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Development of sacrificial anode from Al, Mg, and Ti from iron Ore tailings

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ABSTRACT

This investigation used aluminium, magnesium, iron ore tailings, and low-carbon steel. Iron ore tailings (5–30 wt% Mg and 50 µm in size) in an aluminium matrix formed the anode. In 0.5 M NaCl solution, the weight loss, corrosion rate, and electrochemical properties were measured. Samples A to E have corrosion rates of 0.43, 0.28, 0.36, 0.08, and 0.11 mm/yr, respectively. SEM/EDS examination revealed the presence of elemental Al, Mg, O, and Si in the anode. The XRD patterns indicate intermetallic compounds such as iron nitride (Fe_3N), aluminium silver (Ag-Al), and manganese zirconium (Mn_2Zr). In samples A, B, and C, Al and Mg formed a protective coating on the anode, while C and Si reduced passivation and released electrons to protect the steel. IOTs and Mg in the aluminium matrix improve the anodic corrosion resistance. The observed improvements in corrosion resistance highlight the potential of these sacrificial anodes for practical applications in corrosion protection systems.

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Sacrificial anode; iron ore tailings; Al-Mg-Ti; electrode potential; corrosion

1. Introduction

Large amounts of concentrates and tailings are processed from abundant iron ore (haematite and magnetite) in our region. The concentrate is used in the production of steel, either by direct reduction or blast furnace routes. Iron ore tailings are typically in the form of slurries devoid of iron (Fe) but likely contain trace amounts of other elements as well as a higher concentration of silica. The tailings are disposed of as waste by being used to patch potholes in sections of bad roads in developing countries. Based on 2014 Brazilian production, approximately 275.5 million tons of waste were disposed of in landfills and tailing dams in 2014 [1]. The tailings also contain other unmined or unprocessed materials, which are better than being used for the purpose of covering potholes. It has been reported that unused tailings are now being utilised by Nigeria's petroleum sector to coat pipelines to prevent corrosion [2]. Instead of dumping it as a waste to fill up portholes, Moreso can be used as a doping material to create heterogeneity in the aluminium anode so that it can continuously oxidise to form an appropriate anode that will not passivate. Heterogeneous materials, such as other metallic materials, hasten corrosion in an effort to prevent passivation. For instance, the presence of IOTs and Fe prevents aluminium from continuously deteriorating and from becoming a passive anode. This material may form additional oxidising agents. When there is no direct current or when an impressed current system is available, the use of heterogeneous aluminium anodes would enable continuous oxidation without developing passivation, making this system useful.

The development of sacrificial anodes from Al, Mg, and Ti using iron ore tailings presents a multifaceted challenge that encompasses materials science, metallurgy, and corrosion protection. The selection of suitable alloy compositions for sacrificial anodes is crucial because it directly impacts the performance of the anodes in cathodic protection applications, as demonstrated by Campos et al. [3]. Moreover, these materials are useful for industry, as discarded iron ore tailings can create mounds that seep into the earth, which can discourage agriculture in the region. Many attempts have been made to further utilise tailings and slimes through different routes [4]. However, potential applications of iron ore tailings include those in the ceramic industry, alkali-activated materials, and geopolymers. There has not been much real use of these materials on an industrial or commercial scale. The development of new materials such as zeolites and mesoporous silica has led to a number of scientific breakthroughs [5]. Various approaches for the comprehensive utilisation of iron ore tailings have been analysed. Sacrificial anode protection is a method of preventing corrosion of metallic structures situated in electrolytes. In practical applications, the structures most commonly provided with protection are constructed of iron or steel (including stainless steel), and the electrolytes are most often soil and water [6–8]. Sacrificial protection is primarily intended for metal surfaces permanently

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exposed to seawater or marine sediments. Sacrificial anode protection is often fully effective at preventing severe corrosion in a tidal zone and has a corrosion-reducing effect on surfaces intermittently wetted by seawater [9].

Historically, the effects of sacrificial anodes in the protection of steel have not been overemphasised because environmental factors such as rainfall, humidity, and temperature are the major driving forces responsible for the corrosion problems common in structures in our environment [10]. However, one of the most important ways to prevent this problem associated with corrosion is through sacrificial anode protection.

Sacrificial anodes, as a form of cathodic protection (CP), are highly active metals that are used to prevent a less active material surface (steel) from corroding when exposed to aggressive conditions. Sacrificial anodes, such as zinc, aluminium, and magnesium, are created from a metal alloy with a more negative electrochemical potential and are used to protect less active metals, such as steel, from corrosive environments [11]. A sacrificial anode is intended to be dissolved to protect other metallic components without an external power source [12]. The anode provides a fairly uniform distribution of current but with a low output, which increases with increasing quantity [13]. Sacrificial protection prevents corrosion by converting all the anodic (active) sites on the metal surface to cathodic (passive) sites by supplying electrical current (free electrons) from an anode [14]. When enough current is applied, the whole structure will be at one potential; thus, anode and cathode sites will not exist [15].

Aluminium alloys are widely utilised for protecting steel structures due to their excellent current conductivity and the supply of a large number of electrons for protection per unit mass, as reported by Abedin and Saleh [16]. In saline media, pure and unalloyed aluminium materials adopt a relatively noble solution potential, attributed to the formation of a thin, continuous, adherent, and passive layer of γ-Al_2O_3 on their surface, which prevents further release of electrons for steel surface protection [17]; [18]; [19]. However, the presence and volume fraction of second-phase particles as alloying elements, such as zinc, magnesium, indium, tin, and titanium, hinder or prevent the formation of surface films on aluminium [20]. According to Jiang et al. [21], the performance of aluminium anodes is significantly influenced by the alloy composition, emphasising the importance of understanding the relationships between metallurgical processing and the anodic response of alloys. Recent research by Su et al. [22] has demonstrated that microalloying aluminium anodes with certain metallic composite oxides can significantly improve anode life and reduce costs.

