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Experimental investigation on discarded aluminum can waste as an anodic anti-corrosion agent for steel in reinforced concrete under aggressive environments

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Abstract
Corrosion of concrete reinforcement can reduce the service life of buildings, especially in aggressive environments such as coastal areas, where salt content and high humidity accelerate corrosion. Sacrificial Anode Cathodic Protection (SACP) is a commonly utilized method of protecting structures from corrosion by using metals such as zinc (Zn), aluminum (Al), and magnesium (Mg) as sacrificial anodes. However, the high cost of these metals has prompted research into more economical and environmentally friendly alternatives. In this study, recycled aluminum from the beverage can waste was melted at 600˚C and then formed into a circle with a diameter of 11 cm to investigate the utilization and effectiveness of recycled aluminum compared to zinc as a sacrificial anode in the SACP process. The measurement of corrosion potential involved the assessment of current density, on-potential, off-potential, rest-potential, and depolarization. The recycled aluminum anode exhibited a depolarization value of 680 mV, demonstrating that waste cans could serve as an effective sacrificial anode to protect concrete structures.

Keywords:
Anode;
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INTRODUCTION

Reinforced concrete structures play a crucial role in creating strong and durable buildings, especially in critical infrastructure such as bridges and skyscrapers. However, reinforcing steel embedded in reinforced concrete structures is often subject to chloride-induced corrosion, presenting a significant problem for concrete structures [1, 2, 3]. Reinforced concrete is a mixture of concrete and steel intended to reinforce and withstand tensile forces. This reinforcing bar is specifically designed to reinforce concrete in a working area [4][5]. Depending on the cause and environmental conditions, damage to reinforced concrete can take several forms, including cracks due to excessive loads, surface erosion, and corrosion. In addition, extreme temperature changes and freeze-thaw cycles can accelerate concrete degradation, resulting in reduced structural performance [4, 6, 7]. Corrosion in concrete is a chemical or electrochemical reaction between reinforcement steel and layers of concrete with corrosive properties [8][9]. The corrosion occurs naturally. The metal recombines with oxygen, which concurrently recombines with the raw material during the metallurgical extraction of metal production [10, 11, 12]. Structural damage caused by corrosion can shorten the service life of a structure, as it leads to a reduction in the cross-sectional area of the reinforcing steel, weakening its load-bearing capacity [13][14].

Cathodic protection (CP) is a widely employed method for preventing corrosion, particularly in steel structures situated within an electrolyte environment. This system operates by utilizing electron current to reduce the steel's potential to the surrounding environment, thereby achieving a protection potential at which the steel remains free from corrosion [15][16]. Sacrificial Anode Cathodic Protection (SACP) represents one of the most prevalent methods. It serves as a corrosion protection method, adopting the anode and cathode techniques [17][18]. The potential difference between the sacrificial anodes and the steel causes an electron flow from the anodes to the steel.

Aluminum, zinc, and magnesium have been frequently employed as sacrificial anodes in various applications [2, 19, 20]. Beverage cans are recognized for their high aluminum content composition, consisting of 93.75% Al, 4.82% Mg, 0.27% Mn, and Fe by 0.26% [21]. Aluminum possesses lightweight properties (specific gravity = 2.7 g/cm^3), exhibits high thermal and electrical conductivity, and demonstrates high resistance to corrosion due to a thin oxide layer sticking firmly on its surface [22][23].

Research indicates that the waste generated from used beverage cans has the potential to be a sacrificial anode, as explained by [24][25] However, previous studies have not addressed the significant potential of utilizing waste cans as anodes in concrete to mitigate environmental effects. This research seeks to address and mitigate the corrosion of reinforcing bars in reinforced concrete through the innovative application of recycled aluminum sourced from used cans, serving as sacrificial anodes in cathodic protection. In addition to reducing waste, this research offers a new perspective, as no study has evaluated the incorporation of used cans in reinforced concrete SACP systems. Therefore, this research addresses the corrosion rate of reinforced concrete by comparing the potential and effectiveness of recycled aluminum in preventing corrosion in aggressive environments through the application of the SACP method.

