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Comparative Corrosion Resistance of Imported and Locally Produced Graphene Coatings on API 5L X56 Pipeline Steel

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***Abstract*-- Corrosion of pipeline steel remains a major challenge in the oil and gas industry due to continuous exposure to hostile environments, leading to increased maintenance costs from material degradation. This study evaluates the corrosion resistance of API 5L X56 steel coated with epoxy paint, imported graphene paint, and locally produced graphene paint using the weight-loss method. The coated steel specimens were immersed in three corrosive media: 3.5% seawater, 1 M hydrochloric acid (HCl), and sodium hydroxide (NaOH), for exposure periods of 120, 240, 360, 480, and 600 hours. The results showed that the corrosion rate generally decreased with increasing immersion time for all coatings, indicating the formation of stable protective films. In seawater and HCl, the epoxy coating exhibited the highest corrosion resistance, while the imported graphene paint demonstrated superior performance in the alkaline (NaOH) environment. The locally produced graphene paint also provided significant corrosion protection, with its corrosion rate stabilizing after prolonged exposure and approaching that of the imported graphene coating. Overall, both graphene-based coatings significantly enhanced the corrosion resistance of API 5L X56 steel during prolonged exposure to aggressive media, with the imported graphene coating showing the best performance. The findings demonstrate that locally produced graphene paint is a promising, cost-effective alternative for corrosion protection of pipeline steel and has considerable potential for application in the oil and gas industry.**

***Keywords*-- API 5L X56 steel; Corrosion protection; Graphene coating; Epoxy coating; Weight-loss method; Seawater; Hydrochloric acid; Sodium hydroxide.**

I. INTRODUCTION

This document is template. We ask that authors follow Corrosion of steel structures remains one of the most significant challenges facing the oil and gas industry, resulting in substantial economic losses, reduced operational efficiency, and increased safety risks. Pipeline steels such as API 5L X56 are continuously exposed to aggressive environments, including seawater, acidic solutions, and alkaline media, which accelerate material degradation and shorten service life. Protective organic coatings, particularly epoxy coatings, have long been employed to isolate steel surfaces from corrosive environments because of their excellent adhesion, chemical resistance, and mechanical properties [1-2].

However, conventional epoxy coatings may contain micropores and microcracks that permit the penetration of water, oxygen, and chloride ions, eventually leading to coating degradation and substrate corrosion [3-7].

Graphene, a two-dimensional carbon nanomaterial consisting of a single layer of sp^2-bonded carbon atoms arranged in a honeycomb lattice, has attracted considerable attention due to its exceptional mechanical strength, chemical stability, thermal conductivity, and impermeability to gases and liquids. Since its discovery, graphene has emerged as a promising nanofiller for improving the protective performance of polymer coatings. When uniformly dispersed within an epoxy matrix, graphene creates a highly tortuous diffusion path that significantly delays the penetration of corrosive species, thereby enhancing the corrosion resistance of coated metals [8-10].

Recent studies have demonstrated that graphene oxide (GO), reduced graphene oxide (rGO), and functionalized graphene substantially improve the barrier properties, mechanical strength, adhesion, and durability of epoxy coatings. The corrosion protection efficiency of graphene-based coatings depends on several factors, including graphene concentration, dispersion quality, orientation, functionalization, and compatibility with the polymer matrix. Proper functionalization minimizes agglomeration and promotes homogeneous dispersion, leading to denser coatings with fewer defects and superior long-term corrosion resistance [4], [7], [9] [10-12].

Although imported graphene materials have demonstrated excellent anticorrosion performance, their relatively high cost and limited availability restrict widespread industrial application, particularly in developing countries. Consequently, there is increasing interest in developing locally produced graphene coatings that can provide comparable corrosion protection at lower production costs. However, limited information is available regarding the comparative performance of locally produced graphene coatings against imported graphene coatings under different corrosive environments, particularly for API 5L X56 pipeline steel.

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Therefore, this study evaluates the corrosion resistance of API 5L X56 steel coated with epoxy paint, imported graphene paint, and locally produced graphene paint using the weight-loss technique. The coated specimens were exposed to three aggressive media, namely 3.5% seawater, 1 M hydrochloric acid (HCl), and sodium hydroxide (NaOH), for an immersion period of 600 hours. The findings provide a comparative assessment of the protective performance of conventional epoxy and graphene-based coatings and demonstrate the potential of locally produced graphene as a cost-effective corrosion protection material for oil and gas pipeline applications.

