



## The effect of Magnesium addition on the performance of Aluminium-Zinc-Copper alloy as a sacrificial anode in seawater

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### Abstract

This paper presents an experimental investigation on effectiveness of the addition of magnesium (Mg) on the performance of aluminium-zinc-copper (Al-Zn-Cu) alloy as a sacrificial anode to protect low carbon steel in seawater. The chemical compositions of mild steel sample, Aluminium alloyed and that of the medium (seawater) were determined using optical emission spectroscopy. Samples of Al-Zn-Cu alloy alloyed with 0.5%, 1.0% and 1.5% by weight of magnesium were prepared and produced by casting technique to produce the sacrificial anodes. Subsequently, the anodes were mechanically joined with the mild steel by force-fitting them together to produce specimens for corrosion test. The effectiveness of the sacrificial anodes for the protection of mild steel in seawater was examined using the gravimetric technique (for a period of 168 – 2016 hours) and potentiodynamic analysis. The results showed that the Al-Zn-Cu-1.0% Mg gave the maximum protection efficiency of 99.85% (for 2016 hours) and 99.98% through gravimetric and potentiodynamic analysis respectively, better than the efficiency of 99.26% (for 168 hours) and 99.53% (for 336 hours) attained by adding Zinc and Tin respectively to the aluminium alloy in previous studies. Thus, the addition of Mg to Al-Zn-Cu alloy was effective and suitable as a sacrificial anode in seawater.

## 1. Introduction

Corrosion is the degradation of metallic materials due to electrochemical and chemical reactions, which can lead to component failure in a variety of industrial environments [1]. The problem of metallic corrosion is one of the significant proportions; in economic terms, it has been estimated that approximately 5% of an industrialized nation's income is spent on corrosion prevention and the maintenance or replacement of products lost or contaminated as a result of corrosion reactions [1]. Familiar examples include the rusting of automotive body panels, radiator and exhaust components [2]. Gualdrón *et al.* are of the view that in the environment, corrosion control and prevention of metallic and constructional materials represents a very important and fundamental problem [3]. Most equipment, devices and constructional materials use in industries are made from metals and alloys under different conditions are susceptible to corrosion under harsh chemical environment [4]. These metallic materials, such as steels, are significant in economic development and sustainable growth of a country [5].

In an attempt to mitigate corrosion, as one of the menaces the industrial world has been facing for a very long time, several preventive methods, which include the use of other elements as sacrificial anode have been used [1]. Other several techniques abound for correcting the menace of corrosion also include the use of inhibitors, a protective coating, cathodic protection, among others. Cathodic protection (CP) is

employed mainly in many industries and marine environments to control corrosion, and sacrificial anode cathodic protection is greatly employed to protect oil pipelines, marine and some domestic structures [1]. With this system, an electric current is applied by the employment of dissimilar metals with the driving voltage being created by the potential generated between the two metals in the electrolyte. The electrochemical behaviour of sacrificial anode materials is of vital importance for the reliability and efficiency of cathodic protection systems for seawater exposed structures [6].

Metals and their alloys are engineering materials which are widely used in different applications in industries due to their desirable mechanical properties, availability and ease of fabrication [7]. The materials are still prone to corrosion which resulted in the gradual deterioration of their mechanical properties when exposed to corrosive environments [8]. Meanwhile, steel is among a large number of different metals and metal alloys that must be protected from corrosion [9, 10]. Aluminium is cheap and readily available, very light in weight, and highly corrosion-resistant [2]. To improve its efficiency, Aluminium is alloyed with other elements like zinc (Zn), magnesium (Mg), and copper (Cu), among others. The usefulness of pure aluminium as an anode material in seawater is reduced significantly by the formation of a protective oxide film, which limits both its current and potential output.

Studies have shown the effects of addition of some elements, like Mg, Cu, Zn, Ba, on the structural features and mechanical properties of Al-Si-Cu alloy [11,12,13]. Addition of any or combination of these elements enhances the efficiency of the aluminium anodes by encouraging oxide films breakdown (depassivation) and/or shift the metal's operating potential to a more electronegative direction [14]. The effect of the addition of magnesium content on mechanical properties and microstructure of Al-Zn-Cu alloy had been investigated [13]. It was discovered that the presence of magnesium in the alloy improved some properties of the material. There was precipitation hardening that eliminated micro segregations, thus improving the alloy mechanical properties. This called for the present study, by examining the effectiveness of magnesium on the performance of Al-Zn-Cu alloy as a sacrificial anode to mild steel in seawater; the main objective of this study.

## 2. Material and Methods

### 2.1. Equipment

The equipment used in this study includes Crucible furnace, Lathe, Toledo Mettler Balance JL602-GE, Optical Emission Spectroscopy (Model Number Spectromaxx LMF06 Spark Analyzer Pro Maxx Version 1.02.0001 Software), Potentiostat (AUTOLAB PGSTAT 204N).

