mix design, concrete cover and coating application

The quality of concrete is of major importance in determining the durability of reinforced concrete structures. Although concrete is a dense material, it contains pores and many of these pores are interconnected to form a network of channels that allow water and oxygen, both important to steel corrosion, to penetrate into the concrete. For this reason, a low water/cement ratio will lead to either a lower number of pores or smaller pores in the concrete, both of which can lead to a reduction of concrete permeability and to conductivity of the concrete. In addition to selecting a lower cement ratio in the concrete, the selection of the cement type and the addition of mineral admixtures such as silica flume, fly ash and slag will play a significant role in reducing the corrosion rate of reinforcement in concrete.

An adequate layer of concrete to the first layer of reinforcing steel may under some circumstances, delay the ingress of chloride ions. The adequate depth of concrete cover is normally stated in various standards, subject to the exposure condition of the structure. The minimum depth of concrete cover must be adjusted to allow for tolerances caused by construction practices.

For dense, high quality concrete with adequate concrete cover, carbonation induced corrosion of the embedded steel is not considered to represent a major problem, however, for concrete structures in marine environments, regardless of the quality of concrete and the thickness of the concrete cover, it appears that it is only a matter of time before detrimental amounts of chloride reach the embedded steel through the concrete covers or concrete cracks and cause reinforcement corrosion and concrete spalling.

The penetration of chloride takes place through uncracked concrete mainly by capillary absorption and diffusion. When a relatively dry concrete is exposed to salt water, the concrete will absorb the salt water relatively fast and wetting and drying of the concrete especially in tidal zones can accelerate the accumulation of high concentration of salt in the concrete. Furthermore, similar areas of concrete with similar exposure conditions will have variation in the concrete deterioration process as it is very difficult to ensure homogeneity of concrete after being placed.

In certain applications where a 100 year design life requirement is specified for structures located in marine environments, the use of various chloride diffusion modelling, carbonation modelling and durability assessment of other deterioration mechanisms may lead to the theoretical development of concrete mixes and design covers that may provide theoretically a 100 year design life. Typical concrete used for such applications is 50MPa compressive strength concrete with, for example, a binder combination of 52% Shrinkage Limited (SL) cement, 25% fly ash, 23% blast furnace slag, 600Kg/m3 cement content, 0.38 W/C ratio, 75 mm concrete cover and 500 microstrain drying shrinkage at 56 days. There is no doubt, that the use of such concrete will lead to a substantial increase in the design life of a structure in a harsh marine environment, however there are many other factors that could not be considered in the modelling process, such as concrete cracking; wetting and drying effect in accelerating the rate of chloride penetration; early-age exposure to seawater before the concrete has gained sufficient maturity and density; high temperatures during concrete placement;

homogeneity of the concrete; workmanship problems especially in relation to concrete cover; and finally, the nature of the formation of the corrosion cell due to chloride ingress within the structure which only requires ingress of chloride to the steel level at various crack locations to start the development of unlimited numbers of corrosion cells within the concrete itself.

Coating the external surfaces of concrete may in 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.

Corrosion resistant reinforcement

The final and most important line of defence against corrosion is the reinforcing steel. As a measure for preventing the corrosion of steel in building concrete, various types of corrosion resistant reinforcement have been used in the past.

Epoxy coated reinforcement

Epoxy coated rebars are carbon steel coated with stable organic coatings (epoxies) to serve as a barrier for isolating the steel from moisture, chloride ions and oxygen to prevent corrosion.

Epoxy coated rebars were introduced in the mid 1970s in the United States as means of extending the useful life of reinforced concrete bridge components by minimising concrete deterioration caused by corrosion of the reinforcing steel. The epoxy coatings are intended to prevent moisture and chlorides from reaching the steel.

There are various documentations regarding this subject with some of the documents showing favourable performance of epoxy coated rebars especially when used in areas of low corrosion risk.