METHOD

This research began with testing the properties of fine (sand) and coarse (gravel) aggregates according to Standarisasi Nasional Indonesia (SNI). The concrete was immersed in water with a salt concentration of 3.5% by volume to simulate the impression of an aggressive marine environment. In addition, to determine the properties of salt water, such as seawater, two tests were performed: a power of hydrogen (pH) test using a pH meter and a dissolved oxygen (DO) test by calculating the DO levels after titration.

Concrete serves two primary purposes: one is for test specimens, and the other is for concrete properties. The protected concrete was also cured for 28 days using wet bags. Subsequently, the cable was attached to the concrete reinforcement to facilitate half-cell potential readings. After the curing period of the concrete, an evaluation of its properties was conducted by testing the compressive strength.

The anode fabrication began by melting discarded aluminum cans at 600°C, followed by the molding of the material into circular shapes with a diameter of approximately 11 cm, as demonstrated in Figure 1. The anodes were subsequently coated with a 50:50 mixture of gypsum and bentonite backfill combined with distilled water. Once the backfill was applied, it was attached to an acrylic support, and the anodes were placed inside a drilled section of the concrete. Subsequently, a hole was drilled 11 cm from the end of the concrete specimens to accommodate the anchor. The coated anodes were subsequently connected to the pre-installed anchor, as illustrated in Figure 2. The SACP method safeguarded metal structures from corrosion by utilizing more reactive metals as anodes. These anodes oxidized more readily, releasing electrons and corroding faster than the protected metal (cathode). The electron flew from the anode to the cathode, facilitated by a cable conductor, preventing corrosion of the metal structure. Recycled aluminum anodes were fabricated and analyzed using X-ray fluorescence (XRF), a non-destructive technique that rapidly determines the elemental composition of a material [26]. Further analysis was conducted using a scanning electron microscope (SEM) to examine the arrangement of particles of varying sizes in a 2D representation [27].

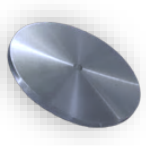


Figure 1. Recycled aluminum anode

Figure 2. Sacrificial Anode Cathodic Protection (SACP) method

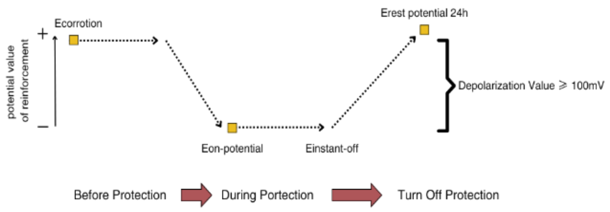


Figure 3. Mechanism for measuring the potential value of the depolarization method

In concrete curing, half-cell potential readings were obtained using a multimeter and reference electrode based on ASTM C876-15. Figure 3 displays corrosion potential readings taken in three stages: on-potential, instant-off potential, and residual potential over 24 hours at seven points spaced 10 cm apart. The cathodic protection effectiveness standard was determined by a depolarization value ≥100 mV, calculated from the difference between the instant-off potential (E_{off}) at anode disconnection and the potential after 24 hours [17][28].

This study involved water testing, an acidity test (pH) with a pH meter, and a dissolved oxygen (DO) test by employing tap water as a dry-wet simulation with the incorporation of 3.5% salt in a volume of 100 ml each.

Material

This research involved the preparation of four concrete specimens, each measuring 25 × 40 × 10 cm, and reinforced with two BJTP 280 steel bars. Compressive strength testing of the concrete resulted in a value of 34.4 MPa, indicating that the concrete successfully achieved the planned compressive strength of 30 MPa. Additionally, four anodes were fabricated using discarded aluminum cans, such as those from soft drinks and similar products. These used beverage cans were sourced from a landfill in Gamping, Yogyakarta. This research aims to utilize the aluminum content in cans as a sacrificial anode to protect the reinforcing steel in concrete from corrosion.

Mix Proportion and Specimen Design of Anode

Four anode test specimens were fabricated utilizing recycled beverage cans. The production of one anode required approximately 30 used cans, requiring a total of around 120 used cans for four anode specimens. The anodes were molded into a circular shape with a diameter of 11 cm and fabricated to a thickness of 0.5 cm.

RESULTS AND DISCUSSION

Physical Properties of Aggregate

Fine aggregate test results are listed in Table 1, while coarse aggregate test results are summarized in Table 2. These test results indicate that both fine and coarse aggregates met the SNI requirements.

