Grout Acidification of Ribbon Anode in Impressed Current Cathodic Protection Systems in Concrete Structures

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Abstract

Impressed current cathodic protection (ICCP) for reinforced concrete structures is an established technology which can provide long term corrosion prevention solutions for reinforced concrete structures. While this technology has proven to be very effective for the corrosion protection of reinforced concrete structures, one of the main maintenance problems associated with this technology in Australia is the occurrence of grout acidification, as the bulk of these systems are installed in tidal and splash zones. This paper verifies a methodology for the prevention of grout acidification in ICCP systems. The results presented in this paper confirm that insufficient anode embedment, often combined with poor quality control and workmanship during ICCP system construction, allow water to ingress to the ribbon anode and these are the primary causes of localised grout acidification. The results also confirm that the application of sufficient grout to encapsulate the anode in conjunction with a cementitious waterproofing coating, which eliminates localised water ingress to the ribbon anode, can minimise the occurrence of grout acidification problems in ICCP installations.

Keywords

"Grout Acidification", "Impressed Current Cathodic Protection", "Anode", "Concrete", "ICCP"

Introduction

Reinforced concrete is still the primary fundamental composite material used for building much of today's highly efficient structures. Reinforced concrete failure is mainly caused by corrosion of the steel reinforcement due to the destabilisation of the oxide layer formed on the steel surface during the hydration process of the concrete. When the oxide layer of the steel partly or completely breaks down, either as a result of carbonation or chloride contamination of the concrete, the corrosion process can initiate. This means that the electrochemical potential of the steel becomes more negative and forms anodic areas in some locations, while in other portions of the steel the passive layer will remain intact and will form cathodic areas.

Impressed current cathodic protection (ICCP) is a commonly applied method for protecting reinforced concrete structures where chloride induced corrosion is the primary cause of reinforcement corrosion. ICCP was first introduced to Australia in the 1980s, and since then ICCP systems have become widely used for the corrosion protection of concrete structures in marine environments [1]. However, in recent years, the maintenance of ICCP systems has become problematic. This has not been due to the failure of ICCP systems in providing corrosion protection to the structures. Rather, it has been due to various issues associated with the high maintenance requirements of some system components [2]. Grout acidification has been identified as one of the problems with ICCP systems operating in marine environments, particularly in the tidal and splash zones of wharves and bridges. In addition to the aesthetic issues associated with grout acidification, if left unrepaired, it may impact on the performance of the ICCP system and the long-term corrosion protection of the structure. The topic of this paper is related to the repair of grout acidification in existing ICCP installations, and the provision of measures to eliminate this problem in new installations.

Grout Acidification

The phenomena of acidification at the anode in ICCP systems is well documented [2, 3]. It is understood that the cause of acidification is attributed to the production of chloride gas generated at the anode [4, 5], excessively in circumstances when an ICCP system is not designed or operated correctly and current density at the anode is high. This type of uniform acidification along the anode is unrelated to exposure conditions, atmospheric or tidal, but to anode current density.

There are three relevant standards for impressed current cathodic protection. These include; The European International Standard ISO 12696:2016 [6]; NACE (US) Standard SP 0290 – 2007 [7]; Australian Standard AS 2832.5 – 2008 [8]. Each standard recommends a current density of 110 mA/m² at the anode surface, however this is in relation to anode life, rather than any issues related to grout acidification around the anode. Global standard bodies [6-8] and anode manufacturers [9] have adopted the limit put in place by the Strategic Highway Research Program National Research Council Washington, DC [5].

However, in the past decade, the issue of localised acidification has become evident in numerous ICCP installations operated within the recommend maximum current density of 110 mA/m^2. Based on first hand site experience, papers [2, 3] identify that acidification is believed to be caused by the ingress of water to the anode causing a redistribution of current along the anode, known as localised current dumping. This type of acidification has been commonly reported, as most ICCP applications in Australia are for marine structures situated in tidal and splash zones [2, 3]. Observations of affected structures suggest that direct exposure of the ribbon anode to water is the primary cause of the localised acidification and grout deterioration process. These papers provide information on what are believed to be the contributing factors to the acidification issue, however, do not provide any long term tested solutions. The only reference in the current standards [6-8] for managing potential grout acidification problems is found in AS 2832.5 – 2008 [8], which states;

In tidal/splash zones, factors such as the proximity of anode materials relative to the concrete surface, the anode detailing, the type of grout selected, and the use of an oxygen diffusive barrier, can all impact on the likelihood that anode backfill failure will occur.