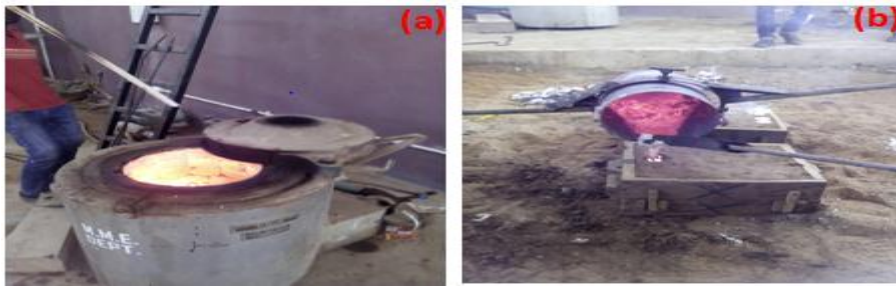
### 2.2. Materials preparation

#### 2.2.1 Preparation of test samples (Al-Zn-Cu alloy alloyed with 0%, 0.5%, 1.0%, 1.5% Mg by weight)

Aluminium alloy samples comprising of Mg varied between 0.5 and 1.5 wt% earlier produced through casting operations for a previous study [13] was used. The casting operation was carried out by melting each of the elements/metals in the sequence of Zn, Mg, Al and Cu based on their melting temperatures in a furnace. The highest furnace temperature was 1110°C with the total melting time of about 90 minutes. The casting procedure involved the fabrication of wooden patterns, making a green sand mould, melting of the scraps using a diesel-fired bale out furnace and pouring of the molten melt into the prepared mould (Figures 1 - 3). After pouring, cylindrical-shaped samples produced were allowed to solidify and then cooled at normal room temperature. The samples were then machined into the various standard shapes and dimensions for further experimental tests.



Figure 1: Mould Box for samples



**Figure 2:** (a) Stirring of hot metals for homogenization (b) Tong used to separate slag from molten alloy.

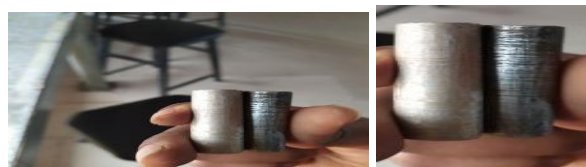


**Figure 3:** (a) Pouring of molten alloy into mould (b) Solidify cast alloys

### 2.2.2 Preparation of anode specimen for corrosion test

In this study, the materials used include aluminium-copper-zinc-magnesium alloy, mild steel pipe, seawater, acetone, fine rubber bung and ethanol. The metals, mild steel pipe, acetone, and ethanol were purchased from an outfit in a market in Ilorin, Kwara State, Nigeria. While, the seawater used in this research was obtained from the beach in Victoria Island, Lagos State, Nigeria.

Four each of Al-Zn-Cu alloy (cylindrical shape of a diameter 40 mm and length 70 mm) alloyed with 0%, 0.5%, 1.0%, 1.5% Mg by weight earlier produced through casting operations (as earlier mentioned in section 2.2.1) were then cut to a dimension of 30 mm diameter and 60 mm length, and a hole of 1 mm was drilled on each specimen for ease suspension/hanging in the media and for identification (labelling) following the guidelines in ASTM G1 [15]. Each of the mild steel samples was also cut to a dimension of 30 mm diameter and 60 mm length, and a hole of 1 mm diameter was drilled as done earlier on the alloyed samples. Each of the Al-Zn-Cu-Mg alloy sample and a sample of mild steel were then coupled by force-fitting them together to produce samples of a sacrificial anode. Figure 4 shows the sample after it was produced by a forced fit.



**Figure 4:** The sample after fitting to form an anode specimen.

### 2.3. Determination of the mild steel composition

The chemical compositions of the mild steel used in this research were analyzed using an Optical Emission Spectroscopy (Model - Spectromaxx LMF06 Spark Analyzer Pro Maxx Version 1.02.0001 Software) at Midwal Engineering Limited, Lekki, Lagos State, Nigeria using ASTM E 415 guidelines [16].

### 2.4. Testing for the effectiveness of the sacrificial anodes for the protection of mild steel in seawater

To evaluate the effectiveness of the Aluminium alloy specimens (sacrificial anodes) for the protection of mild steel in seawater, both gravimetric technique and potentiodynamic analysis were adopted.

#### 2.4.1 Gravimetric technique

Pre-immersion cleaning of the specimen was carried out following the ASTM guidelines [15]. The samples were ground, degreased in ethanol, and then dried in acetone. The grades of emery paper

sequentially used in grinding the samples were 800, 600, 400, 320 and 120 grit of emery paper in line with the practice of earlier researchers [17,18,19,20]. By ASTM G4 standard, a 120 grit finish is generally acceptable [21]. This process was well flushed with distilled water to wash away the debris/metal particles which were capable of being embedded at the surface of the specimen. The specimens were then cleaned using a chemical cleaning method narrated in ASTM G1 [15]. It was degreased in ethanol and dried in acetone, and immediately stored in a desiccator.

