EXAMINING THE PERFORMANCE OF CATHODIC PROTECTION TECHNOLOGIES IN REINFORCED CONCRETE STRUCTURES IN ACCORDANCE WITH AUSTRALIAN STANDARDS

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ABSTRACT

Over the past four decades, impressed current cathodic protection (ICCP) has become a predominant method for safeguarding major reinforced concrete infrastructure in Australia against chloride-induced corrosion. In recent years, the introduction of new galvanic and hybrid anode systems has offered potential solutions for reducing monitoring costs associated with ICCP.

This paper conducts a comprehensive analysis of years of monitoring data, comparing the performance of ICCP, galvanic, and hybrid anode installations on various bridges across Australia.

This paper presents data on the comparative effectiveness of these corrosion protection systems, in accordance with the applicable protection criteria detailed in Australian Standard AS 2832.5 – 2008 (R2018).

Keywords: Corrosion, cathodic protection, impressed current, galvanic anode, hybrid anode

1 INTRODUCTION

Impressed Current Cathodic Protection (ICCP) for reinforced concrete structures is a well-established technology that offers long-term corrosion protection for reinforced concrete structures in marine environments. Over the past 40 years, this technology has been widely implemented across numerous structures in Australia, becoming the preferred choice for asset owners seeking to safeguard against chloride-induced corrosion.

Sacrificial Anode Cathodic Protection (SACP) and Hybrid Anode Cathodic Protection (HACP) have recently experienced substantial growth. These systems are becoming increasingly popular due to their simplicity and low monitoring and maintenance requirements.

The selection of the optimal corrosion protection system for structures affected by chloride-induced corrosion typically involves consideration of several factors. These include the cause and extent of concrete deterioration, the level of corrosion activity, the continuity of the embedded rebar, the size and location of the structure, the remaining service life and the cost and maintenance requirements of the chosen repair method.

This paper presents the basic theory of ICCP, SACP and HACP systems, and a review of the performance of these corrosion protection systems installed on various marine structures in Australia. The review is based on the cathodic protection criteria of Australian Standard for steel in concrete AS 2832.5 – 2008 (R2018) (1).

2 CATHODIC PROTECTION CRITERIA

The protection criteria in Australian Standard, AS 2832.5 – 2008 (R2018) (1) are as follows:

> *The overriding requirement providing for safe and effective operation of the cathodic protection system is that no instantaneous 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 KCI.*
>
> *The initial and continuous adjustment of the cathodic protection system shall be based on meeting at least one of the following criteria which are listed in no priority order:*
>
> *(a) Potential decay criterion. A potential decay over a maximum of 24 h of at least 100 mV from the instantaneous OFF potential.*
>
> *(b) Extended potential decay criterion. A potential decay over a maximum of 72 h of at least 100 mV from the instantaneous OFF potential subject to a continuing decay and the use of reference electrodes (not potential decay sensors or pseudo reference electrodes) for the measurement extended beyond 24 h.*
>
> *(c) Absolute potential criterion. An instantaneous OFF potential (measured between 0.1 s and 1 s after switching the D.C. circuit open) more negative than -720 mV with respect to Ag/AgCl/0.5M KCI.*
>
> *(d) Absolute passive criterion. A fully depolarized potential, or a potential which is continuing to depolarize 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 KCI.*

2.1 Applicability of Protection Criteria

During the operation of a cathodic protection system, changes in the concrete chemistry will occur over time and this will affect the stability of permanently embedded reference electrodes. The variations in readings can be significant and may affect readings which relate to absolute values. However, a depolarisation test to confirm protection levels will not be affected provided the reference electrode is stable during the period of depolarisation. Calibration of references is routinely required if the depolarisation criteria are not used.

Criterion a) and b) will not be impacted by the calibration of embedded reference electrodes. For criterion a), true or inert reference electrodes can be used for assessment, while for criterion b), only true reference electrodes can be used as required by the standard.

For criterion c), the absolute potential criterion can be applied to all concrete elements located in immersed conditions as the permanent reference electrodes located in water can be calibrated against a portable Ag/AgCl/0.5M KCI reference electrode. However, for true reference electrodes located in atmospheric concrete elements, the use of criterion c) and d) may not be accurate as calibration of reference electrodes located in concrete cannot be performed after installation.

All of the systems assessed in this paper were installed to protect tidal and/or atmospheric zones. For these systems, criterion a) has been used as the primary criterion for system adjustment for the ICCP systems and for the assessment of system performance of the SACP and HACP systems.