Upon reviewing the applicable standards [6-8] associated with anode installations in concrete, it is apparent that there are no specific details or requirements associated with the method of installation of anodes in tidal/splash zones. None of the above-mentioned standards address the issue of grout acidification.

<u>Industry Response</u>

Developments in overall system design, as well as close reviews of system performance over the years have led to the continual improvement of ICCP systems, with the aim of minimising weaknesses in system design [2]. Some developments include changes to anode installation details, the development of new high pH grout materials used for encapsulation, and the trial of cementitious waterproofing systems for the anode slot cuts [3]. One method currently being trialed in the industry [2, 3] is the application of cementitious waterproofing coating on top of anode installations. Following grout repairs at anode locations, a cementitious waterproofing layer was applied on the top and sides of the anode slot cut, with the aim of sealing potential de-bonding or movement cracking between the original concrete and the grout material [2, 3]. This method has been implemented in recent years on numerous structures in Australia, however no experimental laboratory research has been undertaken to understand its effectiveness.

Materials, Methods & Experimental

Experiments were conducted using cylindrical concrete samples installed with ribbon anode, mirroring a typical CP-protected concrete pile in a wharf or bridge structure. Each concrete sample was cylindrical in shape and had a diameter of 150 mm and a height of 300 mm. On each cylinder there were four identical anode slot cuts, each 30 mm wide and 20 mm deep, providing 20 mm cover to each anode. Four mild steel bars, each with a length of 330 mm and a diameter of 25 mm, were placed in the centre of each cylinder replicating the steel reinforcement and acting as the cathode. All four bars were welded together in two locations to ensure sufficient electrical contact between these bars and were encapsulated by concrete. The concrete samples replicated installations of ribbon anode with a typical anode design and grouted with the same low resistivity repair mortar suitable for ICCP applications. After casting, the concrete samples were left to cure for 30 days in atmospheric conditions. This was followed by anode installation and backfilling. Samples were then stored in a lab environment (23^{o}C, 65% humidity) for a minimum of 30 days prior to any additional surface preparation, coating application or testing. Prior to the application of a cementitious waterproofing coating (for select samples), scabbling of the surface was carried out with a mechanical wire brush followed by the application of cementitious waterproofing coating by hand brush. Samples with a cementitious waterproofing coating was left to cure (in lab conditions) for a minimum of 48 hours prior to sodium chloride solution immersion and testing.