The prepared samples from the desiccator were individually weighed using a Toledo Mettler balance JL602-GE, to determine their initial weight ( $W_1$ ). The specimens were then fully immersed in beakers, each containing 300 ml of seawater as shown in Figure 5 for periods between 24 to 2016 hours. The specimens were then removed from the beaker and immediately cleaned by rinsing under running water, degreased in ethanol, and dried in acetone to remove the corrosion products formed on the surfaces and edges of the specimens in line with the practices of earlier researchers [17,22,23]. Immediately after the corrosion test, each of the specimens was weighed to obtain its final weight ( $W_2$ ). The loss in weight in each specimen during the corrosion test was determined using Equation 1. Figures 6a & b show sample(s) with and without the corrosion product on the edges and surfaces of the sample before the cleaning process respectively.

$$\text{Weight Loss} = W_2 - W_1 \quad (1)$$

Where:  $W_1$  = Initial weight, and  $W_2$  = Final weight.



Figure 5: The samples immersed in the environment (Seawater)



Figures 6: (a) Sample of the specimen before post immersion cleaning  
(b) Samples of the specimens after the corrosion test (gravimetric technique)

The rates of corrosion damage were calculated by dividing the weight gradient by the multiplication of the total surface area of the sample with the time of exposure in an hour as presented in Equation 2.

$$\text{Corrosion Rate (gcm}^{-2}\text{h}^{-1}) = \frac{\Delta W}{AT} [17,18,22] \quad (2)$$

Where:  $W$  = Initial weight in g;  $W_2$  = Final weight in g;  $D$  = Densities of the metals in g;  
 $A$  = Total surface area of the cylindrical rod;  $T$  = Time in hours;  $K = 8.76 \times \text{mm/y}$

#### 2.4.1.1 Determination of protection efficiency

The individual sample's protection efficiency was determined using Equation 3 as previously adopted by Muazu & Yaro [24]. This is done to determine the quantitative level of the mild steel sample protection by the anode within the test periods.

$$P.E = \frac{W_2}{W_1} \times 100 \quad (3)$$

Where:  $W_2$  = current weight, and  $W_1$  = previous weight

#### 2.4.2 Potentiodynamic analysis

The potentiodynamic analysis was carried out at the Autolab Section of Corrosion and Electrochemical Laboratory of the Federal University of Technology, Akure, Nigeria. The instrument used was the AUTOLAB PGSTAT 204N instrument as shown in Figure 7. It involved changing the potential of the working electrode and monitoring the current which was produced as a function of time and potential.



**Figure 7:** The Potentiodynamic setup

The potentiometer had three-electrode cells which were the working electrode, counter electrode and the reference electrode that were assembled at room temperature. The samples for the Potentiodynamic analysis were prepared following ASTM G5-94 guidelines [25]. The coupons (Figure 8) of the anode were cut to a thickness of 10 mm and a diameter of 14 mm. The coupons were embedded in resin. After the samples were cured, the coupons were carefully removed (Figure 9).

Each metal sample was attached to the working electrode and dipped alongside the counter electrode and the reference electrode into the mixture in a crucible. The electrolyte used for this study was natural seawater.

The working electrode was polished with different grades of emery papers until the surfaces were smooth. The open-circuit corrosion potential was carried out for 30 minutes until a stable value of  $E_{corr}$  was attained. The linear polarization study was carried out from cathodic potential of -250 mV to an anodic potential of +250 mV with a scan rate of 1.0 mVs<sup>-1</sup> to determine the current density, corrosion rate, the anodic beta and cathodic beta.



**Figure 8:** Samples before curing.



**Figure 9:** Samples after curing.

### 3. Results and discussion

#### 3.1 Compositional analysis of the materials used in this study

The results of the elemental composition analysis of the mild steel rod and that of Aluminium alloy used in this research are presented in [Tables 1, a and b](#) respectively.

**Table1a:** Compositional Analysis of Mild Steel

Element	(Wt. %)	Element	(Wt. %)	Element	(Wt. %)
C	0.12300	Cu	0.24600	Ca	0.01050
Si	0.20400	Nb	0.00310	Ce	<0.00100
Mn	0.93900	Ti	<0.00020	Sb	0.00170
P	0.01740	V	0.00850	Se	0.00250
S	0.05910	W	<0.00500	Te	0.00350
Cr	0.25600	Pb	<0.00100	Ta	0.05420
Mo	0.02190	Sn	0.01310	B	0.00220
Ni	0.07430	As	0.03410	Zn	0.00380
Al	<0.00050	Zr	<0.00100	La	0.00049
Co	0.00700	Bi	<0.00100	Fe	97.90000

**Table1b:** Compositional Analysis of Aluminium Alloy

Element	(Wt. %)	Element	(Wt. %)
Mg	0.0010	Cu	1.5600
Al	80.1600	Zn	17.1400
Si	ND	Sn	0.0068
P	ND	W	0.0162
S	0.1030	Pb	0.0410
V	ND		
Cr	0.0204		
Mn	0.0775		
Fe	0.9083		
Ni	0.0172		

