

# Development of the Galvanic Anode Performance Test for Assessing the Longevity of Galvanic Anodes for Reinforced Concrete Structures

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The NACE impact report (2016) states that nearly 50% of reinforced concrete (RC) structures experience major repair in about 10 y. The existing approach of patch repair does not address the root cause and may not be durable—resulting in re-repair and huge economic loss. Galvanic anodes (GAs) are gaining widespread acceptance to achieve maintenance-free repair life for a few decades. However, a few GAs with inadequate characteristics are prematurely failing (within a few months). There are no short-term test methods to evaluate the longevity of GAs. Therefore, this work focuses on developing a short-term test method (galvanic anode performance [GAP] test) to assess the longevity of GAs. For this, the GAP specimen was designed by simulating CP-protected RC structure as follows: (i) GA embedded in bedding mortar (i.e., anode), (ii) nichrome mesh (i.e., cathode simulating rebars in RC structures), (iii) position of anode and cathode, (iv) application of potential difference (0.5 V, 1 V, 5 V, 10 V, 20 V, and 30 V) to accelerate the degradation of GAs, and (v) electrolyte to simulate conductivity of concrete. Applied potentials >5 V could not capture the difference in characteristics of GAs. However, potential differences of 0.5 V, 1 V, and 5 V could show the true behavior of GAs in various exposure conditions. Then, an approach is proposed to evaluate the service life of GAs. Possible reasons for the premature failure of anodes were investigated by evaluating pH and pore volume of encapsulating mortar. The GAP test can help practicing engineers estimate the longevity of GAs. AQ1  
AQ2

KEY WORDS: cathodic protection, concrete, corrosion, galvanic anode, service life, steel

## INTRODUCTION

Corrosion of reinforcement is one of the major deterioration mechanisms in reinforced concrete (RC) structures.<sup>1</sup> NACE impact report states that about 50% of structures hit repair within 10 y from the time of construction.<sup>2</sup> Personal interactions of authors with a few leading contractors in India reveal that many large infrastructures, such as high-rise buildings, undergo repair even before the buildings are ready to occupy. Patch repair using partial or full replacement of concrete is widely practiced. However, they do not address the root cause of the corrosion of rebar—leading to continuous corrosion and failure of repair. Electrochemical repair such as cathodic protection (CP) can extend the service life of the repair. CP systems for concrete can be categorized into two: (i) impressed current CP system and (ii) galvanic anode (GA) CP system.<sup>3-4</sup> This paper focuses on the latter system; the former will not be discussed herein. The effectiveness of repair using GAs depends on the characteristics of anode metal, encapsulating mortar (EM), and tie-wires. Various inadequate quality GAs (without considering the characteristics of these elements) are available for an inexpensive price than the GAs which can provide long-term protection. Clients prefer to use inexpensive anodes as the manufacturers of those GAs falsely

claim the long-term performance of GAs. Also, the authors could not find any test method and performance-based specifications which can help in the selection of good quality GAs. This is one of the reasons that inadequate quality GAs is used in the concrete repair industry. Authors have recently patented a short-term test method (named galvanic anode performance [GAP] test),<sup>5</sup> which can evaluate the long-term performance of GAs, and this paper presents the development of the GAP test.

The remaining paper is arranged as follows: first, a review of the literature on the repair of concrete structures without and with CP is presented. Then, factors affecting the performance of GAs and available test methods to evaluate the performance of GAs are discussed. The rest of the paper focuses on the development of the GAP test. For this, the experimental program and corresponding results are presented for the selection of (i) cathode material, (ii) cathode to anode ratio, (iii) potential to be applied, and (iv) the electrolyte and level of electrolyte is presented. Then, the proposed GAP test procedure is demonstrated. Further, an approach is presented to estimate the service life of GAs by evaluating the performance of two widely used GAs. Then, possible reasons for the failure of GAs are investigated, and mechanisms of failure of various GAs are proposed.

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1.1 | Repair of Reinforced Concrete Structures

Figure 1(a) shows a schematic of a typical patch-repaired RC structure. Here, spalled concrete is chipped off and replaced with repaired concrete (without chlorides). Therefore, the embedded steel is in contact with (i) chloride-free patch concrete and (ii) parent chloride-contaminated concrete. Due to chemical differences, the surface corrosion potential of steel in these regions is different—leading to the formation of corrosion cells and accelerating the propagation of corrosion. This phenomenon is known as the halo effect.<sup>6-11</sup> Such inadequate repairs can lead to repeated repair every 5 y,<sup>7</sup> which soon may result in a large number of<sup>12-14</sup> RC structures needing repair. Therefore, a durable repair strategy is required.

CP using GAs is a well-established corrosion prevention/protection technique used for the protection of metallic structures. The application of CP was extended to RC structures in 1955 (about 70 y ago). However, the use of CP in RC structures is gaining interest in the past few decades. In India, the repair of RC structures using CP with GA has increased by 100 times from 2010 to 2020.<sup>7</sup> Figures 1(b) and (c) show a schematic and photograph of GA connected to the steel rebar, respectively. The principle of CP is to polarize the embedded steel from its free corrosion potential to the cathodic regime.<sup>15-16</sup> When GAs are electrically connected to steel rebars and embedded in concrete, additional electrons get transferred to the steel rebar, which repels chlorides away from the surface of the steel rebars.<sup>16-17</sup> The reduction of chloride ions at the steel surface can reduce the susceptibility of steel rebars to corrosion. The availability of additional electrons on the steel rebar surface results in additional cathodic reactions<sup>7</sup>—leading to the formation of additional hydroxide ions, which can passivate the steel

rebar. Therefore, GAs can protect steel rebars from corrosion and increase the time interval between repairs.

1.2 | Factors Affecting the Performance of Galvanic Anodes

Figure 1(d) shows the photograph and schematic of typical GAs used to repair RC structures. The performance of GAs depends on the characteristics of elements of the GA system: (i) anode metal, (ii) EM, and (iii) tie-wire (corrosion-resistant metal).

1.2.1 | Anode Metal

The choice of anode metal plays an important role in the efficiency of GAs. The following characteristics can affect the performance of GAs: (i) electronegativity of metal, (ii) efficiency to supply current in the highly resistive system, and (iii) percentage change in volume of corrosion products. The choice of metal also depends on the resistivity of the electrolyte surrounding the GA. For example, the corrosion potential of magnesium alloys is highly negative—making it dissolve too vigorously in seawater and protect the metallic structures. Therefore, magnesium-based anodes are used where the resistivity of surrounding material is up to 1,000 Ω·cm; say, river water, soil, mud, etc.<sup>18</sup> Zinc or zinc alloy-based GAs can be used for structures with a resistivity greater than 1,000 Ω·cm. The applicability of these GAs was investigated for metallic structures,<sup>19</sup> where the resistivity of the vicinity is less than 1 K·Ω·cm. whereas, the resistivity of concrete is in the range of 10 kΩ to 300 kΩ.<sup>20-21</sup> However, similar GAs are used for RC structures with highly resistive concretes. In addition, the

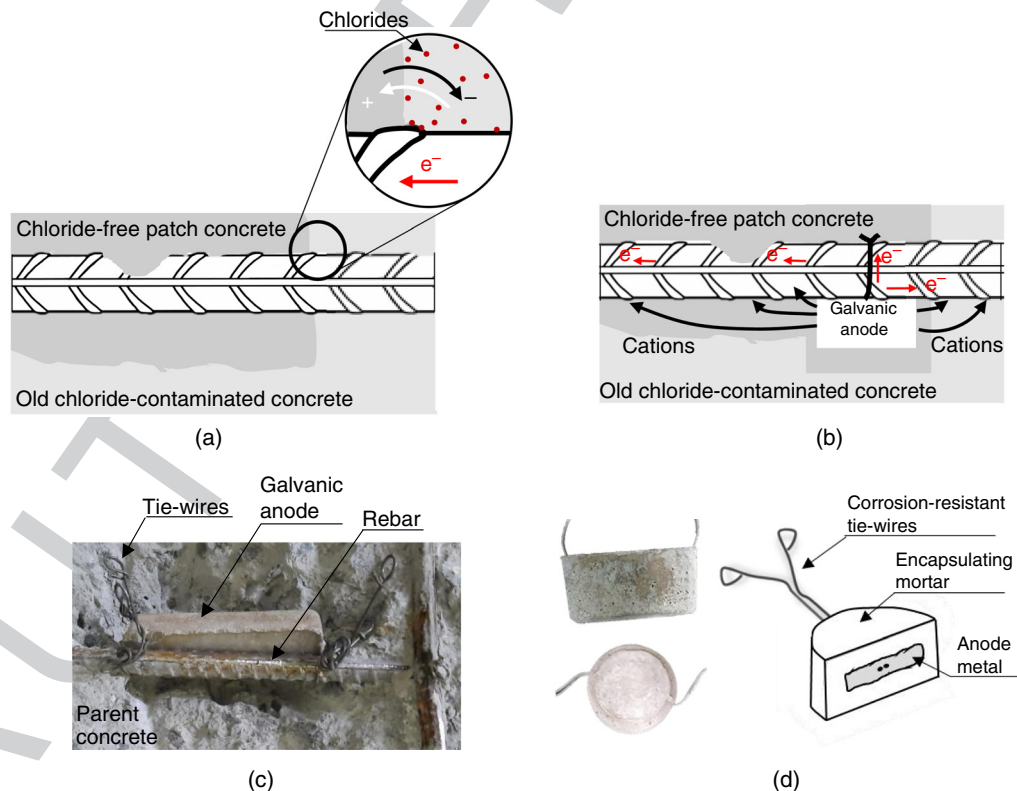


FIGURE 1. CP of RC systems using GAs. (a) Patch repair without GA, (b) patch repair with a GA, (c) photograph of GA connected to a rebar for CP, and (d) photographs and schematic of typical GAs for the repair of RC structures.

corrosion products of anode metal should not be much higher than the pristine metal to avoid expansive pressure on the EM and surrounding concrete. Considering these, zinc or zinc alloys are used for the CP of RC systems. However, the performance of these GAs for RC systems needs to be evaluated.