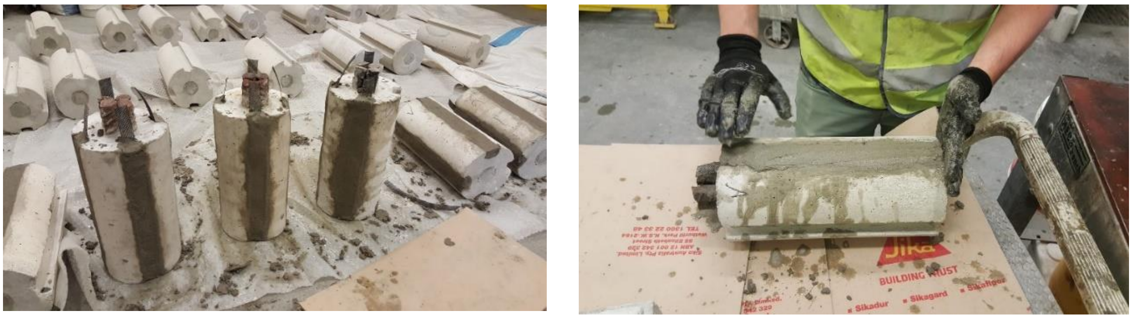

Figure 1 – Concrete sample anode installation

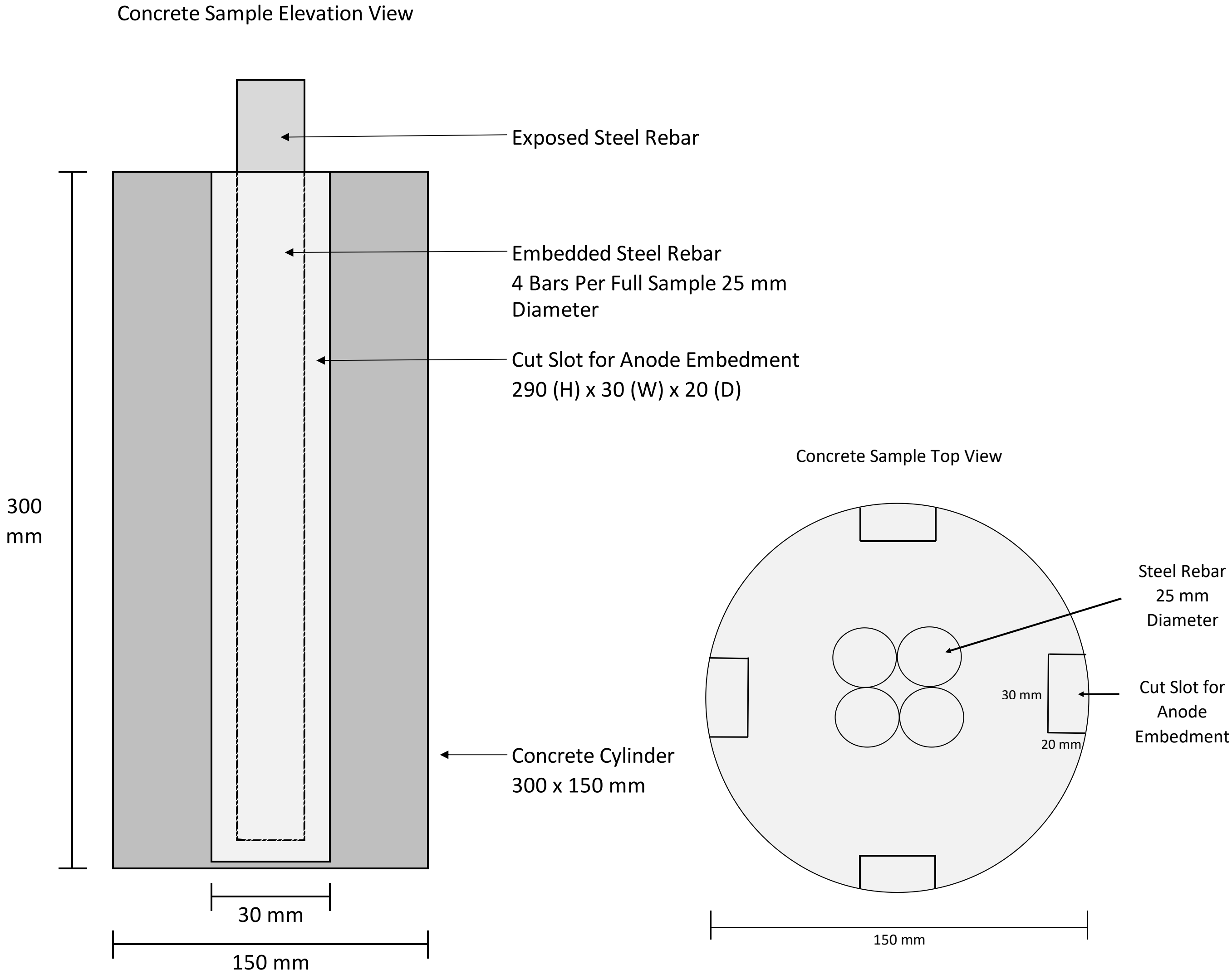

Figure 2 – Concrete sample schematic

To simulate a marine environment, samples were placed in sodium chloride solution. The salt water solution was formulated based on the average salinity of ocean water, which has a salt concentration of 35 parts per thousand, or 35 g of salt per litre of water. The salinity of the solutions was constant for all test samples during the experiments.

Since the process of acidification is quite slow, accelerated testing in a laboratory environment was used to provide information which otherwise may take several years to collect. A system for accelerated testing had to be developed for this work (see table 1). Accelerated testing was undertaken by increasing the current output to the anode multiple times over what is required in general ICCP system applications. Accelerated laboratory experiments were conducted over a period of 225 days. It is important to note that the application of accelerated testing may have some side effects and a study into these effects has not been conducted as part of this research.

The technical specification for the mixed metal oxide (MMO) titanium ribbon anode used in these experiments specifies an expected design life of 100 years [9]. For the following experiments, the effect of accelerated testing on the MMO coating of the anode was not considered. As no prior published research of this type had been conducted, extensive testing was carried out in various experiments during this period. This paper focusses on two main experiments with supporting findings from preliminary experiments.

