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Research Paper

Corrosion Susceptibility of Aluminium Step Tile Roofing Sheet

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ABSTRACT

Step tile aluminium roofing sheets are exposed to the three conditions that necessitate the occurrence of SCC. These conditions are: The tensile stresses as a result of residual stresses from the manufacturing process; a susceptible alloy and a humid or water environment. In view of this, the study aimed at investigating the corrosion susceptibility of Aluminium step tile roofing sheets. The linear polarization resistance method was used in this study to determine the corrosion rate/susceptibility of aluminium roofing sheet. This is because it has an edge over the other non-destructive test methods because it is suitable for both laboratory and in-service conditions. Results show that Aluminium has a high resistance to oxidation when subjected to an external potential as a result of corrosive environment. However, with a corrosion density value of 7.44µA/cm^2, the study concludes that Aluminium step tile roofing sheets are susceptible to high degrees of corrosion. Also, with a corrosion penetration speed of 0.081 mm/yr, it would take a minimum of 12 years for a 1mm thick Aluminium roofing sheet to corrode along the depressed regions.

Keywords: Corrosion, Susceptibility, Polarization, Resistance, Potential.

1. INTRODUCTION

This present study is on metallic corrosion which is defined as an attack on a metallic material by the reaction with its environment. [1] This attack is destructive and can be either chemical or electrochemical, thus reversing the metal to its original or combined state. It is a known fact that metals are extracted from their ores in which they occur in combined stable states as oxides, carbonates, sulphides, halides, silicates, sulphates. When they are exposed to the environment, they interact with it and inevitably spontaneously revert back to their original states. This phenomenon is known as corrosion.

Corrosion has been implicated in the collapse of bridges with numerous fatalities. Corrosion is one of the causes of ruptures of pipes carrying crude oil and gases. This type of corrosion causes fatalities and extensive damage to the environment, with the consequence of huge financial costs required for clean ups, repairs and replacement of damaged equipment, as well as payment of compensations to affected communities. Airplanes are not left out in the corrosion phenomenon. [2] What might appear to be innocuous stains surface that were indeed tell-tale signs of pitting corrosion had led to catastrophic plane crashes. The woes of corrosion are inexhaustible and seen in the entire spectrum of structures, machines and components.

It is no gain-say that shelter is a basic necessity of man. A shelter could be in a form of a residential building, hospital building, church building, event centre building, a factory building, etc. In all these types of buildings, roof is one of the necessary components that make up the building. Rooftops receive most of the atmospheric elements which are incident on buildings. As a result, roofing materials are carefully chosen to resist and protect the interior from adverse atmospheric conditions. Such material should particularly be resistant to corrosion in addition to mechanical strength. To this end, different types of roofing materials have evolved over the years. Some of the roofing materials commonly used on buildings are; Asphalt shingles, wood shingles, clay and concrete tiles, slate, metals (steel, aluminium, zinc and copper), fibre cement [3] with particular reference to metallic roofing sheets, several factors are considered in choosing the right roofing material. The prevailing climatic condition of the region within which the project is being carried out tends to be a primary factor. Other factors include but not limited to cost, ease of installation, durability, ruggedness, style, aesthetic value, etc.

A major factor considered by engineers in ascertaining structural integrity and economy in the use of metallic roofing sheets is corrosion. This is as a result of the reactions taking place between the material and the environment. The rate of corrosion differs from metal to metal, thus there is varying resistance among metals when exposed to the same atmospheric conditions. The process of chemical reversion or corrosion is accelerated by air pollutants such as acid rain, salts and the presence of dissimilar metals.

Metal roofing is ideal for homes that have either a flat or steep roofline; it offers durability that is hard to match. Metal roofing comes in a variety of options to choose from - tin, zinc, aluminium, copper, and galvanized steel. This wide range of options gives metal roofing an edge above other types of roofing. [4]

However, over the years, aluminium roofing sheet have become the builders choice for roofing of all types of building facility. This is due to its advantages of durability, longevity, aesthetics and comparatively low cost in the long run when compared to galvanized iron or steel sheets. The commercial aluminium roofing sheets are readily available in two common designs, viz; corrugated and step tiles roofing sheets.

