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Early age electrochemical behavior and initial effectiveness of waste-derived Al–Zn hybrid sacrificial anodes on steel bar corrosion control in geopolymer concrete

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Abstract
Problems related to waste, particularly metal and battery waste, represent a significant and growing environmental challenge. While recent studies have explored either waste-derived materials in geopolymer concrete or conventional sacrificial anodes for corrosion protection, the integrated application of hybrid waste-based sacrificial anodes with supplementary cementitious systems for effective and sustainable cathodic protection in reinforced concrete remains largely unexplored. This study presents a novel approach by simultaneously utilizing aluminum can waste and used battery materials as an Al-Zn hybrid sacrificial anode system combined with fly ash and rice husk ash–modified geopolymer concrete for corrosion mitigation. The primary objective of this research is to evaluate the effectiveness of waste-based sacrificial anodes in inhibiting reinforcement corrosion while maintaining the mechanical performance of concrete. The study employed an experimental investigation with mechanical property evaluation and electrochemical monitoring. The results of early connection demonstrated that geopolymer concrete containing 6% rice husk ash and 94% fly ash of precursor achieved the optimal performance, exhibiting a depolarization value exceeding 100 mV, reduced corrosion potential in half-cell measurements, and a stable anode current output, confirming effective cathodic protection according to SACP criteria. Corrosion behavior was assessed through half-cell potential and depolarization measurements, while concrete performance was verified using key mechanical and durability indicators. These findings indicate that a waste-based sacrificial anode system offers a promising, environmentally sustainable alternative for corrosion protection in reinforced concrete infrastructure.

Keywords:
Al-Zn sacrificial anodes;
Cathodic protection;
Depolarization criterion;
Electrochemical performance;
Reinforced concrete;

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INTRODUCTION

Reinforced concrete beams are one of the structural elements of buildings that play a crucial role in maintaining the stability and functionality of buildings [1]. However, this advantage is not without its fundamental weakness, particularly the susceptibility of reinforcing steel to corrosion. Corrosion is a natural phenomenon resulting from chemical or electrochemical reactions between materials and their environment, which in the long term can lead to serious structural degradation [2, 3, 4]. Corrosion causes a reduction in the area of reinforcement, which results in a decrease in the capacity of structural elements. In recent decades, failures caused by steel corrosion have attracted global attention [5][6]. The National Association of Corrosion Engineers (NACE) reported that direct losses due to corrosion reached US$276 billion, equivalent to 3.1% of Gross Domestic Product (GDP). This fact confirms that corrosion is a major problem, not only technical but also economic [7].

In addition to corrosion issues, the use of cement as a primary ingredient in concrete mixes has a substantial impact on the environment. The Chatham House research institute noted that the cement industry contributed approximately 8% of global carbon dioxide (CO_2) emissions. Furthermore, Indonesia faces serious challenges in waste management, particularly waste from beverage cans and batteries. According to Indonesia's Ministry of Environment (MoE) through the National Waste Management Information System (SIPSN), verified national data indicate that only 48.88% of waste is properly managed, while 49% of final disposal sites (TPAs) still operate under open dumping practices (2025 verified data published in 2026). Accordingly, this situation demands material engineering solutions that not only improve concrete performance but also support sustainability principles [8][9].

Various approaches have been developed to reduce concrete's susceptibility to corrosion, one of which is the Cathodic Protection (CP) method [10, 11, 12, 13]. Previous researchers studied the utilization of used beverage cans as sacrificial anodes using the cartridge system [14]. Despite extensive research on CP systems for reinforced concrete, most studies rely on commercially manufactured sacrificial anodes and focus primarily on electrochemical performance without integrating waste-derived materials into both the anode and concrete matrix. Furthermore, the combined influence of waste-based Al-Zn hybrid sacrificial anodes and supplementary cementitious materials, such as rice husk ash (RHA), on long-term corrosion mitigation and concrete durability remains insufficiently explored. As a result, the electrochemical compatibility and depolarization effectiveness of fully waste-integrated CP systems are not yet well established. However, using this waste without purification resulted in unstable protective currents, thus limiting its effectiveness. This gap also opens up opportunities for further development.

This research developed a new sacrificial anode based on a mixture of aluminum and zinc from the refining of used cans and battery waste, called Al-Zn hybrid anodes. Aluminum in used cans and zinc in primary batteries have great potential to replace conventional anodes. The combination of the two is projected to produce a more stable protection current. In addition, this research also employed rice husk ash (RHA) and fly ash (FA) as a geopolymer precursor and partial backfill material constituent. RHA with its high silica content plays a role in increasing the resistance of concrete to aggressive environments [15, 16, 17, 18, 19]. To strengthen the effectiveness of the CP system, environmentally friendly backfill materials consisting of 75% recycled gypsum, 20% rice husk ash, and 5% glass waste were also deployed. This research presents a new solution in the form of an Al-Zn hybrid anode system in geopolymer concrete. Geopolymer concrete is known to be more environmentally friendly than conventional concrete and has better resistance to corrosion [15, 20, 21, 22, 23]. However, its use encounters various limitations, such as variations in the quality of raw materials, sensitivity to the mixing and curing process, and the cost of activator materials. Therefore, the development of the Al-Zn hybrid anodes is expected to overcome these weaknesses by providing active external protection to the reinforcement, while supporting the concept of sustainability through the utilization of waste as a new resource.