Anode Installation and Workmanship in Stopping Localised Water Ingress

Experiment 1 compared two samples (four combined anodes each), shown in Fig.3. Testing consisted of sample 1 (uncoated) and sample 2 (coated) with construction and embedment of the anodes identical in both. However, in sample 2, an additional 2.5 mm cementitious waterproofing coating was applied to the external surface. All anodes were fully encapsulated with grout. Both samples were tested under the same conditions, partially immersed in sodium chloride solution. Each sample was powered by its own transformer rectifier unit (TRU) to ensure equal current distribution, while also allowing for voltage monitoring. Experiment 1 was carried out over 92 days, and an equivalent of 14.9 years of current was applied based on steel density of 20 mA/m^2 of steel surface [8]. The accelerated testing calculations are detailed in the Table 1.

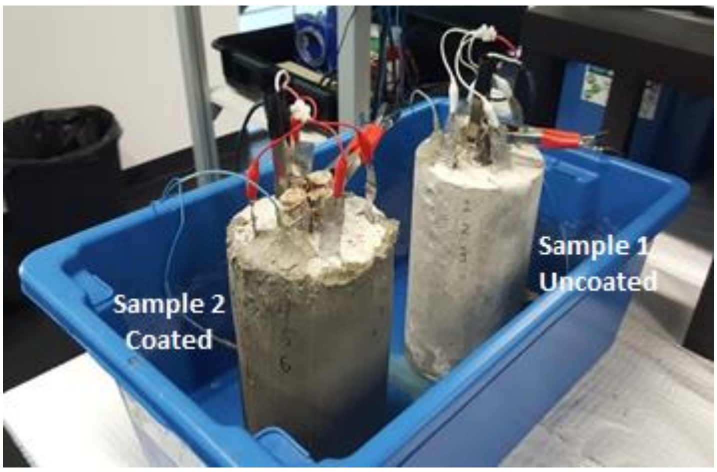

Figure 3 - Experiment 1, sample setup

Minimising Acidification with Coating Application

For experiment 2, an identical grout encapsulation defect was created for each anode, and comparisons were made between the samples with and without a cementitious waterproofing coating.

Experiment 2 was comprised of one sample with four independent anodes as shown in Fig. 4. At each anode slot, a 10 mm hole was drilled through the grout material to the anode surface, to simulate defects which may occur from structural movement, grout shrinkage, insufficient anode cover and/or poor workmanship. Continuity testing between the drilled anode location and the anode's external portion was conducted and a resistance of less than 2 ohms was confirmed. Based on the technical data sheet requirements for the cementitious waterproofing material, a 2.5 mm coating was applied on the surface of anodes 3 and 4, filling in the holes and encasing the two anode slots with cementitious waterproofing coating as shown in Figs. 4 (c) and (d). The sample was partially immersed in salt water solution for the duration of the experiment. Each anode was separately powered by one of four power supply units in this experiment. Experiment 2 was carried out over 38 days, with an equivalent of 16.5 years of current applied based on a design current density of 20 mA/m^2 of steel surface [8]. The accelerated testing calculations are detailed in the Table 1.

(a) Anode 1 Uncoated | (b) Anode 2 Uncoated | (c) Anode 3 Coated | (d) Anode 4 Coated

Figure 4 – Experiment 2, sample preparation prior to testing

Accelerated Testing Calculation - Experiment 1				
Current Impressed During Experiment	21 Days @ 20mA	21 Days x 24h x 0.02A	10.08	Amps-h
	13 Days @ 150mA	13 Days x 24h x 0.15A	46.80	Amps-h
	58 Days @ 100mA	58 Days x 24h x 0.1A	139.20	Amps-h
	92 Days Total		196.08	Amps-h
Current Required Based on the Surface Area of Steel, to Provide a Current Density of 20mA/m² on the Steel Surface	Steel Surface Area	3.14 x 0.025m x 4 (Steel Bars) x 0.25m	0.075	m²
	Current Required	0.075m² x 20mA/m²	1.50	mA
	Use 1m Anode With A Capacity of 5.2mA			
	Anode Capacity Used	1.5mA / 5.2mA	28	%
Accelerated Testing Calculation	Amp Hours Required For Normal Protection	92 Days x 24h x 0.0015A	3.31	Amps-h
	Actual Amps Applied		196.08	Amps-h
	Accelerated Effect of Current Used	196.08A / 3.31A	59.24	Amps
	Total Equivalent Use of CP Current	59.24 x 92 Days	5450	Days
	Total Equivalent Use of CP Current	5450 Days / 365 Days	14.9	Years