When epoxy coated rebars have been used in substructures that are exposed to a severely corrosive environment, the epoxy coated rebars did not perform well. Significant premature corrosion of the epoxy coated rebars was observed in many structures after 5-10 years from the date of construction.

The main reasons for the failure of the epoxy coated rebars are:

- Under-film corrosion because of the migration of water, oxygen and chlorides through the concrete and epoxy to the steel surface;
- Wet adhesion loss resulting in the separation of the coating from the substrate; and
- Disbondment of the epoxy coating from the reinforcing steel which starts at coating defects.

It is the authors' opinion that the use of epoxy coated rebars for corrosion prevention should not be considered under any circumstances. In areas of low corrosion risk, the use of carbon steel with high performance concrete and good concrete cover is sufficient to prevent any corrosion from occurring. If the oxide layer which forms around the steel is not damaged due to carbonation or chloride ingress, there should be no issues with corrosion. For the areas of high corrosion risk in marine environments, the use of epoxy coated rebars will not under any circumstances provide the adequate corrosion prevention to extend the life of the structure.

Galvanised steel reinforcement

Steel reinforcing bars can be protected with a coating applied by dipping properly prepared steel bars into a molten bath of zinc.

Hot-dipped galvanised coatings for reinforcing bars have been used over the last fifty years in many countries to improve the service life of concrete structures.

Galvanising constitutes a means to extend the service life of rebars in concrete structures that will be subjected to carbonation. A substantial increase of the service life of the structure can be achieved by using galvanised steel.

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 required for the use of galvanised reinforcement. 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

The term stainless steel refers to a group of corrosion resistant steels containing a minimum of 12% chromium. Various alloying additions (nickel, titanium, nitrogen.etc) can be added to provide different mechanical and corrosion properties. The use of stainless steel in concrete is related to its capacity to resist corrosion in chloride-contaminated structures.

Stainless steel reinforcement has been used in various countries in structures that are located in aggressive environments. Stainless steel has been used in construction joints or critical gaps between columns and decks. There are no extensive performance data available from long-term use of stainless steel as reinforcement in concrete.

Because of the very high cost of stainless steel reinforcement, 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 of a reinforced concrete element in the tidal/splash zone. Galvanic corrosion in this case between stainless steel and carbon steel should be investigated.

Corrosion inhibitors

Corrosion inhibitors are chemicals that can be added to the concrete to decrease the corrosion rate. The inhibitors can be subdivided into three categories, anodic inhibitors, which are used to reduce the anodic reaction rate, cathodic inhibitors, which are used to reduce the cathodic reaction rate, and mixed inhibitors which are used to reduce cathodic and anodic reaction rates.

The inhibitors are used as a preventive measure for new reinforced concrete structures in aggressive environments with a known future risk of chloride-induced corrosion. Corrosion inhibitors are marketed separately as admixtures or they are present in the repair product used for conventional patch repair.

There are various questions in relation to the application of corrosion inhibitors as admixtures to reinforced concrete. Some of these questions are related to the long-term experience with corrosion inhibitors, the effect of corrosion inhibitors 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.

In general, 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.

