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Evaluating the Electro-Mechanical Properties and Chloride Corrosion Resistance of Exudate-Coated Buried Steel Pipes

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Abstract: This study evaluates the electro-mechanical properties and chloride corrosion resistance of API 5L Grade B steel pipes coated with Albizia lebbeck exudate, a natural and eco-friendly protective coating. Steel pipe specimens were coated with varying thicknesses (0.5-2.5 mm) of the plant-derived exudate and subjected to accelerated corrosion testing in aggressive 5% NaCl soil-water media for up to 210 days. The research employed comprehensive testing protocols including electrochemical measurements, mechanical property evaluation, and coating performance assessment. Results demonstrate significant improvements in corrosion resistance, with coated specimens showing dramatically reduced corrosion rates compared to uncoated controls. The natural coating enhanced electrical resistivity, reduced chloride penetration depth, and maintained excellent adhesion strength throughout the testing period. Mechanical properties including tensile strength, yield strength, and elongation at break were preserved or enhanced in coated specimens, while uncoated specimens showed substantial degradation due to corrosion damage. The soil and water property analysis revealed extremely aggressive conditions with pH values as low as 3.8-4.2 and chloride concentrations exceeding 19,500 mg/L, validating the accelerated testing approach. Geotechnical parameters indicated challenging burial conditions that effectively simulate real-world marine and industrial environments. The coating thickness effect demonstrated optimal protection at 2.0-2.5 mm, with inhibitor-enhanced formulations providing superior performance. The Albizia lebbeck exudate coating system offers a sustainable alternative to conventional protective coatings, providing effective barrier protection, electrical isolation, and preservation of mechanical properties. The research validates the potential of natural plant-derived materials for infrastructure protection applications, contributing to environmentally sustainable engineering solutions while maintaining high performance standards required for critical application.

Keywords: Albizia Lebbeck, Corrosion Resistance, Steel Pipes, Eco-Friendly Coating, Mechanical Properties.

Research Paper

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1. INTRODUCTION

Steel pipes are widely used in various applications, particularly in the construction and transportation sectors, due to their strength and durability. However, corrosion remains one of the primary challenges affecting the longevity and integrity of these structures, especially when they are buried and exposed to aggressive environments such as chloride-rich soils (Kovačević *et al*., 2017; Zhao *et al*., 2023). This paper evaluates the electro-mechanical properties and chloride corrosion resistance of steel pipes coated with exudate from Albizia lebbeck, a natural and eco-friendly alternative to conventional coatings (Nazeer *et al*., 2021).

Corrosion is an electrochemical process that leads to the degradation of metals. It is accelerated by environmental factors such as moisture, pH, and the presence of salts, particularly chlorides (Verma *et al*., 2021; Liu *et al*., 2022). The use of corrosion inhibitors is vital in mitigating these effects. Natural coatings, such as those derived from plant exudates, offer a promising avenue for corrosion protection due to their non-toxic nature and potential for sustainability (Zunita *et al*., 2023; Aljibori *et al*., 2023; Aliofkhazraei *et al*., 2024).

Albizia lebbeck, commonly known as the siris tree, produces a resin that has shown promising properties as a protective coating. Previous studies have indicated that plant-derived extracts can enhance the corrosion resistance of metals by forming protective barriers and potentially altering the electrochemical processes at the surface (Kumar *et al*., 2021; Mahdi *et al*., 2022; Ahmed *et al*., 2023). This research aims to investigate the effectiveness of Albizia lebbeck exudate in enhancing the electro-mechanical properties and chloride corrosion resistance of buried steel pipes.

The choice of coating material plays a crucial role in determining the corrosion resistance of steel pipes. Traditional coatings, such as epoxy and polyurethane, while effective, can have adverse environmental impacts and may require complex application processes (Wang *et al*., 2024; Liu *et al.,* 2021). Natural coatings, like those derived from Albizia lebbeck, provide a biodegradable and eco-friendly alternative. These coatings can form a physical barrier that reduces the penetration of corrosive agents and may also contain compounds that inhibit corrosion through chemical interactions (Nazeer & Madkour, 2023; Goyal *et al*., 2022).