Accelerated Testing Calculation - Experiment 2				
Current Impressed During Experiment	3 Days @ 30mA	3 Days x 24h x 0.03A	2.16	Amps-h
	7 Days @ 50mA	7 Days x 24h x 0.05A	8.40	Amps-h
	15 Days @ 70mA	15 Days x 24h x 0.07A	25.20	Amps-h
	13 Days @ 60mA	13 Days x 24h x 0.06A	18.72	Amps-h
	38 Days Total Per Power Unit		54.48	Amps-h
	4 Power Units Used in Experiment	4 (Power Units) x 54.48 Amps/h	217.92	Amps-h
Current Required Based on the Surface Area of Steel, to Provide a Current Density of 20mA/m² on the Steel Surface	Steel Surface Area	3.14 x 0.025m x 4 (Steel Bars) x 0.25m	0.075	m²
	Current Required	0.075m² x 20mA/m²	1.50	mA
	Use 1m Anode With A Capacity of 5.2mA			
	Anode Capacity Used	1.5mA / 5.2mA	28	%
Accelerated Testing Calculation	Amp Hours Required For Normal Protection	38 Days x 24h x 0.0015A	1.37	Amps-h
	Actual Amps Applied		217.92	Amps-h
	Accelerated Effect of Current Used	217.92A / 1.37A	159.06	Amps
	Total Equivalent Use of CP Current	159.06 x 38 Days	6044	Days
	Total Equivalent Use of CP Current	6044 Days / 365 Days	16.5	Years

Table 1 – Accelerated testing calculations experiments 1 and 2

Results

<u>Minimising Localised Grout Acidification with Defect Free Grout Encapsulation</u>

The aim of experiment 1 was to assess whether the installation of sufficient grout cover and good workmanship can stop the ingress of water to the anode. The experiment confirmed this hypothesis. During experiment 1, no acidification was visible on the grout/water surface on either sample under the testing conditions described in Section 2.1. The two samples were cut open using a concrete saw for a detailed inspection.

The visual results revealed similar levels of acidification around the anodes in both samples. There was no evidence that water had penetrated to the ribbon anode, via a crack or defect in both the coated and uncoated cylinders. Due to the lack of localised water ingress, the acidification around the anode was found to be uniform along the length of the ribbon anode. This type of acidification is caused by high current density due to the accelerated testing. The visual inspection also revealed that grout acidification occurred at the anode/grout interface, and the concrete had not visually degraded from the acidification.

No evidence was found to suggest that anodes installed with sufficient grout cover, which do not exhibit any signs of cracking, will suffer from localised grout acidification causing localised grout deterioration.

Figure 5 – Experiment 1, uncoated sample

Figure 6 – Experiment 1, coated sample

The visual conclusion from experiment 1 was that acidification will occur around the anode during high current density, and/or during long term operation of ICCP. The most likely causes of localised grout acidification is poor anode installation detail during construction, specifically, insufficient cover to the anode and inadequate anode encapsulation. In the samples, the grout cover to the anode was 20 mm. It appears that properly applied grout had prevented water ingress to the level of the anode. In this case, the additional measure of cementitious waterproofing coating application was not required, however it did affect the circuit resistance of the samples which will be discussed in Section 3.3.

<u>Stopping Localised Water Ingress by Cementitious Waterproofing Coating</u>

The aim of experiment 2 was to test the performance of the cementitious waterproofing coating in providing protection and stopping the ingress of water to the anode with the incorporation of a standardised and uniform defect between the test anodes. A dissection of the concrete sample was carried out after the 38-day experiment. Two images Figs. 7 and 8 were taken after the dissection of the concrete sample; Fig. 7 showing the drilled location, under the water level, at the point of water ingress to the anode, and Fig. 8 above the water level.

It was evident that the increased level of acidification at the point of water ingress greatly increased the level of grout deterioration as seen in Fig. 7 anodes 1 and 2. In Fig. 7, there is minimal acidification around anodes 3 and 4 where a cementitious waterproofing coating was applied on the external slot cut surface. Fig. 8 shows that all anodes located above water level exhibited minimal grout acidification.