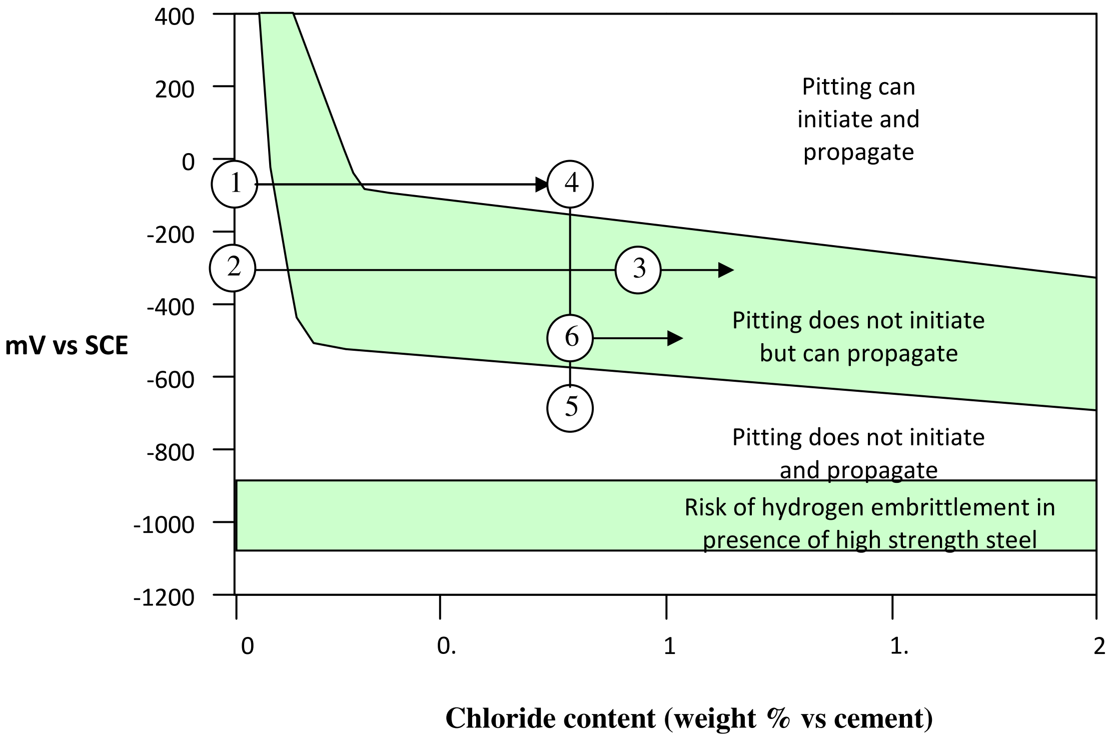
Cathodic prevention

Steel embedded in alkaline-free chloride concrete is in the passive condition. This passivity breaks down when the level of chloride content exceeds the threshold and pitting corrosion can initiate.

Cathodic prevention 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 basic philosophy of cathodic prevention is that a much smaller cathodic prevention current is required to prevent pitting corrosion compared to a higher current requirement to suppress ongoing corrosion. The cost of the application of cathodic prevention is substantially lower than the cost of the application of cathodic protection.

The conditions for pitting initiation and propagation were pointed out by Pourbaix who during the 1970s introduced the concept of "imperfect passivity" and "perfect passivity" intervals. The different domain of potentials is shown below. As can be seen from the graph, for cathodic prevention, a modest lowering of the steel potential can produce a significant increase in the critical chloride level. The free corrosion potential of steel ranges from –200mV to 0mV versus saturated calomel electrode (SCE). Pitting corrosion can take place if the chloride level exceeds 0.4%w/w cement.

If a cathodic prevention current is applied to steel in chloride-free concrete, this will allow the steel to remain passive even when the chloride reaches a considerably high content. The cathodic prevention current produces hydroxide ions at the steel surface and causes the chloride ions to move toward the anode away from the steel.



Graph showing: cathodic prevention (1→2→3→); cathodic protection restoring passivity (1→4→5→); and cathodic protection reducing corrosion rate (1→4→6→)

When cathodic prevention is applied, the initiation of a new pit is prevented but pitting can propagate. For this reason cathodic prevention has to be applied before corrosion initiates and must be maintained throughout the service life of the structure. If pitting corrosion has initiated, the current capacity typical for cathodic prevention will no longer be sufficient and cathodic protection current would be required.

The use of cathodic prevention for prestressed steel will eliminate the risk of hydrogen evolution because a lower current is required to prevent the initiation of pitting corrosion. A typical operating current for cathodic prevention ranges from 1-2mA/m² of steel. The cathodic prevention design current density is normally 10mA/m² of steel surface. The design for a cathodic prevention system, system monitoring and operation is similar to cathodic protection. The main difference is related to the lower current density requirement and the ease of installation during construction.