Moreover, iron ore tailings have been found to be efficient, socially beneficial, and environmentally friendly [23]. The value of these materials has been further enhanced by their use as replacements for aggregates in concrete [24] and construction bricks [25]. These findings underscore the potential of iron ore tailings for various applications, ranging from construction materials to environmental remediation. The comprehensive utilisation of iron ore tailings has been investigated, leading to the development of innovative methodologies for their utilisation, such as roasting and their use as concrete composite admixtures, as reported by Tang et al. [26]. Additionally, studies have explored the influence of iron ore tailings as fine aggregates on the strength of ultrahigh-performance concrete, revealing promising results, as demonstrated by Zhou et al. [27] and Tian et al. [18]. Furthermore, the preparation of iron ore tailing-based super-hydrophobic coatings and their use as reinforcing fillers in copolymers have been investigated, highlighting their potential in advanced material applications [22,23].

To safely protect steel in a chloride environment, the addition of iron ore tailings would help with this investigation. However, X-ray fluorescence (XRF) investigations of the tailings, which were originally believed to be waste, revealed the presence of additional valuable minerals that were locked up in the original iron ore and used to increase the potential of aluminium.

The raw materials used in the production of anodes may not be readily available in our country. This limits the production of this kind of anode material in Nigeria. We have what can be used to replace what they have used. In this work, the depassivation of an aluminium film during its use as a sacrificial anode for the protection of steel in chloride environments is a point of interest. Thus, this research aimed to develop an aluminium-magnesium (Al-Mg) base alloy with iron ore tailings to aid in the continuous dissolution of aluminium as a sacrificial anode for the corrosion protection of carbon steel pipeline structures in marine environments. In addition, the synthesis of Al-Mg alloys activated with iron ore tailings was analysed using X-ray fluorescence (XRF), scanning electron microscopy (SEM/EDS), and X-ray diffraction (XRD), while the electrochemical behaviour in a NaCl environment was examined using a linear polarisation mechanism.

2. Materials and methods

2.1. Materials

Cast Al and Mg ingots, iron ore tailings, and low-carbon steel were used as study materials. The iron ore tailing mixture was acquired from Ajaokuta, Kogi State,

Nigeria. X-ray fluorescence (XRF) (Hitachi High-Tech Analytical Science, and HORIBA, Japan) was used in an initial study to establish the materials' elemental makeup. Iron ore tailing was subjected to a particle sieve examination to determine the average size of the resulting particles. The sand-casting technique was employed to create various anode compositions of aluminium, magnesium, and iron ore tailings. Table 1 shows the varying proportions of the elements.

2.2. Electrical conductivity

Each sample was secured using a wooden screw, with one end linked to a potentiometer and the other to a galvanometer in series using a portable eddy current electrical conductivity metre (48 kHz; Thermo Fisher Scientific, U.S.A.). The positive terminal of the galvanometer was connected in series with the wooden screw, and the negative terminal was connected to the jockey key. Thereafter, a resistance box was connected to one end of the potentiometer, and the other terminal was linked to the longer length. The key and the potentiometer, however, were both linked to the battery. Equations 1 and 2 were used to determine the resistivity and conductivity, respectively, using the obtained data.

$$\rho = (RA)/L(\Omega m) \tag{1}$$

$$Conductivity(\sigma) = \frac{1}{\rho}(inverse\ of\ resistivity)(\Omega/m) \tag{2}$$

From Equations 1 and 2, L represents the length of the anode produced, A is the cross-sectional area, ρ is the resistivity and R is the resistance.

2.3. Electrochemical measurements

The electrochemical measurements were accomplished by the potentiodynamic polarisation technique using a three-electrode setup. The cast Al-Mg alloys activated with iron ore tailings served as the working electrode (WE), with a platinum rod serving as the counter electrode and Ag/AgCl serving as the reference electrode. The anode and the other electrodes were immersed in 0.5 M NaCl solution. For the open-circuit potential (OCP), the setup was left in the environment for approximately 20 mins. Thereafter, the sample was anodically polarised from −250 mV to +250 mV. To ensure that the results from the experiment could be replicated and repeated, the experiments were run intermittently three times for each anode composition. The polarisation scan structure and the relationship between the current and voltage were used to evaluate the corrosion response of the cast alloys.

2.4. X-ray diffractometry analysis

The phase composition of the aluminium matrix composites utilised in this investigation was determined using a Bruce D2 phaser machine (Bruker AXS, Inc., Billerica, Massachusetts, U.S.A.) with an X-ray source of cobalt K radiation (= 1.7890). The test was run by scanning the sample at a speed of 37 s across a range of 2θ angles from $^{10^\circ}$ to 90° for potential diffraction directions. By comparing the d-spacings of the analysis results with those of standard reference patterns, it was possible to determine the amount of metal or intermetallic material in the metal matrix composites.

2.5. Scan electron microscopy/energy dispersive spectroscopy (SEM/EDS)

The samples were coated with platinum, an electrically conductive material, and deposited on the sample either by low-vacuum sputter coating or high-vacuum evaporation. The specimen is placed in a chamber with relatively high pressure, short working distance, and differential pumping of the electron optical column to maintain a sufficiently low vacuum at the electron gun. The high-pressure region around the sample in the field emission gun scanning electron microscope (FEG-SEM) (Thermo Scientific Phenom Pharos G2 FEG-SEM, U.S.A.) neutralises the charge and amplifies the secondary electron signal. Low-voltage SEM is typically conducted in a FEG-SEM because field emission guns (FEGs) are capable of producing high primary electron brightness and small spot sizes even at low accelerating potentials.

