

ELECTROCHEMICAL CORROSION INHIBITION OF COBALT-GRAPHENE NANO-COMPOSITE ON MILD STEEL IN ACIDIC CORROSION ENVIRONMENT

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ARTICLE HISTORY:

Received: 12 September, 2023.

Revised: 24 February, 2024.

Accepted: 26 February, 2024.

Published: 12 June, 2024.

KEYWORDS:

Corrosion, Cobalt, Graphene, Inhibitor, Nanocomposites, Nanomaterials.

ARTICLE INCLUDES:

Peer review

DATA AVAILABILITY:

On request from author(s)

EDITORS:

Patrick Akpan

FUNDING:

None

Abstract

There is a continuous need for effective corrosion control materials and the recent advances in nanotechnology show that nanomaterials can play significant roles in corrosion control. Graphene nanoparticles are a well-known nanomaterial and have been employed in various functions including corrosion control. The electrochemical investigation was conducted to ascertain the inhibition efficiency of cobalt graphene nanocomposite. Coupon preparation involved marking out different 30 x 30 mm² mild steel coupons that were subjected to corrosion in an acidic environment. Three different compositions of the composite used for the study includes 0.70 weight (wt)% cobalt /0.30 weight (wt)%, graphene, 0.55 weight (wt)% cobalt /0.45 weight (wt)%, graphene, 0.85 weight (wt)% cobalt /0.15 weight (wt)%, graphene respectively. The corrosion tests were open circuit potential and linear sweep Voltammetry. Characterization was done using Scanning Electron Microscope (SEM), The chemical characteristics of the inhibitor were achieved using Energy dispersive X-ray, Spectroscopy EDX, Parameters used for the corrosion analysis are corrosion rate, polarization resistance, and electric potentials analysis. It was observed that the composite with 0.85 weight% cobalt and 0.15 weight% graphene exhibited the best anti-corrosion property with the best inhibitor efficiency at a concentration of 0.4 grams. The addition of graphene nanoparticles improved the mechanical properties of the composite's microstructure." The synthesized nanocomposite can be applied for corrosion control either as an inhibitor or as a coating. The nanocomposite, cobalt-graphene was therefore proven to be a good anti-corrosion material at a low concentration of graphene. This is an improvement in corrosion resistance and it is believed to serve as a good coating due to its adsorption properties.

1.0 INTRODUCTION

Cobalt-graphene nanocomposite materials are said to possess both mechanical and tribological properties concurrently. While cobalt exhibits desirable properties for anti-corrosion applications, including high wear resistance, a high melting point, low toxicity, low friction, and good corrosion resistance at elevated temperatures, it is often underutilized in its pure form due to cost considerations, its relative abundance, and the lower cost of its sister metal, nickel. However, recent research has unveiled a promising avenue: cobalt can be effectively used as a composite with practical reinforcement and may offer a viable alternative to nickel and chromium for corrosion control. This innovative approach often involves the incorporation of graphene, a

HOW TO CITE:

Ashibudike, O. E., Iweriolor, S., and Oreko, B. U. "Electrochemical Corrosion Inhibition of Cobalt-Graphene Nano-Composite on Mild Steel in Acidic Corrosion Environment", *Nigerian Journal of Technology*, 2024; 43(2), pp. 261 – 271; <https://doi.org/10.4314/njt.v43i2.9>

nanomaterial renowned for its remarkable properties." [1,2].

Even though cobalt possesses desirable properties for anticorrosion functions, its underutilization in its pure form is primarily due to cost considerations, its relative abundance, and the lower cost of its sister metal. However, today researches have proven that it can be used as composite with practicable reinforcement and can show replacement for Nickel and chromium in corrosion resistance. One of these astonishing reinforcements is graphene which possesses remarkable mechanical properties like high resistance to wears and tears, corrosion, etc, hence producing an affordable composite with improved properties when combined with cobalt. Graphene has high surface to volume ratio which makes it suitable for dispersed nanoparticles[3]. The question of the optimum percentage of graphene in the composite has been a topic of concern and represents a major research gap that this study seeks to address, forming the core objective of our research interest.

Corrosion in mild steel can lead to structural degradation, reduced durability, and potential failures, making it crucial to understand the underlying mechanisms and factors influencing the corrosion process [4]. Graphene also possesses desirable properties for corrosion control [5]. Its unique features include remarkable mechanical strength, unusual electrical properties, very tiny thickness, solid lubricant, high wear and corrosion resistance [6,7,8]. Graphene as a nanomaterial is positioned in two-dimensional layers of carbon atoms having the hexagonal lattice structure and sp^2 hybridization [9,10]. It is a new material which originated from sp^2 hybridized carbon atoms. Graphene is therefore considered as a desirable potential reinforcement for most composite coatings [11]. Findings have proven that the incorporation of graphene particles into a composite reduces the coefficient of friction of the composite and hence enhances its corrosion resistance[17, 18]. And this is why it can be housed in a cobalt matrix to produce a better corrosion inhibition material. Even when incorporated in alloy metals on welded joints, graphene also improved the tensile strength and the general mechanical properties of the joint[12]. This demonstrates the significant impact that graphene can have when combined with metals, whether as composites or alloys, offering the potential for enhanced corrosion resistance.