II. Materials And Methods

API 5L X56 steel pipe, commonly used in the oil and gas industry for pipeline applications, was selected as the substrate material for this study. The steel specimens were coated with three different protective paints: a locally produced graphene paint, an imported graphene oxide paint, and a commercial epoxy paint (used as the control).

The locally produced graphene paint was prepared using graphene powder (B25 mesh size), acetone (99% purity), and deionized water. Acetone constituted 25% of the solvent mixture, while deionized water was added to maintain the desired solubility parameter of the dispersion. A total of 3 g of graphene powder was dispersed in the solvent mixture and sonicated using a VWR ultrasonic processor for different durations of 2, 4, and 6 hours to investigate the influence of sonication time on graphene dispersion

2.1 Preparation of Imported Graphene Oxide Paint

The imported graphene oxide paint was formulated using the chemical composition presented in Table 1.

Table 1: Chemical Composition of Imported Graphene Oxide Paint

Chemical	Amount (g)	Ratio
Alkyd resin	1.5g	4
Kerosene	1 litre	1
Silicon	0.5kg	1
Cobalt	0.01kg	1
Mix drier	0.5kg	1
Titanium oxide	2kg	1
Graphene oxide	0.03g	1

Initially, alkyd resin and kerosene were mixed in a ratio of 4:1. Titanium dioxide was then incorporated into the mixture to enhance the surface area and improve the coating properties.

Subsequently, silicon, cobalt, and the mixed drier were added to improve the viscosity, drying characteristics, and overall stability of the paint. After thorough stirring, graphene oxide was introduced into the mixture to obtain the imported graphene oxide coating.

2.2 Corrosive Media

Three corrosive environments were used to evaluate the corrosion resistance of the coated steel specimens, namely sodium chloride (NaCl) solution, hydrochloric acid (HCl), and natural seawater. The chemical composition of the seawater used in this study is presented in Table 2

Table 2: The chemical contents of Seawater.

Chemical	Ion Concentration (g)	Proportionality Sality
Chloride	19.345	55.03
Sodium	10.752	30.59
Sulphur	2.701	7.68
Magnesium	1.295	3.65
Bromide	0.145	0.41

2.3 Corrosion Testing

Steel specimens coated with the locally produced graphene paint, imported graphene oxide paint, and commercial epoxy paint were immersed in each corrosive medium. The immersion depth was maintained at 2 cm for all samples to ensure uniform exposure conditions. The epoxy-coated specimen served as the reference sample for evaluating the corrosion protection performance of the graphene-based coatings.

The chemical composition of the API 5L X56 steel used in this study is presented in Table 3

Table 3: The chemical composition of X56L in conformity

API56L	Carbon (%)	Silicon (%)	Magnesium (%)	Phosphorus (%)	Nickel (%)	Tin (%)	Surplus (%)
X56I	**0.16**	**0.45**	**1.65**	**0.020**	**0.065**	**0.04**	**0.00**

III. Results And Discussion

Table 4 presents the corrosion rates of epoxy-coated API 5L X56 steel immersed in 3.5% seawater, 1 M HCl, and NaOH for up to 600 hours. In all media, the corrosion rate generally decreased with increasing exposure time, indicating improved protection by the epoxy coating during prolonged immersion.

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Table 4: Corrosion Rate of Epoxy-Coated API 5L X56 Steel

Time (Hours)	Corrosive Medium		
	Seawater (3.5 %)	HCl (1 M)	NaOH
120	0.71	-0.08	0.20
240	0.05	-0.03	0.08
360	0.04	-0.03	0.08
480	0.03	-.0.03	0.08
600	0.03	-0.02	0.07

The highest initial corrosion rate was recorded in 3.5% seawater (0.71 at 120 h), which decreased significantly to 0.03 after 600 h, suggesting effective resistance to chloride-induced corrosion over time. In NaOH, the corrosion rate declined steadily from 0.20 to 0.06, demonstrating good coating stability in an alkaline environment. The 1 M HCl samples exhibited small negative values throughout the test period, which may be attributed to experimental uncertainty or slight weight gain due to surface film formation rather than actual corrosion. Overall, the epoxy coating provided effective corrosion protection in all three corrosive media, with performance improving as the immersion time increased.