Dissolve Oxygen and pH Testing

The value of water content and properties was derived from the measurements of DO and pH levels in water, carried out under both dry and dry-wet cycle conditions, with simulated seawater with 3.5% salt. Table 3 depicts the results. The results signify that the DO level of PDAM water was 1.5 mg/l and salt water was 2 mg/l, revealing a lower oxygen content in PDAM water. Meanwhile, the pH of PDAM water was 8.9, whereas the pH of salt water was 7.82, suggesting a greater acidity in salt water.

Compressive Strength Test

The compressive strength test was performed on ten cylindrical samples, each measuring 30 cm in height and 15 cm in diameter. Testing was conducted on 7, 14, 21, and 28 days after the concrete was cast.

Table 1. Fine aggregate (sand) test results

Feature	Result	Range	Standard
Specific Gravity	2.50	2.5-2.7	SNI 1970:2016
Water Content	3.4%	<6.5%	SNI 1971:2011
Sludge Content	0.5%	<5%	SNI S-04-1989F

Table 2. Coarse aggregate (gravel) test results

Feature	Result	Range	Standard
Specific Gravity	2.69	2.5-2.7	SNI 1969: 2016
Water Content	0.57%	<1.0%	SNI 1971:2011
Abrasion	20.45%	<40%	SNI 2417:2008

Table 3. Dissolve oxygen and pH test results

Type Water	Dissolved Oxygen (mg/l)	pH
Tap Water	1.5	8.9
Salt Water	2	7.82

Figure 4 illustrates that the compressive strength test followed the SNI 1974:2011 standard, with the highest recorded value of 34.3 MPa at 28 days. Additionally, these results indicate that larger concrete specimens exhibited greater dynamic split tensile strength.

Analysis of Aluminum Content Using XRF and SEM

Figure 5 reveals the results of the XRF analysis, leading to the conclusion that the anode material, derived from used cans, contained chemical elements of aluminum (Al), silicon (Si), phosphorus (P), sulfur (S), chloride (Cl), and others. The graph illustrates that aluminum constituted the largest percentage of content, recorded at 23.94%. Figure 6 demonstrates a test sample of a used can anode. XRF analysis revealed an aluminum concentration of only 27.18%, suggesting that the sample contained a significant proportion of light elements such as carbon, hydrogen, oxygen, and nitrogen. Due to the irregular structure of the sample, it did not fit appropriately within the standard XRF vial, limiting the analysis primarily to voids. This structural inconsistency affected the accuracy of the test results. However, the maximum aluminum concentration in the recycled material was still reflected in the XRF data. The presence of mixed aluminum alloys from post-consumer scrap has presented additional challenges, as their diverse composition complicates both processing and analysis.

Figure 7 displays a clearer surface of the aluminum anode derived from used cans, depicted at a magnification of 100x as observed through an SEM, revealing the results of the remaining melting, characterized by micropores. It pictures the surface of the residual melting, appearing as black dots on the anode. These slag particles, originating from the surrounding environment or the anode's microstructure, have contributed to the formation of galvanic cells, leading to uneven erosion and premature failure, particularly in harsh environments such as seawater exposure [29][30].

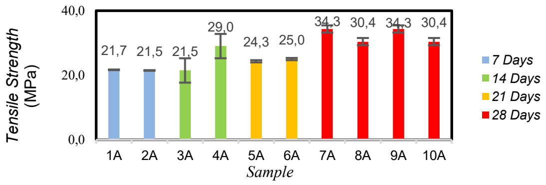
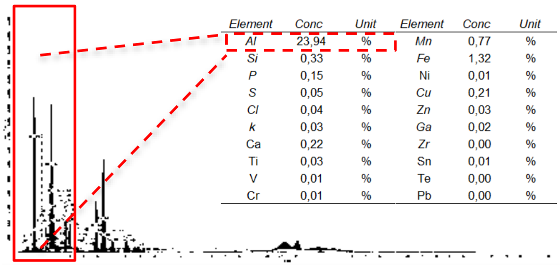


Figure 4. Concrete compressive strength results



Element	Conc	Unit	Element	Conc	Unit
Al	23,94	%	Mn	0,77	%
Si	0,33	%	Fe	1,32	%
P	0,15	%	Ni	0,01	%
S	0,05	%	Cu	0,21	%
Cl	0,04	%	Zn	0,03	%
k	0,03	%	Ga	0,02	%
Ca	0,22	%	Zr	0,00	%
Ti	0,03	%	Sn	0,01	%
V	0,01	%	Te	0,00	%
Cr	0,01	%	Pb	0,00	%

Figure 5. XRF recycled-aluminum

Previous studies indicate that aluminum anodes do not always exhibit a homogeneous microstructure, causing variations in the barrier oxide layer from one sample to another. Consequently, this inconsistency reduces the corrosion protection efficiency of the sacrificial anode, ultimately affecting its overall performance [31].