In prior investigations, The wear and corrosion behaviour of a coating made up of cobalt and graphene oxide nanoparticles have been studied in the context

of corrosion control. For instance, Liu et al. [13] conducted an extensive study on the wear and corrosion behavior of a coating comprising cobalt and graphene oxide nanoparticles. This study demonstrated the potential of graphene nanoparticles to enhance corrosion resistance by preventing the corrosive medium from penetrating the coating. Furthermore, the addition of these nanoparticles refined the grains, increased hardness and wear resistance, and introduced a lubricating property within the coating, leading to a reduction in the coefficient of friction [14,15,16].

Another notable research effort centered on cobalt-graphene composites and pure cobalt coatings fabricated through electro-deposition on a steel substrate. The scanning electron microscope (SEM) analysis revealed an even distribution of graphene particles within the cobalt matrix, with the structural morphology of the cobalt-graphene composite coating being finer than that of the pure cobalt film. The wear behavior tests indicated that both the cobalt composite and pure cobalt coating outperformed the ordinary steel substrate [17, 18]. Importantly, the incorporation of graphene particles in the cobalt coating reduced both the total volume of material loss and the friction coefficient of the cobalt film [19,20,21,22].

Graphene nanocomposite has also been developed with other metal matrices like zinc. The works of Salih et al [23] developed graphene oxide/zinc oxide nanocomposite for electrochemical analysis and it was observed that the composite showed a significant improvement in both electrocatalytic and electrical conductivity measured from the cyclic voltammeter. In 2020, graphene was successfully inserted as a nano filler into the cobalt matrix, however, an optimum percentage composition of the composite constituents to produce a composite with a perfect corrosion resistance was not established. While the presence of graphene nano-platelets in metal matrix will improve the corrosion resistance, hardness, and wear resistance of the composite formed from it, the core challenge with the insertion of graphene in metal matrix is the decision on the appropriate percentage of graphene in the composite that can produce the best corrosion resistance ability. Graphene added to metal matrix composite exceeding a certain threshold may have a negative impact on the tribological and mechanical property of the composite [24].

Building upon the insights gained from previous studies on graphene's role in corrosion resistance, this research seeks to address a significant gap in our understanding of the determination of the optimal



composition of cobalt-graphene nanocomposites for superior corrosion resistance. Specifically, the study aims to evaluate the effectiveness of cobalt acetate graphene nano-composites as anti-corrosion materials in the context of severe acidic corrosion, with the ultimate goal of providing valuable recommendations for their practical.

2.0 MATERIALS AND METHODS

The materials used for this experiment include; the inhibitor (the cobalt graphene nanocomposite), the acidic corroding medium (Concentrated Hydrochloric acid), the electrochemical corrosion set up, coupon made from mild steel, ethanol and acetone for washing and cleaning, abrasive for etching and measuring scale.

2.1 Preparation of the Inhibitor (Cobalt-Graphene Nanocomposite)

Three different compositions for the composite were synthesised and used as inhibitors for the analysis. The synthesis of the cobalt-graphene nano-composite involved first the reduction of graphene oxide to graphene and then the combination with cobalt as explained below.

2.1.1 Synthesis of cobalt-graphene nanocomposite (70/30wt%)

1.2g of graphene oxide was mixed with 200ml of the plant extract and stirred in a mechanical magnetic stirrer for 3 hours to reduce the graphene oxide to graphene. The solution was covered with aluminium foil before stirring. Then 2.8g of cobalt nanoparticles was added into the solution and stirred for four hours at 70°C. The solution was allowed to cool to room temperature while still being covered with aluminium foil. The resultant solution was filtered and the obtained product was dried in a laboratory oven. The dried product is the cobalt-graphene nanocomposite and it was collected and stored in a sample bottle. The obtained nanocomposite is a composite composition of 70% cobalt and 30% graphene.

2.1.2 Synthesis of cobalt-graphene nanocomposite (55/45wt%)

0.45g of graphene oxide was mixed with 80ml of the plant extract and stirred in a mechanical magnetic stirrer for 3 hours to reduce the graphene oxide to graphene. The solution was covered with aluminium foil before stirring. Then 0.55g of cobalt nanoparticles was added and the solution was stirred for 4 hours at 70°C. The solution was allowed to cool to room temperature while still being covered with aluminium foil. The resultant solution was later filtered and the obtained product was dried in a laboratory oven. The

dried product is the cobalt-graphene nano-composite and it was collected and stored in a sample bottle. The obtained nanocomposite is a composite composition of 85% cobalt and 15% graphene.