3 Cathodic Protection Technology

When steel corrodes in concrete, the electrochemical process is comparable to that of a battery. In a battery, electrons which are generated because two dissimilar metals are exposed to an acidic solution (paste or gel in conventional batteries) which corrodes one metal and creates a harmless reaction in the other. This corrosion reaction at the 'anode' generates electrons that are consumed by the 'cathode'.

When steel reinforcement begins to corrode in concrete, a small area becomes the positive pole (anode) and another much larger area becomes the negative pole (cathode). The corrosion current flows out of the steel at the anode (the corroding part), passes through the concrete and to another part of the steel where there is no corrosion occurring (the cathode). This current flow is called the corrosion circuit, and the steel dissolved at the anode forms iron oxide.

In a practical battery, the electrical connection between positive and negative poles can be disconnected. The circuit is then broken and the dissolution of metal stops.

In concrete, the corrosion circuit is buried in the structure and the electrical current running through the concrete cannot easily be disconnected. Cathodic protection technology is based on stopping the current from running through the concrete by providing a new current from an external source via an external anode in contact with the concrete. The flow of electrons between the new anode and the reinforcing steel changes the previously positive poles (anodes) into current receivers. Therefore, all of the reinforcement becomes the negative pole or cathode, and hence the name 'cathodic protection'.

For reinforced concrete structures, there are three types of cathodic protection systems; Impressed Current Cathodic Protection (ICCP), Sacrificial Anode Cathodic Protection (SACP) and Hybrid Anode Cathodic Protection (HACP).

3.1 Impressed Current Cathodic Protection (ICCP)

Impressed current cathodic protection (ICCP) is a well-established technology for the corrosion protection of reinforced concrete structures. All aspects related to the design, installation, monitoring and protection criteria for ICCP systems are documented in global standards such as the NACE Standard SP 2290-2007 (2), International Standard ISO 12696:2012 (3) and the Australian Standard AS 2832.5 – 2008 (R2018) (1).

Impressed current cathodic protection involves the installation of an external anode within the concrete (or at a finite distance from the concrete, with continuous electrolyte connectivity between the anode and cathode) to provide protection to the embedded steel. The application of cathodic protection current promotes the development of steel passivity as a result of the production of hydroxyl ions at the steel-concrete interface which stabilise the protective passive film on the steel reinforcement (4). The protective oxide layer inhibits the formation of anodic and cathodic sites on the embedded steel, and this stops the corrosion reaction. There are two common types of anodes which are used in most concrete ICCP systems in Australia. Both anodes use Mixed Metal Oxide (MMO) activated Titanium mesh, however with a variance in shape and the method of installation.

3.2 Sacrificial Anode Cathodic Protection (SACP)

This technology has become increasingly attractive in recent years because of its simplicity and low monitoring and maintenance requirements. The anode which is normally made from zinc, is connected to the reinforcing steel and the potential difference between the zinc and the steel causes a protection current to flow from the zinc to the steel. Galvanic anodes in concrete are usually supplied with proprietary backfill which provides space for the products of anodic dissolution. Most of the recent innovation and research in galvanic anode technology has been associated with the backfill material.

For many years, galvanic anode systems have been installed in conjunction with concrete patch repairs to reduce the occurrence of the incipient anode effect and to prolong the life of the patch repair. The installation of galvanic anodes had been traditionally viewed as an additional low-cost corrosion prevention measure. Normally, no monitoring system is installed for this type of applications. The long-term performance of anodes cannot be assessed or verified.

In recent years, SACP systems have been installed for global cathodic protection of reinforced concrete elements in bridges and wharves such as piles, headstocks… etc. The anodes are installed in most cases in drilled holes at selected spacing. For some structures, reference electrodes are installed in selected elements to monitor the level of corrosion protection. The monitoring system is installed for information only as the cathodic protection current from the SACP systems cannot be adjusted. The performance of these systems is assessed based on the applicable Australian Standard for steel in concrete AS 2832.5 – 2008 (R2018) (1). However, achieving compliance with the AS2832.5 criteria, particularly over the long-term, has proven challenging with SACP in concrete.

3.3 Hybrid Anode Cathodic Protection (HACP)

HACP systems differ from purely galvanic systems in their approach to corrosion protection. HACP technology involves the application of a temporary impressed current, followed by permanent galvanic protection. Initially, an impressed current is applied to realkalize active pits, halting active corrosion and restoring the reinforcing steel to a passive state. After a pre-determined period, the steel's passivity is expected to be maintained by galvanic anodes embedded in the concrete.

HACP system design is based on assumptions related to the estimated cathodic protection current required for the initial phase to passivate the reinforcement, and then the maintenance current required for the galvanic protection phase to maintain passivity of the reinforcement.