Among these designs, the step tile design may naturally show signs of deterioration at regions of depression that form the step design after some years of service life. These depressions as a result of impacts will cause stress within the aluminium sheet (especially the depressed regions), and possibly alter the grain structure of that region. Normally, heat treatment should be carried out on the aluminium sheet once the step tile design (depression) must have been completed.

However in a bid to reduce cost, most companies do not carry out further heat treatment on this roofing sheet. Therefore it is imperative to investigate the corrosion susceptibility of aluminium step tile roofing sheet considering the high demand of this important material in the roofing of all types of buildings. Aluminium is a light-weight malleable metal which as a result of its numerous engineering, economic and aesthetic advantages has become a choice roofing material. It forms aluminium oxide (Al_2O_3) which acts as a corrosion protective layer over the material when it comes in contact with water. Owing to ease of formability, these sheets are commercially available in various thicknesses, surface areas and designs. One of such design is the corrugated step tile aluminium roofing sheet. This design is usually impressed on the material at regular intervals without heat treatment. However, it is expected that the depressed regions possess built up stresses due to compressive forces employed when impressing the step tile design on the aluminium sheets. These stresses are capable of altering the grain structure of aluminium and subsequently affect its physico-chemical properties. Therefore, it is imperative to decipher the effect this built up stresses have on the corrosion susceptibility of aluminium roofing sheets during its service life.

The aim of the work is to study the corrosion susceptibility of aluminium step tiles roofing sheet.

The objectives are:

- To establish the corrosion potential of the depressed areas of aluminium step tile roofing sheet,
- To establish the rate at which this corrosion affects the material,
- To establish how long it will take such corrosion to set in.

This investigation is important since corrosion must occur in metals and alloys because they want to revert to their stable/natural states. Therefore there must be checks to be put in order to reduce the losses and costs incurred to the barest minimum. Outcome of the study will prove to be a helpful tool in deciding if aluminium step tiles roofing sheets should be heat treated after production before onward loading for sales. This study is limited to the depressed regions of aluminium step tile roofing sheet. The corroding medium is that of a very weak acidic medium. This is done with reference to an acidic medium set up in acid rain falls.

2. METHODOLOGY

2.1 Materials

The Aluminium step tile roofing sheet used in this work was collected from "First Aluminium Plc, Portharcourt". [5] reported that this alloy (Al-Mn) is known and referred to as 3SR in the aforementioned company. They highlighted that this alloy used in producing aluminium roofing sheets are processed thus; melting in reverberating furnace, casting using direct chilled (D-C) casting machine, preheating (homogenization), hot rolling at 2High mill, annealing and cold rolling, etc.

The chemical composition of the sample is as shown in Table 1.

Table 1: Chemical composition of 3SR Alloy.

Alloy	Composition (Weight %)										
	Al	Mn	Si	Fe	Cu	Mg	Cr	Ti	Zn	Ni	V
3SR	98.900	0.251	0.152	0.210	0.050	0.011	0.007	0.008	0.050	0.002	0.006

Source: Chukwudi, et al., (2012).

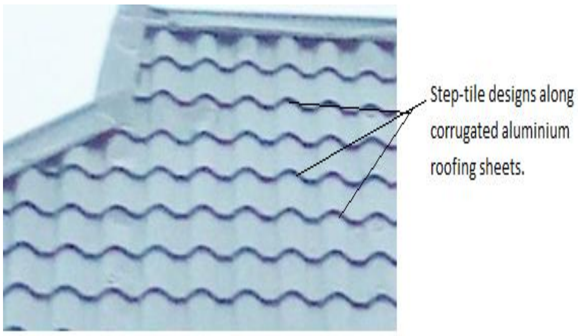

Figure 1: Picture showing installed step-tile aluminium roofing sheet.

2.2 Experimental Procedure

According to [6] non-destructive test methods generally utilized for measuring corrosion rate include: Tafel plot, linear polarization resistance, electrochemical noise, A.C. impedance, and electrical resistance. The main advantages of electrochemical techniques include sensitivity to low corrosion rates, short experimental duration, and well-established theoretical understanding. On the other hand, the gravimetric weight loss measurement is a destructive technique for determining the average rate of corrosion. The linear polarization resistance method has an edge over the other non-destructive test methods because it is suitable for both laboratory and in-service conditions.