2.1.3 Synthesis of cobalt-graphene nanocomposite (85/15wt%)

0.15g of graphene oxide was mixed with 75ml of the plant extract and stirred in a mechanical magnetic stirrer for 3 hours to reduce the graphene oxide to graphene. The solution was covered with aluminium foil before stirring. Then 0.85g of cobalt nanoparticles was added and the solution was stirred for 4 hours at 70°C. The solution was allowed to cool to room temperature while still being covered with aluminium foil. The resultant solution was later filtered and the obtained product was dried in a laboratory oven. The dried product is the cobalt-graphene nanocomposite and it was collected and stored in a sample bottle. The obtained nanocomposite is a composite composition of 85% cobalt and 15% graphene.

2.2 Preparation of the Coupon

The coupon was prepared from mild steel plate of 99.166wt% iron, 0.150wt% carbon, 0.46wt% manganese, 0.17wt% silicon, 0.030wt% sulphur, 0.011wt% phosphorus, 0.009wt% nickel and 0.004wt% aluminium. Figure 1 showed the mild steel plate used for the study. It is a hot rolled steel plate gotten from Rizhao Steel Holding Group Co Limited China. The steel plate was later taken to the mechanical laboratory at the Federal University of Petroleum Resources, Effurun Nigeria where it was machined into the appropriate coupon sizes as shown in Figure 2.



Figure 1: Mild steel plate used to make the coupon

The preparation of the coupon involved marking out different 30 x 30 mm square sizes from the plate. Then each size was carefully cut and appropriately machined to obtain a smooth metal piece as shown in Figure 2. Then a very tiny hole was bored into the



metal piece as seen in Figure 3, where it could be suspended by a thread during corrosion test. It was later machined again to remove any extra metal part that may extract as a result of the drilling. They were subjected to chemical treatment to ensure proper degreasing and cleaning then later washed with ethanol and dried with acetone. The obtained metal piece is the coupon and it is stored in a dry environment to avoid being corroded before used.



Figure 2: Cutting of the steel plate into small coupon sizes



Figure 3: Drilling hole into the coupon

2.3 Preparation of the Acidic Corroding Environment

The environment used for this test was concentrated hydrochloric acid. The solution was 4.9M of hydrochloric acid. The gravimetric calculation of the solution was determined using Equation 1 and the required volume was calculated using Equation 2.

$$\text{Stock concentration } (C_1) = \frac{\text{specific gravity} \times \% \text{ Purity of acid} \times 10}{\text{molar mass of the acid}} \quad (1)$$

Where, Specific gravity of HCl = 1.18 g/cm³, % purity of HCl acid = 36%, Molar mass of acid = 36.46 g/mol.

$$\text{Stock concentration } (C_1) = \frac{1.18 \times 36 \times 10}{36.46}$$

$$\text{Stock concentration } (C_1) = 11.65\text{M}$$

Calculating for the required volume of stock

$$C_1V_1 = C_2V_2 \quad (2)$$

Where, C_1 = Concentration of the stock, C_2 = Required molarity of the acid (in this case 4.9), V_1 = Volume of stock solution needed to prepare the 4.9M acid and V_2 = Volume of acid required (1000 ml)

Therefore, from $C_1V_1 = C_2V_2$

$$V_1 = \frac{C_2 \times V_2}{C_1}$$

$$V_1 = \frac{4.9 \times 1000}{11.65}$$

$$V_1 = 420.6\text{ml.}$$

Hence 420.6ml of the acid stock was used to prepare 4.9M solution which was used as a strong acid corroding environment.

2.4 Inhibitor used

The inhibitor used for the experimental test is cobalt-graphene nanocomposite. The composite was prepared into various compositions to access their protection effectiveness so as to determine the best composition with optimum protection.

2.5 Electrochemical Corrosion Test

The electrochemical corrosion test was carried out at Istrifia Enterprise, Nigeria. The Autolab Nova software was used to read the Open Circuit Potential (OCP) and LSV data. The reference electrode was saturated in Ag/AgCl and the counter (auxiliary) electrode was platinum rod and then the working electrode was the metal to be tested. Two different concentrations (0.2g and 0.4g) of the cobalt graphene composite were tested each in 50ml of 4.9 molar concentration of Hydrochloric acid. The 0.2g solution was sample 2 and the 0.4g solution was sample 3 while sample 1 was control solution. The control solution had no composite (inhibitor) solution rather only the corroding environment (HCl). Each test was done for five minutes at a room temperature of 28°C at a scan rate of 0.1 mV/s and repeated thrice to obtain optimum results which were used to generate plots of OCP and LSV.

The corrosion test was done and the electrochemical analysis was also done and the current density (J_{corr}) and corrosion potential (E_{corr}) were measured from the corrosion test. Equations 3 and 4 were used to determine the corrosion rate and the inhibition efficiency. A good corrosion inhibitor is expected to have high inhibition efficiency even at low concentrations. Though its efficiency will increase as the concentration increases to a certain level.

$$CR = \frac{J_{corr}(E_w)}{nF\ell} \quad (\text{mm/yr}) \quad (3)$$

Where, J_{corr} is the current density measured in A/cm², E_w is the equivalent weight of the corroding specie (mild steel), ℓ is the density of the corroding specie (metal) measured in g/cm³, n is the number of



electrons present in the reaction, F is faraday's constant.