The results in [Table 1a](#) revealed that the carbon (C) and the iron (Fe) contents in the steel were 0.123 wt% and 97.9 wt% respectively. This is an indication that the rod was low carbon steel. The steel sample also belonged to AISI 1109 steel class by AISI-SAE E-219 classification of steel [\[26\]](#). The carbon contents in low carbon steel ranges from 0.05 wt% - 0.25 wt% carbon [\[2\]](#). Steels with composition of C = 0.08 - 0.123%, Mn = 0.60 - 0.09% and P = 0.040 max are also classified as AISI 1109 steels in AISI-SAE E-219 [\[26\]](#). From the results in [Table 1b](#), Aluminium (80.16%), Zinc (17.14%) and Copper (1.56%) constitute the major elements in the material. Though, it was observed that the alloy contain some other constituent elements which were regarded as minor elements. The presence of these minor elements was as a result of the fact that the material was Aluminium scrap. Zahedi *et al.* revealed that Aluminium alloys do contain Fe, a result of alloy processing and handling [\[27\]](#).

#### 3.2 Physico-chemical analysis of the seawater

The results obtained from the Physico-chemical analysis of the seawater are as presented in [Table 2](#), which shows the level of total dissolved solids (TDS) in the seawater to be 6,290.00 ppm. The value was within the TDS stipulated range of 5000-10,000 ppm in seawater. Waters with TDS in the range of 1,500-15,000 ppm are also labeled as brackish water [\[28\]](#). Moran also gave 500 – 30,000 ppm and 30 – 40,000 ppm as the range for TDS in seawater and brackish water respectively [\[29\]](#). Concentration of TDS in brackish water typically ranges between 1,000 and 10,000 mg/l [\[30\]](#). The high salt content in the

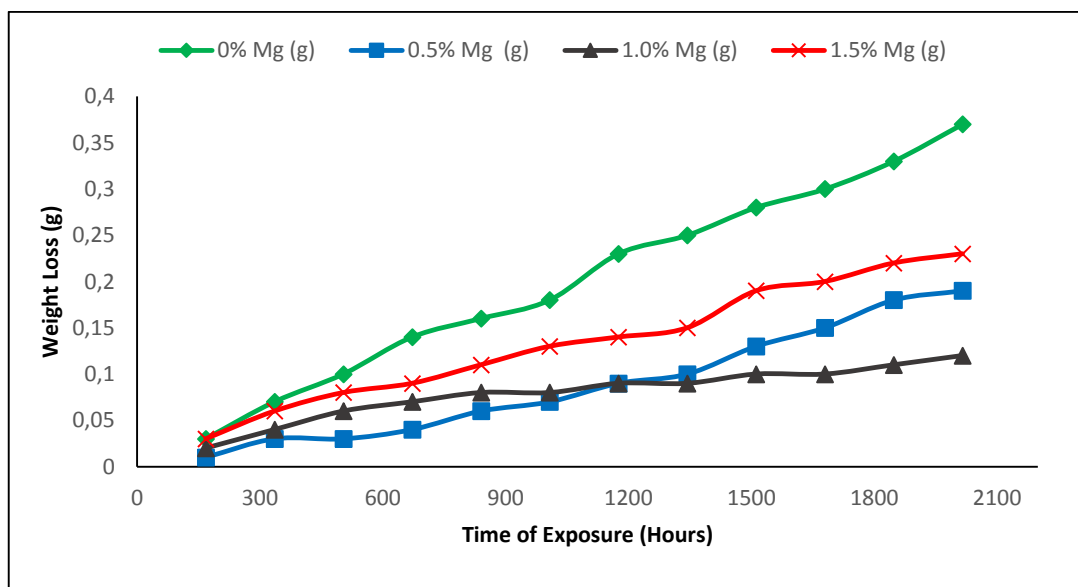
seawater with a value of 557.18 ppt attributed to its higher conductivity value of 12,580.00  $\mu\text{S}/\text{cm}^3$  [31]. The higher the salt contents in water, the higher its electrical conductivity [32]. The pH of the seawater from the analysis was 7.6, which falls within the acceptable range. The pH of seawater is typically limited to a range between 7.5 and 8.4 [33].

**Table 1:** Physico-Chemical Analysis of the Seawater

	PARAMETERS	STATION 1
1	Temperature ( $^{\circ}\text{C}$ )	26.750
2	pH	7.600
3	Conductivity ( $\mu\text{S}/\text{cm}^3$ )	12,580.000
4	TDS (ppm)	6,290.000
5	$\text{DO}_2$ (ppm)	8.270
6	Salinity (ppt)	557.180
7	Calcium (ppm)	1,527.040
8	Magnesium (ppm)	554.740
9	Sodium (ppm)	509.030
10	Potassium (ppm)	169.670
11	Iron (ppm)	0.027

### 3.3 Gravimetric technique

The variation of weight loss throughout exposure in the seawater is shown in Figure 10. Generally, weight loss in the sacrificial anode specimens increased with the period of exposure in respect of the level of Mg-alloyed to Al-Zn-Cu alloy. This is an indication that the presence of Mg in the alloyed material makes it serve as good corrosion inhibiting material. Also, the rate of weight loss in the specimens during the time of exposure in the seawater decreased as the concentration of the Mg in the alloyed material increased. This is similar to the results of the research carried out by Umoru & Ige [34], which observed that the weight loss of the Al alloy decreases as the concentration of Tin increases.