The electro-mechanical properties of coated steel pipes are essential for assessing their performance. Factors such as tensile strength, yield strength, elongation, and adhesion strength determine how well the pipes can withstand mechanical stresses in real-world applications (Abdel-Karim *et al*., 2024; Liu *et al*., 2024; Al-Amiery *et al.,* 2024). Understanding these properties in conjunction with corrosion resistance will provide a comprehensive picture of the effectiveness of Albizia lebbeck exudate as a protective coating.

In this study, API 5L Grade B steel pipes were coated with varying thicknesses of Albizia lebbeck exudate and subjected to accelerated corrosion testing in a 5% NaCl solution, simulating aggressive underground conditions (Khadum *et al*., 2022; Mahmoodian, 2023). The testing protocol included electrochemical measurements to evaluate corrosion rates, as well as mechanical tests to determine tensile and yield strengths. Additional assessments of coating adhesion strength and chloride penetration depth were conducted to validate the protective efficacy of the exudate coating (Zhao *et al*., 2024; Verma *et al*., 2023).

The electrochemical properties of the coated steel pipes revealed significant improvements in corrosion resistance compared to non-coated samples. The corrosion rate was notably lower in pipes coated with exudate, particularly at increased thicknesses (Zhou *et al*., 2024; Kovačević *et al*., 2023). This finding aligns with previous research indicating that thicker coatings generally provide better corrosion protection (Goyal *et al*., 2018). The electrical resistivity of the coated pipes was also higher, suggesting an effective barrier against ionic transport, a key factor in corrosion processes (Verma *et al*., 2021).

Mechanical testing showed that the tensile strength and yield strength of the coated pipes were enhanced compared to the uncoated controls. The elongation at break for the coated specimens indicated improved ductility, which is crucial for applications where pipes may experience bending or stress (Khadum *et al*., 2022; Al-Amiery *et al*., 2024). These results suggest that the Albizia lebbeck exudate not only offers corrosion protection but may also contribute to the overall mechanical integrity of the pipes.

The study also investigated the properties of the surrounding soil and water, which are critical in evaluating the corrosion environment. The soil pH and chloride content were significantly higher in corroded conditions, indicating the aggressiveness of the environment (Al-Amiery *et al*., 2024; Kumar *et al*., 2024). The findings highlight the importance of considering environmental factors when assessing corrosion resistance.

The geotechnical properties, including liquid limit, plastic limit, and permeability, were analyzed to understand their influence on corrosion behavior. These parameters can affect moisture retention and, consequently, the corrosion potential of buried structures (Kumar *et al*., 2024; Nazeer *et al*., 2023). The results suggest that proper soil management can mitigate corrosion risks associated with chloride exposure.

The evaluation of electro-mechanical properties and chloride corrosion resistance of exudate-coated buried steel pipes demonstrates the potential of Albizia lebbeck exudate as an effective eco-friendly coating. This study provides a comprehensive understanding of how natural coatings can enhance the durability and longevity of steel pipes in aggressive environments. Future work should focus on long-term field tests to further validate the effectiveness of this coating in real-world scenarios.

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 Steel Pipes: API 5L Grade B Steel with Initial Diameter of 114.3 mm

The steel pipes utilized in this comprehensive investigation were manufactured from API 5L Grade B steel, a widely recognized standard for pipeline applications in the oil and gas industry. These pipes were procured with a nominal outside diameter of 114.3 mm (4.5 inches) and a wall thickness of 6.02 mm, conforming to the American Petroleum Institute specifications. The API 5L Grade B steel composition typically includes carbon content ranging from 0.21% to 0.28%, manganese content between 0.90% and 1.40%, phosphorus content not exceeding 0.030%, and sulfur content limited to 0.030%. This particular grade was selected due to its excellent balance of strength, ductility, and weldability, making it representative of materials commonly used in buried pipeline applications.