3. Results and discussion

3.1. Compositional characterization with X-ray fluorescence (XRF)

The X-ray fluorescence (XRF) analyses are presented in Tables 2 and 3. The chemical compositions of the as-

Table 1. Weight-percent ratios for the developed Al-Mg-IOT anodes.

Sample	A (70Al-30Mg)	B (70Al-5IOT-25Mg)	C (70Al-15IOT-15Mg)	D (70Al-30IOT)	E(100Al)
Al (wt%)	70	70	70	70	100
IOT (wt%)	0	5	15	30	0
Mg (wt%)	30	25	15	0	0

received aluminium, magnesium, iron ore tailings (IOT), and cast anodes are shown. The iron ore tailings consisted of Al, Fe, Zn, Ti, and Cr, all of which can be found in anodes A through E. Anode E, which served as the control, was the last anode to be cast during the casting operation using the same crucible. As a result, the purportedly pure aluminium anode was combined with the residues of the other elements that were discovered in the crucible. Tin (Sn) and iron (Fe) were described as degenerating impurities in sacrificial magnesium anode systems by E. Jung-gu et al. [28]. When used as sacrificial anodes, titanium (Ti) in the range of 0.03–0.05 wt. % improves homogenous dissolution, enhancing the electrochemical properties of aluminium, such as current capacity and anode efficiency [29]. Salinas et al. [30] reported that a Zn content in the range of 1–5 wt% was the principal factor causing a reduction in the corrosion efficiency in Al-Zn sacrificial anode systems. Magnesium (Mg), one of the most effective and economical metals, has a current efficiency limit of less than 50% when used as an underground sacrificial anode [31,32]. The corollary from the XRF analysis suggested that Sample D may not be a strong contender for good Al-Mg sacrificial anodes because of the negligible wt. % of Ti and a low amount of Fe present.

Table 2. X-ray fluorescence (XRF) compositions of the major elements in the as-received materials.

ELEMENTS	Al	Mg	IOT
Mg	1.9941	68.217	0.0000
Al	97.1543	27.5890	7.3093
Si	0.0000	3.3476	10.4801
Ti	0.0000	0.0446	0.4181
Cr	0.0083	0.0033	0.3470
Mn	0.0446	0.0294	0.2110
Fe	0.3876	0.2331	44.2337
Ni	0.0694	0.0371	0.1119
Cu	0.0000	0.0249	2.1222
Zn	0.1409	0.0730	0.1795
Sr	0.0136	0.0829	0.0000
Pb	0.0000	0.0222	0.0510
Sn	0.0611	0.1143	0.2601
Sb	0.1160	0.1711	0.1922
P	0.0000	0.0000	0.0549
S	0.0000	0.0000	0.1203
K	0.0000	0.0000	0.5383
Ca	0.0000	0.0000	0.0500
V	0.0000	0.0000	0.0775
Co	0.0000	0.0000	0.9726
As	0.0000	0.0000	0.0000
W	0.0000	0.0000	5.2780
Au	0.0000	0.0000	2.2401
Ag	0.0000	0.0000	0.0016
Rb	0.0000	0.0000	0.0032
Nb	0.0000	0.0000	0.0056
Mo	0.0000	0.0000	0.1832
Cd	0.0000	0.0000	0.0000

3.2. Electrical conductivity

Figure 1 shows the electrical conductivity of the anodes produced in comparison with that of steel. The capacity of a material to conduct and discharge electrons must be determined by that substance's conductivity; otherwise, the material may become passive. Figure 1 reveals that the conductivity of Sample D varied from that of the control (Sample E). All of the samples had different electrical conductivities. This suggests that, as can be observed in samples A, B, C, and Steel, the conductivity processes vary depending on compositional differences (Table 3). In comparison to the other anodes and steel, Sample B exhibited higher conductivity. The variations in titanium content might also be the main cause of the different electrical conductivities of the anodes.

3.3. Corrosion behavior of the Al-Mg alloy activated with iron-ore tailings

Figure 2 and Table 4 present the results of the corrosion potential/current density and potentiodynamic polarisation curve analyses, respectively.

Developed anode sample D has the lowest corrosion rate of 0.08 mm/yr, whereas sample A has the highest corrosion rate of 0.43 mm/yr, as observed in Table 4. The corrosion potential of sample D is more positive than that of steel, which has values of −584.83 mV Ag/AgCl and −775.37 mV Ag/AgCl. In this system, the anode to be protected from corrosion would be connected to a less noble (i.e. more electronegative) metal in the galvanic series with the pipeline. However, an impressed current system is needed to protect against a less noble metal, that is, a metal or anode that requires a high current capacity [31]. The potential of sample D as an anode is elevated to a more noble position by the addition of IOTs and magnesium, as shown in Figure 2 and Table 4. Steel is more susceptible to corrosion in a chloride environment, as shown in Table 4; hence, protection is needed sacrificially.

Table 3. X-ray fluorescence (XRF) compositions of the cast Al-Mg alloy activated with IOTs.

