A Rapid Test to Screen the Functionality of Galvanic Anodes for Cathodic Protection of Reinforced Concrete

Ryan Cobbs1*, Rene Brueckner1, Chris Atkins2, Arpit Goyal3

1Mott MacDonald, Materials and Corrosion Technology, Bristol, UK
2Mott MacDonald, Materials and Corrosion Technology, Altrincham, UK
3Thapar Institute of Engineering and Technology, Patiala, Punjab, India

Abstract. Galvanic anodes are increasingly popular in the repair, rehabilitation, and maintenance of reinforced concrete structures suffering from chloride-induced corrosion for the added durability benefits. There is a consensus among engineers that demand will increase due to ageing infrastructure stock, climate change, and the option to reuse structures which is a logical solution to help reduce carbon emissions. New manufacturers will likely emerge to meet the needs of a growing market. However, there is no standard for galvanic anodes for use in concrete. In theory, products may come to market that fail to work as anodes, and hence corrosion may not be arrested, and repeated intervention could be required. This paper presents a methodology that has been developed for demonstrating anodes function as intended in a short-term test. Anodes were cast into concrete, and drive voltage, resistivity, and resultant current were measured when connected to an external cathode. The test setup was applied to several commercially available galvanic anodes. All anodes achieved a current output of 0.35 mA in this experimental setup. This could provide a rapid test to screen anodes new to the market. The analyses show inherent anode behaviour varied with different manufacturers, and there were also performance differences among replicate anodes. Such behavioural characteristics may affect the long-term performance of the anodes. These results provide new data on galvanic anodes and demonstrate the potential need for standardisation in the industry.

1 Introduction

Many case histories of concrete repairs have shown premature failures within the first 10-years [1]. This is common in chloride-contaminated reinforced concrete structures due to incipient anode effects, which move corrosion around the structure [2]. The source of chlorides may be from external de-icing salts, chloride-containing spray, internal admixtures and/or aggregates.

Galvanic anodes are installed within the concrete repairs to avoid incipient anodes forming on the embedded steel [3]. By introducing a sacrificial anode to the corrosion process, steel will become the cathode, and further chemical reactions help maintain the passivation of the steel reinforcement. This technique may be referred to as galvanic cathodic protection (GCP) and is based on the principles of potential difference [4].

Categories of galvanic anodes for reinforced concrete can be differentiated between embedded discrete and surface applied anode systems [2]. Discrete anodes are installed in patch repairs or non-repaired concrete in pre-drilled cavities to protect larger areas from corrosion. The anodes consist of zinc enced in proprietary mortar on the production line, or in-situ (i.e., anode grouting) and incorporate an integral wire that forms the electrical connection with the reinforcement. Surface applied anodes comprise sheets of zinc and thermally sprayed zinc or aluminium.

The design of discrete anodes is principally based on the required lifetime and net anode mass derived from the oxidation reaction given in the equation below [2].

\[ \text{Zn} \rightarrow \text{Zn}^{2+} + 2e^- \quad (1) \]

Faraday’s law states, one mole of zinc (65.38 g) releasing two moles of electrons corresponds to 193 kC. From this, 1 kg of zinc provides 820 Ah. For example, 10-year design life and design current density of 1 mA/m^2 steel equate to 87.6 Ah and 0.1 kg of zinc. However, the service life of anodes is an issue, and this is usually considered in the design stage using utilisation and efficiency factors.

Available data on the performance of discrete anodes for reinforced concrete is limited [5-7].

This paper presents a methodology developed for demonstrating discrete anodes function as intended in a short-term test. The anodes were cast into concrete, and the drive voltage, resistivity, and current was measured when connected to an external cathode. This test setup was applied to several commercially available anodes.

* Corresponding author: ryan.cobbs@mottmac.com
2 Materials and Methodology

2.1 Galvanic Anodes

Anodes from different manufacturers were collected and are named with a number and letter, denoting the manufacturer and mass of zinc, respectively, as detailed in Table 1. Different masses of zinc were used to investigate the effects of surface area on the anode performance. The manufacturers use different shapes for the anodes shown in Figure 1.

Table 1. Anodes Used in Experimental Programme

<table>
<thead>
<tr>
<th>Anode Ref.</th>
<th>Mass of Zinc (g)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>60</td>
<td>Solid zinc, encased in proprietary mortar</td>
</tr>
<tr>
<td>1B</td>
<td>100</td>
<td>Solid zinc, encased in proprietary mortar</td>
</tr>
<tr>
<td>2A</td>
<td>60</td>
<td>Solid zinc, encased in proprietary mortar</td>
</tr>
<tr>
<td>2B</td>
<td>100</td>
<td>Solid zinc, encased in proprietary mortar</td>
</tr>
<tr>
<td>3A</td>
<td>60</td>
<td>Perforated zinc, encased in proprietary mortar</td>
</tr>
<tr>
<td>3B</td>
<td>100</td>
<td>Perforated zinc, encased in proprietary mortar</td>
</tr>
</tbody>
</table>

Figure 1: Selection of anodes used in the experiment.