The efficiency of an inhibitor was calculated according to the following equation:

$$\text{Inhibitor Efficiency} = \frac{\text{CR uninhibited} - \text{CR inhibited}}{\text{CR uninhibited}} \times 100\% \quad (4)$$

Where, CR uninhibited is the corrosion rate of the uninhibited system. CR inhibited is the corrosion rate of inhibited system.

2.6 Characterisation of Materials

Characterisation was done to study the effect of the corrosion of the metal and most importantly the damage mechanism and the sustained cracks. The characterization was also done on the composite (which was used as the inhibitor) to study its basic properties and also to explain and relate these properties to its corrosion resistance performance on the metal. The characterisation done in this research include Scanning Electron Microscope and Energy Dispersive X-ray Spectroscopy.

2.7 Characterisation with Scanning Electron Microscope (SEM)

Scanning Electron Microscope was used to study the surface character of the samples both at micro and nanoscale. The surface of the sample to be examined was placed in a vacuum and bombarded with a finely focused beam of electron. These electron beams, then scanned over the surface of the specimen, penetrated the surface, interacted with the specimen hence lead to x-ray emission, electron backscattering and secondary electron emission and as well provided information about the topography of the sample. This then produced a high resolution and long depth of field images of the sample surface called micrograph which was used to explain the sample surface characteristics, the nature of the structure, flaws or cracks, contaminants or any corrosion products.

The samples were examined with a JEOL-JSM-7600F Scanning Electron Microscope interfaced with Energy Dispersive X-ray analysis system. At an accelerating voltage of 15kv, the SEM micrographs were obtained at system magnifications of 8000x, 9000x and 10000x.

2.8 Characterisation with Energy dispersive X-ray Spectroscopy

The energy dispersive x-ray spectroscopy was used to determine the chemical characteristics of the inhibitor sample. It showed the elements present and their compositions. It was obtained by the interaction of the X-ray and the sample. The sample was clamped into the system of SEM-EDX Analyser at an accelerating

voltage of 15kv. The spectra were obtained using JEOL-JSM-7600F SEM-EDX analyser.

3.0 RESULTS AND OBSERVATION

Results of the electrochemical analysis to evaluate the anti-corrosion property of the cobalt graphene nanocomposite are shown below. Open Circuit Potential (OCP) and Linear Sweep Voltammetry (LSV), analysis on corrosion comparison graphs tafel plots, scanning electron Microscope (SEM) and Energy Dispersive X-ray (EDX) were presented.

3.1 Electrochemical Analysis of Cobalt Graphene (0.7/0.3wt%)

Figures 4 and 5 are the the Open Circuit Potential (OCP) and Linear Sweep Voltammetry (LSV) analyses provide valuable insights into the corrosion resistance of the 0.7/0.3% wt cobalt-graphene composite inhibitor. The potential values observed here are consistent with findings in previous studies [25]. Our results indicate that, in the absence of an inhibitor (control sample1), the corrosion potential is significantly lower, signifying a higher susceptibility to corrosion. This aligns with the common understanding that inhibitors can elevate the corrosion potential and reduce susceptibility to corrosion [26].

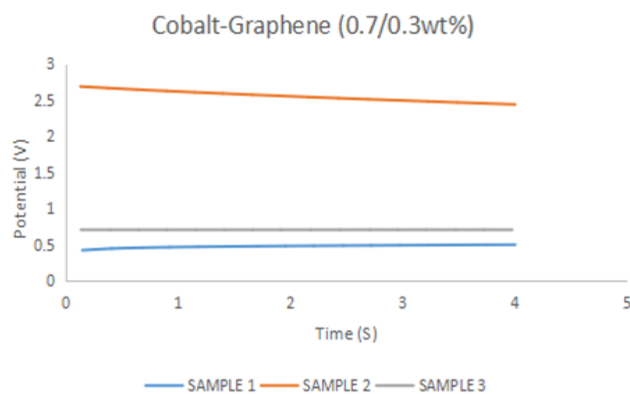


Figure 4: The open circuit potential graph for samples immersed in acid solution with cobalt-graphene

Sample 1 (control) had a potential below 0.5volts while Sample 2 and 3 have higher potentials. This shows that the sample without any inhibitor in the corroding medium was more susceptible to corrosion attack. Sample 2 had the highest potential at around 2.7volts across the periods. It contained 0.2g of the inhibitor in the corroding medium and exhibited a higher positive potential value and polarization resistance thus being less susceptible to corrosion. The graph line is almost linear showing that the corrosion mechanism in the environment at that particular period is homogenous. Figure 4 which can be likened to the shape of a building staircase showed that sample



2 with 0.2g of inhibitor allowed lower current density over potential. It displayed more passive features as the potential increases. At a higher potential, the Sample 1 (control) allowed more current density hence corrosion penetration.