### 1.2.2 | Encapsulating Mortar

The corrosive environment (high pH, availability of moisture at anode metal surface, etc.) around anode metal can keep the anode metal active.<sup>11</sup> To create this environment, EM is prepared with (i) activators such as halide<sup>22-23</sup> and alkalis<sup>24</sup> and (ii) humectants such as lithium bromide, lithium nitrate, calcium chloride, etc.<sup>22,25-26</sup> However, some manufacturers provide the EM with combinations of high or low porosity, with or without activators, high or low pH, and high or low resistivity of EM. To keep zinc active, it is essential to provide surrounding with adequate pH, such as >13.6 or <8. If EM fails to provide a corrosive environment for the service life, then GAs fail prematurely. Therefore, the literature recommends the EM with porosity >20% of total volume and pH >13.6 throughout the life of GAs.<sup>8,11</sup>

### 1.3 | Tie-Wires

These are provided for an electrical connection between zinc metal and rebars. Therefore, it is essential that the surface of the tie-wire should be free of rust. Therefore, corrosion-resistant metals are recommended.<sup>11</sup> Another challenge with tie-wires is the way they are connected to the anode metal. GAs are available with the following connections between tie-wires and anode metal: (i) welding, (ii) partially diecast, and (iii) diecast for the full length of the anode metal. Welded tie-wires may break off during installation of GAs or the welded region may preferentially corrode, which will result in loss of electrical connection.<sup>27</sup> Partially diecast tie-wires may protect the steel rebars until the zinc has been corroded for the length, where the tie-wires are diecast with the GAs. When two or more tie-wires are placed close to each other, they may support crevice corrosion due to moisture between these tie-wires. Mechanisms of such corrosion are discussed in Kamde, et al.<sup>11</sup> Therefore, the best practice is to place two or more tie-wires sufficiently distant and diecast for the entire length of anode metal or diecast a tie-wire for the entire length of anode metal.

### 1.4 | Test Methods to Evaluate the Performance of Galvanic Anodes

As discussed, various types of GAs are available, many of them are not able to provide long-term protection of RC structures. However, these inadequate-quality GAs are available due to the unavailability of “performance-based” guidelines for the selection of GAs for RC structures.<sup>11</sup> Much literature reports the long-term performance (ranging from 1 y to 20 y) of galvanic.<sup>8,11,25,28-29</sup> These approaches are time-consuming and may not be suitable as a test for the selection of GAs.

Dugarte and Sagüés introduced a test method to evaluate the performance of GAs by comparing the polarization behavior of GAs.<sup>26</sup> However, the test results give qualitative information after 4-y long testing, which is too long for most of the clients to wait for the results. The literature reports test methods based on the constant current method to evaluate the service life of GAs for metallic structures,<sup>30-31</sup> where anodes are forced to withdraw a specific current by adjusting the potential difference between anode and cathode. The end of testing is defined by the consumption of anode metal, which is

usually not the case in GAs used in concrete systems. GAs used in concrete systems can fail due to inadequate characteristics of anode metal, EM, and tie-wires. As there are no short-term test methods available to assess the quality of these GAs, manufacturers are able to push the poor-quality GAs in repair industries. Therefore, a short-term test method is needed to be developed to assess the performance of GAs, which is the foci of this paper.

## RESEARCH SIGNIFICANCE

The patch repairs without CP can result in repeated repairs of RC structures—leading to the cost of corrosion of nearly 4% of worldwide GDP.<sup>32</sup> The use of CP using GAs can reduce the cost of corrosion. However, many inadequate-quality GAs are available at an inexpensive price, which are reported to prematurely fail. However, clients prefer those GAs due to the low capital cost of repair. Premature failure of GAs will relegate the good technology such as CP of RC structures with GAs. This paper is a step toward eliminating the inadequate quality GAs by providing a short-term test method to evaluate the longevity of GAs.

## DEVELOPMENT OF GALVANIC ANODE PERFORMANCE TEST METHOD

As discussed in the *Introduction* section, in a CP-protected system, rebar is the cathode, GA is the anode, and concrete is the electrolyte. In addition, there is a potential difference between rebar and GA due to their electronegativity. Table 1 summarizes the experimental design adapted for the development of the GAP test. Temperature and relative humidity (RH) are two critical parameters in corrosion evaluation and can contribute to variability in test results. Therefore, all experiments were performed under controlled conditions with an ambient temperature of 25±2°C and ambient RH of 65±5%. The first task is to identify the elements for the GAP test setup; the following approach was adapted to mimic the CP-protected RC systems: (i) anode was the GA to be tested; (ii) cathode material needs to be selected such that it simulates rebar (large surface area in RC structures), however, considering the size of the planned small size test setup, the selected cathode should still have large surface area. For this, there could be many options, however, mesh with a large surface area and made with corrosion-resistant material could be the best choice. Therefore, nichrome mesh was selected as the cathode.

The next step is to decide the appropriate size of the cathode, which is discussed later in this paper; (iii) concrete characteristics, such as pH and ionic conductivity, are most important concerning the working of GAs in concrete systems. Therefore, either concrete or material with similar characteristics as concrete should be selected for the test specimen. The use of concrete for the test specimen could make the specimens too huge and heavy. The intention of the development of this test method is to make it simple and easy to conduct in laboratory conditions. Therefore, the mortar was selected for the preparation of the test specimen. The placement and size of each of these elements are crucial for the test method, which is discussed later in this section.

In addition, one of the essential stages is to accelerate the corrosion of anode metal without influencing the natural degradation of GAs. Therefore, various potential differences between anode and cathode were applied to select feasible potential differences, which could reveal the true

Elements for GAP Test Setup	Variables	Number of Specimens
The ratio of the surface area of cathode to anode metal, $A_C/A_A$	1, 3, 5, 10, 20, and 25	6
Selection and design of cathode and anode	Nichrome mesh and GA	2
	Nichrome mesh and GA embedded in bedding mortar	
Selection of potentials to be applied (V)	30, 20, 10, 5, 2, 1, and 0.5	21
Position of the cathode (nichrome mesh)	Embedded in mortar and placed around the galvanic anode	9
	Placed around the specimen	
	Placed below the specimen	
Level of electrolyte, H (mm)	0, 10, and 40	9
Applied potential difference to estimate the longevity of GAs (V)	5, 1, and 0.5	18
	<b>Total</b>	65

Note: All of the experiments were performed in controlled conditions with temperature  $25\pm 2^\circ\text{C}$  and RH of  $65\pm 5\%$ .

characteristics of GAs and help accelerate the degradation of GAs. The effects of the selection of a wide range of potential differences in the characteristics of GAs are presented later in this paper.

### 3.1 | Selection and Design of Cathode and Anode

#### 3.1.1 | Ratio of the Surface Areas of Cathode and Anode ( $A_C/A_A$ )

The purpose of the cathode in the GAP test is to draw current from GAs. Therefore, the cathode should be corrosion-resistant material with a large surface area. Any corrosion-resistant material could be a good choice; the authors have selected nichrome mesh considering their good experience with nichrome mesh. To decide the size of the cathode, the following ratios of the surface areas of the cathode and anode metal ( $A_C/A_A$ ) were investigated: 1, 2, 3, 5, 10, 20, and 25. To prepare the test specimen, the protruding tie-wires from one side of GAs were cut (i.e., cut tie-wire at the place where it protrudes out of EM). To avoid the corrosion of tie-wires, which might affect the measured current, then, the ends of cut tie-wires were sealed with a thick layer of epoxy. Figure 2(a) shows test setup 1 with a cathode of various sizes connected to the negative

terminal and GA connected to the positive terminal of the DC power source maintained at 1 V. The justification for the selection of 1 V is presented later. Unfilled markers in Figure 2(c) show that the output current was increasing as the size of the nichrome mesh increased. The curve is asymptotic to abscissa after the  $A_C/A_A$  was about 20. Therefore, the nichrome mesh could be selected as 20 times the surface area of the anode metal to be tested. However, it was reported that when GAs are dipped in solution/water for more than 20 min, the leaching of ions from EM occurs, which will alter the characteristics of GA. Therefore, GA is required to be embedded in a cementitious system. The effect of the cementitious system is investigated next.