Hence, in this study, the linear polarization resistance method is used to determine corrosion parameters such as Ohmic resistance (R), Polarization resistance (R_p), Tafel slopes (β_a and β_b), Stern-Geary constant (B), Corrosion potential (E_{corr}) and Corrosion current density (I_{corr}).

2.3 Circuitry of the Setup

The circuitry proposed by [6] was adopted in the design of the experimental setup. The setup is based on the linear polarization resistance method and it is integrated in a way that the data can be generated to calculate the Ohmic resistance of the aluminium roofing sheet and Tafel slopes required for calculating I_{corr} more accurately. The setup for the purpose of this study utilized H/H_2SO_4 electrode (SHE) as the reference electrode. The part of the integrated circuitry for measuring the half-cell potential using a H/ H_2SO_4 electrode (SHE) as a reference electrode is similar to that specified by ASTM C 876-99. [7] The principle of internal resistance determination for a cell is employed to obtain the ohmic resistance. The galvanostatic technique is used to determine the polarization resistance. [8]

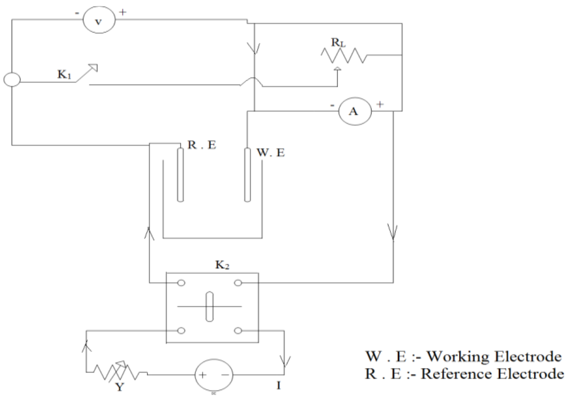

Figure 2: Schematic layout of the experiment circuitry setup.

2.4 Data Generation Using the Developed Setup

2.4.1 Preparation of the Test Piece

Commercially available Aluminium step tile roofing sheet (Al-Mn) alloy was used in this present study. The depressed region, having a dimension of 80mm length, 30mm width and 1mm thickness was cut out. Then ¾ of its length was dipped into a solution of 0.0001M of H_2SO_4. The procedure for the measurement of corrosion potential and generation of data required to determine the Ohmic resistance, and polarization resistance as suggested by [6] was adopted.

2.4.2. Corrosion Potential (E_{corr})

Keeping key switches K_1 and K_2 off, the corrosion potential E_{corr} is recorded allowing a sufficient response time of 30–60 seconds for measurements to stabilize. If the corrosion potential is low, the voltmeter reading is not stable and fluctuates; consequently, the reading after 30–60 seconds waiting period was considered as the representative value.

2.4.3. Data for Ohmic Resistance (R)

For determining the Ohmic resistance (R), different value of resistances R_L was set in the standard decade box resistor and values for V_L data were generated keeping key switch K_1 on and key switch K_2 off. 15 values of V_L are recorded by setting different values of R_L in increasing order with a gap of 15 s between two consecutive readings. Where R_L and V_L are load resistors and voltages respectively.

2.4.4. Data for Polarization Resistance (R_p)

A cathodic polarizing current, I , is applied and the resulting potential recorded by keeping key switch K_1 off throughout the experiment and key switch K_2 on. The current is applied in steps until the maximum value of the overvoltage, (value of potential by which E_{corr} is shifted as a result of polarization), is reached, which is usually 10 to 20 mV for the polarization curve to be in the linear range, with the help of a variable resistor, Y, which helps to keep the resistance of the circuit high enough to maintain a constant current. A cathodic current of 2 μA was applied, and subsequently, a step wise increment of 2 units effected up to a value of 22 μA. Voltmeter reading was recorded after a response time of 30 seconds at each current step. At this time, the reading of the voltmeter was not stable; hence, the response time was extended till a stable voltage reading is achieved.

2.4.5. Calculation Procedure for Corrosion Parameters

The Ohmic resistance (R), Polarization resistance, Tafel slopes (β_a and β_c), Stern-Geary constant (B), and Corrosion current density (I_{corr}) were determined, as described by Shamsad, et al., (2014).