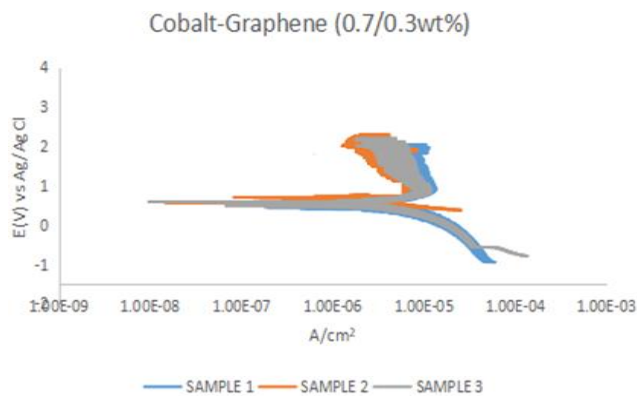


Figure 5: The linear sweep voltammetry graph for samples immersed in acid solution with cobalt-graphene

Tables 1 present parametric data for the corrosion analysis. Sample1 had no inhibitor hence had a higher current density with subsequent higher corrosion rate. However, it had a lower potential and polarization resistance. Sample 2 showed better corrosion property, it allowed lower current density and showed a higher polarization resistance and higher inhibitor efficiency. The corrosion property of this composite can be attributed to the effect of the phytochemicals present in it and its adsorption ability towards the metal.

Table 1: Corrosion data of cobalt-graphene (0.7/0.3wt%)

Samples	Inhibitor conc.(g)	E _{corr} (V)	J _{corr} (A/cm ²)	CR (mm/year)	PR (ohms)	Surface coverage	IE %	C/θ	θ/(1-θ)	log θ	logC
1	0	0.44306	5.6268E-06	0.065383	24.915	0					
2	0.2	0.57551	3.5630E-06	0.041402	32.789	0.3667	36.6777	0.5452	0.5792	-0.4355	-0.6989
3	0.4	0.48194	4.9207E-06	0.057178	26.242	0.1254	12.5491	3.1874	0.1434	-0.9013	-0.3979

Table 2: Corrosion data of cobalt-graphene (0.55/0.45wt%)

Samples	Inhibitor conc.(g)	E _{corr} (V)	J _{corr} (A/cm ²)	CR (mm/year)	PR (ohms)	Surface coverage	IE %	C/θ	θ/(1-θ)	log θ	logC
1	0	0.33229	5.63E-06	0.065383	16.354	0	0		0		
2	0.2	0.57551	3.54E-06	0.041181	24.915	0.3701	37.0157	0.5403	0.5876	-0.4316	-0.6989
3	0.4	0.69543	2.73E-06	0.031738	51.163	0.5145	51.4583	0.7773	1.0600	-0.2885	-0.3979

3.2 Electrochemical Analysis of Cobalt Graphene (0.55/0.45wt%)

Figure 6 and 7 below are Open Circuit Potential and Linear Sweep Voltammetry graph. For the 0.55/0.45wt% cobalt-graphene composite, the observed potential values follow the trend seen in similar research [27.28]. Sample 1, with no inhibitor, exhibits a lower potential and, therefore, higher corrosion susceptibility. However, the addition of the composite inhibitor (Sample 3) shows a substantial increase in corrosion resistance. This is consistent with the principle that inhibitors improve corrosion resistance, especially at higher concentrations.

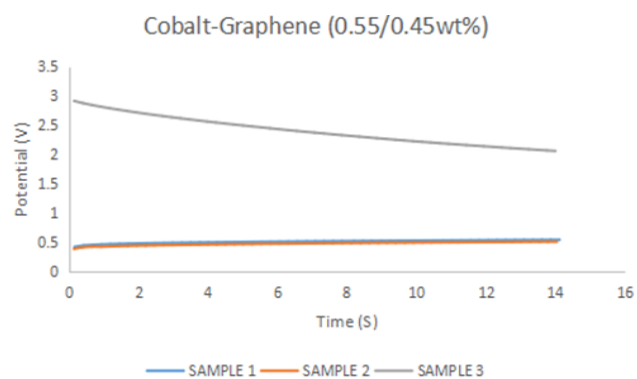


Figure 6: Open circuit potential graph for samples

immersed in acid solution with cobalt-graphene (0.55/0.45wt%) nanocompositeainhibitor

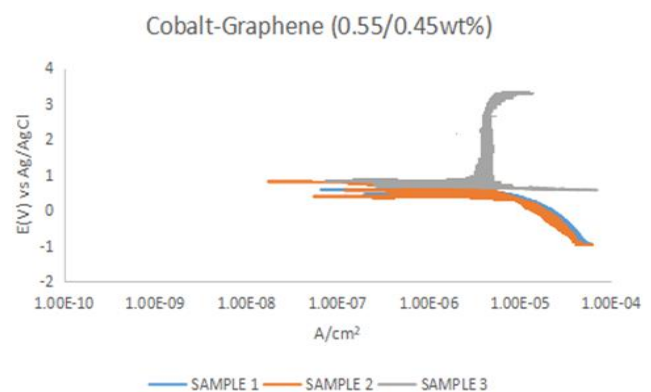


Figure 7: Linear sweep voltammetry graph for samples immersed in acid solution with cobalt-graphene (0.55/0.45wt%) nanocompositeas inhibitor