#### 3.1.2 | Design of Anode

The application of CP using GAs is different in concrete systems than in aqueous systems due to ionic resistivity or conductivity of concrete, pore distribution in concrete, and pH of the cementitious system. These characteristics cannot be obtained when steel is protected using GAs in an aqueous system. The use of concrete in GAP specimens can make them bulky, heavy, and too large to handle. To avoid these and to achieve the characteristics of concrete, the mortar was chosen over concrete to provide ionic resistivity or conductivity, pore

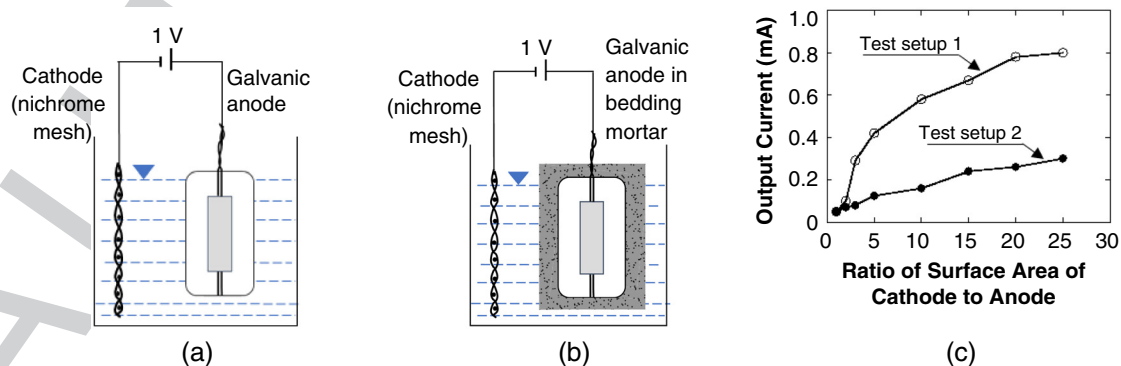


FIGURE 2. Selection of ratio of the surface area of a cathode to anode for GAP test. (a) Anode: GA, (b) anode: GA in bedding mortar, and (c) effect of the ratio of the surface area of the cathode to anode on output current.

distribution, and pH surrounding GA. To prepare the specimens for this set of testing, the tie-wires from one end of GAs were cut at the intersection of tie-wire and EM. If any tie-wire was found to be protruding, it was covered with heat-shrink tube. The gap between the heat-shrink tube and tie-wire was filled with low viscosity epoxy. The tie-wires from the other side of GAs were covered with a heat-shrink tube, and the gap between tie-wire and the heat-shrink tube was filled with low viscosity epoxy. Then, this system, except the shrink tube covered tie-wires, was embedded in 5 mm thick bedding mortar made with ordinary Portland cement (OPC): sand: w/b of 1:2.75:0.5. Note that the thickness of bedding mortar was chosen to be 5 mm based on authors' experience. A cover thickness lower than 5 mm may lead to cracking due to shrinkage of bedding mortar, and the cover thicker than this will add additional electrical resistance between the anode and cathode, which may reduce the output current—may lead to a long testing duration. The intention of the GAP test is to evaluate the performance of GAs in a short time (say, a few months); therefore, 5 mm of bedding mortar was selected. Figure 2(b) shows test setup 2 with nichrome mesh of various sizes connected to the negative terminal and GA embedded in bedding mortar is connected to the positive terminal of DC power source maintained at 1 V. The filled markers in Figure 2(c) show that the output current was increasing as the size of the nichrome mesh increased until 15 times the surface area of anode metal (i.e.,  $A_C/A_A = 15$ ). However, the increase in output currents for  $A_C/A_A$  ranging from 1 to 5 and from 5 to 10 was about twice and similar, respectively. Considering this, the intended small size of the specimen, and other challenges (discussed later), the  $A_C/A_A = 5$  was selected. The results obtained here are expected to be valid for other potential differences too. However, other variables such as the position of the anode and cathode, level of electrolyte, etc., may not be valid for all of the potential differences. Therefore, the next section focuses on the selection of potential differences for the GAP test.

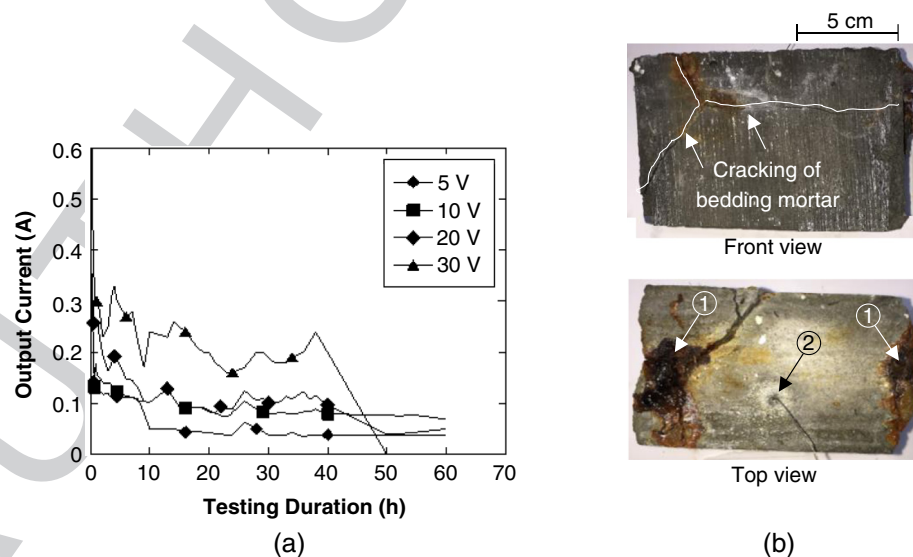
### 3.2 | Selection of Potential to be Applied

The selection of potential differences to be applied should be made in such a way that it could help in (i) evaluating

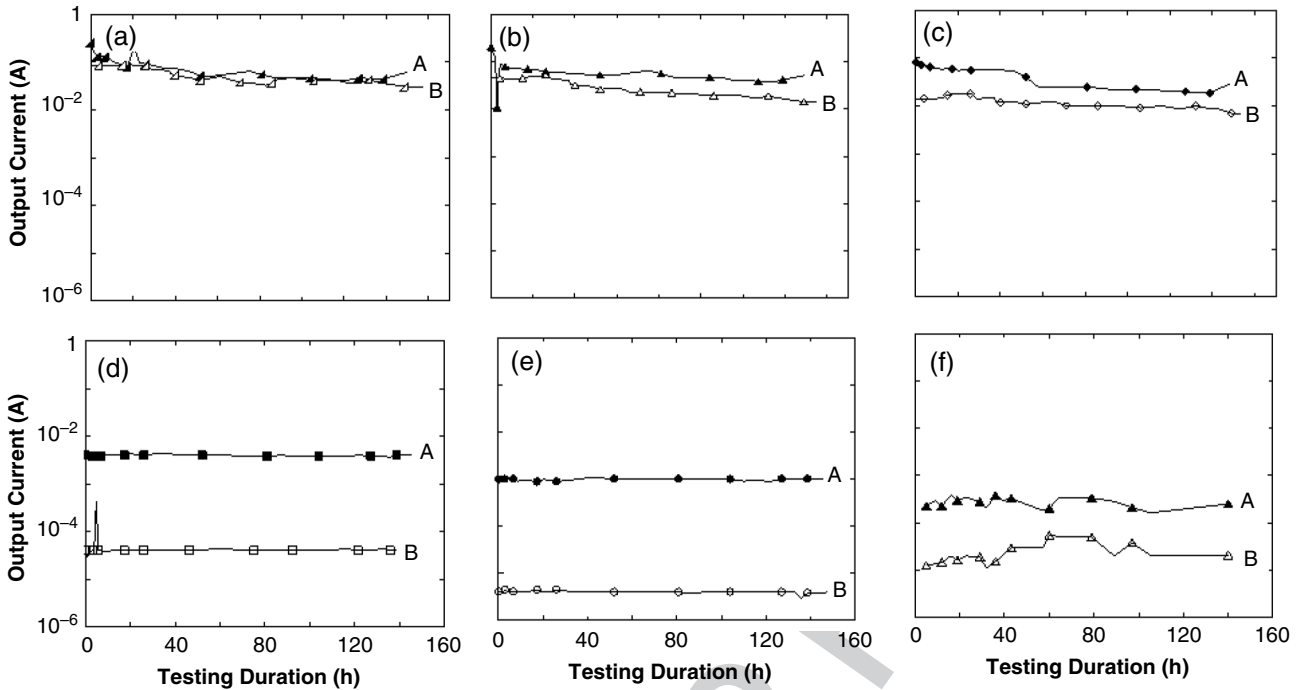
the long-term performance (say, for one or two decades) of GAs in a short time (say, in about four to 6 month); (ii) performance of GAs in various exposure conditions (such as mild, moderate, and severe chloride environments); and (iii) early-age performance (i.e., the ability to accelerate the steel passivation). Therefore, the effect of a wide range of potential differences (30 V, 20 V, 10 V, and 5 V) across the anode and the cathode were studied using the test setup similar to that explained in the *Design of Anode* section (see Figure 2[b]).

