MATERIAL SELECTION AND CORROSION ASSESSMENT OF GALVANIZED ROOFING SHEET: POTENTIODYNAMIC INVESTIGATION, MATHEMATICAL MODELING AND SIMULATION

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ABSTRACT

Galvanised roofing sheet is widely used in the construction and building industry. However, the challenge caused by corrosion under service failure has led to this present work. This study presents the experimental investigation and simulated prediction of the selective material in 3.5 % NaCl condition. The corrosion resistance properties were examined using the potentiodynamic polarization technique and COMSOL. The mathematical modeling and simulation analyzed when done with model geometry in a single electrolyte domain and predicted for 1, 6 and 12 months for a sample labeled A-E. The results show that sample C provide lower corrosion deformation among all sample under investigation with R_p of 234.24 Ω , and C_R of 0.51052 mm/y and corr value of -1.2837 (V) compare to sample A with higher corrosion rate of 2.9085 mm/yr and corr of -1.489 (V).

Keywords: Materials, Simulation, Degradation, Polarization, Corrosion, Galvanized.

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INTRODUCTION

The perverse nature and the trend of degradation of roofing sheets with galvanized steel is a global interest owing to its application to housing and construction demand.¹ In an attempt for the steel to return to its natural state due to environmental activities become a ceaseless concern. An environmental factor that arises from corrosion induces mechanisms like moisture, humidity, rainwater, climate change etc posed quick metal degradation and failure to galvanized steel in service.^{2,3} Corrosion challenge is a global concern and it shortens metal lifespan especially with surfaces that are exposed to the harsh condition.⁴ Corrosion condition with this harsh situation comes in various forms like thermal instability, ionic exchange, and chemical interaction, precipitation of corrosion products called white rust and temperature activities.⁵ With an increasing method to curtail the corrosion product present at the steel interface, numerous researches to develop protection as surface-active technology has been exploring. Such a method involves among others electroplating, a hot dipping process, flame retardant coating, cold spray and electroless coating.⁶⁻⁸ Zinc galvanized steel has been prominent in recent times due to its application in exterior roofing construction purposes.⁹⁻¹² It has resilient mechanical properties, ease in fabrication, lower-cost implication, and practical technology in terms of reproducibility in quantities.¹³⁻¹⁶ Production of several grades of zinc galvanized steel is numerous in demand due to its application and ease in manufacturing against other protective coatings.¹⁷⁻¹⁹ Also, the ease in the manufacturing process is done by both local professional and industrial experts especially in the developing nations where the demand for local and low-cost housing are required.²⁰⁻²² For instance, Nigeria in particular has close to ten brands of this zinc galvanized steel from prominent dealers and manufacturing industries.²¹⁻²³ The quality of this corrugated galvanized steel produced in Nigeria which is subjected to the same control corrosion condition is seen to differs in response, resulting in the accelerated failure in service.²² Different perspectives and the assumption by users of this steel, engineer and building expert has provided notion and reason for the investigation of this study, that is, the effectiveness of the produce zinc galvanized steel

that could retard corrosion failure.²²⁻²⁴ This becomes an essential need to evaluate the trend of corrosion damage from the selected Galvanized steel roofing sheet to reduce incensing failure and continuous cost of replacement. Thus, this study aimed to optimize the performance behavior of galvanized roofing steel sheets in simulated 3.5 % NaCl through experimentation and mathematical modeling.

EXPERIMENTAL

Preparation of Galvanized Roofing Steel Sheet Samples Used For Various Tests

The Galvanized roofing steel sheet samples used for this paper are five (5) with the same corrugation number of eight (8) and branded gauge of 0.15 mm. The roofing sheets were cut into a test piece for electrochemical and mechanical test.¹² The samples used for the electrochemical test were of dimension (20x20) mm while those for the mechanical test had corrugation number of two (2) and dimension (160x280) mm. The zinc coating mass or weight is carried out using a galvanized steel sheet of (50x50) mm and 50 % HCl as the stripping or de-coating medium. Samples used for the bending test have a width of 80 mm and length of 160 mm.

Electrochemical Testing of the Galvanized Roofing Steel Sheet Samples

The corrosion tests were carried out using 3.5 % NaCl, as the test mediums following G3/G102 standard practice for electrochemical measurement using the three-electrode system with AUTOLAB potentiostat and NOVA software install in a computer system as shown in Fig.-2 The galvanized roofing sheet steel samples acted as the working electrode, the graphite rod acted as the counter electrode while the glass body calomel containing potassium chloride serves as the reference electrode. The experiment was carried out between the voltage of -1.5 V and 1.5 V at a scan rate of 0.01 m/s and step of 0.0025. This experiment gave the prediction of the OCP (Open circuit potential), the corrosion rate in millimeters per year, the corrosion current density, the corrosion potential and the polarization resistance of the test samples.