Figure 6 showed that Sample 1 and Sample 2 had much lower potential at around 0.4v for over a long period of time. Sample 3 displayed a higher potential at 2.7v at the beginning of the test and at around 2.4v after 14s, hence possessed more corrosion resistance with lower current density when compared to Samples 1 and 2. Therefore, it was proven that Sample 1 with no inhibitor showed far lower corrosion resistance

while Sample 3 which had a higher concentration of the composite inhibitor showed more corrosion resistance. This is in line with the standard that a good inhibitor increases its potency with increase in concentration.

Table 2 is the obtained data from the experimental and computational analysis of cobalt-graphene (0.55/0.45 wt%). Sample 1 had no inhibitor resulting in zero inhibitor concentration and exhibited a poor corrosion property. It had a lower potential and allowed more corrosion current density, lower polarization resistance (PR), hence higher corrosion rate. The best sample is the third sample where an inhibitor of 0.4g was added to the acid medium. It had a higher potential, allowed lower current density with higher polarization resistance hence lower corrosion rate. The polarization of this sample is 51.16Ω and it had an inhibitor efficiency of 51.45%. These are quite higher than those for other samples in this test.

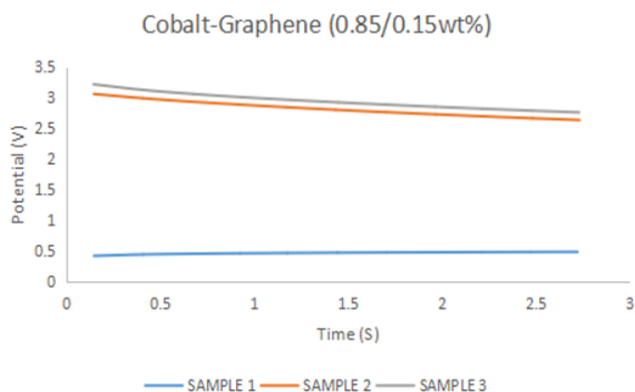


Figure 8: Open circuit potential graph for samples immersed in acid with cobalt-graphene (0.85/0.15wt%) nanocomposite inhibitor

3.3 Electrochemical Analysis of Cobalt Graphene (0.85/0.15wt%)

Figures 8 and 9 are Open Circuit Potential and Linear Sweep Voltammetry graph for the corrosion analysis of samples immersed in acid, with cobalt graphene nanocomposite (cobalt and graphene composite mixture ratio of 85% and 15% as the inhibitor). The Open Circuit Potential is a graph of potential against time when there is no current passage while the Linear Sweep Voltammetry is a graph of Potential against corrosion current density. The analysis of the 0.85/0.15wt% cobalt-graphene composite aligns with corrosion studies [29] and supports the idea that a higher concentration of the composite inhibitor is associated with better corrosion resistance. The noticeable increase in noble corrosion potential for sample 3 is in line with the typical behaviour of good inhibitors. This suggests that the inhibition efficiency

is enhanced at higher concentrations, a phenomenon documented in corrosion literature [30].

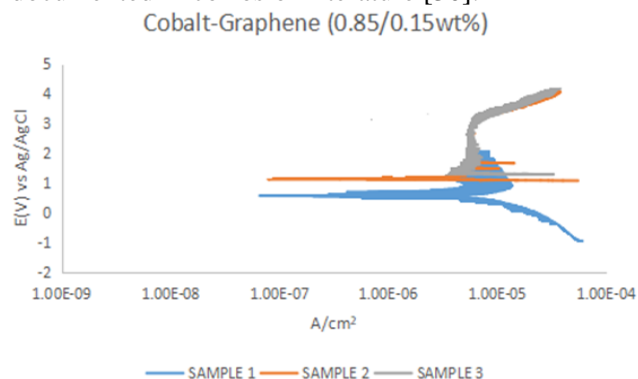


Figure 9: Linear sweep voltammetry graph for samples immersed in acid with cobalt-graphene (0.85/0.15wt%) nanocomposite inhibitor

From Table 3, it was observed that Sample 3 had the highest noble corrosion potential, lower corrosion rate, higher inhibitor efficiency, a very good polarization resistance (PR), and allowed lower corrosion current density. It was also observed that polarization resistances of Sample 3 was about twice that of sample 1 and it had a corrosion rate that was approximately thrice less than that of Sample 1. Since Sample 3 had 0.4g of the inhibitor, and sample 1 had no inhibitor, it therefore proves that this inhibitor is a good inhibitor for this case. A total comparison of the corrosion rate was done from the results of the three different concentrations (0.2 and 0.4g each in 50ml of 4.9M of hydrochloric acid).