Figure 3(a) shows that after continuous application of 30 V, 20 V, 10 V, and 5 V for about 1 h, the output current from GAs was stabilized to about 0.3 mA, 0.2 mA, 0.15 mA, and 0.05 mA, respectively. Application of 30 V potential difference resulted in the heating of test specimens. After about 20 h of application, some specimens started to crack due to heat and expansive pressure by the corrosion products of zinc and tie-wires. Figure 3(b) shows the top and front view of the specimen after the application of 30 V potential difference for 50 h, the specimen had cracked, and tie-wires were severely corroded—indicating that the potential difference of 30 V is too high and may not mimic the natural process of corrosion of GA. Therefore, another set of experiments was conducted by applying lower potential differences. As mentioned earlier, this test method should also be able to evaluate the performance of GAs. To evaluate this, two widely used GAs (anodes A and B) were selected, and different potential differences (say, 20 V, 10 V, 5 V, 2 V, 1 V, and 0.5 V) were applied across the anode and cathode.

Figure 4 shows the average output current from three each of anodes A and B when potential differences of 20 V, 10 V, 5 V, 2 V, 1 V, and 0.5 V were applied across the anode and cathode. The output current from anodes A and B were approximately the same when the potential differences of 20 V and 10 V were applied. However, when potentials such as 5 V were applied, the higher efficiency of anode A was evident with a higher output current than anode B. Therefore, the potential differences of 10 V or more may not be a good choice to evaluate the difference in the performance of GAs. With further reduction in the applied potential differences, the difference



**FIGURE 3.** Effect of applied potential difference (between GA specimen and nichrome mesh) on output current and failure of anodes. (a) Output current from GA system bedding mortar and (b) specimen after subjected to 30 V potential difference between anode and cathode for 50 h. 1: Corroded tie-wires and 2 connection wires from embedded nichrome mesh.

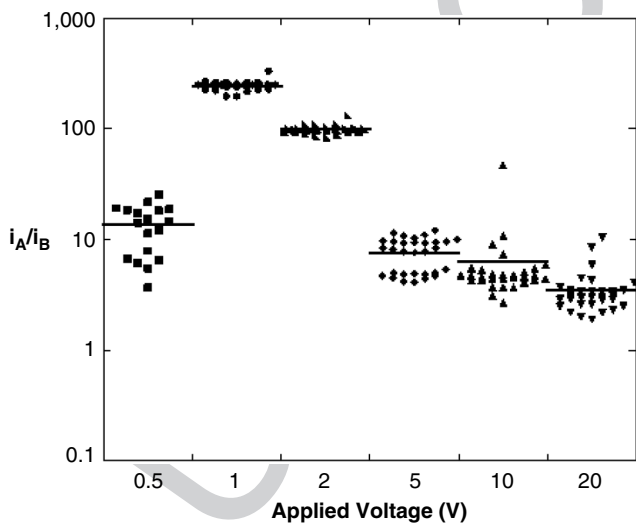


**FIGURE 4.** Output current from two widely used GAs (say, A and B) for various applied potential differences. (a) 20 V, (b) 10 V, (c) 5 V, (d) 2 V, (e) 1 V, and (f) 0.5 V.

in output current was increased—indicating that the application of lower potential differences could closely reveal the efficiency of GAs in natural conditions. Figure 5 shows the scatter plot for  $i_A/i_B$  from a total of 18 specimens at various ages of testing for various applied potentials.  $i_A$  and  $i_B$  are output currents from anodes A and B, respectively. The markers in the plot

indicate  $i_A/i_B$  calculated at times 1 h, 6 h, 12 h, 48 h, 72 h, and 140 h. The horizontal line is drawn at the average of  $i_A/i_B$  for each applied potential. The average  $i_A/i_B$  were 3.5, 6.5, 7.6, 100, 245, and 13.5 for applied potential differences of 20 V, 10 V, 5 V, 2 V, 1 V, and 0.5 V, respectively. This indicates that the higher the potential difference applied, the effect of applied potential difference inducing changes in the mechanisms that may not occur in natural conditions and hence, do not reflect the characteristics of GAs. In other words, when high potential differences are applied, the effect of resistivity of bedding mortar, EM, and anode metal/EM interface is negligible, which does not indicate the true behavior of GA. Also, the coefficient of variation (COV) in the obtained  $i_A/i_B$  for lower applied potential differences of 1 V and 2 V was significantly lower than that when high potential differences (say 5 V, 10 V, and 20 V) were applied. Considering the highest  $i_A/i_B$  and lowest COV in  $i_A/i_B$ , the authors selected 1 V to evaluate the efficiency of GAs and represent the situation with a moderate level of corrosion of steel in concrete. Also, 0.5 V and 5 V may be used if GAs are expected to be used when corrosion of steel bars is expected to be mild and severe, respectively.

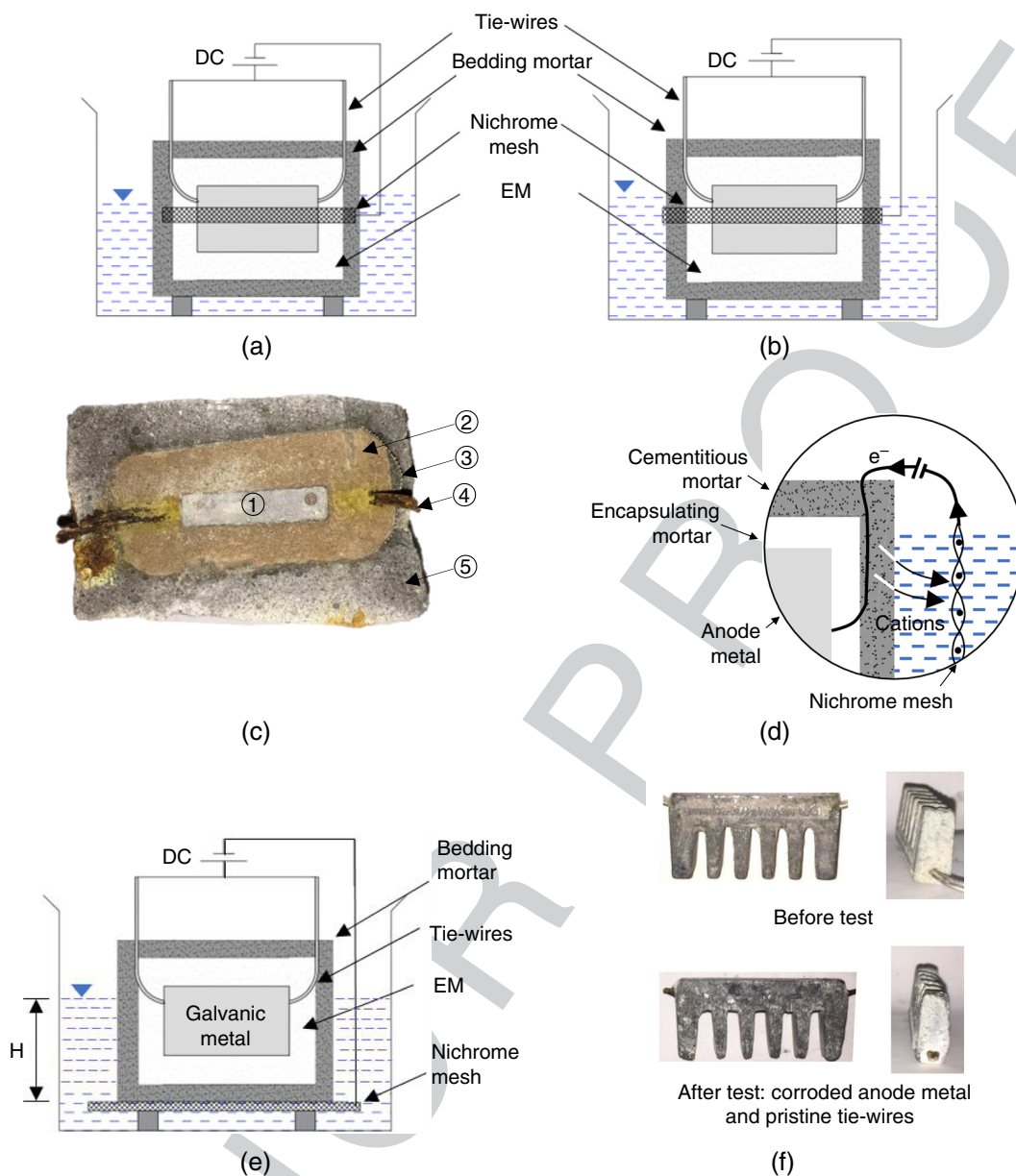
$\mu =$	13.6	246.0	99.3	7.6	6.3	3.5
COV =	0.47	0.09	0.09	0.36	1.26	0.5



**FIGURE 5.** Ratio of output current from anodes A and B [ $i_A$  and  $i_B$  are output currents from anodes A and B, respectively]. The markers in the plot indicate  $i_A/i_B$  calculated at times 1 h, 6 h, 12 h, 48 h, 72 h, and 140 h. The horizontal line is drawn at the average of  $i_A/i_B$  for each applied potential.  $\mu$  is the average and COV is the coefficient of variation of  $i_A/i_B$  for each applied potential].