Sample	Al	Mg	Fe	Zn	Sn	Ti	Cr
A	63.5832	35.2963	0.4713	0.1458	0.0852	0.036	0.0176
B	73.4473	25.0832	0.6292	0.3781	0.049	0.0344	0.008
C	81.4623	17.5765	0.4041	0.2152	0.0602	0.0385	0.007
D	97.4476	0.9222	0.2521	0.1439	0.0319	0.0072	0.0084
E	98.1369	1.1056	0.3484	0.1505	0.0335	0.0129	0.0084

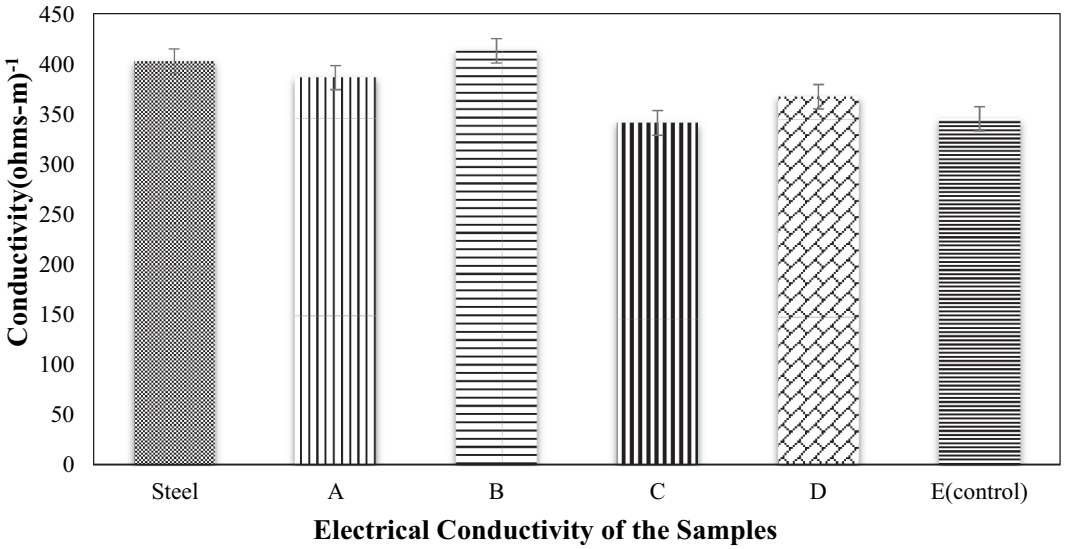

Figure 1. Electrical conductivity of Al-Mg anodes with IOTs in comparison with steel.

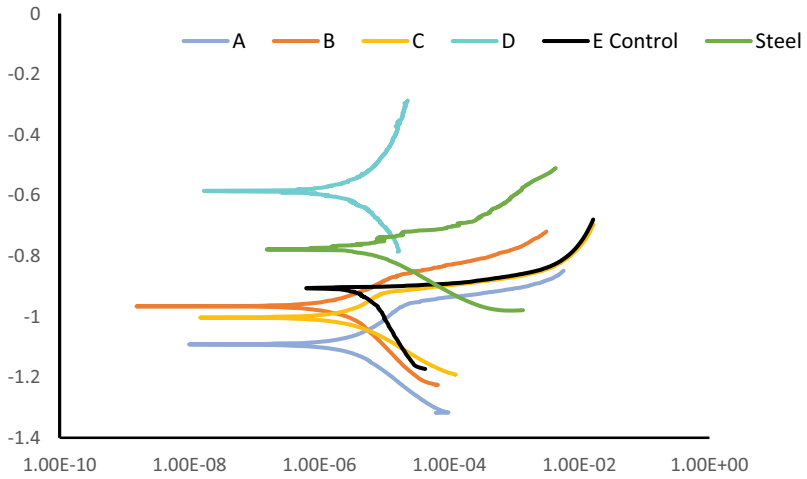

Figure 2. Potentiodynamic polarization curves for the anodes immersed in 0.5 M NaCl solution.

Table 4. Corrosion potentials and corrosion current densities of the Al-Mg alloys produced.

Sample	i_{corr} (μAcm^{-2})	E_{corr} (mV Ag/AgCl)	β_c (mV)	β_a (mV)	Corrosion rate (mm/yr)
A	8.897	−1061.00	187.82	168.71	0.43 ± 0.0020
B	6.157	−965.58	218.76	122.32	0.28 ± 0.0015
C	7.136	−1003.00	149.49	191.62	0.36 ± 0.0010
D	2.808	−584.83	4258.00	2334.00	0.11 ± 0.0015
E (Control)	5.039	−911.29	334.91	19.11	0.21 ± 0.0020
STEEL	10.907	−775.37	1207.00	8.26	2.25 ± 0.0025

3.4. Varying weight percent of iron ore tailings (IOTs)

Figure 2 shows that Sample E has almost the same potential as steel, which likely indicates that pure aluminium forms a passive film that hinders the corrosion of the anodes. Sample A has a corrosion potential of −1.06 V (Ag/AgCl), which is far below that of steel at −0.78 V (Ag/AgCl). The potentiodynamic polarisation curves in Figure 4 indicate that samples A, B, and C tend to be more susceptible to corrosion, more electronegative, and more anodic than steel. Samples A, B, and C will supply more electrons to protect the steel. These anodes may be used as sacrificial protection agents for steel in a NaCl environment. Furthermore, sample A is more active at protecting steel than samples B and C. Moreover, sample D cannot be used as a sacrificial anode to protect steel in a NaCl environment because it has improved corrosion resistance, whereas the other samples have an electrode potential below that of steel according to the potentiodynamic polarisation curve.