There are two common types of HACP system:

Type 1: The original hybrid anode system consists of galvanic anodes made of zinc and installed in backfill material in drilled holes in the concrete. The anodes are connected by individual cables to junction boxes and to temporary power supply units. The cathodic protection current is delivered to the structure through these anodes for a pre-determined duration of time during the first stage of the process to passivate the steel. The duration of the impressed current phase is related to the resistivity of the concrete and the ability of the system to deliver the required current at the maximum permitted circuit voltage to reach the specified current requirements for this phase. Following completion of the initial impressed current phase, the temporary power supply units are removed, and the anode cables are connected to the steel for phase 2 of the galvanic protection treatment. Normally, such a system would incorporate embedded reference electrodes for all circuits and permanent monitoring to assess whether additional current injection is required during the life of the system.

The installation requirements of Type 1 HACP systems are similar to the installation of impressed current systems in terms of cabling, junction boxes and reference electrodes. The hybrid anodes are installed in drilled holes in the concrete. In comparison to a ribbon anode ICCP system, the hybrid anode installation is more labour intensive and is more destructive due to the number of holes required for anode installation. The key difference between HACP systems and ICCP systems is that for HACP systems there is no permanent power supply unit to deliver ongoing cathodic protection current and there is no requirement for the ongoing maintenance of a power supply unit.

Type 2: A more recent development is HACP systems combining the impressed current phase and the galvanic anode into one HACP anode. This is achieved my incorporating a battery within the galvanic anode itself. Unlike Type 1 HACP systems, no external power is required for phase one, and this minimises cabling, junction boxes, and power supply units. The installation process is simplistic and similar to that of a normal SACP system. It is important to note that Type 2 HACP systems incorporate a permanent battery in each anode. Once phase 1 is completed, during which the battery provides current, the depleted battery remains permanently embedded within the concrete element.

4 Cathodic Protection System Performance

For the purpose of the assessment work included in this paper, the process was based on the following five categories:

1) **Meeting protection criteria**: 24 h decay greater than 100 mV.
2) **Approaching protection criteria**: 24 h decay greater than 80 mV and less than 100 mV.
3) **Provision of some level of protection**: 24 h decay greater than 50 mV and less than 80 mV.
4) **Provision of minimal level of corrosion protection:** 24 h decay greater than 30 mV and less than 50 mV.
5) **No corrosion protection:** 24 h decay between zero and 30 mV.

In this paper, the performance of the following anode systems was assessed:

ICCP Systems: Installations using MMO ribbon and MMO discrete anodes. The data was extracted from 3 ICCP systems operating for 8 years (Structure 1), 10 years (Structure 2) and 22 years (Structure 3). The data was assessed based on a total of 52 embedded reference electrodes in the three structures. The protected areas were the splash and atmospheric zones of the structures.

SACP Type 1: Installations with zinc anodes installed in drilled holes and encapsulated with proprietary backfill mortar injected into the holes. The data was extracted from 2 SACP systems operating for 3 years. The data was assessed based on a total of 24 embedded reference electrodes in both structures. The protected areas were the splash and atmospheric zones of the structures.

SACP Type 2: Installations with alkali activated zinc anodes (precast zinc in mortar) which can be embedded in the concrete cover or in drilled holes in concrete. The data was extracted from 4 SACP Type 2 systems which were operating for 3 years. The data was assessed based on a total of 29 embedded reference electrodes in the 4 structures. The protected areas were the splash and atmospheric zones of the structures.

SACP Type 3: Installation with alkali-activated distributed large zinc anodes used for overlay applications. For the SACP type 3, data was extracted from 1 structure operating for 3 years. The data was assessed based on 16 embedded reference electrodes in the pile caps and piers of this structure. The anodes were installed in the concrete overlay/jacket to provide corrosion protection to embedded steel in the original concrete.

HACP Type 1: Installation with a two-stage anode system, consisting of an impressed current phase powered by an external supply to passivate the steel, followed by a galvanic phase for ongoing protection. Data was collected from 152 embedded reference electrodes in 2 large concrete structures and monitored over 3 years. The protected areas were the splash and atmospheric zones of the structures.

HACP Type 2: Installation with a two-stage anode system, with an impressed current phase powered by a battery embedded within the anode. Data was analysed from 8 embedded reference electrodes in 2 piers, monitored over three years. The system provided protection within the splash zones, with anodes containing a 16Ah battery and 200 g of zinc installed within the concrete cover in a high-chloride environment.