**Figure 10:** Weight loss (g) of the sacrificial anodes in the seawater within the time (hours) of exposure

Though, the alloy with 1.5% Mg concentration did not follow this trend. The reduction in weight loss may be a result of the sacrificial anodes protecting the mild steel from corroding, thereby forming passive films. Passivation occurs when metals are oxidized to insoluble corrosion product which forms an adherent, protective film [35]. This is similar to the results of the research carried out by Umoru & Ige

[34], which observed that the weight loss of the Al alloy decreases as the concentration of Tin increases. Meanwhile, the specimens with 1.0% Mg recorded the lowest weight loss during the period of exposure, followed by the specimen with 0.5% Mg, 1.5% Mg and lastly 0.0% Mg. Thus, the sacrificial anode sample with 1.0% Mg had the best corrosion inhibiting capacity. The 0.0%, 0.5%, 1.0%, and 1.5% Mg Al-Zn-Cu (specimens) alloy recorded a weight loss of 0.37g, 0.15g, 0.12g, and 0.23g respectively after 2016 hours of exposure in the seawater as shown in Figure 10. This indicates that weight loss is dependent on the concentration of the Magnesium (Mg) except for the specimen with 1.5% Mg. This level (1.5%) served as the limit level at which the passive films formed with the addition of Mg to the alloy was protective. Though, the addition of magnesium (magnesium) to Aluminum alloys can impart good corrosion resistance [36] within the concentration level of 0.5 – 1.0%.

### 3.3.1 The corrosion rate of the sacrificial anodes

The variation of corrosion rates within the 24 - 2016 hours of exposure is shown in Figure 11. The results revealed that the specimen with no Mg (0% Mg-Al-Cu-Zn alloy) recorded the highest corrosion rate throughout exposure in seawater, which revealed the effectiveness of Mg in Aluminum alloy as a suitable element for the sacrificial anode.

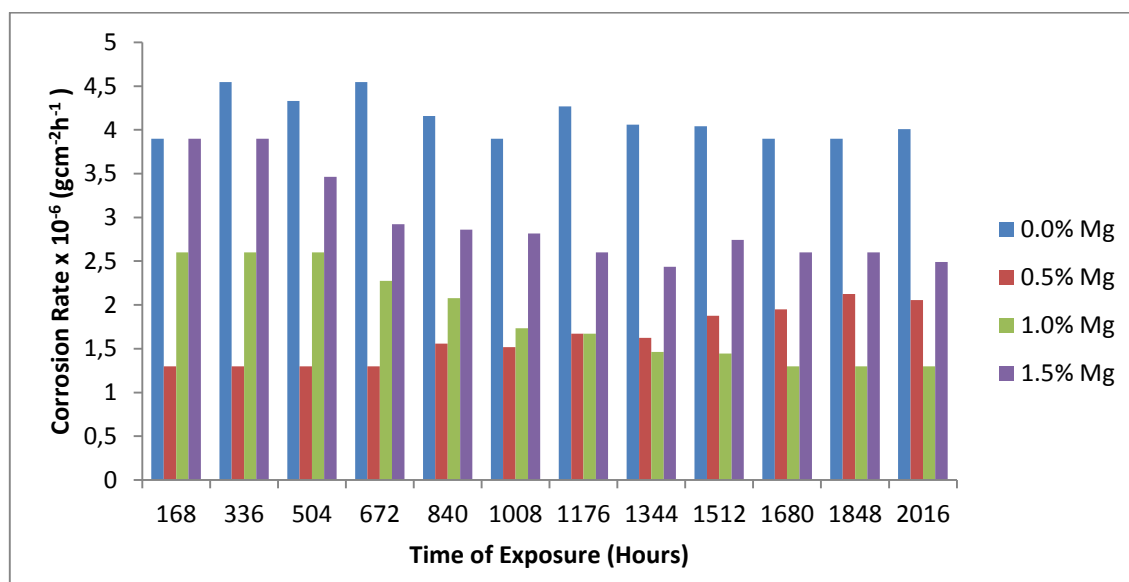


Figure 11: Corrosion rate of the sacrificial anodes in the seawater within the time of exposure

After 24 hours of exposure, the specimen with 0.0% Mg recorded corrosion rate of  $3.898 \times 10^{-6} \text{ gcm}^{-2}\text{h}^{-1}$  compared to that of other specimens (Al-Cu-Zn-Mg alloy) with 0.5 Mg ( $1.299 \times 10^{-6} \text{ gcm}^{-2}\text{h}^{-1}$ ), 1.0% Mg ( $2.599 \times 10^{-6} \text{ gcm}^{-2}\text{h}^{-1}$ ) and 1.5% Mg ( $3.898 \times 10^{-6} \text{ gcm}^{-2}\text{h}^{-1}$ ). More so, the specimen with 0%, 0.5%, 1.0%, and 1.5% Mg in Al-Zn-Cu alloy recorded a corrosion rate of  $4.007 \times 10^{-6} \text{ gcm}^{-2}\text{h}^{-1}$ ,  $2.057 \times 10^{-6} \text{ gcm}^{-2}\text{h}^{-1}$ ,  $1.299 \times 10^{-6} \text{ gcm}^{-2}\text{h}^{-1}$ , and  $2.491 \times 10^{-6} \text{ gcm}^{-2}\text{h}^{-1}$  respectively after 2016 hours (Figure 11). This shows the effectiveness of the Mg in alloyed aluminium as a sacrificial anode. This discovery was in line with the results of the study of Rana *et al.* that Magnesium addition improves the corrosion properties of Aluminum alloys [36]. The results also revealed that the concentration of Magnesium in Al-Zn-Cu alloy has effect on the corrosion rate of the specimens.