Figure 10 gives an illustration of this comparison. It can be seen that at 0.2g of inhibitor, cobalt-graphene 0.85/0.15 showed a lower corrosion rate compared to that of cobalt-graphene 0.7/0.3 and 0.55/0.45 which were almost at the same level. At 0.4g of the inhibitor, the cobalt-graphene 0.85/0.15 also showed lower corrosion rate than others, though cobalt-graphene 0.55/0.45 showed a lower corrosion rate to that of 0.7/0.3. At this concentration, the cobalt-graphene 0.7/0.3 exhibited higher corrosion rate even higher than that for 0.2g.

This therefore confirms that cobalt-graphene with (cobalt being 0.7wt% and graphene being 0.3wt %) is not a good inhibitor. This is unlike that of cobalt-graphene (with cobalt being 0.85wt% and graphene being 0.15wt %) which has shown lower corrosion rate at the two levels and much lower corrosion rate at an increased concentration. It therefore means that nanocomposite of cobalt and graphene will exhibit a good corrosion resistance property if the composite mixture is most readily suitable [26].



From all the results it can be observed that the nanocomposite solution of cobalt 85% of the composite mixture and graphene 15% of the composite mixture had the best corrosion resistance property. This outstanding feature is attributed to cobalt being basically a passivating element to corrosion, but most importantly graphene at lower concentration in the composite contributed in the improvement of the composite corrosion and mechanical performance. This was so because the nano-sheet of the incorporated graphene created a thin film corrosion resistance layer along the cobalt pores which blocked the penetration of corrosion species and hence reduced the total area of the metal in contact with the corrosion solution. This is in agreement with the research reported on “cobalt-graphene electrode-sites: corrosion properties”. The addition of graphene did not only improve the corrosion property,

it also helped in the reduction of the material wear rate and improved other mechanical properties as well

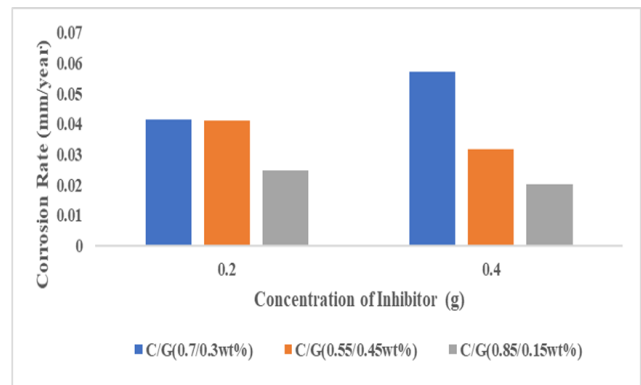


Figure 10: Comparison of the corrosion rate and inhibitor concentration

Table 3: Corrosion Data of Cobalt-Graphene (0.85/0.15wt%)

Samples	Inhibitor conc.(g)	E _{corr} (V)	J _{corr} (A/cm ²)	CR (mm/year)	PR (ohms)	Surface coverage	IE %	C/θ	θ/(1-θ)	log θ	log C
1	0	0.57551	5.63E-06	0.065383	24.915	0	0		0		
2	0.2	1.1375	2.14E-06	0.024866	77.97	0.6196	61.9687	0.3227	1.6294	-0.2078	-0.6989
3	0.4	1.3443	1.75E-06	0.02036	93.534	0.6886	68.8604	0.5808	2.2113	-0.1620	-0.3979

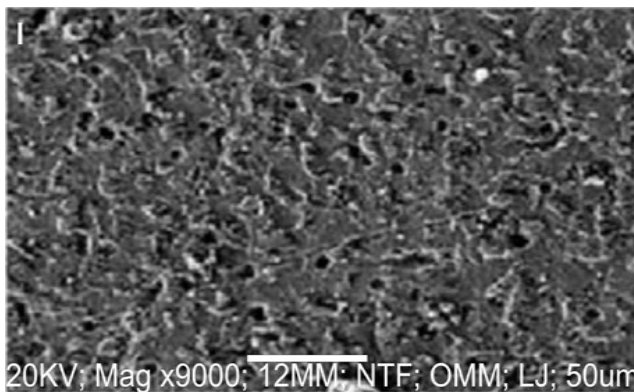


Figure 11: SEM of the corroded coupon under the acid without inhibitor

3.4 Scanning Electron Microscope Results

The Scanning Electron Microscope (SEM) images of the coupon's surface confirm the inhibitor's adsorption mechanism and formation of protective films. These findings are consistent with research which demonstrated how inhibitors adsorb onto metal surfaces, creating protective layers that impede corrosion. The observed scales and the barrier they form are indicative of effective inhibitor action [31]. Though the inhibitor influenced a shift on the corrosion potential, its major inhibiting technique was based on adsorption on the metal surface. The adsorption of the inhibitor led to the production of films on the metal surface which acted like a two-fold barrier between the electrolyte and the actual metal. This was shown as the scales on the SEM image on

Figure 12. Corrosion being an electrochemical process therefore was retarded since the corrosion route has been distorted by the action of the inhibitor. The presence of the phytochemicals in the inhibitor contributed in building a physisorption mechanism on the inhibitor. This is why it is believed that the nanocomposite will do better as a corrosion resistant material when used as a coating.