5 Data Analysis

5.1 Impressed Current Cathodic Protection Systems

TABLE 1 - ICCP SYSTEM DATA

ICCP Systems		
Structure 1	Achieving protection criteria	94%
	Approaching protection criteria	6%
	Some level of corrosion protection	0%
	Minimal level of corrosion protection	0%
	No corrosion protection	0%
Structure 2	Achieving protection criteria	100%
	Approaching protection criteria	0%
	Some level of corrosion protection	0%
	Minimal level of corrosion protection	0%
	No corrosion protection	0%
Structure 3	Achieving protection criteria	80.96%
	Approaching protection criteria	9.52%
	Some level of corrosion protection	9.52%
	Minimal level of corrosion protection	0%
	No corrosion protection	0%

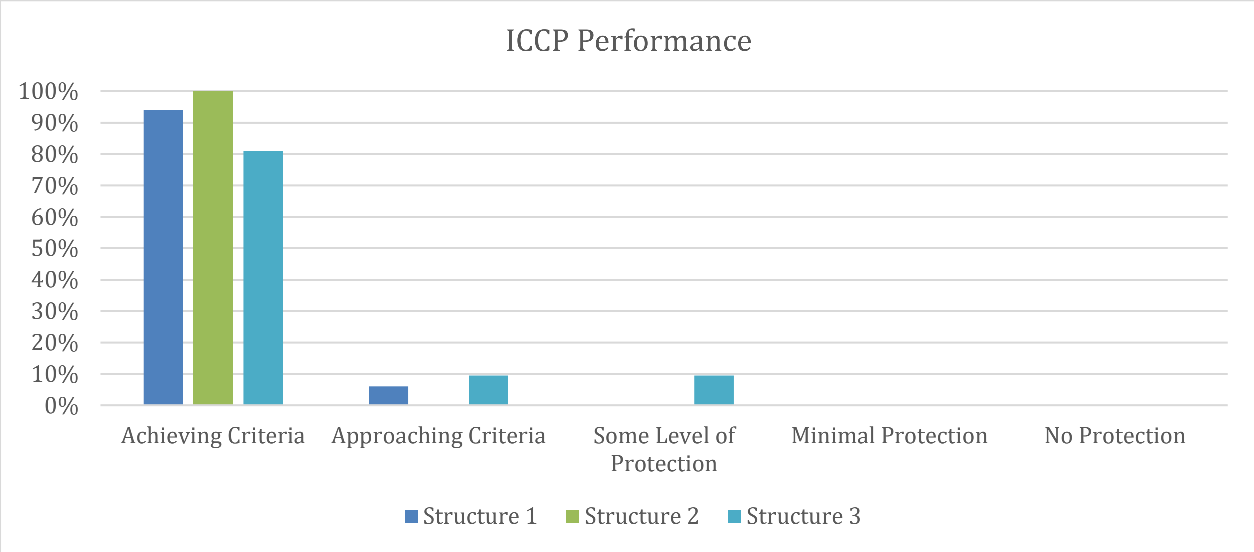

FIGURE 1 - ICCP PERFORMANCE

5.2 Sacrificial Anode Cathodic Protection Systems

5.2.1 SACP Type 1

TABLE 2 – SACP TYPE 1 DATA

Sacrificial Anode Systems – Type 1		Year 1	Year 2	Year 3
Structure 4	Achieving protection criteria	0%	0%	0%
	Approaching protection criteria	0%	0%	0%
	Some level of corrosion protection	0%	0%	0%
	Minimal level of corrosion protection	0%	0%	0%
	No corrosion protection	100%	100%	100%
Structure 5	Achieving protection criteria	5.55	0%	0%
	Approaching protection criteria	0%	0%	0%
	Some level of corrosion protection	0%	0%	0%
	Minimal level of corrosion protection	22.22%	5.55%	11.11%
	No corrosion protection	72.25%	94.45%	88.88%