2.4.6. Determination of Ohmic Resistance

The $1/R_L$ and $1/V_L$ values are plotted keeping $1/R_L$ on the x-axis and $1/V_L$ on the y-axis. The slope and y-axis intercept of the best-fit straight line joining these points were noted down. The ratio of the value of the slope to the value of intercept gives the value of the Ohmic resistance, R. The value of the Ohmic resistance was utilized for compensating the Ohmic drop mathematically.

2.4.7. Determination of Polarization Resistance

A graph of I versus ε values are plotted and a straight line best-fitted. The slope of the best-fitted straight line is taken as R_p. I is the recorded polarized data, while the values for ε are determined from the relation given below.

$$\varepsilon = E - E_{corr} \qquad (1)$$

Where: E_{corr} = measured value of the corrosion potential without applying polarization current.

E = V= recorded polarization data values.

2.4.8. Determination of Tafel Slopes (β_a and β_c) and Stern-Geary Constant (B)

The values of β_a and β_c are determined by best-fitting the polarization data into the polarization equation shown in equation (2).

$$2.3R_p I_i = \frac{\beta_a\beta_c}{\beta_a+\beta_c}\left[exp\left(\frac{2.3\varepsilon_i}{\beta_a}\right) - exp\left(\frac{2.3\varepsilon_i}{\beta_c}\right)\right]$$ [9] (2)

Values of R_p, I_i and ε_i are recorded polarized values, several possible combinations of the values of β_a and β_c are tried within their minimum and maximum values of 120 mV to 240 mV corresponding to B-value in the range of 26 mV to 52 mV. [10] The final values of β_a and β_c are the value corresponding to the minimum value of the sum of squares of the differences of left-hand side and right-hand side values of equation (2). The determined values of β_a and β_c are used to determine the Stern-Geary constant, B, using equation (3).

$$B = \frac{\beta_a\beta_c}{2.3\,(\beta_a+\beta_c)}$$ [11] (3)

2.4.9. Determination of Corrosion Current Density (I_{corr})

I_{corr} is calculated using equation (4).

$$I_{corr} = \frac{B}{R_p A_s} \qquad (4)$$

Where A_s = cross-sectional area of sample

2.4.10. Equivalent weight (μ_{eq})

The equivalent weight for pure metals is the ratio of the atomic weight to the number of electrons transferred.

$$\mu_{eq} = \frac{\mu}{n}\text{ (amu)} \qquad (5)$$

2.4.11. Corrosion Rate Calculation

In this study, the corrosion rate is expressed as penetration rate and as mass loss rate.

When expressed as penetration rate, equation (6) is employed.

$$\bar{v}_p = \mu_{eq} k_p \frac{i_{corr}}{\rho}$$ [12] (6)

Where μ_{eq} = equivalent weight (amu)

k_p = proportionality constant = 327.2 mm kg $(A.\ m.\ y)^{-1}$

ρ = density kg/m^3

When expressed in mass loss rate, equation (7) is employed.

$$\bar{v}_m = \mu_{eq} k_p i_{corr}$$ [12] (7)

Where k_p = proportionality constant = 0.8953 mg. m^2. $(A.\ m^2.\ d)^{-1}$

3. RESULTS

3.1 Experimental Results

The results obtained for the various tests are presented in the following sections in the form of tables and figures

3.1.1 Corrosion Potential

The corrosion potential was recorded to be 109 mV. This depicts the voltage of the circuit in which the depressed region in the Aluminium roofing sheet was subjected to during the experiment.

3.1.2 Ohmic Resistance

The readings obtained for the determination of the ohmic resistance are recorded in table 2.