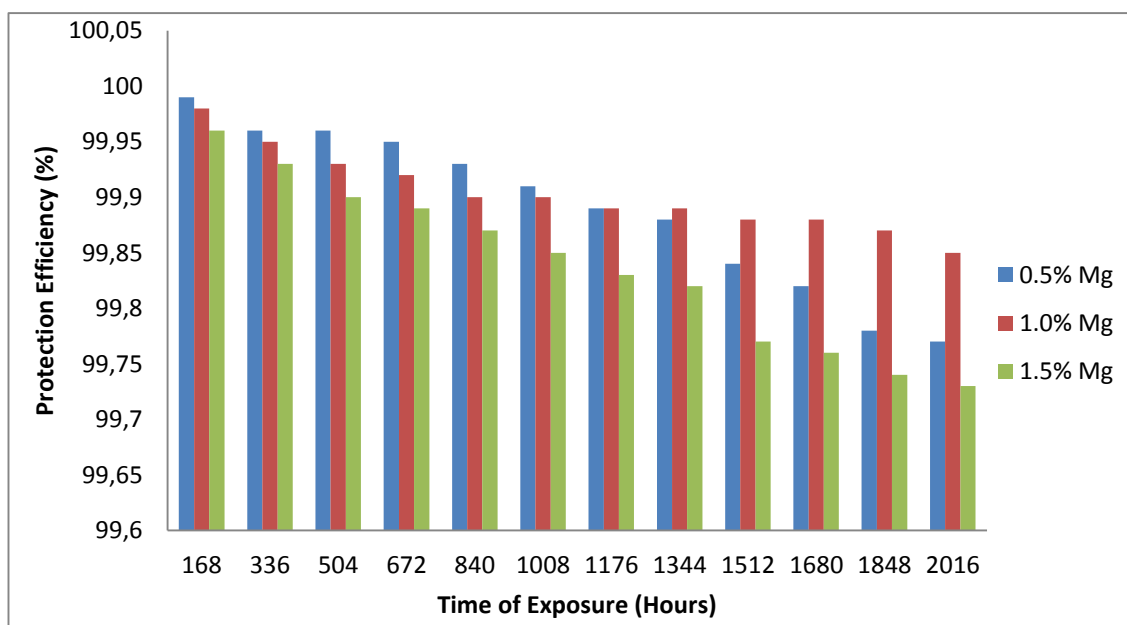
### 3.3.2 Protection Efficiency Analysis

The protection efficiencies of each sample for 2016 hours are shown in Figure 12. Generally, all the specimens containing Mg element have significant values of protection efficiencies, irrespective of the



level of Mg in the specimens. Meanwhile, at the initial stages of the investigation (168 – 1176 hours), the specimen with 0.5% Mg recorded the highest protection efficiency (99.99%), followed by the specimen with 1.0% Mg (99.97%) and lastly specimen with 1.5% Mg (99.95%). This is similar to Muazu & Yaros' observation in their studies [24]. This implies that the sacrificial anode sample with 0.0% Mg was found to be most susceptible to corrosion attack than other samples. However, as the period of exposure increased (1176 – 2016 hours), the protection efficiencies of the specimen with 1.0% Mg progressively reduced (99.97-99.85%).

The higher protection of efficiency of 0.5% Mg at initial stage was as a result of the fact that the oxide layer of alumina formed was stable at initial time of exposure (168 – 1176 hours) which caused retardation in the rate of dissolution of the metal. Meanwhile, due to the fact that the stable oxide formed got broken as the time of exposure increased (1176 – 2016 hours), in which further dissolution of the metal could no longer be protected, the efficiency reduced. Re-passivation, which is the physical detachment of metal from the bulk sacrificial anode, makes the missing metal not useful for cathodic protection attributed to the decrease and low efficiency [37].



**Figure 12:** Protection efficiencies of the sacrificial anodes in the seawater within the time (hours) of exposure

The results shown that the specimen with 1.0% Mg was with least susceptible to corrosion attack as the specimens stayed in the seawater for a longer period of exposure. The specimens (Mg-Al-Zn-Cu alloy) with 0.5%, 1.0%, and 1.5% Mg recorded protection efficiency of 99.77%, 99.85%, and 99.73% respectively after 2016 hours as shown in Figure 12. The Protection efficiencies of the specimens (at longer periods in the medium) increased as the concentration of the Magnesium increased. This is similar to the result of the research carried out by Muazu & Yaro [24], which showed that the Aluminium with the highest composition of Zinc gave the best protection efficiency. Though the specimen with 1.5% Mg composition did not follow this trend, Magnesium addition improves the corrosion properties of Aluminum alloys [34]. This study shows that 1.0% Mg was the most suitable proportion required to form a sacrificial anode suitable for protection of the mild steel in seawater.