2.2 Concrete Specimens

Concrete cylinders of 200 mm × 100 mm were prepared. The anodes were suspended at the centre of the moulds during casting.

The concrete used to produce the specimens consisted of two BS EN 1504 Class R4 repair products, which are differentiated by the letters M and N in Table 2.

Table 2. Specimens used in experimental programme

<table>
<thead>
<tr>
<th>Anode</th>
<th>Concrete M</th>
<th>Concrete N</th>
<th>Concrete N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mix M1</td>
<td>Mix N1</td>
<td>Mix N2*</td>
</tr>
<tr>
<td>1A</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>1B</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>2A</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>2B</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>3A</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>3B</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

*The amount of water added was the same for mixes M1 and N1 and reduced by 25% for mix N2 to assess the effects this would have on anode current output.

To help verify the quality of the mixing procedure, compressive strength tests were carried out at 28 days.

2.3 Conditioning and Resistivity

The specimens were cured at 20 °C for 14 days for mixes M1 and N1 and 7 days for mix N2 due to time constraints. After, the specimens were transferred to humidity-controlled chambers set at constant 70 % RH day 14 to 35 and 85 % RH day 35 to 49, inclusive. The N2 specimens were transferred to come conditions approximately of 40-60 % RH day 14 to 21, inclusive. The humidity in the chambers was adjusted at scheduled intervals to influence the concrete resistivity and allow for this effect on anode current output to be investigated.

Table 3 details the testing schedule with reference to the associated humidity conditions.

Table 3: Testing Schedule

<table>
<thead>
<tr>
<th>Humidity</th>
<th>Day of Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix M1</td>
<td>Mix N1</td>
</tr>
<tr>
<td>100%</td>
<td>21</td>
</tr>
<tr>
<td>70%</td>
<td>28 and 35</td>
</tr>
<tr>
<td>85%</td>
<td>42 and 49</td>
</tr>
<tr>
<td>40-60% (room)</td>
<td>21</td>
</tr>
</tbody>
</table>

In addition, specimens without anodes were to cast to measure electrical resistivity.

2.4 Experimental Set-up

The specimens were placed in water and connected to an external cathode, as demonstrated in Figure 2.

Figure 2. (1) specimen, (2) cathode, (3) cathode connection, (4) anode connection, & (5) 500 Ω resistor.

The drive voltage was measured between the anode and cathode as they were disconnected, utilising a high impedance multimeter. A steel plate 45 cm long × 25 cm wide × 1 mm thick served as the cathode and was entirely submerged in tap water. Fresh tap water was used for every test. The specimens were partially submerged to a depth of 100 mm and connected to the cathode using electrical wire. The current output was then obtained by assessing the voltage drop across a 500 Ω resistor. A
second measurement was recorded for each test by switching the leads on the multimeter to check for errors. The time between measurements was quick.

The concrete resistivity was measured utilising the ‘4-point/Wenner’ technique with a Proceq Resipod. For this, plain control samples were used as the anodes would interfere with the measurement [8].

3 Results

3.1 Compressive Strength and Resistivity

Concrete M1 and N1 had a compressive strength of 59 and 73 N/mm², respectively, both had a standard deviation of less than 1.5 N/mm². This was considered to indicate uniformity across the relevant specimens. The resistivity measurements are given in Table 4.

Table 4. Concrete Resistivity Measurements

<table>
<thead>
<tr>
<th>Days</th>
<th>Resistivity (kΩ·cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mix M1</td>
</tr>
<tr>
<td>7</td>
<td>15.5</td>
</tr>
<tr>
<td>14</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>13.1</td>
</tr>
<tr>
<td>28</td>
<td>20.0</td>
</tr>
<tr>
<td>35</td>
<td>24.6</td>
</tr>
<tr>
<td>42</td>
<td>28.0</td>
</tr>
<tr>
<td>49</td>
<td>28.3</td>
</tr>
</tbody>
</table>

Varying resistivity was expected as mix M and N are likely to contain different constituents and proportions. The increases in resistivity with aging are demonstrated across all samples, increasing rapidly within 28 days, and then gradually stabilising. Mix N2 with reduced water content and exposed to lower RH resulted in a significantly higher resistivity at 21 days compared to Mix N1 which would be expected [9].

3.2 Anode Driving Voltage

The driving voltage varied across anodes from different manufacturers, as demonstrated in Figure 3. All anodes had a minimum driving voltage of 365 mV in a composition of fresh tap water and using the same steel plate as a cathode.

From this graph, it can be observed that 60 g anodes are less powerful than 100 g anodes.

Type 1 anodes were more consistent with age and across mix M and N. However, there was more spread in the unit-to-unit driving voltages as shown in Figure 4.