Current

The current test was performed daily to detect changes in the anode current protecting the rebar by supplying electric current from an external power source connected between the anode and the rebar [2][32].

The concrete anode recycled aluminum (BNAA) test specimen in Figure 8a demonstrates a rise in the current of 1.71 mA within the protected reinforcement. The graph illustrates that, under dry conditions, the current exhibited a tendency toward stability. It indicates that in the dry condition, the anode was not aggressive in protecting the reinforcement. Figure 8b displays that after 25 days, a fluctuating current was observed under the dry-wet cycle condition due to corrosive impacts, activating the anode to protect the reinforcement. The anode effectively protected the steel against corrosion. Nonetheless, following a period of protection, a reduction in the current value of the dry state was observed, ultimately stabilizing at an average of 0.47 mA.

Figure 6. Sample recycled-aluminum anode

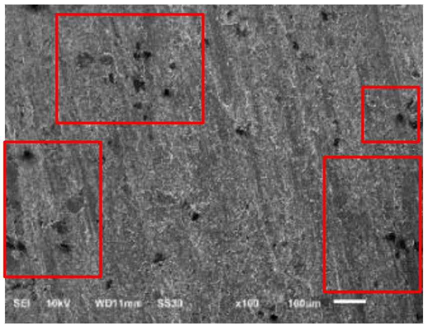
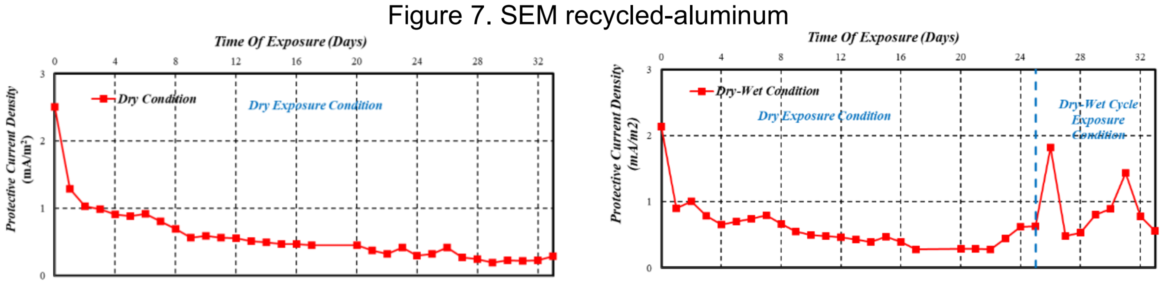


Figure 7. SEM recycled-aluminum



a) b)

Figure 8. The results of the current density of (a) dry and (b) dry-wet cycle conditions

However, in the dry-wet cycle test, the current value was more effectively protected. The results of this study align with previous research, disclosing a negative correlation between the effect of electrolyte pH and the current production efficiency [33].

Rest-Potential

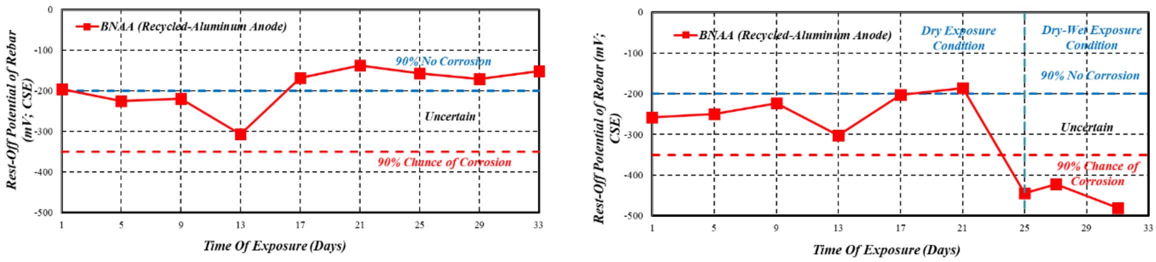
Rest potential refers to the potential value of the anode when the metal exists in a condition devoid of any protective current flow from the anode. The residual potential value was employed to determine the susceptibility of the reinforcement to corrosion; the more positive the residual potential value of the reinforcement, the less susceptible it is to corrosion [2][34].