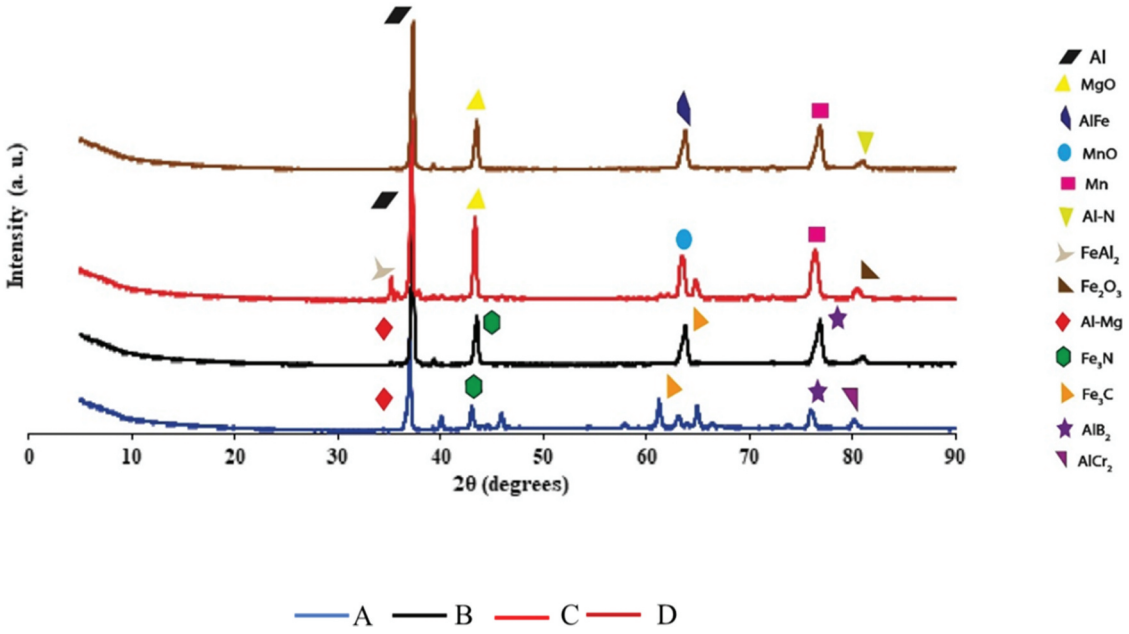

Figure 3. X-ray diffraction patterns of the Al-Mg alloy activated with and without iron ore tailings (IOTs).

3.5. X-ray diffractometry of the Al-Mg alloy activated with iron ore tailings

Figure 3 provides information on the X-ray diffraction analysis and the chemical composition of the anode produced by the admixture of aluminium, magnesium, and iron ore tailings (IOT).

Figure 3 XRD image showing the presence of the intermetallic compounds aluminium boron(AlB_2),aluminium chromium ($AlCr_2$),aluminium iron ($FeAl_2$),haematite (Fe_2O_3),cementite (Fe_3C),iron nitride (Fe_3N), magnesia (MgO), aluminumnitride (Al-N) and aluminium magnesium(Al-Mg), among others. However, these compounds are identified as minor peaks, except for Al-Mg and Al, which contain major peaks. The minor peak shows the existence of low intensities. The presence of magnesium and cementite protects the anode from the steel anodically because a protective film was not generated on the surface of the anode, which was less stable than that of aluminium. The intermetallic compounds influenced the behaviour of the anodes by increasing their susceptibility to corrosion. Song and Atrens [33] affirm that the passive film on magnesium is less stable than that on aluminium. The presence of magnesium and titanium reduced the tendency of the aluminum matrix to form films. As observed, single-phase materials have more corrosion resistance than materials composed of heterogeneous compounds. The heterogeneous phases cause the formation of more anodic sites than cathodic sites, which promotes corrosion.The anode offered protection sacrificially because a protective film was not generated on the surface, and the electro-potential was far below that of the steel. The elements present in sample D show that there is interaction between the

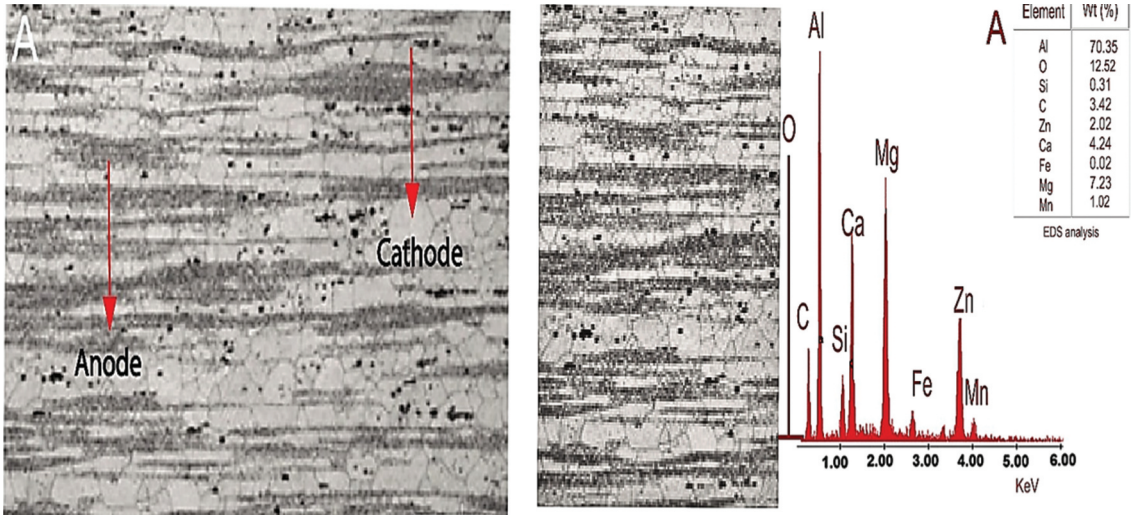

Figure 4. Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) results for sample A.

admixtures of the constituents to form the anode. All the phases present confirm that the anode may not provide protection to the steel. That is, sample D has more corrosion resistance than does the steel. Al, which is the base matrix, dominates the alloy. The other phases present are the intermetallic phases and impurities in the Al-Mg alloy.