The objectives of this study are to develop Al-Zn hybrid sacrificial anodes derived from aluminum cans and used battery waste materials, to evaluate the cathodic protection performance of the proposed system through depolarization criteria, half-cell potential, and current density measurements, and to compare different levels of rice husk ash (RHA) replacement in order to assess their effectiveness in improving concrete durability under cathodic protection conditions. The novelty of this study lies in the integrated use of waste-derived Al–Zn hybrid sacrificial anodes and RHA-modified concrete to form a fully waste-based cathodic protection system, with performance explicitly validated using electrochemical depolarization criteria rather than corrosion potential alone. This approach provides new insights into the electrochemical–material interaction between sacrificial anodes and sustainable concrete mixtures, which has not been systematically addressed in previous studies.

MATERIAL AND METHOD

Method

The experimental procedure began with a comprehensive literature review to establish the research framework and relevant cathodic protection performance criteria. Materials and testing equipment were then prepared, followed by the fabrication of waste-derived Al-Zn hybrid sacrificial anodes. Material characterization and preliminary property tests were conducted prior to concrete mixing. Fresh concrete properties were evaluated to ensure workability and mixture stability, after which reinforced concrete specimens incorporating sacrificial anodes and backfill materials were cast and cured. Hardened concrete properties were subsequently tested to assess mechanical performance and durability. The effectiveness of the cathodic protection system was evaluated through electrochemical measurements, including half-cell potential monitoring and current output assessment, and verified using depolarization testing in accordance with established cathodic protection criteria. Finally, all experimental data were systematically analyzed to evaluate the performance of the waste-based sacrificial anode system. The schematic experimental procedure is depicted in Figure 1.

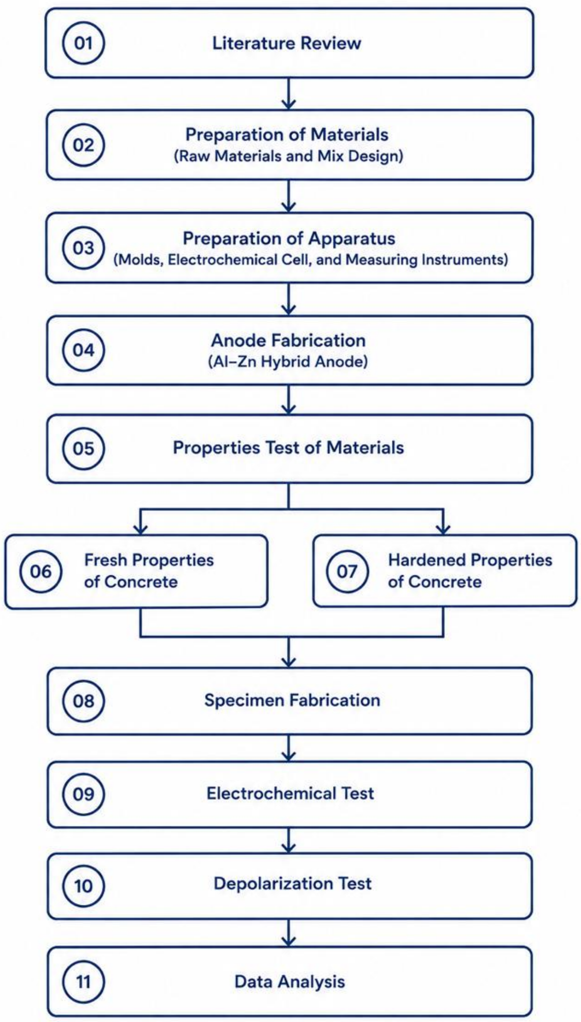


Figure 1. Experimental Procedure

The manufacture of geopolymer concrete test specimens was carried out with a curing process for 28 days, with several tests such as compressive strength, split tensile strength, shrinkage, and absorption. The compressive strength test was performed according to SNI 03-1974-1990 with readings at the ages of three, seven, and 28 days, and the average value of three test specimens for each variation. Then, the split tensile test was conducted on the 14th day following SNI 03-2491-2002. The shrinkage test was run based on SNI 8140-2016, with tests on three different sides. The absorption test was carried out based on SNI 03-6433-2000, with observations on the diameter, height, and weight of the test specimens.