Polarization changes in the recycled aluminum anode can be observed from the dry rest potential. A high rest-potential value signifies that the reinforcement is better protected from corrosion. It can be attributed to the generation of hydroxyl ions at the steel bar or cement interface and the repulsion of chloride ions from the vicinity of the rebar due to the application of sacrificial anodes. These secondary effects of cathodic protection cause re-passivation effects of the rebar and move the resting potential to a more positive value [33][34].

In Figure 9a, the dry condition demonstrates a stable value at 90%, exhibiting no sign of corrosion. This finding is supported by previous research [33][34]. Corrosion was accelerated due to the difference in electrical potential between the anode and the cathode. The higher the levels of carbonation and chloride ions, the lower the electrical resistance, resulting in an elevated corrosion rate. In the dry-wet condition, a decreasing pattern was observed, implying a lower polarization effect of the steel reinforcement, as displayed in Figure 9b.

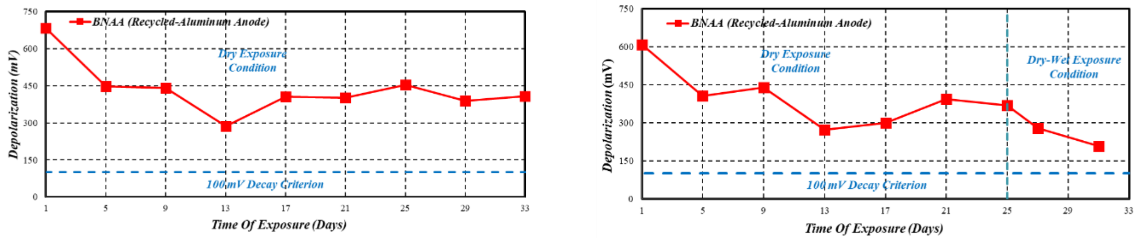
Depolarization

The depolarization test results, as expressed in Figure 10, exhibit the practical effectiveness of recycled aluminum anodes with depolarization values exceeding 100 mV. Under the dry-wet condition, the recycled aluminum exhibited a potential of 207.64 mV, while in the dry condition, a higher potential of 407.61 mV was recorded. Aluminum from discarded cans underwent electrochemical dissolution in water, serving as a sacrificial anode to protect steel reinforcement in submerged concrete. This process leveraged aluminum's high reactivity and water's conductive properties to generate a protective current. The elevated corrosion rate of aluminum enhances protection but necessitates frequent anode replacement [35] As illustrated in Figure 9a, the anode exhibits increased activity in protecting submerged concrete under the dry-wet condition by facilitating ion movement between the aluminum anode and steel cathode in an aggressive environment with high corrosion potential. In the dry condition, the anode remained relatively stable in reinforcing protection. The test results comply with the test standard [28], with depolarization values exceeding 100 mV, confirming the adequacy of cathodic protection.



a) b)

Figure 9.The result of the rest potential of rebar at (a) dry and (b) dry-wet cycle conditions



a) b)

Figure 10. The results of the depolarization value of (a) dry and (b) dry-wet cycle conditions

This study concluded that recycled aluminum, derived from used cans, performed effectively in the SACP method by sustaining corrosion potential in harsh environments, as indicated by a positive potential shift and polarization and depolarization values surpassing 100 mV.

CONCLUSION

The application of recycled aluminum anodes has proven effective in protecting reinforcing structures from corrosion. SEM and XRF analyses confirmed that aluminum was the dominant element, constituting 23.94% of the composition. The anodes demonstrated the ability to maintain corrosion potential even in harsh environments. The observed positive potential shift, along with polarization and depolarization values exceeding 100 mV, indicated that recycled aluminum, such as used cans, was highly effective in the SACP method.

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