Figure 7 – Experiment 2, cross section of sample at the point of water ingress below water level

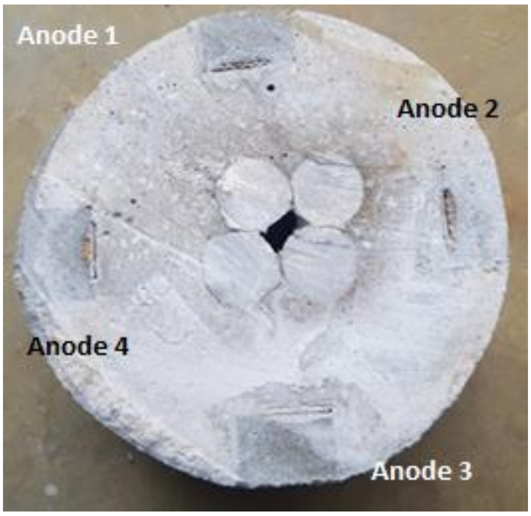

Figure 8 – Experiment 2, cross section of sample at location above water level

A visual inspection of this experiment revealed the following:

- Localised water ingress to the anode can greatly affect the level of acidification and grout deterioration around the anode.
- A 2.5 mm thick layer of cementitious waterproofing coating provided protection to the anode from direct water ingress, as shown in Fig. 7 anodes 3 and 4.
- Where water ingress does reach the anode, as shown in Fig. 7 anodes 1 and 2, a considerable level of grout acidification was evident.
- In locations where the anode was not exposed to direct water ingress as in Fig. 8, the level of grout acidification was minimal.
- There was no visual evidence of acidification causing deterioration of the existing parent concrete surface. All acidification witnessed during the experiment was of the encapsulating grout material.

<u>Increase in Circuit Resistance Caused by Coating Application</u>

An analysis of circuit resistance was carried out with the aim of providing information on the internal effects of the cementitious waterproofing coating on the ICCP system.

As shown in Fig. 9, it was found that the application of a 2.5 mm cementitious waterproofing coating can increase the operating voltage of a system when impressing a set current. An analysis of the voltage trends between the two samples, as depicted in Fig. 9, revealed that the sample with a cementitious waterproofing coating had a significantly higher circuit resistance than the uncoated sample. In this experiment, both samples displayed similar levels of acidification with no evidence of localised water ingress to the anode. Note that in Fig. 9, fluctuations in voltage are due to changes in the current output during the experiment.

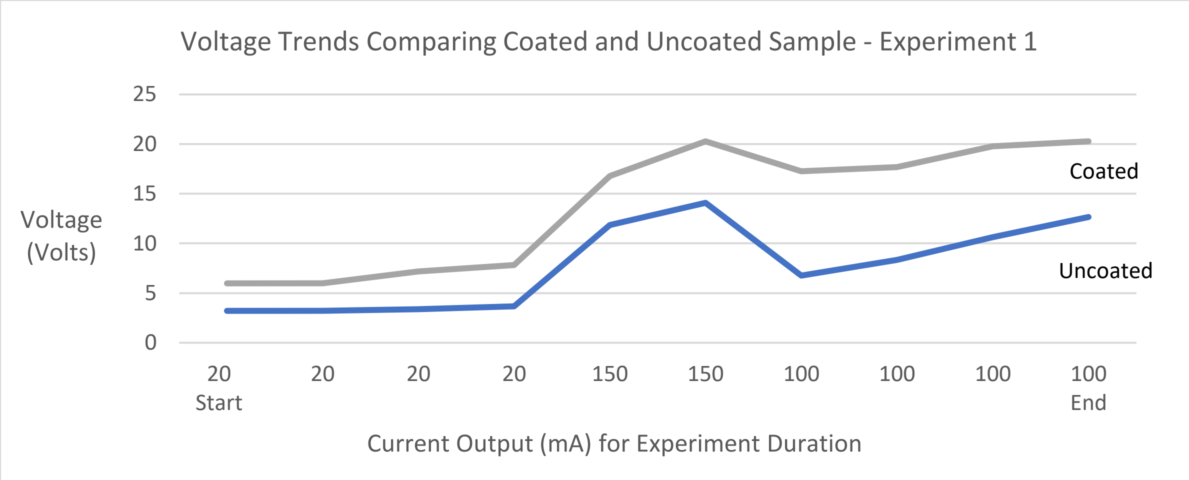

Figure 9 – Experiment 1, voltage trends comparing coated and uncoated samples

Trends show a constant voltage increase over time at set current levels. There are numerous potential causes of this phenomenon. Further research in this area can provide more information, however it is believed that the increase in voltage is caused by a combination of:

- De-bonding between anode and concrete/grout due to acidification causing grout deterioration around the anode surface.
- Passivation of steel, reducing current flow.