Mechanical Modelling and Simulation

The model geometry is shown in Fig.-1 One single electrolyte domain is used, the electrolyte used is sodium chloride (NaCl).³⁻⁷ The left part of the bottom boundary is the surface of the mild steel material, the right part is the corroding zinc alloy, the width of the mild steel and the corroding zinc was varied. The width of the mild steel and zinc alloy were also used as thickness for the electrolyte to study the variation of corrosion rate with the thickness of the electrolyte. Because the alloy will corrode in the model, the right boundary is displaced downwards in the geometry. A small step of height (width + 50mm) is introduced at origin; in the negative y direction is introduced in the geometry to ensure that the topology of the geometry is preserved during the simulation. The vertical boundary of the step belongs to the steel surface.

Fig.-1: Geometry for the Model

The electrolyte was well mixed so that a secondary current distribution can be assumed, solving for the electrolyte potential, ϕ_1 (V), in the domain. The electrolyte conductivity is set to 5 s/m for sodium chloride. The equilibrium (corrosion) potential of mild steel was set to the experimental values and -1.55 V (SCE) is set for the zinc alloy surfaces. This implies that the mild steel acts as a cathode for this galvanic couple, and a cathodic Tafel expression is used to describe the kinetics of the reaction:

$$i_{cat} = i_{0,cat} \cdot 10^{\eta/A_{cat}} \quad (1)$$

Where, $i_{0,cat}$ is the exchange current density (A/m^2) which was assigned to respective roofing sheet samples A, B, C, D and E based on experimental analysis as shown in Table-3.

$A_{cat} = -160mV$ is the Tafel slope. The overpotential, η (V), of an electrode is generally defined as-

$$\eta = \phi_s - \phi_1 - E_{eq} \quad (2)$$

Where, ϕ_s and ϕ_1 are the potentials in the electrode (metal) and electrolyte, respectively, and E_{eq} is the equilibrium potential. For the cathode, different values of equilibrium potentials ($E_{eq,cat}$) were assigned to different samples of roofing sheets labelled A, B, C, D and E based on experimental studies.

The zinc alloy here is the anode of the galvanic couple, oxidizing magnesium according to:

To describe the measured polarization data for this reaction, diffusion-limited anodic Tafel expression for the anodic electrode reaction current, i_{an} (A/m^2) was used.

$$i_{tafel} = i_{0,an} \cdot 10^{\frac{\eta}{A_{an}}} \quad (4)$$

$$i_{an} = \frac{i_{lim}}{1 + \frac{i_{lim}}{i_{tafel}}} \quad (5)$$

Where, $i_{0,an} = 10^{-1} A/m^2$, $A_{an} = 50 mV$, and $i_{lim} = 10^2 A/m^2$ is a limiting current. The equilibrium potential for this reaction was set to $-1.55 V$.

This type of expression can be derived from the assumption of a Nernstian diffusion layer in combination with a first-order dependence of a concentration on the kinetics. The dissolution of zinc metal causes the electrode boundary to move, with a velocity in the normal direction, v (m/s), according to

$$v = \frac{i}{2F} \frac{M}{\rho} \quad (6)$$

Where M is the mean molar mass ($65.38 g/mol$) and ρ is the density ($7.13 g/cm^3$) of the zinc alloy. The model was solved using a time-dependent study, corrosion was simulated during the first 1 month followed by 6 months and 12months respectively after immersion in NaCl. The corrosion rate was calculated using the following relation (Perez, 2004).

$$V_c = \frac{I_{corr} \times M}{z \times F \times \rho} \quad (7)$$

Where, V_c is the corrosion rate (cm/yr), I_{corr} is the corrosion current density (A/cm^2), M is the molar mass $M(Zn) = 65.38 g/mol$, z is the valence of iron $z = 2$, F is the faraday constant $F = 96500 A \cdot s/mol$, and ρ is the density of steel $\rho = 7.87 g/cm^3$. The value of I_{corr} was extracted from COMSOL which was imported into an Excel spreadsheet for further calculations and plotting of data. The data extracted was only for the zinc (anode) because the corrosion takes place at the anode.