The chemical composition of the alloy was homogenized, and heterogeneity resulting from the use of unprocessed waste materials was reduced through the utilization of a controlled melting and casting process to produce the Al-Zn hybrid anode in this study. The melting or casting process promoted a more uniform phase distribution and minimized micro-galvanic effects within the anode material, in contrast to untreated waste, which may contain compositional inconsistencies and localized impurities that result in unstable electrochemical behavior. Due to this enhanced homogeneity, the electrochemical potential and current discharge were more stable during cathodic protection operation. The anode was made by melting waste cans and battery waste using charcoal until the metal reached its melting point, then purified by adding sodium tetraborate in the second melting. It was conducted at the Metal Manufacturing and Fabrication Laboratory, Mechanical Engineering, Universitas Muhammadiyah Yogyakarta (UMY). The resulting anode measured 3cm x 3cm x 0.5cm. These anodes were installed on concrete in the amount of 12 pieces, connected by cables. The anodes were also coated with a backfill with a composition of 75% recycled gypsum, 20% rice husk ash, and 5% glass waste.

This test was conducted using the principle of Sacrificial Anode Cathodic Protection (SACP) (Figure 2), utilizing the potential difference between an anode and a cathode, i.e., an anode such as aluminum, zinc, or magnesium has a lower potential than a cathode, which results in current flow. The anodes were a combination of battery waste (zinc) and can waste (aluminum). Both were melted and refined into a plate. The sacrificial anodes applied in this experiment were fabricated using a waste-derived Al-Zn composition with a weight ratio of 75% aluminum to 25% zinc. The test specimens were designed with three anode installation spacings, particularly

10 cm, 20 cm, and 30 cm, each of which was applied to reinforcing steel bars with two concrete cover depths of 3 cm and 5 cm. Furthermore, each configuration was replicated in geopolymer concrete mixtures prepared using freshwater and seawater to evaluate environmental effects on cathodic protection performance. Based on the combination of anode spacing (3 levels), cover depth (2 levels), and mixing water type (2 levels), a total of 12 experimental variations were produced and evaluated.

After the concrete and anodes were ready, the anodes were installed on the test specimens. During curing, Half-Cell Potential (HCP) readings were taken using a multimeter and reference electrode according to ASTM C876-15 at intervals of every two days starting from days three, five, seven, nine, and so on. It measured the value of potential on the surface of concrete members where the positive pole of the high-impedance volumeter was electrically attached to the reinforcing steel, and the other pole was attached to a reference electrode. The measured potential was then translated into the risk of corrosion of embedded steel inside the RC members. Subsequently, a depolarization test was carried out by connecting the anode to the reinforcement (on-potential), cutting off the current instantly (instant-off potential), and leaving the reinforcement without current for 24 hours (rest potential), as illustrated in Figure 3. The effectiveness of cathodic protection was determined from the potential difference (ΔE) between the instant-off potential and the rest potential, with the success criterion being that the depolarization value reached ≥ 100 mV. Figure 3 exhibits the mechanism for measuring the depolarization potential, from initial protection to disconnecting the anode to assess the effectiveness of cathodic protection.

The depolarization method aims to determine the effectiveness of a cathodic protection (CP) system using a sacrificial anode based on a mixture of aluminum and zinc (Al-Zn hybrid SACP) on corrosion protection in geopolymer concrete. The depolarization method was implemented by measuring the potential difference between the reinforcing steel before and after the protective current was cut off. Protection is considered effective if there is a potential change (depolarization) of ≥ 100 mV.

Material

This study utilized the geopolymer concrete test specimens in the form of blocks measuring 40cm x 20cm x 15cm, with the mix proportion as explained in Table 1. The fine and coarse aggregates were obtained from Kulon Progo with sizes in accordance with SNI 1969-2008 and ASTM C 33-93. Meanwhile, the fly ash was sourced from the remaining fly ash of PT. Surya Karya Setiabudi and the rice husk ash were attained from the remaining burning of rice husks in the Gamping, Sleman, Daerah Istimewa Yogyakarta area. Other materials used as a mixture were sodium hydroxide, sodium silicate, and superplasticizer (Figure 4).