### 3.3 | Placement of Anode and Cathode

Figures 6(a) and (b) show the test setups 1 and 2 to identify the suitable arrangement of the anode and cathode. At first, the nichrome mesh was placed around the GA and embedded in the bedding mortar (see Figure 6[a]). The preparation of the specimen was challenging when the thickness of the bedding mortar was 5 mm. To avoid this difficulty, another arrangement was investigated, where nichrome mesh was placed around but not embedded in mortar (see Figure 6[b]). In both arrangements, after a few hours of testing, the tie-wires were found to be corroding along with anode metal. Figure 6(c) shows a photograph of the autopsied specimen where tie-wires were corroded. Figure 6(d) shows the mechanism of



**FIGURE 6.** Effect of position of the cathode (nichrome mesh) on the failure of anode. (a) Test setup 1: embedded nichrome mesh placed around the GA, (b) test setup 2: nichrome mesh placed around the GA specimen, (c) evidence of corrosion of tie-wires in test setups 1 and 2, (d) possible corrosion mechanism of tie-wires when test setups 1 and 2 are used, (e) test setup 3: nichrome mesh below the GA specimen, and (f) residual anode metal after the GAP test. 1: Residual anode metal. 2: EM. 3: Embedded nichrome mesh around the EM. 4: Corroded tie-wires. 5: Bedding mortar.

corrosion of tie-wires in such cases. When nichrome mesh is placed (embedded or not) around the GAs, the ionic resistance between the anode metal and the nichrome mesh is more than the ionic resistance between tie-wires and nichrome mesh. Therefore, the corrosion cell forms between tie-wires and nichrome mesh, and anode metal do not participate in this corrosion process—leading to corrosion of tie-wires, which does not happen in cathodically protected RC structures. Therefore, another arrangement was adapted, where nichrome mesh was placed below the specimen (see Figure 6[e]). In this case, the ionic resistance between anode metal and nichrome mesh was less than the ionic resistance between tie-wires and nichrome mesh. After a few hours of application

of DC potential, the anode metal was corroded, and tie-wires were found to be intact (see Figure 6[f]). Another approach could be of embedding the nichrome mesh in cementitious mortar, which may replicate the rebars embedded in concrete. However, the placement of nichrome mesh outside the specimen makes it easy to replace the nichrome mesh during test, if required. Therefore, cathode (nichrome mesh) is recommended to be placed outside the mortar in the GAP specimen.

### 3.4 | Selection of Electrolyte

Another step toward standardization of the test method is the choice of electrolyte and its level. The purpose of electrolyte is to provide the ionic conductivity between GA metal and

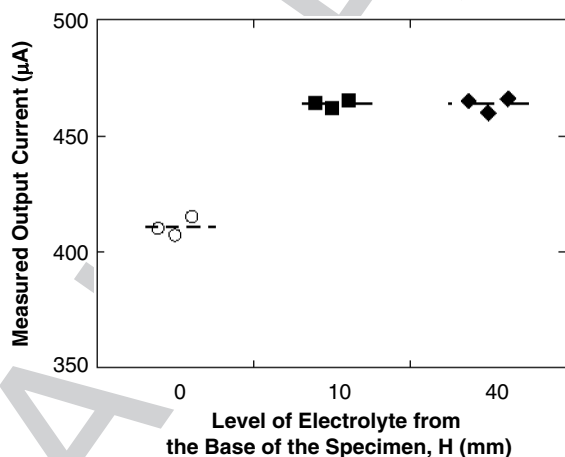
cathode (i.e., nichrome mesh) and help to maintain the characteristics of cementitious mortar (i.e., pH of the cementitious system). An electrolyte with high pH may be a good choice for the electrolyte. Therefore, simulated pore solution (0.03%  $\text{Ca}(\text{OH})_2$  + 2.23% KOH + 1.04% NaOH + 96.6% of distilled water) and saturated calcium hydroxide solution were investigated and had similar output currents. Therefore, either of the electrolytes can be selected. Here, the authors have selected saturated  $\text{Ca}(\text{OH})_2$ . Toward standardization of the test method, the next step is to fix the height of the electrolyte (H, see Figure 6[c]) from the base of the specimen.

To decide the level of electrolyte, H was varied from 0 mm, 10 mm, and 40 mm. The specimens were placed on the nonmetallic stand and the water level was maintained at least for 48 h. Figure 7 shows that the output currents for 0 mm, 10 mm, and 40 mm were about 420  $\mu\text{A}$ , 470  $\mu\text{A}$ , and 470  $\mu\text{A}$ , respectively. The output current was the same for H = 10 mm and 40 mm—indicating that H = 10 mm is sufficient to exploit the full potential of the GA. If the electrolyte solution is maintained to a high level, then the resistance between tie-wires and nichrome mesh may reduce—leading to corrosion of tie-wires, similar to that observed in Figure 6(c). Therefore, the level of electrolyte is recommended to maintain the level of electrolyte 10 mm to 15 mm from the base of the specimen. Note that the specimen is raised using plastic support to facilitate the cathode with sufficient oxygen for the cathodic reactions to occur.

## PROPOSED GAP TEST METHOD

Considering the outputs from the *Development of Galvanic Anode Performance Test Method* section, various elements such as material and position of anode and cathode, potential to be applied, the thickness of bedding mortar, type and level of electrolyte, etc., are proposed based on results from various tests. Figure 8 shows a schematic and photograph of the GAP test. The following steps provide guidance to prepare a GAP specimen and conduct the GAP test

- (i) Select 10 GAs of each type to be tested.
- (ii) Remove the EM (if any) from one of the GAs from each type and clean it to expose the anode metal. Measure the surface area of the anode metal (say, the surface area is A). This anode should not be used for preparing the GAP specimen. The remaining nine GAs to be used to prepare the GAP specimens.



**FIGURE 7.** Effect of the level of electrolyte from the base of GAP test specimen on output current from the anode.

- (iii) Cut insulated electrical wire (for example, copper or tin-coated wires) to a length such that it is sufficient to connect the GAP specimens (presented next) and the DC power source.
- (iv) Peel off the insulation at both ends from copper or tin coated wires.
- (v) Electrically connect the tie-wires of each undisturbed GA to one end of copper or tin-coated electrical wire.
- (vi) Place these GAs with tie-wires in a mold of the required size. The dimensions of the molds vary based on the size and shape of the GA. Choose the mold with a size of about 5 mm to 8 mm more than the GA in each direction. For example, if the GA is a rectangular prism with dimensions ( $x \times y \times z$ ) mm. Then, the size of mold should be  $\approx [(x+8) \times (y+8) \times (z+8)]$  mm). Therefore, either fabricate the mold with the required size or modify the cube or cylinder molds to accommodate the GA. In this work, the 100 mm cube plastic molds were modified by placing a wooden board (wooden planks) to adjust the free space around the GA to be 5 mm to 8 mm.
- (vii) Prepare a bedding mortar with a workable mix. In this work, mortar was prepared using CEM 1:sand:w/b of 1:2.75:0.5. The CEM 1 (Grade 53) was selected with the requirements confirming with IS:12269.<sup>33</sup> Grade II and Grade III silica sands as per IS:383<sup>34</sup> were used in equal proportion by mass. The water-to-binder ratio was 0.5.
- (viii) Place the bedding mortar in the mold for the depth of  $\approx 10$  mm and compact it using steel temping rod (25 mm square face  $\times$  380 mm long with round side handle) to have a base of bedding mortar ( $\approx 5$  mm to 8 mm). Then, place the GA with connection to electrical wires in the mold on the compacted bedding mortar. Now, place the bedding mortar around GA (including the tie-wires). Then, compact the bedding mortar using temping rod. Upon placement of bedding mortar, only the electric wire should be visible out of the mold.
- (ix) After 24 h, demold the specimen and moist-cure the prepared specimen for at least 7 d. Now, the GAP test specimen is ready to test.
- (x) To prepare the cathode, use mesh made of any corrosion-resistant metal. The mesh size should be chosen such that the mesh of five times the surface area of anode metal (see step ii) can be placed below or around the GAP specimen (see step vii). Note that the prepared mesh should be immersed in the electrolyte (presented next). In this work, nichrome mesh with a wire diameter of 1 mm and grid size of 2 mm  $\times$  2 mm was the cathode. Cut the mesh into a square, rectangular, or circular shape with five times the surface area of the anode (i.e., 5A).
- (xi) Place the prepared cathode on a raised stand made of nonconducting material. In this work, longitudinally half cut PVC pipes were used as the stand.
- (xii) Take a plastic pan and place set of stands in the tub (see photograph in Figure 8). Connect the cathode to the negative terminal of the battery using electrical wire.
- (xiii) Place the GAP test specimen on the cathode.
- (xiv) Fill electrolyte (saturated calcium hydroxide) in the pan to the level  $\approx 10$  mm to 15 mm from the base of the GAP specimens. In this work, saturated calcium hydroxide was prepared by mixing  $\approx 3$  g of calcium hydroxide in 1 L of distilled water.