RESULTS AND DISCUSSION

Corrosive Effect of 3.5 % NaCl on the Galvanized Roofing Steel Sheet Samples

The potential polarization data of the galvanized roofing steel sheets are presented in Table-1 and the current curves are represented in Fig.-2. Sample C exhibits the lowest corrosion density of $4.39E-05 A/cm^2$ and the highest polarization resistance. This shows that the exchange of current in the site of the sample was minimal compared to other samples. Sample A has the highest corrosion current density of $2.50E-04 A/cm^2$ which indicates that more chloride ion was able to penetrate the zinc coating compared to other samples. Similarly, Fig.-3 indicates that sample C exhibits the highest corrosion rate among the test samples with a value of $0.51052 (mm/year)$ which shows that this sample will stand a test of time in this corrosive medium over years compared to other samples.

OCP Analysis of the Galvanized Roofing Steel Sheet Samples in 3.5 % NaCl

Figure-4 shows the OCP vs. Time graphs of the galvanized roofing steel sheets samples in 3.5 % NaCl. The OCP is the open circuit potential which is also known to be the steady-state potential of the samples. Comparing the curves in Fig.-4 to the polarization curves in Fig.-2 and Table-1, the potentials (OCP) of

each sample was found to have shifted to more negative values after the polarization experiment. The OCP or the steady-state potentials of the samples were between -1.15 V and -1.2 V.

Table-1: Polarization Data of Galvanized Roofing Steel Sheets Samples in 3.5 % NaCl

SAMPLES	E _{corr} (V)	j _{corr} (A/cm ²)	CR	PR
			(mm/year)	(Ω)
A	-1.489	2.50E-04	2.9085	29.314
B	-1.4747	1.66E-04	1.9267	22.204
C	-1.2837	4.39E-05	0.51052	234.24
D	-1.4819	1.51E-04	1.7568	23.95
E	-1.4388	1.07E-04	1.2404	28.75

Fig.-2: Polarization Curves of Galvanized Roofing Steel Sheets Samples in 3.5 % NaCl

Fig.-3: Corrosion Rates of Galvanized Roofing Steel Sheets Samples in 3.5 % NaCl

The E_{corr} values were more negative compared to the OCP values, indicating that the galvanized roofing steel sheets samples were negatively or cathodically polarized. More so, the OCP curves were close to being straight between 60 and 100 seconds which shows that the steady-state potential was reached within these times.

Fig.-4: OCP Vs Time Graphs of Galvanized Roofing Steel Sheets Samples in 3.5 % NaCl

Electrolyte Potential

The resulting potential distribution of Sample A in the sodium chloride electrolyte after one month is shown in Fig.-5.

Fig.-5: Deformation of Sample A after one month in NaCl (Sodium chloride) Electrolyte

Figure-5 shows the current and potential distribution in the electrolyte and the changed geometry at the end of the simulation after immersing sample A in the sodium chloride acid for one month. Because the electrode currents are highest at the contact point of the metals, the metal dissolution is highest at this point.⁵⁻⁸ The cathode (mild steel) and the anode (zinc alloy) has a contact at distance zero on the plot, the deformation takes place at this contact point which is between distance 0 and 500mm when sample A is immersed in sodium chloride acid for one month. The electrolyte potential increases from 1.0725 to 1.7049V with the lowest values at the cathode (mild steel) and the highest values at the anode (zinc). The intermediate electrolyte values fall within the contact of the two electrodes.

Figure-6 shows the electrolyte distribution for Sample A in sodium chloride acid after six months, the cathode (mild steel) and the anode (zinc alloy) has a contact at distance zero on the plot, the deformation takes place at the contact point between distance 0 and 1000mm when sample A is immersed in sodium chloride acid for six months. The electrolyte potential increases from 1.0719 to 1.7047V with the lowest values at the cathode (mid steel) and the highest values at the anode (zinc).

Figure-7 shows the electrolyte distribution for Sample A in sodium chloride acid after twelve months, the cathode (mild steel) and the anode (zinc alloy) has a contact at distance zero on the plot, the deformation takes place at the contact point between distance 0 and 1000mm when sample A is immersed in sodium chloride acid for twelve months, the deformation is more pronounced when compared with Figs.-5 and 6.

The electrolyte potential increases from 1.0711 to 1.7043V with the lowest values at the cathode (mid steel) and the highest values at the anode (zinc). Figures-5 to 7 confirmed that the deformation of sample A increases with time when immersed in sodium chloride acid electrolyte which is expected.