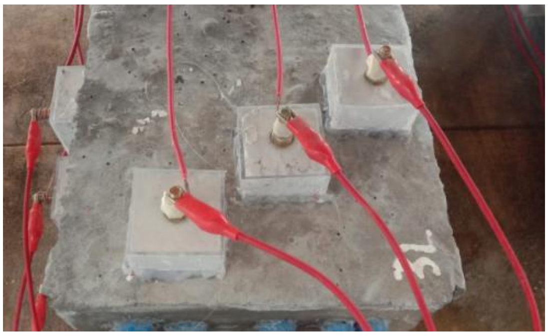


Figure 2. Al-Zn anodes installation

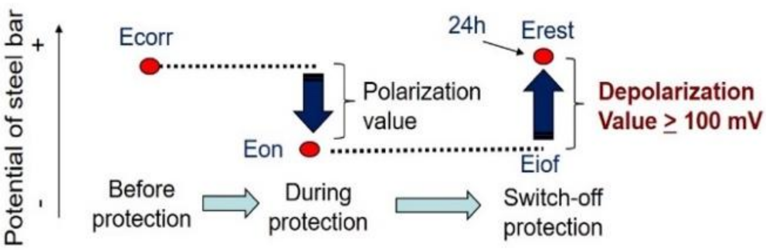


Figure 3. Mechanism for Measuring Depolarization Values

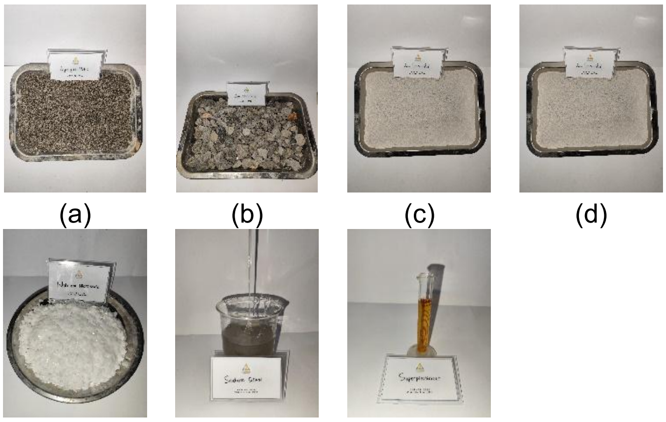


Figure 4. (a) sand, (b) gravel, (c) rice husk ash, (d) fly ash, (e) sodium hydroxide, (f) sodium silicate, (g) superplasticizer

Table 1. Mix proportion for 1 m^3

Material		unit
Water	47.84	L
Coarse aggregate	951.72	kg
Fine Aggregate	774.47	kg
Fly Ash	448.69	kg
Rice Husk Ash	28.70	kg
Sodium Hydroxide (NaOH)	58.58	L
Sodium Silicate (Na_2SiO_3)	146.5	kg
Superplasticizer	9.57	L

The backfill material was a mixture of glass powder, rice husk ash, and gypsum. Then, for the anodes, the materials purchased included aluminum cans, used batteries, charcoal, and borax. The material preparation steps involved weighing, filtering, washing, drying aggregates (sand and gravel), sieving (rice husk ash and fly ash), and preparing activator solutions (NaOH and Na_2SiO_3); as well as preparing concrete and acrylic molds, and cable soldering. Equipment preparation encompassed the use of a mixer, oven, melting furnace, installation of drill bits, and work safety equipment were also prepared to support research activities.

Data Analysis Procedure

The experimental data were analyzed by integrating electrochemical parameters with mechanical and durability responses of the geopolymer concrete. Half-cell potential, current density, and depolarization values were statistically evaluated using mean values and variability to assess cathodic protection effectiveness and compliance with depolarization criteria. Mechanical and durability results were compared across anode spacing, cover depth, and mixing water conditions using comparative trend analysis to identify significant performance differences. The effects of rice husk ash content and environmental exposure were interpreted through systematic comparison, enabling identification of optimal configurations and correlations between anode behavior and concrete durability.

RESULTS AND DISCUSSION

Physical Properties of Aggregate

The results of the aggregate tests are depicted in Table 2 for fine aggregate and Table 3 for coarse aggregate. These results comply with existing standards.

Hardened Properties

Tests conducted on concrete included concrete compressive strength, concrete splitting tensile strength, concrete absorption, and concrete shrinkage tests. Concrete compressive strength tests are the maximum compressive stress that a concrete specimen can sustain under axial loading, typically determined from standard cylinder tests at a specified age. Tests were conducted at three, seven, and 28 days. This test obtained variations with rice husk ash of 6% as presented in Figure 5.

Concrete splitting tensile testing is the indirect measure of its tensile capacity, determined by applying a diametral compressive load to a cylindrical specimen, which generates tensile stresses leading to splitting failure along the loaded plane. A constant loading rate of 0.7 to 1.4 MPa per minute was utilized until the specimen failed. In this study, the best splitting tensile test value was obtained with 0% rice husk ash, as depicted in Figure 6. This result suggests that the absence of RHA preserves the original tensile load-transfer mechanism of the geopolymer matrix, while higher RHA contents may introduce increased matrix heterogeneity that slightly reduces tensile stress distribution efficiency.

Concrete absorption testing was conducted to determine the water absorption of concrete over a specific period of time, and the results unveiled that all variations were in low absorption (less than 3%), as presented in Figure 7. This behavior indicates a relatively dense geopolymer matrix with limited pore connectivity, which is beneficial for restricting moisture ingress and enhancing durability under corrosive exposure conditions.
The shrinkage of the specimens was depicted in Figure 8. From all the specimens' variations presented, the shrinkage was around 3%. The measured shrinkage values were consistently in the range of 2–3%, reflecting the actual behavior of the developed geopolymer system. This relatively high shrinkage is considered a characteristic behavior rather than an anomaly, primarily due to the nature of the geopolymer binder and the materials employed. The incorporation of fly ash and rice husk ash, particularly the high silica content and fine particle size of rice husk ash, contributed to increased susceptibility to volumetric changes associated with moisture loss and structural rearrangement during geopolymerization. Furthermore, the elevated-temperature curing (oven curing) applied in this study accelerated the geopolymerization process but also promoted rapid moisture evaporation and the development of internal stresses, leading to higher shrinkage compared to conventional or ambient-cured systems.