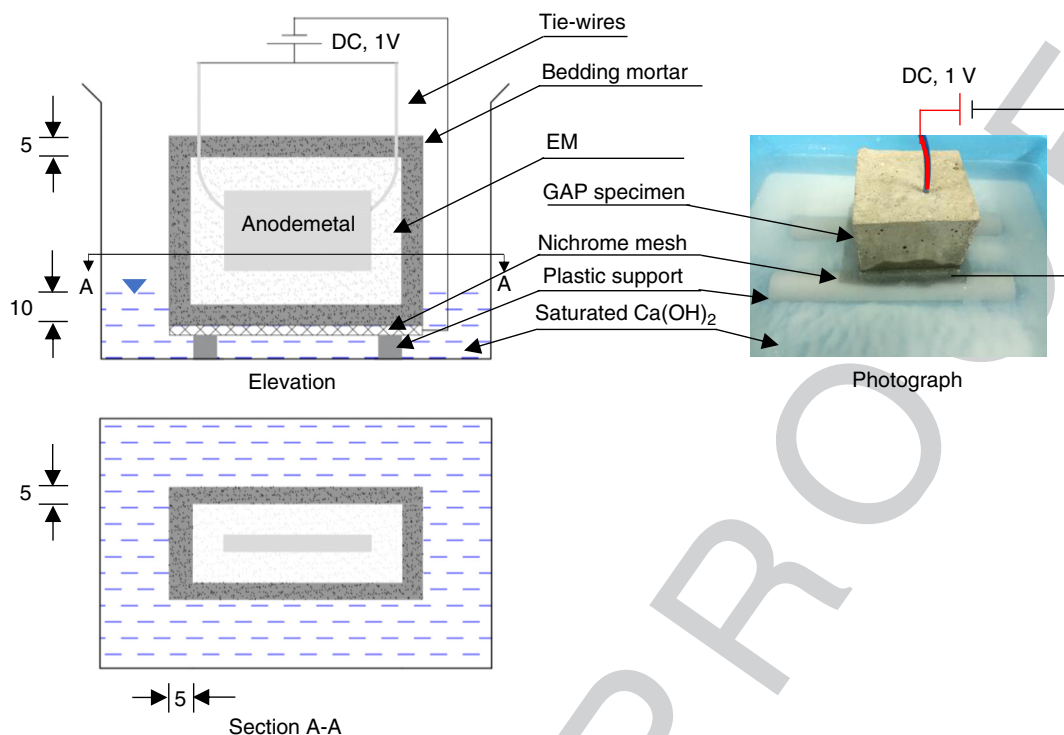


FIGURE 8. GAP test setup. Note: All dimensions are in mm.

- (xv) Connect the positive terminal of the DC power supply to the test specimen (anode) and the negative terminal to the cathode (nichrome mesh). Apply 0.5 V, 1 V, and 5 V to mimic mild, moderate, and severe corrosion conditions of rebars in RC structures, respectively—this makes a total of nine specimens for each type of anodes.
- (xvi) Maintain the laboratory conditions to  $25 \pm 2^\circ\text{C}$  and RH between 65% and 70% throughout the test and ensure that the solution level is maintained to 10 mm to 15 mm from the base of the specimen (as discussed in the *Selection of Electrolyte* section). The electrolyte will evaporate during the test. Therefore, to maintain the level of electrolyte by refilling it twice a week for the whole duration of testing.
- (xvii) Measure the output current from each specimen by connecting an ammeter in series with the circuit and record the output current at least twice in a week until the output current from GA is  $< 0.5 \mu\text{A}$ . The Failure of

GA is defined as the time when at least two consecutive output current from GA is  $< 0.5 \mu\text{A}$ .

- (xviii) Report the results in the following format (see Table 2).
- (xix) A guideline to analyze the collected data and procedure to evaluate the performance of GA is presented next.

### EVALUATION OF PERFORMANCE OF GALVANIC ANODES USING GALVANIC ANODE PERFORMANCE TESTS

#### 5.1 | Performance of Two Widely Used Galvanic Anodes

Two widely used GA types (here, anodes A and B) were selected to evaluate their performance using GAP test. Anode A has anode metal embedded in porous EM with pH greater than 12.5 and anode B has anode metal coated with alkaline coating and embedded in dense EM with pH less than 12.5. To evaluate

AQ4 Table 2. Format for Collection of Output Current from GAP Specimens

Duration of Potential Application (d)	Applied Potential (V)								
	0.5			1			5		
	Output Current from GAP Specimens ( $\mu\text{A}$ )								
	S1	S2	S3	S1	S2	S3	S1	S2	S3
0									
4									
7									
10									
...(n-3)									
n									

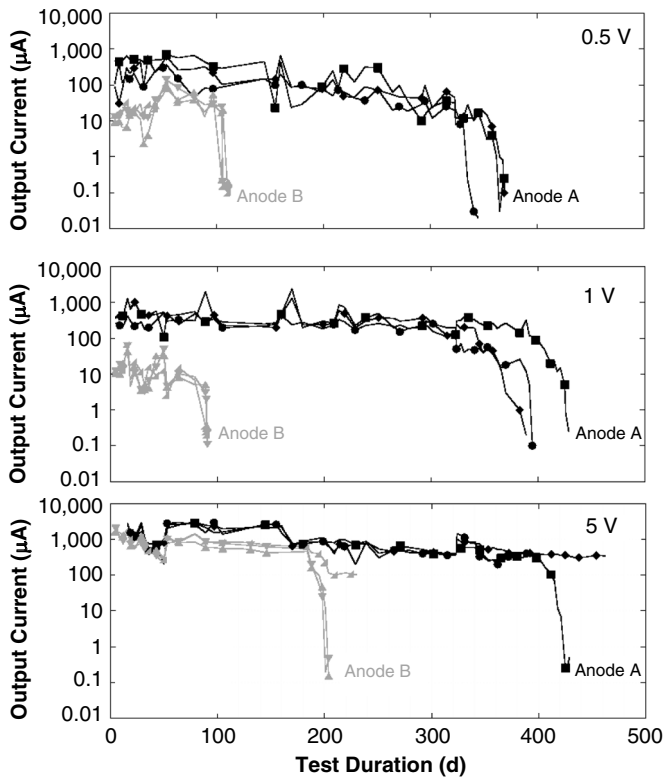


FIGURE 9. Performance of GAs evaluated using GAP test.

the performance of these anodes, three GAP specimens using anodes A and B were cast as described in the *Proposed Gap Test Method* section. Following three different potential differences, 0.5 V, 1 V, and 5 V, were applied across anode and cathode. Figure 9 shows that the output current from anodes A (curves in black) is higher output current than anode B (curves in gray) when 0.5 V and 1 V is applied—indicating that the anode A would provide better protection than anode B. For the cases with 5 V, both anodes A and B have similar output current in for the initial few days of testing—indicating that both anodes A and B can protect the steel rebars from corrosion in severe exposure conditions. Later with continuous application of potential differences for about 100 d ( $\approx$  3 month), anode B could not supply current—indicating failure of anode B for all three cases. In the same exposure conditions, anode A could supply current for about 400 d ( $\approx$  1 y) with the application of 0.5 V and 1 V. With the application of 5 V potential difference, only one specimen failed within the testing duration of 475 d. The other two specimens were in continuous application of 5 V—indicating that the anode A could perform relatively longer than anode B. In short, anode A performed better for any applied potential—indicating that anode A could protect RC structures better and longer than anode B. The results also demonstrate the ability of the GAP test method to differentiate the performance of anodes of different quality.