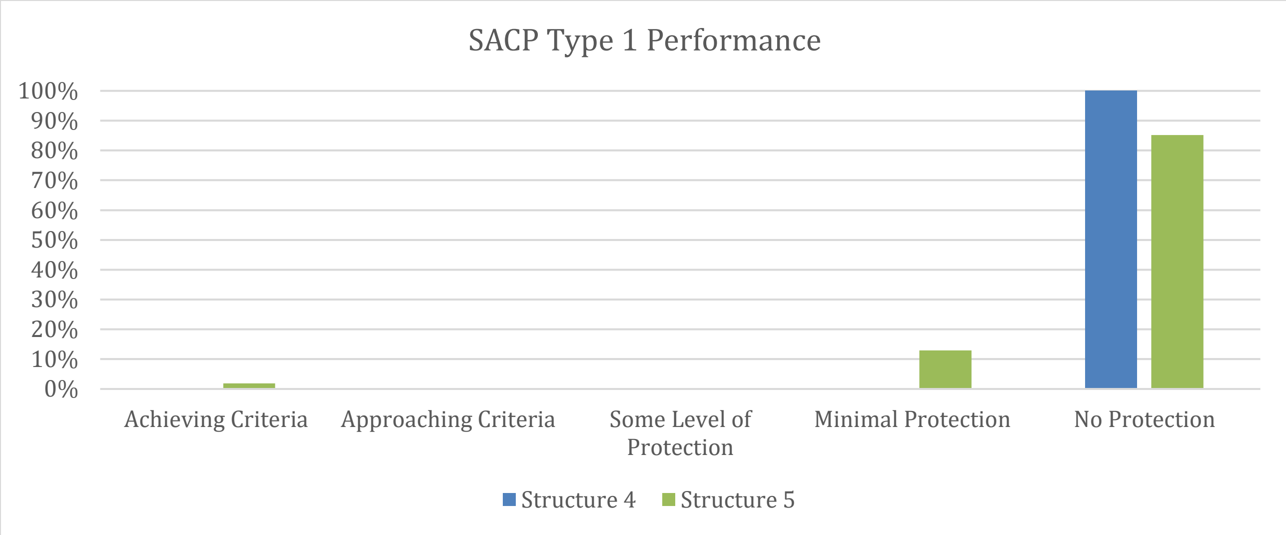

FIGURE 2 – SACP TYPE 1 PERFORMANCE (AVERAGED 3-YEAR DATA)

5.2.2 SACP Type 2

TABLE 3 – SACP TYPE 2 DATA

Sacrificial Anode Systems – Type 2		Year 1	Year 2	Year 3
Structure 6	Achieving protection criteria	0%	0%	0%
	Approaching protection criteria	33.33%	0%	50%
	Some level of corrosion protection	16.6%	50%	0%
	Minimal level of corrosion protection	50%	33.33%	50%
	No corrosion protection	0%	16.66%	100%
Structure 7	Achieving protection criteria	11.1%	0%	22.2%
	Approaching protection criteria	22.2%	11.1%	22.2%
	Some level of corrosion protection	33.3%	33.3%	22.2%
	Minimal level of corrosion protection	22.2%	22.2%	11.1%
	No corrosion protection	11.1%	33.3%	22.2%
Structure 8	Achieving protection criteria	0%	0%	0%
	Approaching protection criteria	0%	10%	30%
	Some level of corrosion protection	20%	70%	60%
	Minimal level of corrosion protection	60%	10%	10%
	No corrosion protection	20%	10%	0%
Structure 9	Achieving protection criteria	0%	0%	0%
	Approaching protection criteria	0%	0%	0%
	Some level of corrosion protection	25%	25%	0%
	Minimal level of corrosion protection	75%	25%	0%
	No corrosion protection	0%	50%	100%