Table 2. Fine Aggregate Test Results

Testing	Results	Range	Standard
Grain Fineness Modulus	2.5360	-	SNI 03-1968-1990
Sludge Content	3.70%	<5%	SNI Decree S-04-1989-F
Unit Weight	1.65 gr/cm^3	1.2–1.76 gr/cm^3	SNI 03-4804-1998
Specific gravity	2.66%	2.5% - 2.7%	SNI 1970-2008
Water Absorption	3.84%	< 5%	SNI 1970-2008

Table 3. Coarse Aggregate Test Results

Testing	Results	Range	Standard
Aggregate Wear	29.77%	<40%	SNI 03-2417-2008
Unit Weight	1.45 gr/cm^3	1.2–1.76 gr/cm^3	SNI 03-4804-1998
Specific gravity	2.60	2.5 - 2.7	SNI 1969-2008
Water Absorption	0.91%	< 3%	SNI 1969-2008

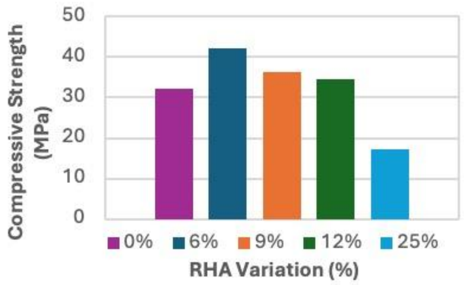


Figure 5. Concrete Compressive Strength Test Results

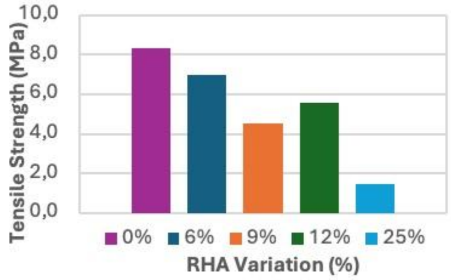


Figure 6. Results of Concrete Split Tensile Strength Test

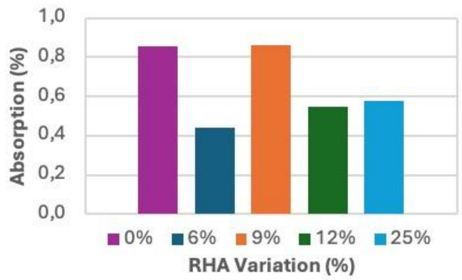


Figure 7. Results of Geopolymer Concrete Absorption Test

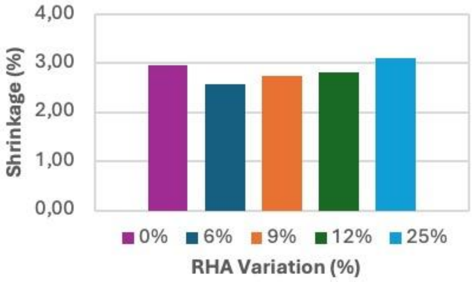


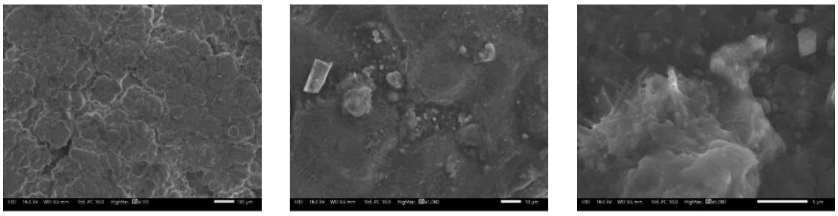
Figure 8. Results of Geopolymer Concrete Shrinkage Test

Aluminum Content Testing Using the SEM Method

Scanning Electron Microscope and Energy Dispersive X-ray Spectrometry (SEM-EDS) testing is a technique for analyzing the microstructure and chemical composition of materials at the micron scale. In cementitious applications, this technique allows for high-accuracy spatial mapping of chemical elements through the acquisition of EDS spectra at each image pixel. Figure 9 exhibits the anode surface made of a mixture of aluminum from used cans and zinc from used batteries at different magnification scales. Figure 10 demonstrates the results of the chemical content analysis from several magnifications, with elements Zn (Zinc), Al (Aluminum), Mg (Magnesium), Si (Silicon), and Ca (Calcium). The largest content was depicted by Zn with a mass percentage of 43.35%, and Al 11.15% as the anode was made by the mixture of purified aluminum can waste and zinc from battery waste.