## 5.2 | Possible Reason for Premature Failure of Galvanic Anode

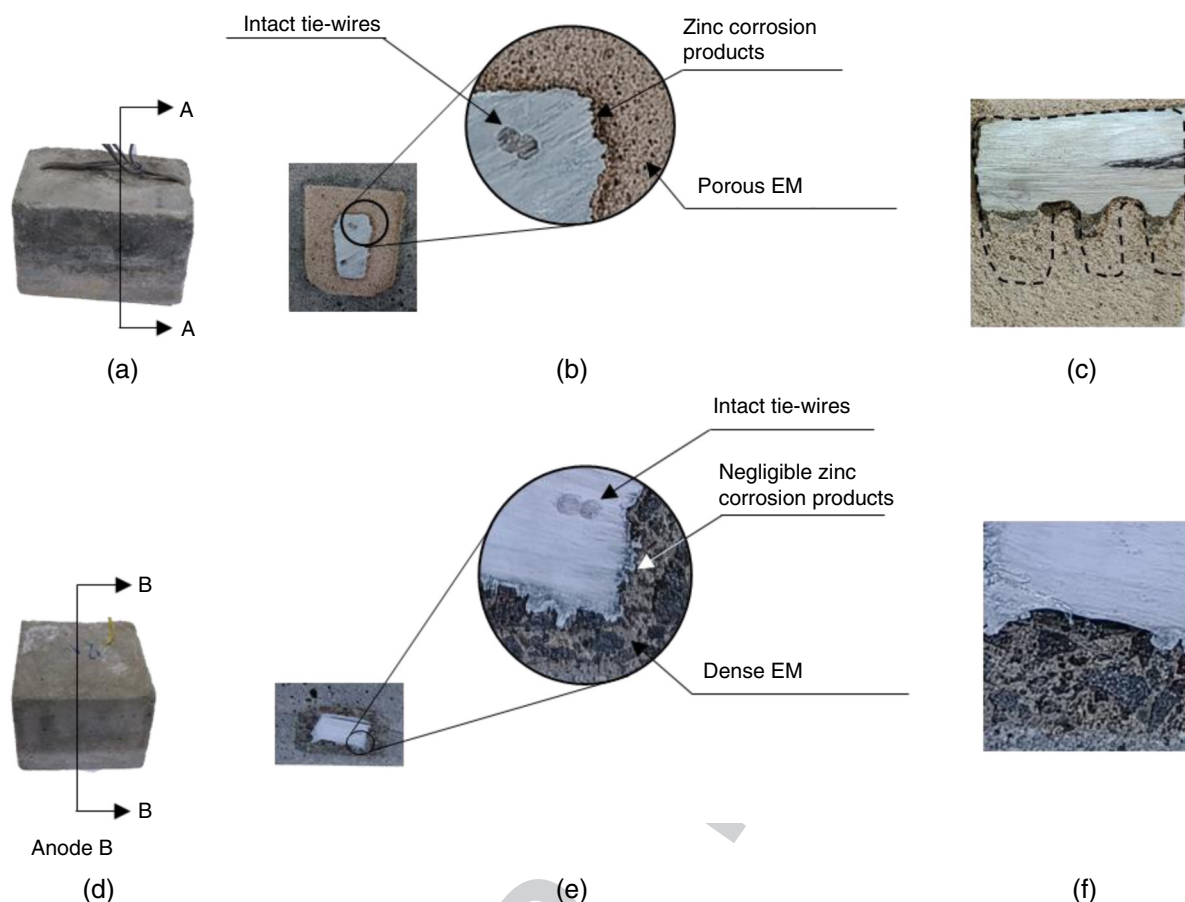
Figure 10 shows the photographs of GAP specimens after the failure of GAs was detected using the GAP test with a potential difference of 5 V between the anode and cathode.

<sup>†</sup> Trade name.

Similar failure patterns were observed for specimens tested under 1 V and 0.5 V. Figures 10(a) and (d) show that at the end of the test, GAP specimens do not have any rust stains or cracking of bedding mortar—indicating that the reduction in the supply of current is due to failure of GAs. Therefore, to investigate the reason for failure, the GAP specimens were cut into two halves. Figures 10(b) and (e) show the cut sections from GAP specimens with anodes A and B, respectively. The close-ups of the cut section show that the tie-wires in both anodes were not corroded. Also, it can be seen that two diecast tie-wires are used in both types of anodes. It was reported that the use of two tie-wires close together may allow a space between them where molten zinc (during diecast) cannot penetrate and may lead to a small space between tie-wires. During the service of GAs in structures, this space may allow moisture to enter in between tie-wires—leading to corrosion of tie-wires.<sup>11</sup> GAP test may not be able to capture such failures, which is a limitation of proposed GAP test. However, the GAP test may help in detecting the failure of GAs due to inadequate characteristics of EM. The close-ups in Figures 10(b) and (e) show that the anode A has porous EM and can allow zinc corrosion products to migrate away from the zinc metal; whereas, EM in anode B has a dense structure, which may offer high resistance and may not allow corrosion products to move away from the zinc metal. The quantification of the porosity of both EM is presented later. Figures 10(c) and (f) show the close-up of the degradation of zinc in anodes A and B, respectively. The dashed line indicates the approximate dimensions of zinc metal at the start of the test. As expected, significant amount of zinc from anode A has got consumed during the test. On the other hand, a negligible amount of zinc was consumed from anode B—indicating that the characteristics of EM can affect the performance of GAs. Therefore, the pH and porosity of EM were evaluated for both anodes and presented next.

The pH of EM from the region close to anode metal (hatched region shown in the inset of Figure 11[a]) was determined using the test procedure prescribed in Sergi, et al.<sup>8,11</sup> Figure 11(a) shows that the average pH of the collected three samples of EM from anodes A and B were 14+ and 6.9, respectively. The rate of corrosion of zinc is high when the pH is greater than 12.5.<sup>35</sup> Therefore, the zinc in anode A would keep corroding until the pH of EM is greater than 12.5, ideally greater than 13.6.<sup>8</sup> On the other hand, the rate of corrosion of zinc at pH between 5 and 12.5 is significantly low.<sup>36</sup> Therefore, anode B would have corroded only until the alkaline coating could provide a corrosive environment (high pH). The pH of the alkaline coating could not be determined due to insufficient sample size.

Another reason for the failure of GA can be the unavailability of fresh zinc surfaces for corrosion. For this, the corrosion product of zinc should diffuse away from the zinc surface through the pores of EM. The total porosity of the EM from the region close to the anode metal (hatched region shown in the inset of Figures 11[a] and [b]) were determined using the mercury intrusion porosimetry (MIP) technique. In this experimental program, three fragments from the EM were collected from hatched region with a total weight of about 0.3 g and a thickness of each chunk  $\approx$  5 mm and used for the tests. Pascal 140–440<sup>†</sup> MIP instrument was used to measure the pore size in the range of 100  $\mu$ m to 3 nm. Mercury was intruded inside the pores of the chunk, and the total volume of mercury intruded was used to estimate the total porosity of the EM samples. Figure 11(b) shows the total pore volume of EM collected from



**FIGURE 10.** Photographs of GAP specimens after the failure of GA were detected using GAP test. (a) GAP specimens after failure of anode A was detected by GAP test, (b) Section A-A: GAP specimen with anode A with two intact tie-wires. The zinc corrosion products were found to be filled in porous EM, (c) significant corrosion of anode metal (dash line indicates the approximate dimensions of anode metal at the start of the test), (d) GAP specimens after failure of anode B was detected by GAP test, (e) Section B-B: GAP specimen with anodes with intact two tie-wires. Negligible corrosion of anode metal was observed, and (f) negligible corrosion of anode metal.

anode A is two times the total pore volume of EM collected from anode B. The higher pore volume indicates that the EM could provide an easier path for corrosion products to diffuse away from the zinc surface and fresh zinc is available for corrosion.

Therefore, GA could be selected by considering the following prescriptive specifications: (i) the pH of EM is greater than 13.6 and (ii) the total pore volume of EM is greater than the desired value (with present knowledge, >20% of the total volume of EM<sup>11</sup>). However, the pH of EM at the beginning of the service of GA does not assure the pH of EM after a few years of service. Also, desired pore volume of EM can vary from case to case. Therefore, the following performance-based specifications are recommended:

- (i) The output current density from the GAP specimen at an applied potential of 0.5 V > the required output current in service (i.e., corrosion current density of steel rebars).
- (ii) Calculated  $t_{in-service}$  (obtained from Equation [2] and output current-duration plot for 1 V) is greater than the desired service life of GA.

### 5.3 | A Way Forward to Estimate the Service Life Galvanic Anodes

The service life of GAs will depend on the demand for electrons from the rebars. The total charge passed during the GAP

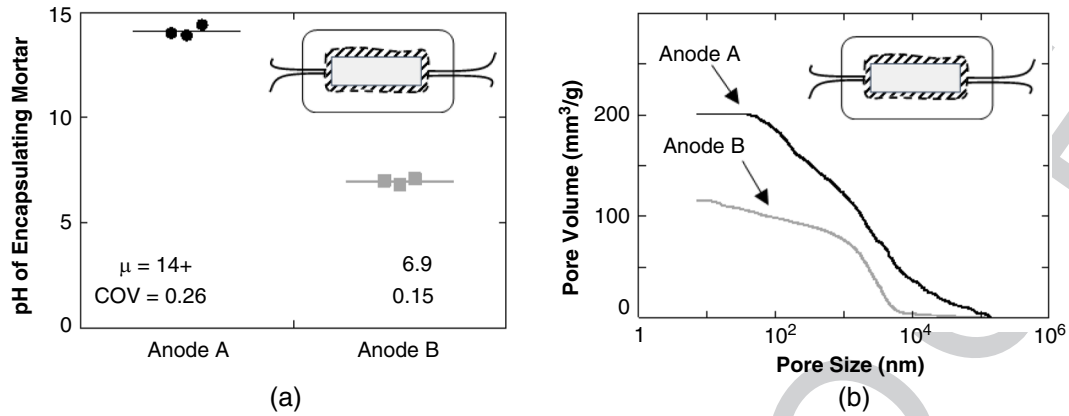
test is expected to be equal to the total charge passed in service. Equation (1) is proposed to estimate the service life of GAs:

$$i_{GAP} \times t_{GAP} = i_{in-service} \times t_{in-service} \quad (1)$$

where  $i_{GAP}$  is the average output current from a node during the GAP test,  $t_{GAP}$  is the time required for the failure of GA,  $i_{in-service}$  is the current required by rebars from GAs to protect rebars from corrosion during service, and  $t_{in-service}$  is the service life of GA in service. Note that the steel rebars in the RC structure do not require the continuous constant withdrawal of current from GAs. The current supplied by GAs depends on the demand by the steel rebars. For example, the rebars may require a high current during the rainy season (i.e., when RH is high) and the same steel rebars may require negligible current during summer (i.e., when RH is low). Therefore, the calculation of service life should reflect these. The time required for the passivation of steel may vary from case to case, which the CP engineer needs to decide. Therefore, Equation (1) can be modified to

$$i_{GAP} \times t_{GAP} = (i_{in-service} \times t_{in-service})_{LowRH} + (i_{in-service} \times t_{in-service})_{HighRH} \quad (2)$$

where  $(i_{in-service} \times t_{in-service})_{LowRH}$  is the total charge passed when RH at the steel-concrete interface is low (negligible corrosion of



**FIGURE 11.** Possible reason for premature failure of anode “B” over anode “A” (hatch in the inset shows the region where samples of EM were collected). (a) pH of EM around the GA and (b) pore structure of EM around the GAs.