Fig. 10 shows the average circuit resistance of the anodes during experiment 2. It is evident that the level of resistivity is much higher for anodes 3 and 4 (Fig. 10) which had cementitious waterproofing coating applied. It is important to note that high resistivity may impact on the operating capacity of an ICCP system as systems are generally limited to a maximum 8 Volts.

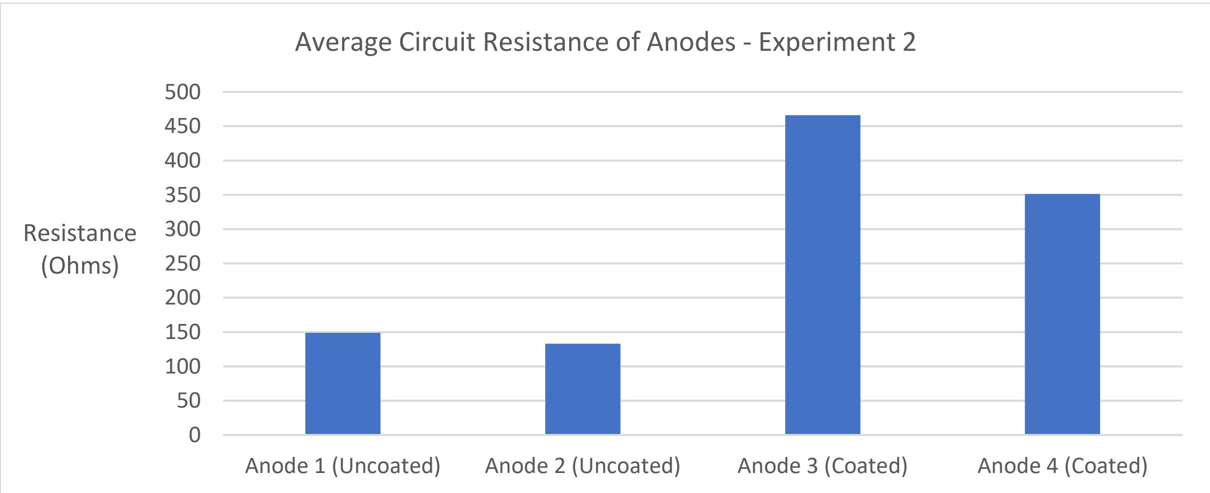

Figure 10 – Experiment 2, average circuit resistance of anodes

Fig. 11 shows the voltage trends of the anodes in experiment 2. It is noted that for anode 4, in the initial stages of the experiment, exhibited lower than expected levels of resistance, however these stabilised during the course of the experiment. It is believed that this could be caused by micro environmental factors around the anode. Fig. 11 shows that the overall voltage readings for the coated samples were much higher. Note that in Fig. 11, fluctuations in voltage are due to changes in current output during the experiment.