Table 5: Corrosion Rates of API 5L X56 steel coated with imported graphene paint

Time (Hours)	Corrosive Medium		
	Seawater (3.5 %)	HCl (1 M)	NaOH
120	0.06	1.38	0.06
240	0.05	0.28	0.06
360	0.04	0.00	0.03
480	0.02	0.00	0.008
600	0.02	0.00	0.004

Table 5 shows the corrosion rates of API 5L X56 steel coated with imported graphene paint in different corrosive media over 600 hours. The corrosion rate generally decreased with increasing immersion time, indicating improved corrosion resistance. In seawater, the corrosion rate reduced from 0.06 to 0.02, while in NaOH it decreased from 0.06 to 0.004, demonstrating excellent protection in the alkaline medium. In 1 M HCl, the corrosion rate dropped sharply from 1.38 at 120 hours to zero after 360 hours, suggesting the formation of a stable protective barrier by the imported graphene coating. Overall, the imported graphene paint exhibited effective corrosion resistance in all the tested environments.

Table 6: Corrosion Rates of API 5L X56 Steel Coated with Locally Produced Graphene Paint

Time (Hours)	Corrosive Medium		
	Seawater (3.5 %)	HCl (1 M)	NaOH
120	0.03	1.25	0.10
240	0.18	0.03	0.04
360	0.03	0.00	0.02
480	0.02	0.00	0.01
600	0.02	0.00	0.01

Table 6 presents the corrosion rates of API 5L X56 steel coated with locally produced graphene paint in different corrosive media over 600 hours. The corrosion rate generally decreased with increasing immersion time, indicating improved corrosion resistance. In seawater, the corrosion rate showed a temporary increase at 240 hours before decreasing to 0.02 at 600 hours. In NaOH, the corrosion rate steadily declined from 0.10 to 0.01, demonstrating good protection in the alkaline medium. In 1 M HCl, the corrosion rate reduced sharply from 1.25 at 120 hours to zero after 360 hours, suggesting the formation of a stable protective film. Overall, the locally produced graphene paint exhibited excellent corrosion protection and performance comparable to the imported graphene coating.

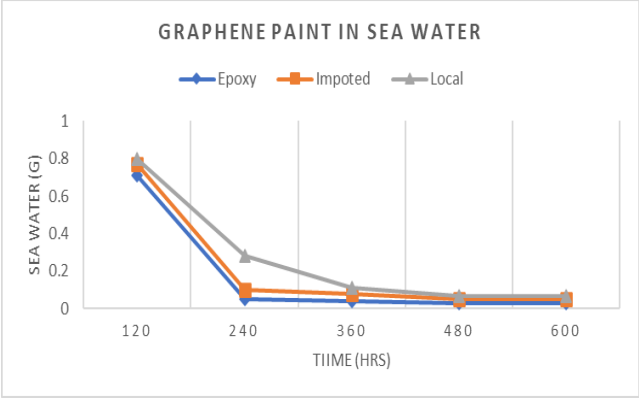

Figure 1: The corrosion behaviour of epoxy coating, imported graphene paint, and locally produced graphene paint in seawater

Figure 1 presents the variation in weight loss (or corrosion effect) of epoxy-coated steel, imported graphene paint, and locally produced graphene paint exposed to 3.5% seawater over 600 hours. All coatings experienced a sharp decrease in weight loss after the first 120 hours, indicating rapid stabilization of the protective films.

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The epoxy coating exhibited the lowest values throughout the exposure period, demonstrating the best resistance to seawater corrosion. The imported graphene paint also provided good protection, with only slightly higher values than epoxy after 240 hours. Although the locally produced graphene paint recorded relatively higher values, it showed a consistent decline with exposure time and reached a stable performance after 480 hours. Overall, the results indicate that both graphene-based coatings significantly improved corrosion resistance in seawater, with the imported graphene paint performing better than the locally produced formulation, while the local graphene paint still demonstrated promising protective capability.