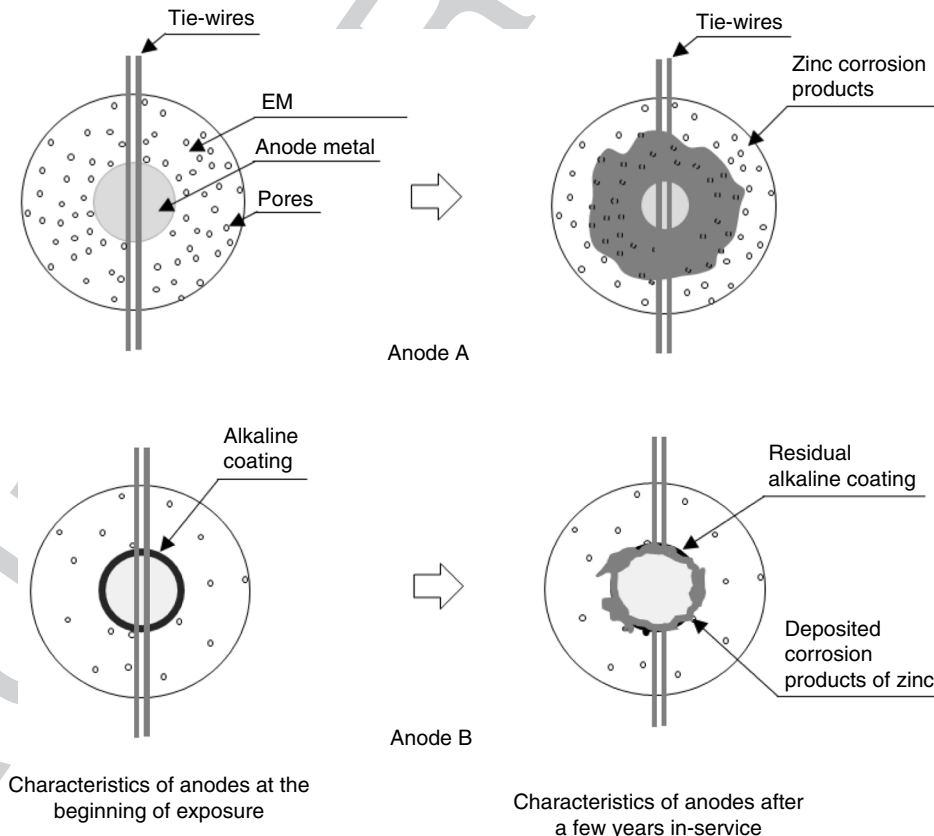
rebars) and  $(i_{in-service} \times t_{in-service})_{High\ RH}$  is the total charge passed when RH at the steel-concrete interface is high (high corrosion of rebars). For the estimation of service life, it is expected from the CP engineer-in-charge to identify the number of months the structure is exposed to conditions such as low and high RH. Also, measure the corrosion rate of rebars during these conditions. These rates of corrosion rebars can be used as the input for  $(i_{in-service})_{Low\ RH}$  and  $(i_{in-service})_{High\ RH}$ .

**5.4 | Degradation Mechanisms of Various Galvanic Anodes**

Figure 12 shows the schematics to demonstrate the degradation mechanisms of the following GAs: (i) anode A: anode

metal embedded in porous-high pH EM and (ii) anode B: anode metal coated with alkaline coating and embedded in dense-high low pH EM.

Figure 12(a) shows the anode metal is embedded in porous EM (the unfilled black circles represent pores) with high pH. Here, the anode metal corrodes due to the high pH of EM surrounding to anode metal. The corrosion products move away from the anode metal surface due to porous EM—facilitating the availability of fresh metal for corrosion. Such anode metal may continue to corrode if the pH of EM surrounding to anode metal does not drop below 13.6 for their service life.<sup>8,11</sup> If pH of EM drops from 13.6, the anodes may stop corroding. Literature report that the pH of lithium-based EM dropped from 14.6 to 13.8 after about 20 y of service.<sup>8</sup> Therefore, if EM is



**FIGURE 12.** Degradation mechanisms of various GAs (note: circular images are selected for simplicity and demonstration purposes only).

adequately designed to provide sufficient hydroxide ions to maintain  $\text{pH} > 13.8$ , then anode metal can continue to corrode and protect rebars from corrosion.

Figure 12(b) shows anodes (here, anode B) with anode metal coated with alkaline coating and dense EM with pH ranging between 7 and 12.5. In such systems, anode metal corrodes only until alkaline coating can provide a corrosive environment (high pH) to anode metal. Once the anode metal corrodes, the corrosion products cannot move away from the anode metal surface due to the low porosity of EM. Therefore, the corrosion products start to accumulate on the anode metal surface—leading to the unavailability of fresh anode metal for corrosion. Therefore, such GAs may prematurely fail.

## SUMMARY AND CONCLUSIONS

This paper presents the steps involved in the development of a short-term test method to assess the longevity of GAs. For this, various experimental programs were conducted to design GAP specimen (i.e., the anode in the test method), cathode (material and size), and electrolyte (material and level of electrolyte) used in the GAP test. Also, a range of potential differences (0.5 V, 1 V, 5 V, 10 V, 20 V, and 30 V) was applied across selected anode and cathode to select potential differences which could reveal the true potentials of GAs. The following are the key elements of the proposed test:

- The GAP specimen can be prepared by embedding the GA in a bedding mortar for a cover of about 5 mm to 8 mm around the GA.
- Any corrosion-resistant material with a higher surface area can be selected as a cathode. In this work, nichrome mesh with a wire diameter of 1 mm and grid size of 2 mm × 2 mm of five times the area of GA was selected as the cathode.
- Solution with high pH such as saturated calcium hydroxide or simulated pore solution can be used as an electrolyte. The level of electrolyte was suggested to be maintained 10 mm to 15 mm above the base of the GAP specimen.
- A potential difference of 5 V or less could identify the difference in the performance of various GAs. Potential differences of 0.5 V, 1 V, and 5 V were recommended to mimic mild, moderate, and severe corrosion conditions of rebars in RC structures.

Considering these, a GAP test method is proposed, which was found to work well in identifying the inadequate quality anodes within a period of 3 to 4 months. The inadequate quality anode was found to prematurely fail due to inadequate characteristics of EM (low porosity and low pH), whereas a good-quality anode could supply current for more than a year due to porous EM with pore volume  $> 20\%$  and high  $\text{pH} > 13.6$ . Based on the type of failures observed, degradation mechanisms for various types of anodes are proposed. For a GA to enable the protection of steel in RC structures for a long duration, the EM must provide a corrosive environment such as high pH, and it must allow anode metal corrosion products to move away from the metal surface through porous EM. Also, a service life model, considering the total charge passed during the GAP test and in-service are constant, was proposed. The service life of anode A was at least three times longer than anode B. Based on this study, the following performance-based specifications for the selection of galvanic anodes were proposed: (i) the output current density from the GAP specimen at an applied potential of 0.5 V  $>$  the required output current in service (i.e., corrosion current density of steel rebars) and (ii) calculated  $t_{\text{in-service}}$  is

greater than the desired service life of GA. The proposed test method can help CP engineers to choose good-quality GAs to achieve a durable repair of RC structures.

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NOTATIONS

$\mu$ :	Average
$A_C/A_A$ :	Ratio of surface area of cathode to anode
CP:	Cathodic protection
COV:	Coefficeint of variation
EM:	Encapsulating mortar
GA:	Galvanic anode
GAP:	Galvanic anode performance
H:	Height of electrolyte from the base of the GAP specimen

$i_{in-service}$ :	Current required by rebars from GAs to protect rebars from corrosion during service
$i_A$ :	Output current from anode A
$i_B$ :	Output current from anode B
$i_{GAP}$ :	Average output current from anode during GAP test
MIP:	Mercury intrusion porosimetry
RC:	Reinforced concrete
$t_{in-service}$ :	Service life of GA
$t_{GAP}$ :	Duration of GAP test