3.6. Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) for the Al-Mg alloy activated with and without iron ore tailings (IOTs)

Figures 4–8 show the SEM and EDS analyses for anode formation from the combination of three state materials: aluminium, magnesium, and iron ore tailings. As shown in Figure 4, Sample A is made up of aluminium, zinc, and magnesium, which are anodic materials. However, the presence of Fe and manganese strengthens the anode. There are two prominent phases in this structure. One of the phases is anodic, while the other is more cathodic. Corrosion occurs as a result of the presence of dual phases. The dark side reveals the anodic side where electrons are transferred to the bright sites (cathode). The EDS results correlate with the findings of Darezereshki et al. [34], who observed the presence of peaks comprising Fe, Si, Mg, Ca, Al, S, Na, and O in the IOT sample in the leachability study of iron oxides from mine tailings in a hybrid of sulphate-chloride lixiviant.

As shown in Figure 5, Sample B reveals more of a uniform structure because of the pronounced dual structure. A portion of the micrograph revealed more anodic effects, while the other side was more cathodic. The corrosion was rapid due to the presence of iron-ore tailings, zinc, and magnesium. However, magnesium and zinc tend to be electronegative in the sacrificial/galvanic series, thereby supplying more electrons to aid rapid corrosion [35]. This limits the rate of passivation, which enhances the rate of corrosion. However, in all the structures, some are dual phases, while some are heterogeneous phases.

As shown in Figure 6, Sample C is made up of aluminium, zinc, and magnesium, which are anodic materials. As observed, there are two prominent phases in this structure. One of the phases is anodic, while the other is more cathodic. Corrosion occurred as a result of the presence of the dual phases. The presence of iron ore tailings prevents the passivation of corrosion, thereby facilitating corrosion. The grain size at one of the sites is relatively coarse, while that at the other site is relatively refined. However, it is worth noting that the presence of Fe and manganese strengthens the anode. Jeon et al. [36] also reported on a simple and efficient technique for recovering gold ions from ammonium thiosulphate media by galvanic interactions between zero-valent aluminium and activated carbon, revealing how gold ions ameliorate the passivation of corrosion.

As shown in Figure 7, Sample D has the same uniform structure. It has a pure lath that has formed a boundary. The thin line of aluminium along the grain boundaries will passivate, that is, form a film that prevents further corrosion. This is a characteristic of aluminium. All metallic materials are subsumed in the matrix. The other metallic elements, magnesium, and aluminium, are subsumed under the aluminium matrix. The aluminium lath was more exposed to the environment, which promoted passivation to prevent further corrosion. However, it had the least negative potential, and the material had more corrosion resistance, which formed a covering along the grain boundaries and all the other metals that were subsumed under it. The aluminium passivation will not protect a sacrificial system because of its higher positive potential. However, an impressive current method (external DC) is needed to protect the anode (which

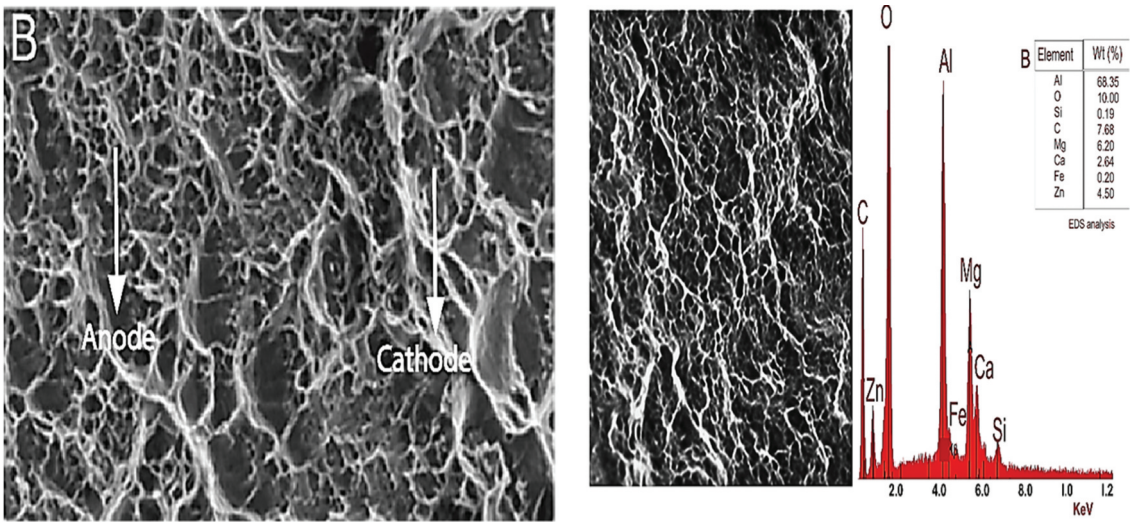

Figure 5. Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) results for sample B.