FTIR Testing on Geopolymer Concrete

FTIR was employed to identify the functional groups and bonding characteristics within the geopolymer concrete matrix, with results expressed in terms of absorption intensity (%T) and wavenumber (cm^{-1}). Figure 11 presents the FTIR spectrum of geopolymer concrete prepared with freshwater, signifying dominant absorption bands associated with Si–O–T (T = Si or Al) asymmetric stretching at approximately 958.34 cm^{-1}, indicative of geopolymer gel formation, and Ca–O–related vibrations at around 421.06 cm^{-1}, which contribute to matrix densification. These phases are associated with reduced ionic transport, thereby supporting the corrosion resistance of the SACP system employing Al-Zn hybrid anodes. Figure 12 illustrates the FTIR spectrum of geopolymer concrete mixed with seawater, where characteristic peaks corresponding to Si–O–T stretching at 1002.53 cm^{-1}, carbonate (CO_3^{2-}) at 1429.32 cm^{-1}, Ca–O vibrations at 429.66 cm^{-1}, and O–H stretching at 3394.28 cm^{-1} were observed. In addition, the presence of a peak at 779.11 cm^{-1}, attributed to Friedel's salt, indicates effective chloride binding within the matrix. The formation of these phases suggests enhanced chloride immobilization and matrix stability, which collectively contribute to improved corrosion resistance and sustained performance of the Al-Zn hybrid SACP system. These results confirm that the geopolymer matrix provides a chemically stable and chloride-binding environment, thereby creating favorable conditions for sustained electrochemical performance and long-term effectiveness of cathodic protection system.



(a) (b) (c)

Figure 9. (a) x100 magnification, (b) x500 magnification, (c) x1000 magnification