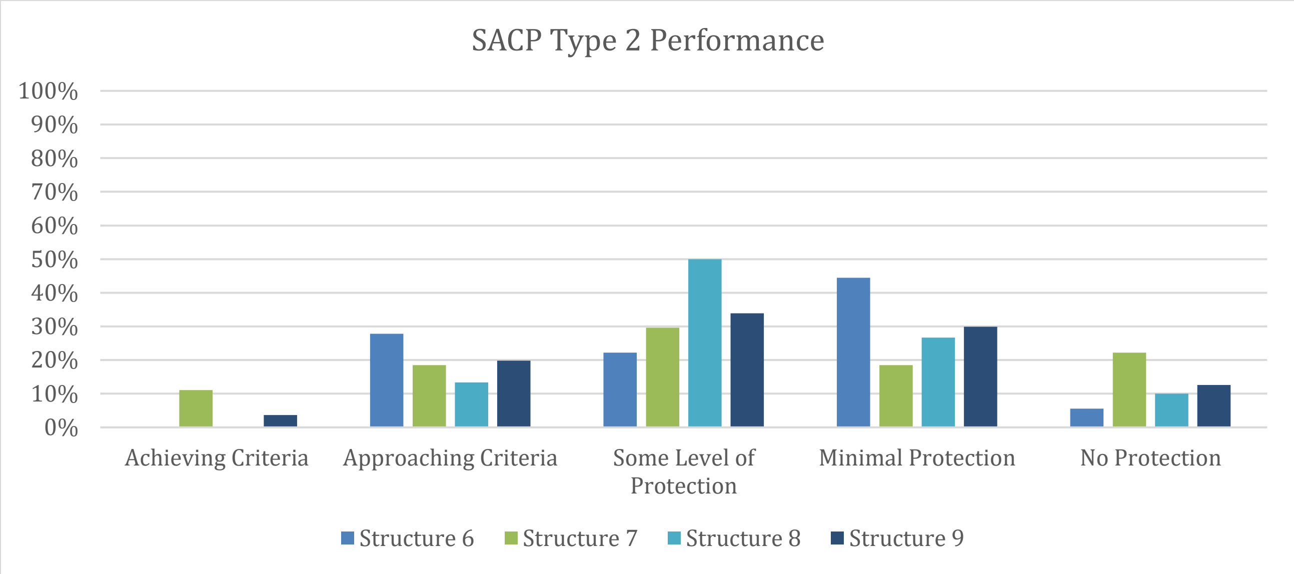

FIGURE 3 – SACP TYPE 2 PEFORMANCE (AVERAGED 3-YEAR DATA)

5.2.3 SACP TYPE 3

TABLE 4 – SACP TYPE 3 DATA

Sacrificial Anode System – Type 3		Year 1	Year 2	Year 3
Structure 10	Achieving protection criteria	93.75%	93.75%	87.5%
	Approaching protection criteria	6.25%	6.25%	6.25%
	Some level of corrosion protection	0%	0%	6.25%
	Minimal level of corrosion protection	0%	0%	0%
	No corrosion protection	0%	0%	0%

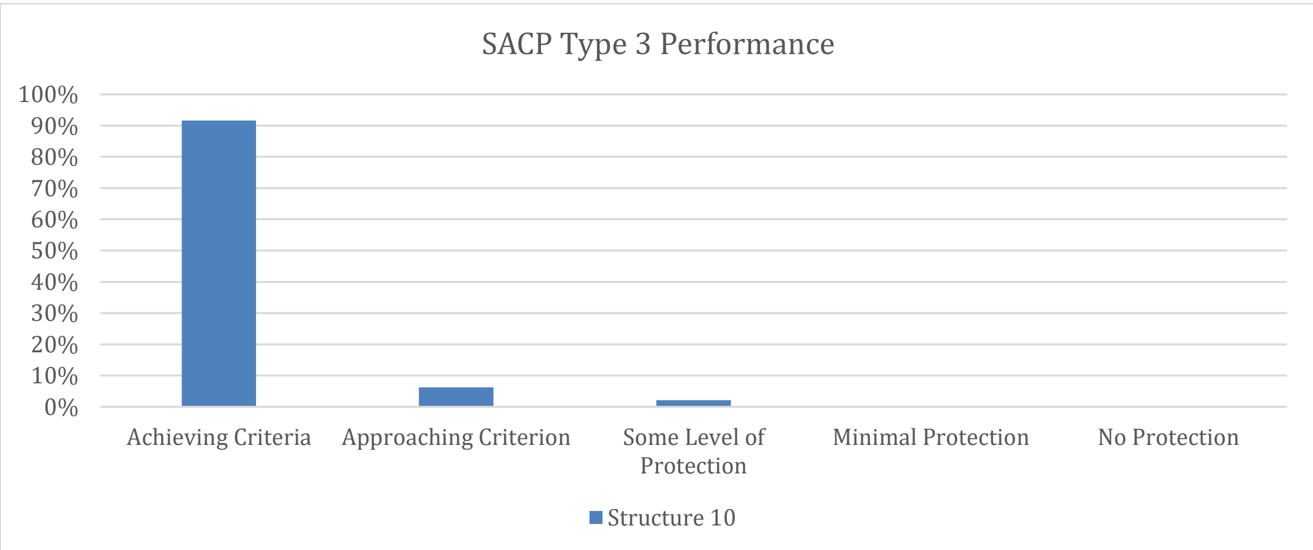

FIGURE 4 – SACP TYPE 3 PEFORMANCE (AVERAGED 3-YEAR DATA)

5.3 Hybrid Anode Cathodic Protection Systems

5.3.1 HACP Type 1

TABLE 5 – HACP TYPE 1 DATA

Hybrid Anode Systems – Type 1		Year 1	Year 2	Year 3
Structure 11	Achieving protection criteria	0%	0%	0%
	Approaching protection criteria	0%	0%	0%
	Some level of corrosion protection	3.50%	0%	0%
	Minimal level of corrosion protection	5.26%	0%	0%
	No corrosion protection	91.24%	100%	100%
Structure 12	Achieving protection criteria	2.10%	0%	0%
	Approaching protection criteria	0%	0%	0%
	Some level of corrosion protection	0%	0%	0%
	Minimal level of corrosion protection	16.80%	0%	0%
	No corrosion protection	81.10%	100%	100%