CATHODIC PREVENTION CASE STUDY – SYDNEY OPERA HOUSE WESTERN UNDER BROADWALK

Chloride-induced corrosion of reinforcement had caused deterioration problems in some of the elements of the substructure of the Sydney Opera House Western Under Broadwalk. During 1996-1997, a major rehabilitation programme was established by the New South Wales Department of Public Works and Services for this structure. As part of this programme, cathodic protection and prevention systems were installed in order to stop the corrosion in the existing elements of the structure (piers and soffit) and to improve the corrosion resistance of the reinforcement of the new precast elements, which were expected to become chloride contaminated.

DESIGN CONCEPT

Materials

Mesh ribbon anode LIDA® grid was used as the anode material throughout. The specifications of the mesh ribbon anode grid are as follows:

- Width: 20 mm
- Thickness: 0.5 mm
- Current output: 5.5 mA/m

This patented CPrev system involves the use of mesh ribbon anode grid attached onto the reinforcing cage with specially designed insulating cementitious material prior to pouring. The anode grid assembly for the precast elements is made of an array of parallel mesh ribbon anode grids supported by the composite cementitious spacer above which the anode elements are secured by means of plastic fixings. The assembly is positioned on the reinforcing steel and fixed by plastic ties. A titanium bus bar is welded to each anode strip to connect them together. The main characteristics of this assembly is that by varying the degree of expansion, the width and the spacing between the parallel strips, the current output of the anode assembly can be easily varied to match the variations of the steel density of the concrete structure[1].

Electrical Zoning

When selecting electrical zones, the following considerations were taken into account:

1) The different environmental conditions of the elements to be protected such as tidal and atmospheric zones.

2) Size of power supply units.
3) Geometry of the structure,

The system was divided into three zones as shown in Table 1 and Figure 2:

Table 1: Electrical Zoning Description

Zone	Element	Environment
6	A-Frame and Tie Beam	Atmospheric
7	A-Frame Base	Tidal/Splash
8	Walkway	Tidal/Splash

The structure was divided into four sections, A, B, C and D. Within each section a substation is installed (total of 4 substations) with a separate DC power supply for each zone of the system[1].

Figure 2: Electrical Zoning of System

Monitoring

The system contained a total of 35 embedded reference electrodes. The type of electrodes used was Silver/Silver Chloride (Ag/AgCl) and mixed metal oxide activated titanium electrodes suitable for long-term use in concrete. As a part of incorporating the new A-frames, tie beams and walkways to the existing structure, prestressing bars were used in the construction of the new reinforced concrete precast elements.As a result of the tidal variation, these elements were subject to combined CPrev current from the embedded grid anode system and from the water anode system installed nearby to protect the piles supporting the western underbroadwalk. In order to avoid the potential overprotection conditions, a special shielding detail was adopted for the prestressing bars. In addition to the application of the shielding detail, some of the reference electrodes were placed in selected locations near the prestressing bars particularly for overprotection monitoring purposes.

Protection Criteria

Australian Standard AS2832.5 provides the following protection criteria for cathodic protection of steel in concrete structures.

No instant off steel/concrete potential shall be more negative than –1100 mV for plain reinforcing steel or more negative than –900 mV for prestressing steel with respect to Ag/AgCl/0.5M KCl.

Adjustment shall be based on meeting one of the following criteria:

(a) A potential decay criterion. A potential decay over a maximum of 24 h of at least 100 mV from instant off.
(b) Extended potential decay criterion. A potential decay over a maximum of 72h of at least 100 mV from the instant off potential subject to a continuing decay and the use of reference electrodes (not potential decay sensors) for the measurement extended beyond 24 h.
(c) Absolute potential criterion. An instant off potential more negative than –720 mV with respect to Ag/AgCl/0.5M KCl.
(d) Absolute passive criterion. A fully depolarised potential, or a potential which is continuing to depolarise over a maximum of 72 h after the cathodic protection system has been switched off, which is consistently less negative than –150 mV with respect to Ag/AgCl/0.5M KCl.