Formation of a stable oxide layer of alumina which resulted to reduction/retardation of the rate at which dissolution of metal occurs during exposure in the media attributed to the low efficiency of the sacrificial anode. Since, the stable oxide layer could not protect further dissolution of the metal because the layer

got broken as the time of exposure increased. Meanwhile, for Al-alloy with 1.0% Mg that recorded the lowest corrosion rate; the depassivation of Aluminium was as result of the second phase ( $\beta$ -phase) particle formed. The increased in the anode efficiency because of reduction in the dissolution resistance of the sacrificial anode was as a result of the breakdown of passive film formed on the surface of  $\text{Al}_2\text{O}_3$  from the second phase particles [38].

Figure 12 revealed a great effect of the addition of Mg to Al-Cu-Zn alloy as sacrificial anode in seawater by attaining the maximum protection efficiency of 99.85% for 2016 hours of immersion. This results revealed the better performance of the presence of Mg in aluminium alloy as sacrificial anode in seawater than that of the presence of Zinc and Tin, where maximum protection efficiency was 99.26% (for 168 hours) and 99.53% (for 336 hours) respectively [24,35].

### 3.3.4 Potentiodynamic technique

The Potentiodynamic parameters obtained from the Tafel plot is presented in Tables 3(a & b). The current density, corrosion rate, potential, the anodic beta and cathodic beta of the alloy samples during the period of exposure in the medium of exposure (seawater) are shown in the results.

**Table 3a:** Potentiodynamic parameters of the samples

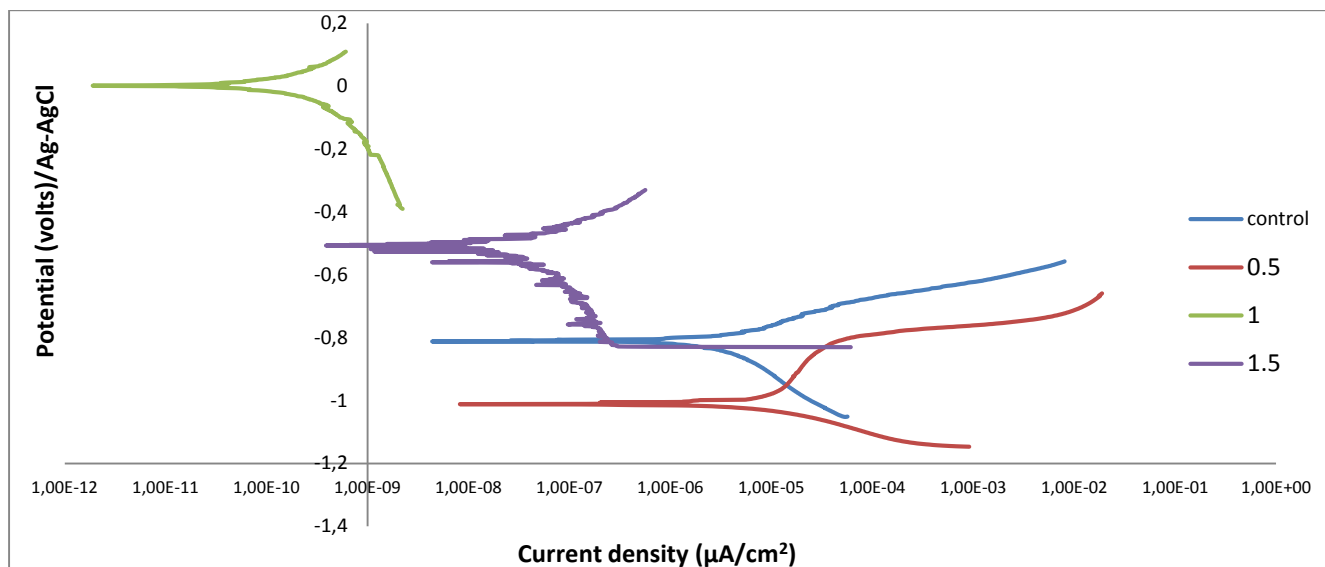
Samples (Mg)	$I_{\text{Corr}}$ ( $\mu\text{A}$ )	$E_{\text{Corr}}$ (mV)	Tafel slope		$R_p$ ( $\Omega$ )
			$\beta_a$ (mV)	$\beta_c$ (mV)	$\frac{\beta_a\beta_c}{2.31I_c(\beta_a+\beta_c)}$
0.0%	-3.669	-812.518	101.359	225.694	-8.2529
0.5%	-9.32	-1011	297.301	86.364	-3108.495021
1.0%	-0.000708855	5.468	476.742	731.419	-176260684.6
1.5%	-0.041035	-510.817	144.876	352.061	-1082769.041