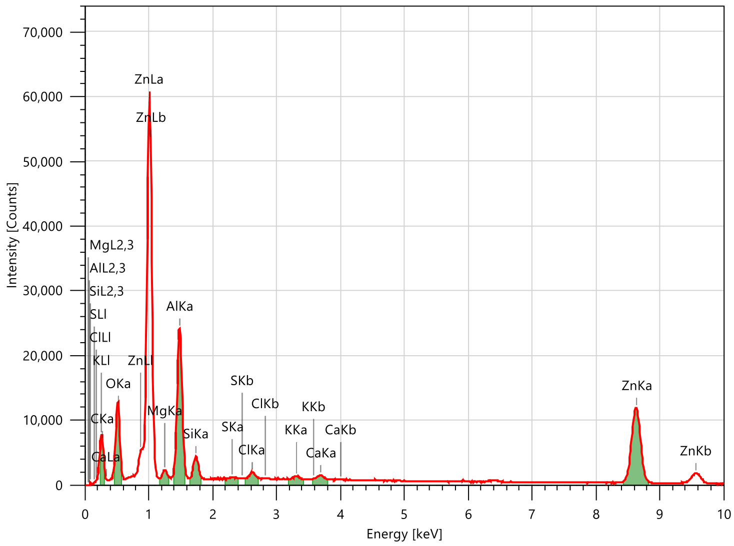


Figure 10. Al-Zn Hybrid Anodes EDS Graph

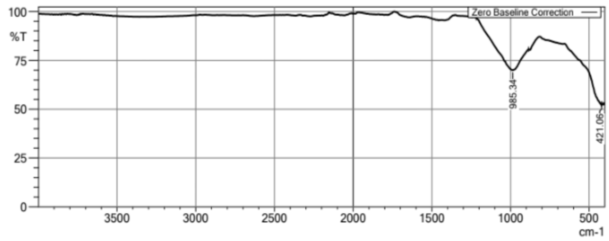


Figure 11. Test Results of Freshwater Mixed Geopolymer Concrete

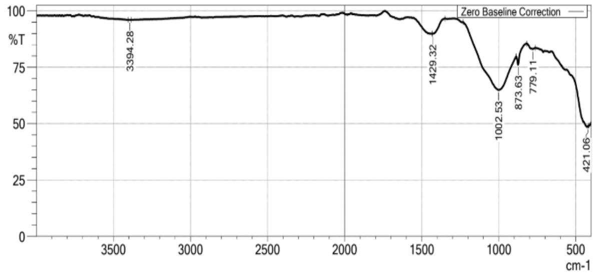
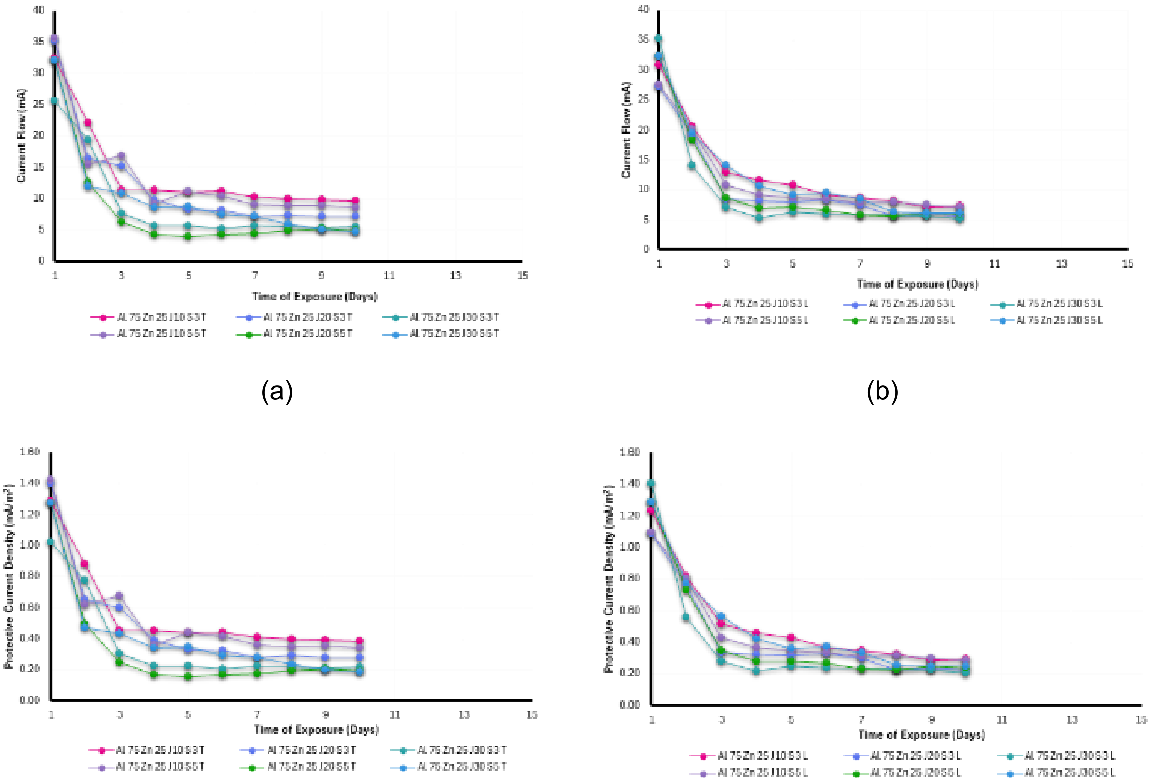


Figure 12. Test Results of Seawater Mixed Geopolymer Concrete

Anode Current Testing

The current test was performed daily to detect changes in the anode current protecting the rebar by supplying spontaneously potential different or electric current from the anode to the rebar. Figure 13 illustrates the results of the current flow and protection current density readings of the anode with a composition of 75% Aluminum 25% Zinc installed on a geopolymer concrete mixture of fresh water and sea water. The results present a stable current value, proving that the reinforcement in geopolymer concrete is supplied with an electric current that can inhibit the rate of corrosion.



(a) (b) (c) (d)

Figure 13. (a) and (b) Results of Current Flow Testing, (c) and (d) Results of Protection Current Density Testing

Depolarization

Figure 14 exhibits that the Al-Zn hybrid anodes can protect reinforced geopolymer concrete from corrosion due to the depolarization value being higher than 100 mV. For example, the Al 75 Zn 25 J10 S3 T reinforcement variation obtained the highest average depolarization value of 296.01 mV on the second day, 262.97 mV on the fourth day, and 228.40 mV on the sixth day. Hence, the Al-Zn hybrid anodes were proven effective in protecting against corrosion.

Comparison to the Previous Anode's Performance

The comparison between the previous circular anode made from unrefined recycled aluminum and the current square anode developed using a refined Al-Zn hybrid anode revealed notable differences in depolarization behavior. The previous anode exhibited an extremely high initial depolarization value of approximately 700 mV [14], followed by a gradual decrease with noticeable fluctuations in the range of 300–500 mV over the exposure period. This high initial response can be attributed to the larger surface area and the presence of material heterogeneity due to the absence of a refining process, which may induce localized electrochemical activity and unstable current output.

In contrast, the refined square anode (Al-Zn hybrid anode) with smaller dimensions (3 × 3 × 0.5 cm) in this experiment demonstrated lower depolarization values overall, generally within a narrower range, but with significantly improved stability over time. The more consistent depolarization trend indicates a controlled electrochemical response, which can be associated with improved material homogeneity resulting from the refining process, as well as a more uniform current distribution due to the smaller geometry.

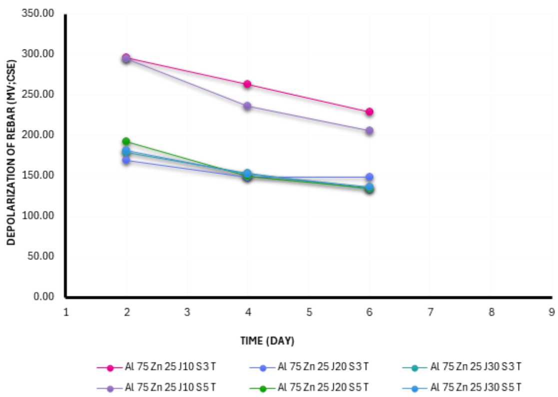


Figure 14. Depolarization Test Results

Although the depolarization magnitude in the present study is lower than that observed in the previous study, the values consistently exceeded the 100 mV depolarization criterion, confirming effective cathodic protection performance.