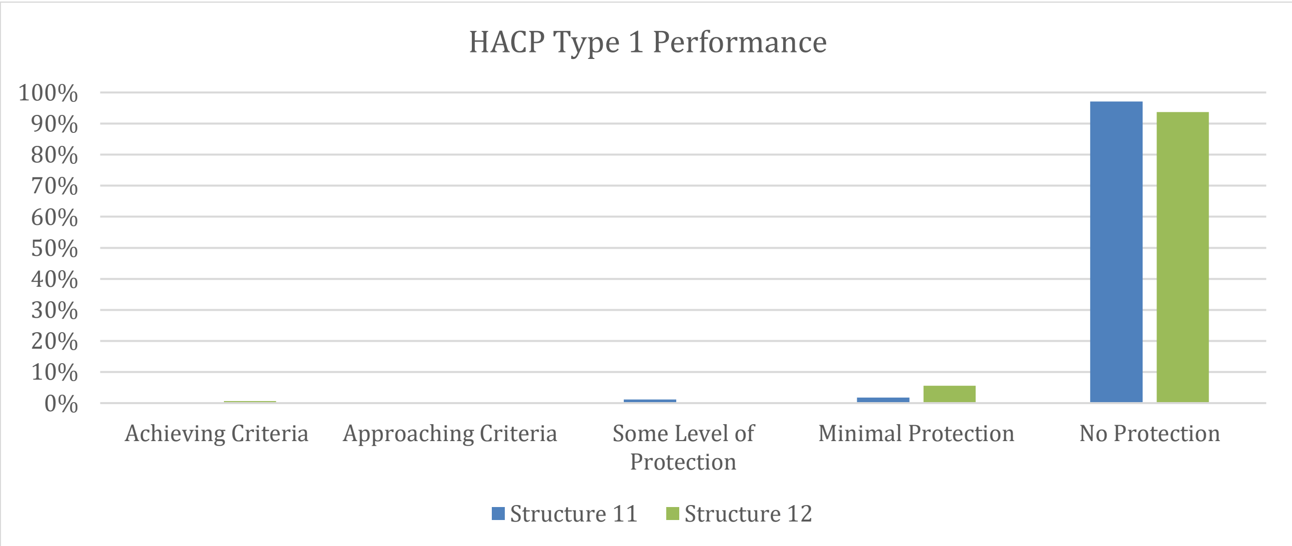

FIGURE 5 – HACP TYPE 1 PEFORMANCE (AVERAGED 3-YEAR DATA)

5.3.2 HACP Type 2

TABLE 6 – HACP TYPE 2 DATA

Hybrid Anode Systems – Type 2		Year 1	Year 2	Year 3
Structure 13	Achieving protection criteria	100%	37.50%	25%
	Approaching protection criteria	0%	25%	25%
	Some level of corrosion protection	0%	37.50%	50%
	Minimal level of corrosion protection	0%	0%	0%
	No corrosion protection	0%	0%	0%