Table 2: Ohmic Resistance of the Sample

R_L (Ω)	V_L (V)	R_L^{-1} ($Ω^{-1}$)	V_L^{-1} (V^{-1})
1000	21.4	0.001000	0.047
1500	23.2	0.000667	0.043
2000	24.8	0.000500	0.040
2500	26.2	0.000400	0.038
3000	27.6	0.000333	0.036
3500	28.8	0.000286	0.035
4000	30.0	0.000250	0.033
4500	31.2	0.000222	0.032
5000	32.2	0.000200	0.031
5500	33.1	0.000182	0.030
6000	33.8	0.000167	0.030
6500	34.4	0.000154	0.029
7000	35.0	0.000143	0.029
7500	35.4	0.000133	0.028
8000	35.8	0.000125	0.028

The equation for the observed trend is given in equation (8). This shows that the slope of the graph is 23.1425 Ω / V and the intercept on the y axis is 0.02661V^{-1}

$V^{-1} = 0.02661 + 23.1425\Omega^{-1}$ (8)

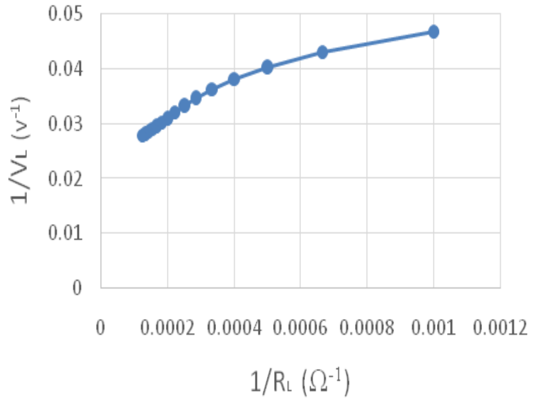

Figure 3: Plot of Ω^{-1}vs V^{-1} for the determination of ohmic resistance

From the equation of the plot, the ohmic resistance was determined as follows:

$$Ohmic\ Resistance, R = \frac{Slope}{Intercept} = \frac{23.1425}{0.02661} = 869.7042\ \Omega$$

The ohmic resistance is the cells opposition to the flow of the corrosion causing current across the cell.

3.1.3 Polarization Resistance

The polarization resistance is the resistance of the specimen to oxidation when subjected to an external potential as a result of a corrosive environment. Table 3 presents readings taking from the set up in order to determine the polarization resistance.

Table 3: Polarization resistance of the sample

I (mA)	E=V (V)	ε (mV) (ε = E-E$_{corr}$)
0.002	112	3
0.004	502	393
0.006	892	783
0.008	1282	1173
0.010	1672	1563
0.012	2062	1953
0.014	2452	2343
0.016	2842	2733
0.018	3232	3123
0.020	3622	3513
0.022	4012	3903

A plot of I versus ε was plotted and the slope of the plot depicts the polarization resistance of the specimen. Figure 4 shows the plot of I versus ε.

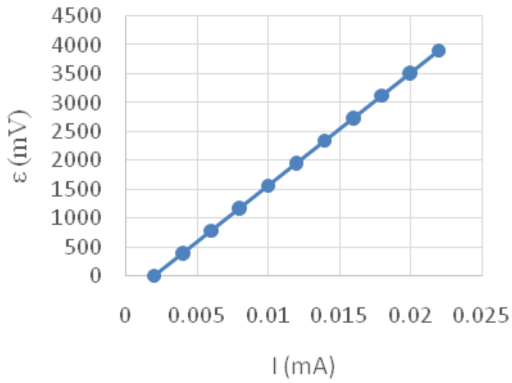

Figure 4: Plot of I vs ε

The plot equation is given in equation (9).

$\varepsilon = -387 + 195000\,I$ (9)

From equation (9), the resistance of the specimen to corrosion is 195000Ω.

3.1.4 Equivalent Weight

The equivalent weight of the specimen was determined using equation (5) as:

$$\mu_{eq} = \frac{\mu}{n} = \frac{37}{3} = 9\ amu$$

3.1.5 Stern-Geary Constant

Stern-Geary constant, B, was determined using equation (3). The Tafel slopes were 0.2 volt and 0.1 volt for β_a and β_c respectively.

$$B = \frac{\beta_a \beta_c}{2.3\ (\beta_a + \beta_c)} = 0.435$$

3.1.6 Corrosion current density

The corrosion current density was determined using equation (4).

$$I_{corr} = \frac{B}{R_p A_s} = \frac{0.435}{195000\ \times 30\mu m^2} = 0.0744\ A/m^2$$

3.1.7 Corrosion rate

The corrosion rate by penetration depth and by mass loss was evaluated using equations (6) and (7).