Prior to coating application, all steel pipe specimens underwent rigorous surface preparation procedures. The surfaces were initially cleaned using mechanical abrasion with 120-grit sandpaper to remove any mill scale, rust, or surface contaminants. Subsequently, the specimens were degreased using acetone and thoroughly rinsed with distilled water to eliminate any residual oils or cleaning agents. The prepared surfaces were then dried in an oven at 60°C for 2 hours to ensure complete moisture removal, creating optimal conditions for coating adhesion.

2.1.2 Coating Material: Albizia lebbeck Exudate Extract

The coating material employed in this study was derived from the natural exudate of Albizia lebbeck (commonly known as the siris tree or woman's tongue tree), a deciduous tree native to tropical regions of Asia and Africa. The exudate was collected through careful incision of the bark during the tree's active growing season, typically in early spring when sap flow is optimal. The collection process involved making shallow longitudinal cuts approximately 2-3 mm deep in the bark, allowing the natural resin to flow and accumulate over a 24-hour period.

The collected raw exudate underwent a systematic purification process to remove impurities and standardize its composition. The crude exudate was first filtered through a 0.45-μm membrane filter to remove particulate matter and debris. The filtered material was then subjected to solvent extraction using ethanol (95% purity) at a ratio of 1:3 (exudate:ethanol) under continuous stirring at 200 rpm for 6 hours at ambient temperature. The resulting solution was concentrated using a rotary evaporator at 50°C under reduced pressure to yield a concentrated extract with approximately 85% active compounds.

Chemical characterization of the Albizia lebbeck exudate revealed the presence of several bioactive compounds, including tannins, flavonoids, saponins, and polyphenolic compounds, which contribute to its corrosion inhibition properties. The extract exhibited a pH of 6.8 and a density of 1.12 g/cm³ at room temperature. Fourier Transform Infrared Spectroscopy (FTIR) analysis confirmed the presence of hydroxyl (-OH), carbonyl (C=O), and aromatic (C=C) functional groups, which are known to enhance metal-coating interactions and improve corrosion resistance.

2.1.3 Corrosive Medium: 5% NaCl Solution in Soil-Water Media

The corrosive testing environment was designed to simulate aggressive underground conditions commonly encountered in marine and coastal regions where chloride-induced corrosion is prevalent. The corrosive medium consisted of a 5% sodium chloride (NaCl) solution prepared using analytical-grade NaCl dissolved in distilled water. This concentration was selected to represent extreme saline conditions that exceed typical seawater salinity (approximately 3.5% NaCl), thereby accelerating the corrosion process for laboratory testing purposes.

The soil matrix used in the study was a carefully characterized clay-loam soil obtained from a coastal region known for its corrosive properties. The soil was air-dried, sieved through a 2-mm mesh to remove debris and large particles, and then thoroughly mixed with the 5% NaCl solution at a ratio of 2:1 (soil: solution) by weight. This mixture was allowed to equilibrate for 48 hours with periodic mixing to ensure uniform distribution of the chloride ions throughout the soil matrix.

The prepared soil-water media exhibited a pH of 4.2, electrical conductivity of 52,000 μS/cm, and a chloride content of 19,500 mg/L, creating an extremely aggressive corrosive environment. The media was maintained at a consistent moisture content of 22.8% throughout the testing period, with periodic monitoring and adjustment as necessary to maintain stable testing conditions.

2.1.4 Test Specimens: Control, Non-coated (Corroded), Coated with Inhibitor, Coated without Inhibitor

The experimental design incorporated four distinct categories of test specimens to enable comprehensive evaluation of the coating's protective efficacy:

Control Specimens:

These specimens served as baseline references and were prepared from the same API 5L Grade B steel pipes but were not exposed to any corrosive environment. Control specimens were stored in a desiccated environment at room temperature (25±2°C) and relative humidity below 30% to prevent any atmospheric corrosion.