Fig.-6: Deformation of Sample A after six months in NaCl (Sodium chloride) Electrolyte

Fig.-7: Deformation of Sample A after twelve months in NaCl (Sodium chloride) Electrolyte

Figure-8 shows the electrode currents at the beginning and end of the simulation of Sample A immersed in sodium chloride acid for one month, as expected the highest current density (85A/m²) is found at the contact point between the cathode and the anode. The current densities at the beginning and end of the simulation are very close. The current density decreases towards the end of the anode (zinc). Figure-9 shows the electrode currents at the beginning and end of the simulation of Sample A immersed in sodium chloride acid for six months, the changes in current densities at the beginning and end of the simulation of Sample A for six months in sodium chloride acid is more pronounced when compared with Fig.-10. Figure-10 shows the electrode currents at the beginning and end of the simulation of Sample A immersed

in sodium chloride acid for twelve months. The changes in the current densities at the beginning and end of the simulation of Sample A for twelve months in sodium chloride acid is more pronounced when compared with the changes for one month (Fig.-8) and six months (Fig.-9), this depicts that the deviation in the current density increases with time.

Fig.-8: Electrode Current Densities at t = 0 and t = 1 month for Sample A in Sodium chloride Electrolyte

Fig.-9: Electrode Current Densities at t = 0 and t = 6 months for Sample A in Sodium chloride Electrolyte

Fig.-10: Electrode Current Densities at t = 0 and t = 12 months for Sample A in Sodium chloride Electrolyte

The resulting potential distribution of Sample B in the Hydrogen Chloride electrolyte after one month is shown in Fig.-11.

Fig.-11 Deformation of Sample B after one month in NaCl (Sodium chloride) Electrolyte

Figure-11 shows the current and potential distribution in the electrolyte and the changed geometry at the end of the simulation after immersing sample B in the sodium chloride acid for one month. Because the electrode currents are highest at the contact point of the metals, the metal dissolution is highest at this point. The cathode (mild steel) and the anode (zinc alloy) has a contact at distance zero on the plot, the deformation takes place at this contact point which is between distance 0 and 500mm when sample B is immersed in sodium chloride acid for one month. The electrolyte potential increases from 1.3896 to 1.719V with the lowest values at the cathode (mild steel) and the highest values at the anode (zinc). The intermediate electrolyte values fall within the contact of the two electrodes. Figure-12 shows the electrolyte distribution for Sample B in sodium chloride acid after six months, the cathode (mild steel) and the anode (zinc alloy) has a contact at distance zero on the plot, the deformation takes place at the contact point between distance 0 and 1000mm when sample B is immersed in Hydrochloric acid for six months. The electrolyte potential increases from 1.3894 to 1.7189V with the lowest values at the cathode (mid steel) and the highest values at the anode (zinc).

Fig.-12: Deformation of Sample B after six months in NaCl (Sodium chloride) Electrolyte

Figure-13 shows the electrolyte distribution for Sample B in sodium chloride acid after twelve months, the cathode (mild steel) and the anode (zinc alloy) has a contact at distance zero on the plot, the deformation takes place at the contact point between distance 0 and 1000mm when sample B is immersed in sodium chloride acid for twelve months, the deformation is more pronounced when compared with Figs.-11 and 12. The electrolyte potential increases from 1.3891 to 1.7188V with the lowest values at the cathode (mid steel) and the highest values at the anode (zinc). Figures-11 to 13 confirmed that the deformation of sample B increases with time when immersed in sodium chloride acid electrolyte which is expected.

Fig.-13: Deformation of Sample B after twelve months in NaCl (Sodium chloride) Electrolyte

The resulting potential distribution of Sample C in the sodium chloride electrolyte after one month is shown in Fig.-14.

Fig.-14: Deformation of Sample C after one month in NaCl (Sodium chloride) Electrolyte

Figure-14 shows the current and potential distribution in the electrolyte and the changed geometry at the end of the simulation after immersing sample C in the sodium chloride acid for one month. Because the electrode currents are highest at the contact point of the metals, the metal dissolution is highest at this point. The cathode (mild steel) and the anode (zinc alloy) has a contact at distance zero on the plot, the deformation takes place at this contact point which is between distance 0 and 500mm when sample C is immersed in sodium chloride acid for one month. The electrolyte potential increases from 1.3037 to

1.7142V with the lowest values at the cathode (mild steel) and the highest values at the anode (zinc). The intermediate electrolyte values fall within the contact of the two electrodes. Figure-15 shows the electrolyte distribution for Sample C in sodium chloride acid after six months, the cathode (mild steel) and the anode (zinc alloy) has a contact at distance zero on the plot, the deformation takes place at the contact point between distance 0 and 1000mm when sample C is immersed in Hydrochloric acid for six months. The electrolyte potential increases from 1.3034 to 1.7141V with the lowest values at the cathode (mid steel) and the highest values at the anode (zinc).