**Table 3b:** Potentiodynamic parameters of the samples

Samples (Mg)	Corrosion rate ( $\text{gcm}^{-2}\text{h}^{-1}$ )	Protection Efficiency (%)
0.0%	0.025937	-
0.5%	0.0065878	74.60
1.0%	0.0000050101	99.98
1.5%	0.00029003	98.88

Figure 13 shows the Tafel plot of the alloy samples with a cathodic potential of -250 mV to an anodic potential of +250 mV. It can be observed from the curve in Figure 13 that Al-Zn-Cu alloyed with 1.0% Mg had the highest corrosion potential, followed by the Al-Zn-Cu alloyed with 1.5% Mg, and finally the Al-Zn-Cu alloyed with 0.5% Mg. The Al-Zn-Cu alloyed with 1.0% Mg had the lowest corrosion rate, similar to the results obtained in gravimetric technique. This is due to the fact that the depassivation of Aluminium was as result of the second phase ( $\beta$ -phase) particle formed. The increased in the anode efficiency because of reduction in the dissolution resistance of the sacrificial anode was as a result of the breakdown of passive film formed on the surface of  $\text{Al}_2\text{O}_3$  from the second phase particles [38]. The current density obtained drifted to the left side of the curve that is more to the negative side. This showed the rate of corrosion was the slowest (Table 3) that signifies high protection efficiency. Then as the level of Mg in the specimens increased from 1.0 to 1.5%, the current density released by the alloy increased, which led to faster corrosion rate. Though, it had corrosion rate better than that of the alloyed with the

0.5 and 0% Mg that released more current to protect the mild steel. Hence, this led to a higher dissipation of ions which enhanced the corrosion rates and make it corroded faster than in the case of specimens with 1.5% Mg and 1.0% Mg that recorded very slow rate of corrosion of  $0.00029003 \text{ gcm}^{-2}\text{h}^{-1}$  and  $0.0000050101 \text{ gcm}^{-2}\text{h}^{-1}$  respectively. Therefore, it could be ascertained that magnesium improves the corrosion properties of an Al-alloy [34].



**Figure 13:** Tafel plot showing potential (volts) of the sacrificial anodes against Current Density ( $\mu\text{A}/\text{cm}^2$ )

From the Tafel plot (Figure 13) and the Potentiodynamic analysis parameters in Tables 3 (a & b), the sample with 0% Mg Al-Cu-Zn alloy had the highest rate of corrosion of  $0.025937 \text{ gcm}^{-2}\text{h}^{-1}$ , followed by that of the specimen with 0.5% Mg with corrosion rate of  $0.065878 \text{ gcm}^{-2}\text{h}^{-1}$ , then by the specimen with 1.5% Mg (with a corrosion rate of  $0.00029003 \text{ gcm}^{-2}\text{h}^{-1}$ ), while the Al-alloy with 1.0% Mg recorded the lowest corrosion rate of  $0.0000050101 \text{ gcm}^{-2}\text{h}^{-1}$ . The results revealed the effectiveness of Mg in Al alloyed to make the material (Mg Al-Cu-Zn alloy) suitable as a sacrificial anode to mild steel in seawater environment up to 2016 hours. The results from Potentiodynamic analysis indicating specimen with 1.0% Mg as a most effective specimen as a sacrificial anode is similar to that obtained from the gravimetric method at 2016 hours of exposure.

## Conclusions

From the experimental results obtained, the following conclusions were drawn:

1. Alloying Al-Cu-Zn alloy with Mg at various compositions affects the performance of the alloy as a sacrificial anode to mild steel in seawater
2. The anode efficiency of Mg Al-Cu-Zn alloy sacrificial anode is dependent on time and concentration of Magnesium.
3. An increase in the composition of the magnesium alloyed with the Al-alloys led to a higher protection of the mild steel in the seawater, but except for the specimen with 1.5% Mg.
4. The Gravimetric and the Potentiodynamic techniques showed that the rate of corrosion of the Aluminum alloy sacrificial anode with 1.0% Mg was extremely slower than that of 0.5% Mg and 1.5% Mg in seawater. But the sacrificial anode with 1.5% Mg had a better corrosion rate compared to the 0.5% Mg.

5. Through the analysis of the corrosion tests' results, it was discovered that Aluminum alloy sacrificial anode with 1.0% Mg will provide the best protection efficiency in the seawater, and will significantly improve the life span. Thus, the material was found effective as a sacrificial anode. n the composition of the magnesium doped with the Al-alloys led to a higher protection of the mild steel in the seawater, but with the exception of the specimen with 1.5% Mg.
4. The Gravimetric and the Potentiodynamic techniques showed that the rate of corrosion of the Aluminum alloy sacrificial anode with 1.0% Mg was extremely slower than that of 0.5% Mg and 1.5% Mg in seawater. But the sacrificial anode with 1.5% Mg had a better corrosion rate compared to the 0.5% Mg.
5. Through the analysis of the corrosion tests' results, it was discovered that Aluminum alloy sacrificial anode with 1.0% Mg will provide the best protection efficiency in the seawater, and will significantly improve the life span. Thus, the material was found effective as a sacrificial anode.

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