Both criteria (c) and (d) assess the system based on absolute values of the measured reading. These criteria need to be used with caution, especially with systems of this age, as the potential of the reference electrode is likely to shift with time. Calibration of references is required to obtain an accurate absolute value, which is very difficult for references in concrete. Criteria that do not rely on absolute value criterion, such as the 100 mV shift, are more reliable when using references of this age, and shall be used for the purposes of this paper.

INSTALLATION

A brief description of the installation carried out in 1995-96 is provided below.

Reinforcing bars were welded together within each element to ensure that electrical continuity exists between them. An assembly of grid anode/cementitious spacers was delivered to site and fixed to the reinforcement cage using plastic ties. Conductor bars were spot welded to strip anodes and anode and steel connections were established for each precast element. Reference electrodes were fixed to the steel cages by means of plastic ties.

Continuity testing of steel bars and short circuit testing between rebar and anode was carried out prior, during and after concrete application. Each precast element was subject to steam curing for 12 hours and then delivered to site. As a part of the testing procedure of precast elements, fixed current was applied to the steel/anode circuit for each precast element. Change of steel potential with respect to embedded reference electrodes or external reference electrodes on the concrete surface were measured. For each type of precast element (walkway, A Frame and mid span tie), extensive potential mapping was undertaken in order to check current distribution and for design verification purposes. A total of 18 A Frames, 17 walkways and 17 mid span ties were cast and delivered to site for installation over a period of approximately 6 months. These new elements replaced the old elements, which were cut out and removed from site due to excessive deterioration problems. All cables from the precast elements were terminated to the 4 substations located along the western underbroadwalk.

System commissioning in 1996 verified all components of the system were operating satisfactorily.

MONITORING DATA

The system was monitored at 6-monthly intervals since 1996. The results collected during each monitoring session includes:

- “As Found” Current and Voltage measurements
- Steel reinforcement potentials to each reference electrode with the system switched on (CP On)
- Steel reinforcement potentials to each reference electrode free of voltage gradient error (CP Instant Off). This measurement is taken 0.1-1s after the system is switched off, which allows measurement of the actual potential immediately prior to depolarisation of the steel.
- Steel reinforcement potential to each reference electrode after the system has been switched off for 24 hours (24 hr Off)
- The “24 hr Decay” potential is then calculated for each reference electrode as follows: 24 hr Decay Potential = 24 hr Off Potential – CP Instant Off Potential
- Adjusted current and voltage values.

Recently, a comprehensive audit of the system was undertaken. The following additional information was obtained:

- Reference electrode audit to identify faulty or unstable references
- Measurement of 24 hr Off and 72 hr Off steel potentials to permanent reference electrodes
- Measurements of CP On, CP Instant Off, 24 hr Off and 72 hr Off steel potentials using a portable Cu/$CuSO_4$ reference electrode on all precast elements. These tests were performed to confirm protection was being maintained on all pre-cast elements (including those that do not have references installed) and to verify permanent reference electrode readings.

Monitoring data since 1996 has been collated in order to assess the overall performance of the system over its operational life. A sample of the data is presented in this paper for discussion.