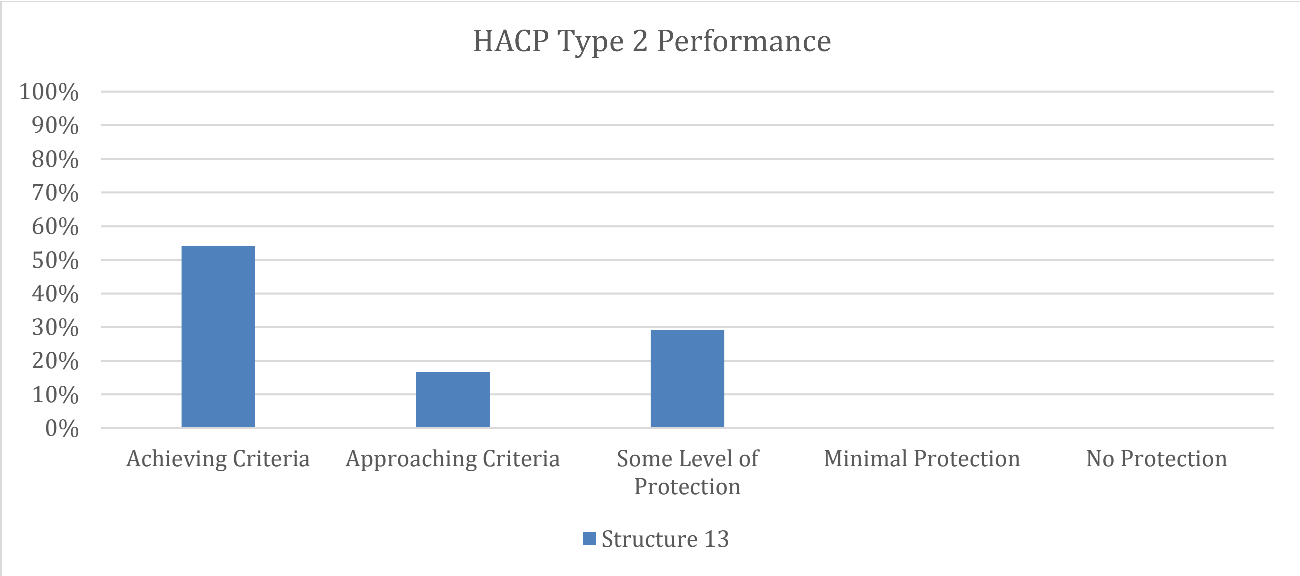

FIGURE 6 – HACP TYPE 2 PEFORMANCE (AVERAGED 3-YEAR DATA)

6 PERFORMANCE ANALYSIS

The following observations were made based on the data presented in this paper:

The design of each system impacts on the performance testing results. This includes the design current density of the system, the suitability of the selected type of anode for the structure, impact of concrete resistivity, selection of locations of reference electrodes and other design factors.

The aim of assessing multiple systems of each technology type was to identify any issues with the anode/technology used and to obtain an overall assessment (trend) regarding the performance of each technology type.

The overall data from the ICCP systems indicates that the high level of corrosion protection in accordance with the applicable standard was achieved. The ICCP systems have capacity for current adjustment for ongoing optimisation of performance.

The SACP Type 1 systems indicated negligible delivery of any corrosion protection. For both systems, the potential of the embedded steel prior to system commissioning (natural potential) was within the same range of the steel potential measured with the system ON or OFF indicating that the entire system is not functional. The level of current delivery is negligible.

The SACP Type 2 systems indicated varied levels of corrosion protection. 24% of the embedded reference electrodes are achieving/approaching the protection criteria based on the Australian Standard (1). 34% indicating some level of protection, 30% are indicating minimal protection and 13% are indicating no protection.

The SACP Type 3 systems, after 3 years of operation, indicated high levels of corrosion protection in accordance with the applicable standard.

The HACP Type 1 systems indicated negligible delivery of any corrosion protection. For both systems assessed in this paper, the potential of embedded steel prior to system commissioning (natural potential) was within the same range of the steel potential measured with the system ON or OFF indicating that the entire system is not functional. It is important to note that the data for HACP Type 1 is retrieved from two large installations with thousands of installed anodes. The level of current delivery is negligible and is consistent with the performance data.

The HACP Type 2 systems indicated a relatively good level of corrosion protection. 71% of the embedded reference electrodes were achieving/approaching the protection criteria based on the Australia Standard and 29% indicated some level of protection. The system was operational for 3 years. The data indicates a reduction of corrosion protection with time, and this may be related to the transfer from the impressed current phase to the galvanic phase.

7 Conclusions

Besides the failure of SACP Type 1 and HACP Type 1 systems to deliver any level of corrosion protection, the overall performance of all remaining systems is consistent with common industry knowledge and historical data related to the performance of electrochemical protection systems.

SACP Type 2 systems returned varied results, however, it is unlikely that these systems can deliver global and ongoing corrosion protection based on the applicable standards. The local use of SACP Type 2 anodes for local corrosion protection and/or in conjunction with patch repair, may provide additional corrosion protection.

SACP Type 3 systems (galvanic anodes in cementitious overlay) can be designed to achieve the protection criteria in the applicable Standards. The retrieved data is based on performance over 3 years only. Ongoing monitoring is required to verify long-term performance.

HACP Type 2 systems can achieve a higher level of corrosion protection than SACP Type 2 systems. It is unlikely that full compliance with the applicable standard can be maintained during the galvanic phase of system operation. The retrieved data is based on performance over 3 years only. Ongoing monitoring is required to verify long-term performance.

Impressed current cathodic protection is the only technology which can deliver corrosion protection over the life of the system in compliance with the applicable standards.

8 References

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9 AUTHOR DETAILS

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	Samir Cheytani has comprehensive experience in the condition assessment of concrete structures affected by steel reinforcement corrosion. He is involved in investigative site work including concrete testing, electrochemical testing, data analysis and the development of rehabilitation solutions for reinforced concrete structures. Samir has completed a Bachelor of Property Economics degree in 2005 from the University of Technology, Sydney (UTS), and a Master of Philosophy in Material Science and Engineering in 2020 from the University of New South Wales (UNSW).