Fig.-15: Deformation of Sample C after six months in NaCl (Sodium chloride) Electrolyte

Figure-16 shows the electrolyte distribution for Sample C in sodium chloride acid after twelve months, the cathode (mild steel) and the anode (zinc alloy) has a contact at distance zero on the plot, the deformation takes place at the contact point between distance 0 and 1000mm when sample C is immersed in sodium chloride acid for twelve months, the deformation is more pronounced when compared with Figures-14 and 15. The electrolyte potential increases from 1.303 to 1.7931V with the lowest values at the cathode (mid steel) and the highest values at the anode (zinc). Figures 14 -16 confirmed that the deformation of sample A increases with time when immersed in hydrochloric acid electrolyte which is expected.

Fig.-16: Deformation of Sample C after twelve months in NaCl (Sodium chloride) Electrolyte

Figure-17 shows the current and potential distribution in the electrolyte and the changed geometry at the end of the simulation after immersing sample D in the sodium chloride acid for one month. Because the electrode currents are highest at the contact point of the metals, the metal dissolution is highest at this point. The cathode (mild steel) and the anode (zinc alloy) has a contact at distance zero on the plot, the

deformation takes place at this contact point which is between distance 0 and 500mm when sample D is immersed in sodium chloride for one month. The electrolyte potential increases from 1.4017 to 1.7196 V with the lowest values at the cathode (mild steel) and the highest values at the anode (zinc). The intermediate electrolyte values fall within the contact of the two electrodes. Figure-18 shows the electrolyte distribution for Sample D in sodium chloride acid after six months, the cathode (mild steel) and the anode (zinc alloy) has a contact at distance zero on the plot, the deformation takes place at the contact point between distance 0 and 1000mm when sample D is immersed in sodium chloride acid for six months. The electrolyte potential increases from 1.4015 to 1.7195V with the lowest values at the cathode (mid steel) and the highest values at the anode (zinc).

Fig.-17: Deformation of Sample D after one month in NaCl (Sodium chloride) Electrolyte

Fig.-18: Deformation of Sample D after six months in NaCl (Sodium chloride) Electrolyte

Figure-19 shows the electrolyte distribution for Sample D in sodium chloride acid after twelve months, the cathode (mild steel) and the anode (zinc alloy) has a contact at distance zero on the plot, the deformation takes place at the contact point between distance 0 and 1000 mm when sample D is immersed in sodium chloride acid for twelve months, the deformation is more pronounced when compared with Figs.-17 and 18. The electrolyte potential increases from 1.4013 to 1.7194 V with the lowest values at the cathode (mid steel) and the highest values at the anode (zinc). Figures-17 to 19

confirmed that the deformation of sample D increases with time when immersed in sodium chloride acid electrolyte which is expected.

Fig.-19: Deformation of Sample D after twelve months in NaCl (Sodium chloride) Electrolyte

Fig.-20: Deformation of Sample E after one month in NaCl (Sodium chloride) Electrolyte

Fig.-21: Deformation of Sample E after six months in NaCl (Sodium chloride) Electrolyte

The resulting potential distribution of Sample E in the sodium chloride electrolyte after one month is shown in Fig.-20. Figure-22 shows the electrolyte distribution for Sample E in sodium chloride acid after twelve months, the cathode (mild steel) and the anode (zinc alloy) has a contact at distance zero on the plot, the deformation takes place at the contact point between distance 0 and 1000mm when sample E is immersed in Hydrochloric acid for twelve months, the deformation is more pronounced when compared with Figs.-20 and 21. The electrolyte potential increases from 1.3839 to 1.7187 V with the lowest values at the cathode (mid steel) and the highest values at the anode (zinc). Figures-20 to 22 confirmed that the deformation of sample E increases with time when immersed in sodium chloride acid electrolyte which is expected.

Fig.-22: Deformation of Sample E after twelve months in NaCl (Sodium chloride) Electrolyte

CONCLUSION

Galvanized steel is effective for a wide range of applications in various manufacturing companies. Galvanized steel roofing sheet which has in several years been produced by the continuous hot-dip coating process as a result of the flexibility of the techniques is still very much in vogue. The choice of Galvanized roofing sheet is borne out of its ruggedness and longevity. When steel is not properly galvanized it will corrode within a short period, which will directly or indirectly affect the economy of a nation.

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