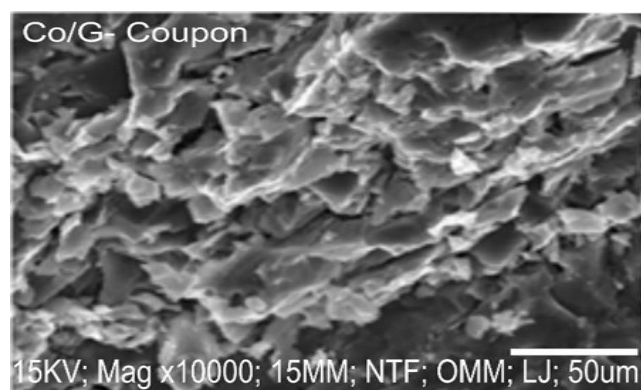


Figure 12: SEM of the coupon under the acid corrosion with cobalt-graphene (0.85/0.15wt%) inhibitor sample 3

Figures 11 and 12 are the Scanning Electron microscope of the coupon when immersed in the acid without inhibitor and with inhibitor respectively. The microgram shows that there was severe corrosion on the coupon without inhibitor as shown in Figure 11. These corrosion sites accelerated and were



concentrated at certain sites which led to the minor holes on those sites as indicated by the dispersed hollow points. This could lead to pitting and subsequent failure of the material in service. Figure 12 is the microgram of the coupon immersed in the acid solution with cobalt-graphene (0.85/0.15wt%) inhibitor or Sample 3. It allowed very low current density hence very little corrosion effect at the beginning. The inhibitor impounded the flow of corrosion current by its adsorption actions.

The inhibitor efficiencies of the three varied concentration of the composite were compared as shown in figure 13. It was observed that at 0.2g of the inhibitors, cobalt-graphene (0.7/0.3wt% and 0.55/45wt%) nano-composite had lower inhibitor efficiency. However, that of 0.85/0.15wt% had higher inhibitor efficiency. At the concentration of 0.4g of inhibitor, the inhibitor efficiency of cobalt-graphene (0.7/0.3wt%) was much lower while that of cobalt-graphene (0.85/0.15wt%) was the highest in the graph. This is also another affirmation that the cobalt-graphene (0.85/0.15wt%) is a good inhibitor.

4.0 CONCLUSION

This research work involved the experimental evaluation of the corrosion resistance capacity of cobalt-graphene nano-composite when used as an inhibitor protecting mild steel from corroding in an acidic medium. An attempt to answer the question of the appropriate composite composition with better corrosion resisting capacity was carried out and it was observed that the composite with 0.85wt% cobalt and 0.15wt% graphene exhibited the best anti-corrosion property with the best inhibitor efficiency. It also allowed lower current density and subsequently had a lower corrosion rate. Characterization on the composite and corroded metal were done and it was observed that the microstructure of the composite gained better mechanical features and subsequently corrosion resistance. The mild steel with cobalt graphene (0.85/0.15wt%) inhibitor showed the best resistance to corrosion. The nano-composite, cobalt graphene was therefore proven to be a good anti-corrosion material at a low concentration of graphene.

A debate on the appropriate percentage of graphene that should be incorporated in the matrix of cobalt to form a good anti-corrosive nano-composite has been on and very little works has been published on this content. This research work therefore affirms that a nano-composite of cobalt-graphene designed for corrosion resistance should have a very much higher percentage of cobalt and lower percentage of graphene. In this work based on the experiments, the

optimum composition of cobalt was 0.85wt% while that of graphene was 0.15wt%. This is also in affirmation with the work of [17,18] where it was proven that though, the addition of graphene on the cobalt matrix improved the mechanical and tribological properties of the composite, it could only do at low concentration.

The synthesised nano-composite can be applied for corrosion control either as an inhibitor or as a coating. It can be used to control corrosion on steel substrate in different asset environments including severe acid corrosive condition. It can be applied for corrosion control in engineering equipment including pipeline, pressure pipes, tank stands, vessels, and even metallic structure of buildings like protectors. It is therefore a benefit to the coating, corrosion, construction, and oil and gas industries in general.

The anti-corrosion property of the nano-composite was assessed as an inhibitor. The nano-composite has shown adsorptive features. It is therefore believed that the material will do better in corrosion prevention as a coating due to the phyto-chemicals which would contribute to physisorption of the inhibitor on the substrate

5.0 ACKNOWLEDGEMENT

We wish to acknowledge Dr E. Elemike and Mr.H. Akpeji of the Department of Chemistry, Federal University of Petroleum Resources, Effurun Nigeria and also Prof. Fayose Sunday of the Bells University, Ota Nigeria.

6.0 CONFLICT OF INTEREST

There is no conflict of interest for this work. The project was sponsored by the authors.

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