SYSTEM PERFORMANCE

General

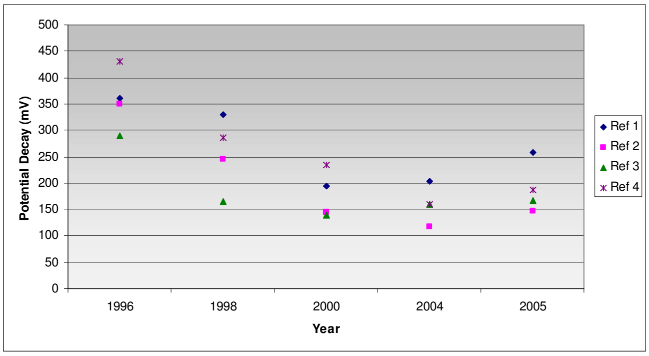
No visible deterioration, spalling or delamination has been observed on any of the precast elements with CPrev installed. In addition, it has been verified with a portable reference electrode that each and every precast element is receiving CPrev current. Therefore, the installed system components such as anodes, conductor bar, cementitious spacer, positive connections, negative connections, cabling, junction boxes and the majority of reference electrodes are still functioning as required with no sign of significant deterioration. The four substation power supply units are generally in good condition, with only a minor number of electronics needed to be replaced over the years. Each component of the system was designed to be reliable in the long-term and these results confirm the design has been adequate.The reference electrodes were tested for stability and for signs of faulty behavior. Only 17% of reference electrodes were deemed to be faulty, most of which were Ag/AgCl type references. These references were excluded from future testing.

System Control

The CP Instant Off potential of the reinforcement measured using the embedded reference electrodes and the CP Instant Off potential of reinforcement measured using an external reference electrode on the concrete surfaces of the precast elements receiving CPrev were maintained below the level that can cause hydrogen evolution due to the prevention current. The power supply units were operating under constant voltage. This confirms that CPrev can be used safely in prestressed concrete structures providing the system is operating in voltage control mode and the maximum operating voltage is limited for the system operation. The main reason for this is the low current required under cathodic prevention conditions.

MONITORING DATA

Figures 3 to 5 below present the 24 hr potential decay values for a sample of the permanent reference electrodes since 1996. The results indicate that in the majority of cases the decay was greater than 100mV, indicating full protection had been maintained.



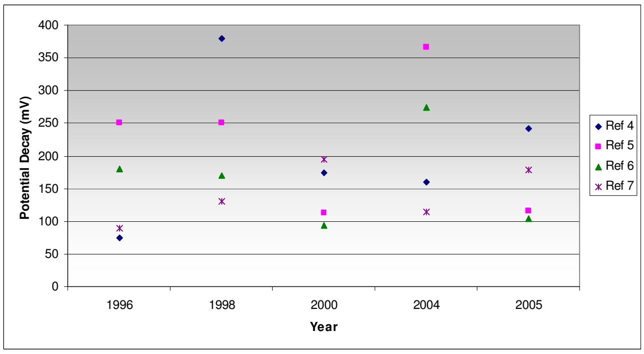


Figure 3: Zone 6 Reference Electrode Potential Decays since 1996 Figure 4: Zone 7 Reference Electrode Potential Decays since 1996

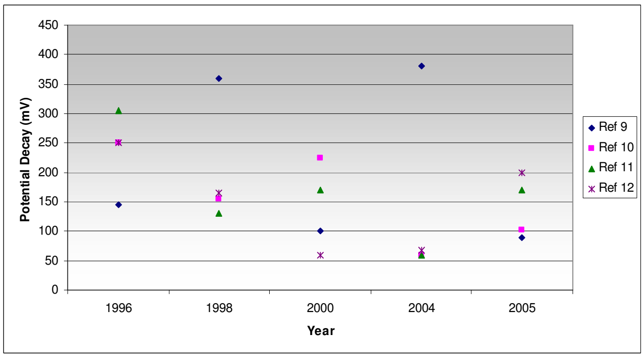


Figure 5: Zone 8 Reference Electrode Potential Decays since 1996

A sample data of the most recent system monitoring is presented in Table 2.