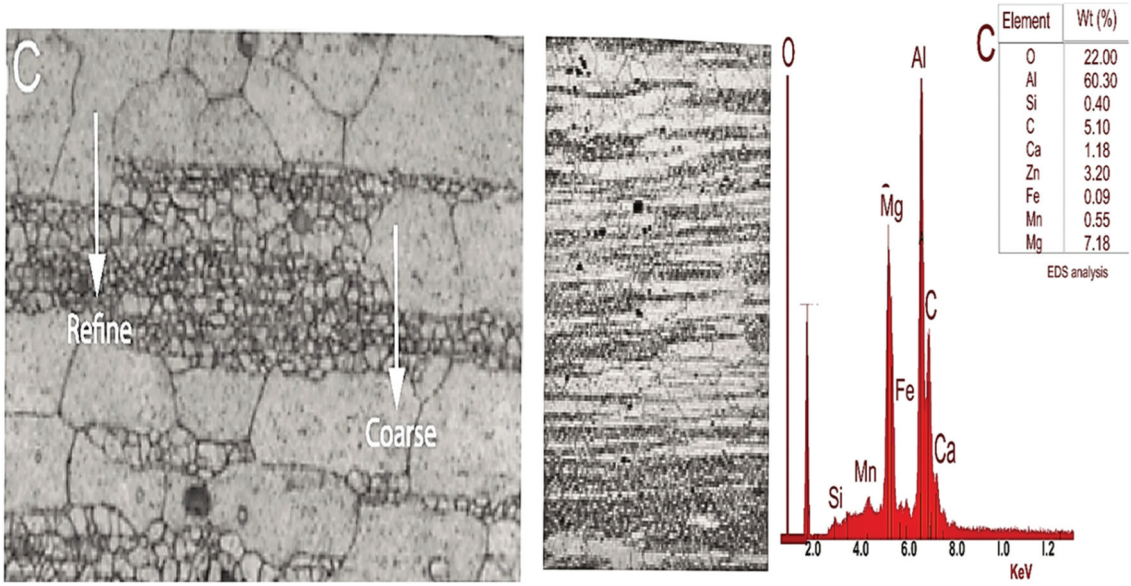

Figure 6. Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) images of sample C.

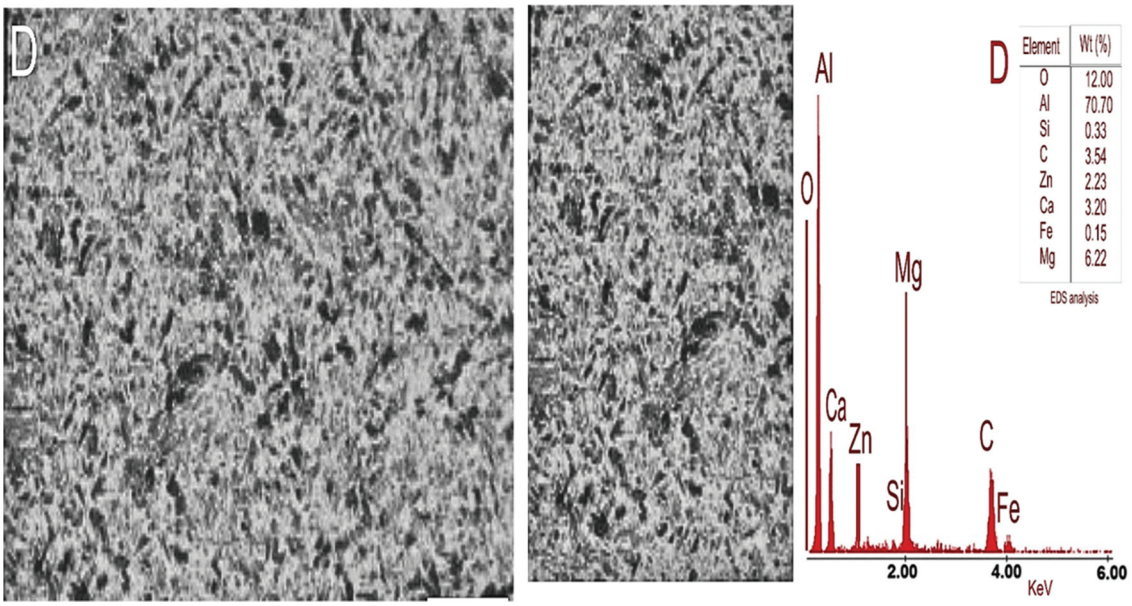

Figure 7. Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) results for sample D.

has a more positive potential than steel). Since aluminium-formed passivation has no profound effect but rather the current method, the application of a hydrogen generation gas generation pattern may support passivation involving the shielding of aluminium by the formation of a relatively hard nonreactive surface film that inhibits further corrosion, as supported by Safarzadeh et al. [37], who identified aluminium and aluminium alloys in municipal solid waste incineration as potential sources of hydrogen gas.

As shown in Figure 8, composition E has one single phase, meaning that anodic sites are absent. However, considering that the anode cannot sacrificially protect the steel structure, the anodic site, which releases electrons to the cathodic site for protection, may be absent for Sample E. Note that the bright site is made of aluminium. It is also observed that the grain boundaries are coarse. Furthermore, a portion of the thin aluminium line was more vulnerable to corrosion in the environment. This process results in passivation to prevent further corrosion. The shielding of aluminium by the formation of a relatively hard nonreactive surface film that inhibits further corrosion at either the anodic or cathodic site is possible, as suggested by Saffarzadeh et al. [37].

SEM/EDS examination of the anode revealed the presence of elemental Al, Mg, O, and Si, while the XRD patterns indicated the presence of intermetallic compounds such as iron nitride (Fe^3N), aluminium silver (Ag-Al), and manganese zirconium (Mn^2Zr). The protective coating formed by Al and Mg on the anode in samples A, B, and C, along with the decrease in

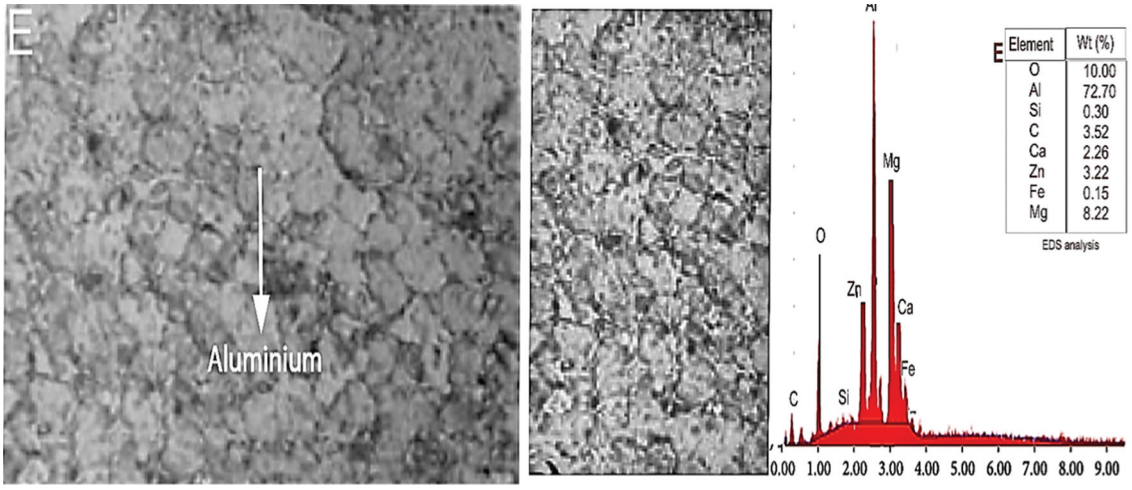

Figure 8. Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) images of sample E.