These findings suggest that while the larger, unrefined anode could produce higher peak depolarization, the refined Al-Zn hybrid anode provided more stable and reliable performance. It indicates that depolarization magnitude alone is insufficient to evaluate cathodic protection efficiency, and that stability and consistency over time are equally crucial for practical SACP applications.

In addition to the comparison with the previous recycled aluminum anode, the performance of the developed Al-Zn hybrid anode can also be qualitatively compared with a commercially available zinc cylindrical ribbed anode (diameter 30 mm and length 130 mm). Based on the current flow results, the zinc anode exhibited a relatively stable current output over the exposure period, ranging between approximately 0.8 and 2.0 mA, depending on the specimen condition [24]. This stable behavior is characteristic of commercially manufactured anodes with controlled composition and well-defined geometry, ensuring consistent electrochemical performance.

When compared to this, the Al-Zn hybrid anode developed in the present study demonstrated a comparable level of current output stability, despite being derived from waste-based materials. While slight fluctuations were observed, the overall trend remained within a controlled range, indicating that the refining process successfully improved the electrochemical consistency of the material. Furthermore, although the absolute current output may differ due to variations in geometry and surface area, the ability of the Al-Zn hybrid anode to maintain stable current flow confirmed its effectiveness as a sacrificial anode system.

This comparison highlights that the proposed waste-based anode could approach the performance characteristics of conventional zinc anodes, particularly in terms of stability, while offering additional environmental and economic benefits. Therefore, the Al-Zn hybrid anode system represents a promising alternative to commercial sacrificial anodes for sustainable cathodic protection applications.

Mechanistic Interpretation

The superior performance observed at 6% rice husk ash (RHA) can be attributed to an optimal balance between matrix densification and geopolymerization efficiency. At this replacement level, finely divided amorphous silica from RHA effectively participates in secondary reaction processes, refining pore structure and reducing ionic diffusivity without disrupting the primary aluminosilicate network. Lower RHA contents provide limited pore refinement, while higher contents tend to dilute reactive binders and introduce microstructural heterogeneity, negatively affecting tensile-related properties and electrochemical stability [25]. It explains why the 6% RHA mixture simultaneously achieved stable mechanical performance and enhanced corrosion resistance.

The effectiveness of the Al-Zn hybrid anode system is further supported by SEM–EDS observations, signifying Zn-dominant regions at the anode surface after exposure. Zinc-rich phases are electrochemically more active and possess a more negative corrosion potential than steel, enabling sustained anodic dissolution and a stable protection current. This Zn dominance promotes uniform current distribution and mitigates premature anode passivation, which is consistent with the measured depolarization values exceeding 100 mV [26]. Similar behavior has been reported in recent studies on Al–Zn-based sacrificial anodes, where Zn enrichment was linked to improved current efficiency and long-term CP stability [26].

The FTIR analysis provided complementary chemical evidence supporting the electrochemical findings. The presence of strong Si–O–T (T = Si, Al) bands confirmed the formation of a dense geopolymer gel, limiting moisture and chloride ingress. In seawater-mixed specimens, the identification of Friedel's salt indicated effective chloride binding within the matrix, reducing the availability of free chloride ions at the steel surface. This chemical immobilization mechanism works synergistically with cathodic protection by lowering the chloride-induced corrosion driving force, a mechanism widely recognized in recent publications on geopolymer and blended cement systems [27]. Notably, differences were observed between freshwater and seawater-mixed concretes. While seawater mixtures introduced higher initial ionic conductivity, which facilitated early current flow and depolarization response, the presence of bound chlorides and secondary salts slightly altered long-term electrochemical behavior. In contrast, freshwater-mixed specimens exhibited more stable matrix chemistry but lower initial conductivity. These results imply that CP performance is governed by a coupled interaction between pore solution chemistry, chloride availability, and anode electrochemical activity rather than conductivity alone [27].

Overall, the integration of optimized RHA content, Zn-dominant Al-Zn hybrid anodes, and geopolymer chemistry establishes a multi-scale corrosion protection mechanism involving electrochemical polarization, chloride binding, and transport limitation. This mechanistic synergy explains the observed stability of protection current and compliance with depolarization criteria, confirming the robustness of the proposed waste-based SACP system.

CONCLUSION

This study demonstrated the feasibility of using sacrificial anodes derived from aluminum cans and battery waste as an environmentally friendly corrosion protection system for geopolymer concrete. The results disclosed that a 6% rice husk ash replacement provided the most stable mechanical performance and durability. In comparison, the Al-Zn hybrid anode system with a backfill of 75% gypsum, 20% rice husk ash, and 5% glass powder achieved effective protection, as indicated by a depolarization value of ≥ 100 mV. Scientifically, this work contributes new insight into the electrochemical effectiveness of fully waste-based Al–Zn sacrificial anode systems integrated with geopolymer concrete. Nevertheless, the findings are limited to short-term laboratory conditions and do not capture long-term anode consumption or field exposure effects. Future studies should address long-term performance, field-scale validation, and optimization of anode and backfill configurations to support practical application.

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