Corrosion rate by penetration

$$\bar{v}_p = \mu_{eq}\, k_p \frac{i_{corr}}{\rho} = 9 \times 327.2 \times \frac{0.0744}{2700} = 0.081\ mm/y$$

Corrosion rate by mass loss

$$\bar{v}_m = \mu_{eq}\, k_p i_{corr} = 9 \times 0.8953 \times 0.0744 = 0.6\ g/m^2 day$$

Table 4: Summary of the results obtained

Parameters Tested	Results Obtained
Ohmic resistance of cell	869.7042Ω
Polarization resistance	195000Ω
Stern-Geary constant	0.435
Tafel slope	β_a = 0.2v; β_c = 0.1v
Corrosion current density(I_{corr})	0.0744A/m^{2}or7.44µA/cm^2
Corrosion rate	$\bar{v}_p$ = 0.081mm/y; $\bar{v}_m$ = 0.6g/m^2 day

4. DISCUSSION

In order to determine the susceptibility of the depressed regions in aluminium step tile roofing sheets to corrosion, an experiment which would give information on the polarization resistance, Stern-Geary constant, Tafel slopes and corrosion current density was set up. The set up consist of an electrochemical cell which has a referenced electrode to be H/H_2SO_4 and the working electrode as the prepared test piece. The corrosion potential of the circuit was noted to be 109mV. This value indicates the voltage across the circuit. Also the circuit ohmic resistance was recorded to be 869.7042Ω. This is the cell's opposition to the flow of electric current through it. The experiment shows that the sample has a high resistance to oxidation when subjected to an external potential as a result of corrosive environment. This is seen in the high value of the polarization resistance (195000Ω) recorded. This high resistance leads to potential drop and it caused the insulative effect of aluminium oxide, (Al_2O_3), film formed on the working electrode surface. However, Fig. 4 shows that although the depressed region offer high resistance to corrosion, it is still possible for these regions to undergo corrosion. [6] opines that the corrosion current density can be classified into different groups for different ranges of the degree of corrosion. These ranges are as follows;

i low corrosion (I_{corr}< 0.1µA/cm^2)
ii medium corrosion (I_{corr}= 0.1µA/cm^2)
iii high corrosion (I_{corr}> 0.1µA/cm^2).

The result of the corrosion current density (I_{corr}), obtained from the study is shown in table 4.3. The sample gave corrosion current density value of 7.44 µA/cm^2.This indicates that the depressed regions of the aluminium step tile roofing sheets are susceptible to high degree of corrosion.

Going by the value obtained in corrosion penetration rate, it can be stated that at the penetration speed of 0.081 mm/y, it would take a minimum of 12 years for a 1mm thick aluminium roofing sheet to corrode along the depressed regions.

5. CONCLUSION

The corrosion susceptibility of aluminium step tile roofing sheets has been successfully investigated in this present work.

Step tile aluminium roofing sheets are exposed to the three conditions that necessitate the occurrence of SCC. These conditions are: The tensile stresses as a result of residual stresses from the manufacturing process; a susceptible alloy and a humid or water environment. The tensile stress initiates the propagation of the cracks. These cracks are often not visible, and there is rarely macroscopic evidence of mechanical deformation of the bulk material, SCC failures are liable to occur without warning. This study investigated the susceptibility of the depressed regions of a step-tile aluminium roofing sheet to corrosion. The linear polarization method was adopted in this study.

The results obtained from this work indicated that the depressed regions of the aluminium roofing sheets are highly susceptible to corrosion. Result from the corrosion penetration rate confirms that corrosion in this region could begin at a minimum of twelve years of in-service condition. However, failure/corrosion before this time could occur probably due to Microbiological Induced Corrosion (MIC) caused by breeding activities of algae, mosses, etc.

6. Recommendation

In order to mitigate the effect of the induced stresses (internal stresses) on the aluminium sheets occasioned by differential deformation during cold working operation, the study recommends that the shingles should be heat treated before been dispatched for installation. Stress relief annealing heat treatment techniques could be employed so as to attain complete recovery from grain distortions and dislocations associated with the actions of the die on the shingles. This would help reinforce the lattice structure of the aluminium, thereby reducing the chances of SCC occurring.

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