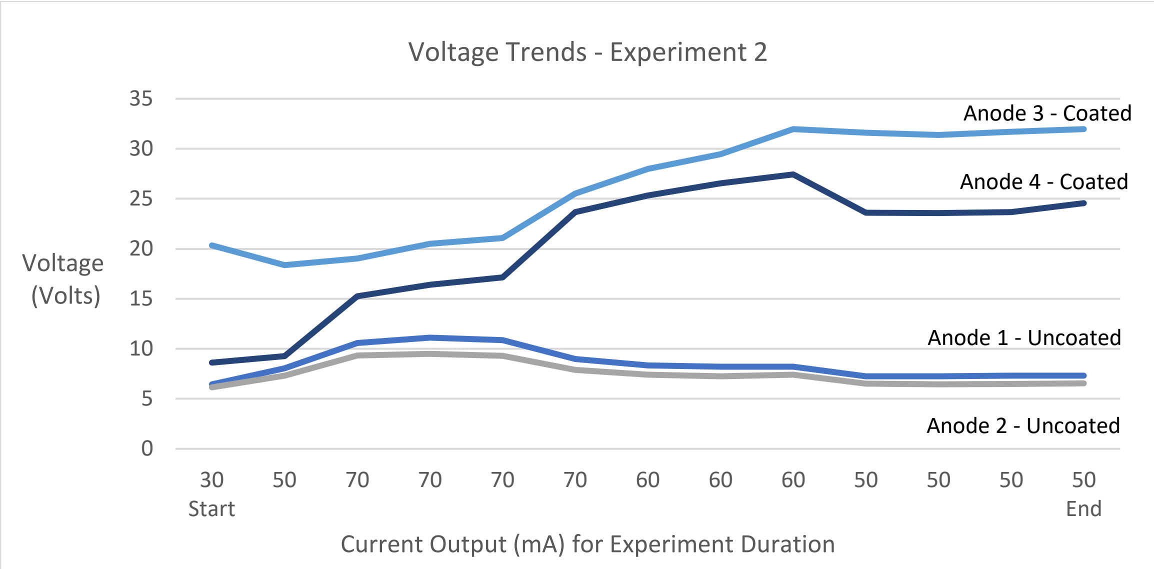

Figure 11 – Experiment 2, voltage trends

Discussion

The results of the research reveal that proper encapsulation of anodes by grout material in water exposure zones, and the application of cementitious waterproofing coating, can eliminate localised grout acidification problems caused by water ingress. From these experiments, it was found:

- Water ingress to the anode has a direct effect on the amount of localised grout acidification formation. The experiments revealed that in locations where direct water contact to the anode occurs, the level of localised grout acidification is greatly increased. This places a priority on minimising water ingress to the anode, since this causes uneven distribution of current along the anode surface which may lead to current dumping. The phenomena of current dumping (or the redistribution of current to specific locations on an anode) will concentrate the formation of grout acidification in that area and this will lead to accelerated grout deterioration. This research has provided evidence that the application of a cementitious waterproofing coating of sufficient thickness (2.5 mm) can eliminate the ingress of water to the anode level (in a laboratory environment) and can fully eliminate localised grout acidification caused by water ingress.

- The research produced no evidence to suggest that anodes which have been installed with sufficient grout cover, in samples with no defects, will be subject to localised grout acidification. For newly installed ICCP systems in concrete structures, well designed anode placement and quality control measures during the anode installation work can minimise the risk, if not entirely prevent, the occurrence of localised grout acidification. However, it is important to note that many structures will have imposed loads and stresses placed on them, and these dynamic external influences have not been simulated in these experiments.

- There was no visual evidence of acidification causing deterioration of the existing concrete surface. All acidification witnessed during the experiments was of the grout material. While is it unlikely that the type of grout contributed to the localised acidification formation seen in these experiments in areas where there was no localised water ingress to the anode, the use of specialised grouts with different characteristics (such as high pH) may prove beneficial. The experiments found that if there is no direct water ingress to an anode, generally uniform acidification along the anode surface will develop. Applying a grout with a high pH may provide some level of limited protection against the formation of uniform acidification, however research in this area is required.

- The experiments revealed that samples with a cementitious waterproofing coating had a higher circuit resistance when compared to uncoated samples. Experiment 1 revealed that in a laboratory environment the addition of a cementitious waterproofing coating may not provide additional acidification protection when compared to defect free samples with sufficient anode embedment. It is important to note that the increase in circuit resistance can impact on the operating functionality of an ICCP system. ICCP systems generally have a maximum operating capacity of 8 Volts. This limiting factor is in place to protect certain components of an ICCP system, such as titanium conductor bars, titanium wire and the operating life of MMO titanium anodes.

The chemical composition of the coating used in these experiments, its impact on ICCP system voltage increases, and the impact of such increases on the long-term operation of ICCP systems were not part of this research work.

Conclusion

The results of the experimental research work presented in this paper confirm that water ingress to the anode has a direct effect on localised grout acidification and grout deterioration.
Insufficient grout encapsulation of the anode and poor quality control during construction are the primary causes of water ingress to the anode.
In a static laboratory environment, adequate grout cover to the anode may be sufficient in eliminating water ingress and minimising the occurrence of localised grout acidification. However, this may not be applicable in the actual structures exposed to dynamic loads and environmental influences.
The results confirm that the application of a 2.5 mm cementitious waterproofing coating can potentially eliminate the ingress of water to anodes in tidal and splash zones minimising grout acidification problems in new and existing ICCP systems.
This research also found that the application of a cementitious waterproofing coating can increase overall ICCP circuit resistance.
The research presented in this paper confirms that the method of applying a cementitious waterproofing coating can provide an increased level of protection against localised grout acidification.

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