![Figure 4. Evolution of driving voltage, type 1 anodes](image)

The larger 1B anodes demonstrate a more consistent driving voltage. A single type 1A anode exhibited the unusual behaviour of the driving voltage consistently moving towards zero, which is not what would be required from an anode and may be indicative of a problem with the experimental set-up or materials used.

Type 2 anodes had the largest driving voltage in each category possibly due to their shape / encasing mortar. The results were more variable as shown in Figure 5.

![Figure 5. Evolution of driving voltage, type 2 anodes](image)

The results were more variable as shown in Figure 5.

Type 3 anodes followed the same trend as Type 2 anodes in mix N2 as shown in Figure 6.

![Figure 3. Average Driving Voltage](image)
3.3 Anode Current Output

All anodes in this experimental setup managed an average current output of 0.35 mA. Figure 7 shows the average current output with standard error bars indicating the variability between specimens.

3.4 Anode Resistance

The anode resistance was derived from Ohm's law. Type 1 anodes were generally consistent with current output across different resistivities compared to type 2 and 3 anodes exhibiting a declining current output. Figure 9 and Figure 10 illustrate the anode resistance.

Figure 6. Evolution of driving voltage, type 3 anodes

It is noted the driving voltage was overall lower in Mix N2 which was subjected to 100 % RH for 14 days and then increased at 21 days at approximately 40-60 % RH.

The difference in driving voltage between different anodes could be due to the proprietary encasing material, shape, and chemical composition of the zinc. The unit-to-unit driving voltage could be variation on a microscopic scale such as alloy composition, impurities, surface condition, humidity variations, etc [10].

Table 5: Reduction in Current Output Start to End

<table>
<thead>
<tr>
<th>Anode type</th>
<th>1A</th>
<th>2A</th>
<th>1B</th>
<th>2B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current output (mA)*</td>
<td>0.09</td>
<td>0.41</td>
<td>0</td>
<td>0.27</td>
</tr>
<tr>
<td>Percentage reduction</td>
<td>15 %</td>
<td>45 %</td>
<td>0 %</td>
<td>28 %</td>
</tr>
</tbody>
</table>

* Resistivity range: of 13-30 kΩ.cm.

The current output tended to reduce with increasing resistivity with the exception of anode 1B. This overall behaviour corresponds well with the 'responsive behaviour' found by Holmes [11] and Sergi [3]. In this respect, type 2 and smaller type A anodes were the most responsive/sensitive to resistivity changes. The sensitivity is hypothesized to be related to the formulation of the encasement material, which is a proprietary component coming from individual manufacturers.
The main conclusions are:

- The anode driving voltage and current output successfully demonstrated the inherent behaviour of different galvanic anodes. In addition, these behaviour characteristics are supported by published literature on responsive behaviour. The variability in replicate anodes corroborates with Dugarte [5].

- In general, the behaviour of the galvanic anodes tested was characterised by the sensitivity in terms of current output with changes in resistivity. This shows certain anodes and larger anodes (type B) could be more efficient.

- The proprietary components of an anode used by individual manufacturers are assumed to be a leading factor in the inherent performance. This includes encasement material, shape, and chemical composition. However, this does not consider the resistivity of the surrounding concrete.

- Adherence to concrete mixing instructions provided by manufacturers has a significant role in the current output from anodes. This could influence the polarisation ability of the anodes and lead to premature failures. The incongruous mix N2 demonstrated a substantial reduction in current output. This emphasises the importance of high-quality control when undertaking concrete repairs for effective anode performance.

- Standardisation of anodes is needed to control the quality and performance of products produced by various manufacturers. This would allow the engineer to make informed decisions on appropriate values for utilisation and efficiency factors.

- This research study compared a range of zinc galvanic anodes currently used in the UK from various manufacturers. The study has successfully developed a testing method that depicts the behaviour of these anodes. The recorded results proved the validity of the test, but to conclude the performance of different anodes requires further research.

- The testing method can now be expanded with more time and more data to develop a standard test used in the industry. They may assure the quality of increasingly sought-after galvanic anodes.

4 Conclusions

The main conclusions are:

- The anode resistance spiked in specimens from Mix N3 after being subjected to 100 % RH for 14 days and then resumed to lower values at 21 days under higher resistivity conditions. Leaving the specimens at 100 % RH for an extended period appears to have affected the performance. The larger type B anodes had lower anodes resistance which shows that they are more efficient than type A.

Figures

Figure 10: Anode Resistance (V/I) Type B anodes

Based on the responsive behaviour discussed in the previous section, type 2 anodes exhibited characteristics of responsive behaviour. Type 1 anodes had a more consistent performance. The anode resistance may indicate how effective the anodes are.

Type 3 anode resistance was not well established due to the limited data points. It is noted that the anode resistance spiked in specimens from Mix N3 after being subjected to 100 % RH for 14 days and then resumed to lower values at 21 days under higher resistivity conditions. Leaving the specimens at 100 % RH for an extended period appears to have affected the performance. The larger type B anodes had lower anodes resistance which shows that they are more efficient than type A.

References