Table 2: Permanent Embedded Reference Electrode Monitoring Results

				Potential of steel reinforcement (mV)			
Reference	Type	Location	Zone	CP ON	CP Instant Off	24 hr Off	24hr Decay
A61	Titanium	A-Frame	6	-291	-272	-14	258
A62	Ag/AgCl	A-Frame	6	-132	-122	+25	147
A71	Titanium	A-Frame Base	7	-334	-316	-93	223
A72	Ag/AgCl	A-Frame Base	7	-408	-394	-215	179
W81	Titanium	Walkway	8	-419	-408	-305	103
W82	Ag/AgCl	Walkway	8	-471	-481	-335	146

The reference electrodes were embedded only in selected precast concrete elements. In order to ensure that all the elements of the structures are receiving CPrev current, external potential mapping testing using a calibrated Copper/Copper Sulphate reference electrode was performed for each element of the structure. This testing includes measuring at selected pre-determined locations on the concrete surfaces the CP On potential, CP Instant off potential and the 24hr and 72 hr Off potentials. The results of the test suggest that the cathodic prevention current is providing full protection to all the elements of the structure. A sample of the results is presented in Table 3 for all zones at various locations.

Table 3: Potential of Steel Reinforcement measured by external reference electrode

Element	Zone	Potential vs Portable Cu/CuSO4 (mV)					
		CP ON	CP Instant Off	24 Hour Off	24 Hr Decay	72 Hour Off	72 Hr Decay
A-Frame	6	-925	-383	-46	337	3	386
Mid-Tie Beam	6	-419	-308	-50	258	3	311
A-Frame	6	-950	-436	-128	308	-69	367
Mid-Tie Beam	6	-483	-462	-64	398	16	478
A-Frame (sub A)	6	-492	-384	-62	322	29	413
Mid-Tie Beam	6	-635	-479	-104	375	-27	452
A-Frame	6	-767	-413	-134	279	-74	339
Mid-Tie Beam	6	-402	-284	-46	238	33	317
A-Frame	6	-887	-459	-244	215	-140	319
A-Frame Base	7	-610	-503	-337	166	-352	151
A-Frame Base	7	-663	-600	-430	170	-495	105
A-Frame Base	7	-815	-673	-444	229	-410	263
A-Frame Base	7	-768	-579	-418	161	-411	168
A-Frame Base	7	-730	-576	-368	208	-354	222
A-Frame Base	7	-843	-633	-408	225	-325	308
Walkway	8	-684	-603	-394	209	-325	278
Walkway	8	-710	-635	-415	220	-456	179
Walkway	8	-860	-700	-468	232	-574	126
Walkway	8	-964	-784	-675	109	-485	299
Walkway	8	-743	-700	-545	155	-495	205
Walkway	8	-920	-860	-723	137	-619	241

The decay values measured by both permanent and portable reference electrodes indicate full protection is being maintained on the structure with the present current and voltage outputs. The results can be used to confirm that the operating currents are satisfactory for protection, although not excessive.

CONCLUSION

In order to improve the corrosion resistance of reinforced concrete structures to be built in marine environments, it is essential to undertake durability assessment, durability design and durability planning as a part of the design phase and construction phase in order to minimise the risk of long term deterioration of the structure.

For any structure located in a marine environment, the exposure conditions should be established and the elements of the structure should be classified based on corrosion risk.

It is the authors' opinion that for any elements of the structure that are classified in the low corrosion risk category, a combination of the use of high performance concrete, good concrete cover and external coating can be used to ensure long term durability of the structure and to increase its life with minimal maintenance.

For any elements of the structure that are classified as high corrosion risk areas, such as the tidal and splash zones, the only economically viable option that can be considered is the use of high performance concrete combined with the use of good concrete cover and the installation of a cathodic prevention system. It is important to note that any cathodic prevention system should be maintained for the life of the structure as an integral part of the maintenance program of the structure.

The use of a suitable type stainless steel reinforcement can also be considered to improve the corrosion resistance of reinforcement. However, this should only be considered only if stainless steel is used for the entire structure and no stainless steel is used in conjunction with carbon steel in order to avoid potential galvanic corrosion problems.

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