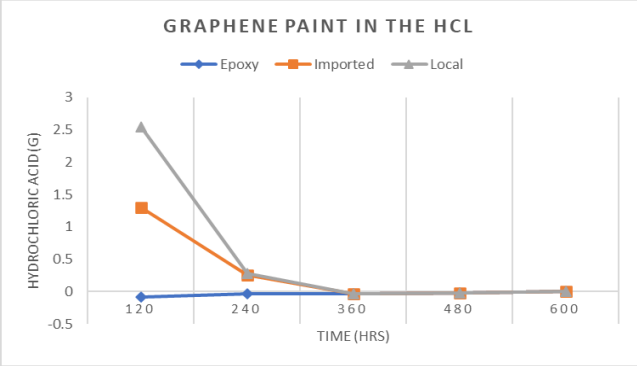

Figure 2: The corrosion behaviour of epoxy coating, imported graphene paint, and locally produced graphene paint in hydrochloric acid (HCl)

Figure 2 illustrates the corrosion performance of epoxy coating, imported graphene paint, and locally produced graphene paint in 1 M hydrochloric acid (HCl) over 600 hours. At 120 hours, the locally produced graphene paint showed the highest weight loss, followed by the imported graphene paint, indicating greater initial susceptibility to the acidic environment. However, both graphene coatings exhibited a sharp reduction in weight loss by 240 hours and approached negligible values after 360 hours, suggesting the formation of a stable protective barrier. The epoxy coating maintained the lowest and most stable values throughout the exposure period, demonstrating the highest resistance to HCl attack. Overall, while the imported graphene paint outperformed the locally produced graphene paint, both graphene coatings showed significant improvement in corrosion resistance with prolonged exposure, confirming their effectiveness as protective coatings in acidic media.

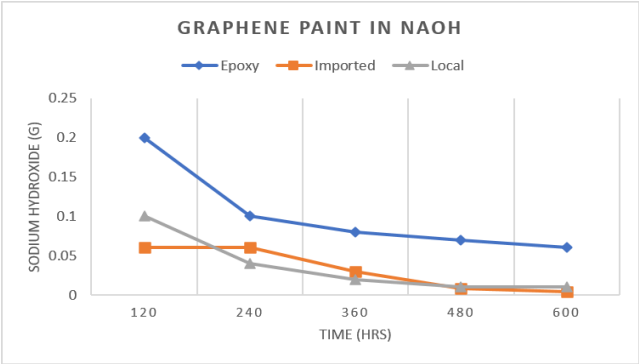

Figure 3: The corrosion behaviour of epoxy coating, imported graphene paint, and locally produced graphene paint in sodium hydroxide (NaOH)

The Figure 3 presents the corrosion behaviour of epoxy coating, imported graphene paint, and locally produced graphene paint in sodium hydroxide (NaOH) over an exposure period of 600 hours. The epoxy coating exhibited the highest weight loss throughout the test, indicating lower resistance to the alkaline environment. In contrast, both the imported and locally produced graphene paints showed lower weight loss values and a gradual decline with increasing exposure time. By 480–600 hours, both graphene coatings reached nearly negligible weight loss, demonstrating excellent stability and protective performance in NaOH. Overall, the results indicate that the graphene-based coatings, particularly the imported graphene paint, provided superior corrosion resistance in the alkaline medium compared with the conventional epoxy coating, while the locally produced graphene paint also exhibited highly promising performance.

IV. Conclusions

This study evaluated the corrosion resistance of API 5L X56 steel coated with epoxy paint, imported graphene paint, and locally produced graphene paint in 3.5% seawater, 1 M HCl, and NaOH using the weight-loss method. The results showed that the corrosion rate generally decreased with increasing immersion time for all coatings, indicating improved stability and the formation of protective surface films. The epoxy coating exhibited the best corrosion resistance in seawater and acidic (HCl) environments, while the imported graphene paint demonstrated superior performance in the alkaline (NaOH) medium.

Although the locally produced graphene paint showed slightly higher corrosion rates than the imported graphene coating, it provided significant corrosion protection and achieved stable performance after prolonged exposure. Overall, the findings demonstrate that graphene-based coatings are effective anti-corrosion materials for API 5L X56 steel and that the locally produced graphene paint has strong potential as a cost-effective alternative for corrosion protection in oil and gas applications. Future studies should investigate the long-term corrosion behaviour of locally produced graphene coatings under extended immersion periods and real field conditions. The influence of graphene concentration, coating thickness, and dispersion quality on corrosion resistance should also be evaluated to optimize coating performance. In addition, electrochemical techniques such as Electrochemical Impedance Spectroscopy (EIS) and Potentiodynamic Polarization should be employed to complement the weight-loss measurements. Microstructural and surface characterization using Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDS), Atomic Force Microscopy (AFM), and X-ray Diffraction (XRD) are recommended to better understand the corrosion mechanisms and the protective behaviour of graphene coatings. Finally, the economic feasibility and large-scale industrial application of locally produced graphene coatings should be assessed for use in the oil and gas industry.

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