passivation and release of electrons by C and Si to protect the steel, are crucial observations. Additionally, the improvement in anodic corrosion resistance due to the presence of IOTs and Mg in the aluminium matrix is noteworthy, as demonstrated by Bertolini et al. [38]; Sharma et al. [39]; Capelossi et al. [40]; Zander et al. [41]; and Gao et al. [42].

The role of intermetallic phases in the localised corrosion of aluminium alloys has been extensively studied, with reports indicating that the Mg-Si phase (Mg_2Si) exhibits similar corrosion potentials to those of the surrounding aluminium matrix or even lower corrosion potentials compared to those of the aluminium matrix [43]. Furthermore, the electrochemical characteristics of intermetallic particles and phases common to aluminium alloys have been investigated, highlighting the variation in pH and the occurrence of sharp gradients across the alloy surface, which significantly impact corrosion behaviour [44]. The formation of a denser oxide surface film due to the presence of a higher density of dislocations and grain boundaries in cryogenic-rolled materials has been linked to increased corrosion resistance, emphasising the influence of microstructural features on corrosion properties [38]. Moreover, the addition of Al to Mg anodes has been explored to enhance the electrochemical performance of aqueous batteries, indicating the significance of the alloy composition in determining anode behaviour [42].

The findings from the investigation align with the literature, emphasising the critical role of intermetallic phases, microstructural features, and alloy composition in influencing the corrosion behaviour of aluminium and magnesium alloys. These observations underscore the complex interplay between elemental composition, microstructure, and electrochemical characteristics, shedding light on the multifaceted nature of corrosion mechanisms in these materials. A comprehensive understanding of these factors is essential for the development of effective corrosion protection strategies and the design of advanced alloy systems with enhanced corrosion resistance.

4. Conclusions

Anodes were produced by sand-casting aluminium and magnesium admixed with iron ore tailings. The following conclusions could be drawn:

(1) The anodes with varying compositions from the admixture of Al-Mg-IOTs have corrosion potentials between −584 mV (Ag/AgCl) and −1061 mV (Ag/AgCl), while those of the steel and aluminium nodes are −775 mV (Ag/AgCl) and −767 mV (Ag/AgCl), respectively. Anodes with more negative potentials could offer sacrificial protection to steel in a chloride environment. Anodes with noble potentials better than steel will function well with an impressed current system.
(2) Compositions A (70Al-30 Mg), B (70Al-5IOT-25 Mg), and C (70Al-5IOT-25 Mg) can be used to make anodes with a higher negative potential for use as sacrificial anodes. The principle of sacrificial anodes establishes that the anode to be used must have a negative potential in the NaCl environment. D and E cannot be used in sacrificial anode systems due to their higher positive potentials.
(3) The XRD analyses indicated the presence of magnesium (Mg) and titanium (Ti), which reduced the passivation potential of the aluminium anode by dissolving the film. Lithium iron oxide ($Li_2Fe_3O_5$), titanium hydride (TiH2), iron nitride (Fe_3N), aluminium manganese silver (Ag_5-Al-Mn), manganese zirconium (Mn_2Zr), and aluminium magnesium (Al-Mg) are among the other intermetallic compounds discovered.

(4) Iron ore tailings, which are regarded as waste, can be used as additives to Al-Mg alloys to improve the anodic potential of sacrificial connection systems for steel in marine environments.

Abbreviations

SEM	Scanning electron microscopy
EDS	Energy dispersive spectroscopy
XRD	X-ray diffraction
Fe_3N	Iron nitride
Ag-Al	Aluminum silver
Mn_2Zr	Manganese zirconium
IOTs	Iron ore tailings
DC	Direct current
CP	Cathodic protection
XRF	X-ray fluorescence
Al-Mg	Aluminum-magnesium
WE	Working electrode
OCP	Open-circuit potential
Sn	Tin
Ti	Titanium
AlB_2	Aluminum boron
$AlCr_2$	Aluminum chromium
$FeAl_2$	Aluminum iron
Fe_2O_3	Hematite
Fe_3C	Cementite
MgO	Magnesia
Al-N	Aluminum nitride
$Li_2Fe_3O_5$	Lithium iron oxide
TiH_2	Titanium hydride
Ag_5-Al-Mn	Aluminum manganese silver
Mn_2Zr	Manganese zirconium
Al-Mg	Aluminum magnesium

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Authors' contributions

This work was carried out in collaboration with all the authors. Authors: B.O. Iwarere, D.T. Oloruntoba, and O.S. Adesina designed the study, performed the experiment, interpreted the results, and wrote the first draft of the manuscript. Authors, O.S. Adesina, O.O. Sanyaolu, P.P. Ikubanni, & A.A. Adediran managed the analyses of the study, managed the literature searches, and performed the graphical editing. All the authors read and approved the final manuscript.

Availability of data and materials

All the data generated or analysed during this study are included in this published article.

Ethical approval

The collection of plant material complied with relevant institutional, national, and international guidelines and legislation.

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