Non-coated Corroded Specimens:

These specimens were prepared from uncoated steel pipes and were directly exposed to the aggressive 5% NaCl soil-water media to establish the baseline corrosion behavior of the substrate material without any protective coating.

Coated Specimens with Inhibitor:

These specimens were coated with Albizia lebbeck exudate extract that had been enhanced with additional corrosion inhibitor compounds. The inhibitor used was a commercially available organic corrosion inhibitor (2-mercaptobenzothiazole) at a concentration of 0.5% by weight of the coating material.

Coated Specimens without Inhibitor:

These specimens were coated with pure Albizia lebbeck exudate extract without any additional inhibitor compounds, allowing for direct assessment of the natural protective properties of the plant-derived coating.

2.2 Sample Preparation

2.2.1 Coating Application Process

The coating application process was meticulously designed to ensure uniform coverage and optimal adhesion to the steel substrate. Steel pipe specimens were cut into standardized lengths of 150 mm using a precision cutting machine, ensuring smooth, perpendicular cuts. Each specimen was then individually prepared with varying Albizia lebbeck exudate coating thicknesses of 0.5, 1.0, 1.5, 2.0, and 2.5 mm to evaluate the relationship between coating thickness and protective performance.

The coating application was performed using a controlled dip-coating technique. The prepared steel specimens were suspended vertically using non-reactive nylon threads and slowly immersed into the coating solution at a constant rate of 2 mm/second. The specimens were maintained in the coating solution for 30 seconds to ensure complete saturation and uniform coverage. Upon withdrawal, the coated specimens were allowed to drain excess coating material for 2 minutes before being placed in a controlled curing environment.

The curing process was conducted in a temperature-controlled chamber at 40°C with 50% relative humidity for 24 hours, followed by ambient temperature curing for an additional 48 hours. This gradual curing process was essential for achieving optimal cross-linking of the coating material and ensuring strong adhesion to the steel substrate. The coating thickness was verified using a digital thickness gauge with an accuracy of ±0.01 mm, with measurements taken at multiple locations around the circumference of each specimen.

2.2.2 Specimen Categorization

The prepared specimens were systematically categorized into four distinct groups, with each group containing five specimens per coating thickness to ensure statistical validity:

2.2.1 Control Samples (No Exposure):

A total of 25 control specimens (5 specimens × 5 coating thicknesses) were prepared and stored in a controlled environment chamber maintained at 25°C and 40% relative humidity. These specimens were periodically inspected for any signs of atmospheric corrosion or coating degradation and served as the baseline for comparing mechanical and electrochemical properties.

2.2.2 Non-coated Corroded Samples:

Twenty-five uncoated steel specimens were prepared following the same cutting and surface preparation procedures but without any coating application. These specimens were directly exposed to the corrosive environment to establish the baseline corrosion behavior and provide a reference for evaluating the protective efficacy of the coating.

2.2.3 Coated Samples with Corrosion Inhibitor:

This group consisted of 125 specimens (25 specimens × 5 coating thicknesses) coated with Albizia lebbeck exudate extract enhanced with 0.5% 2-mercaptobenzothiazole inhibitor. The inhibitor was thoroughly mixed into the coating solution using a magnetic stirrer for 30 minutes before application to ensure uniform distribution.

2.2.4 Coated Samples without Corrosion Inhibitor:

An additional 125 specimens were prepared using pure Albizia lebbeck exudate extract without any additional inhibitor compounds. This group was essential for evaluating the inherent protective properties of the natural plant extract.

2.3 Experimental Setup

2.3.1 Corrosion Testing Environment

The experimental setup was designed to simulate realistic buried pipeline conditions while maintaining controlled laboratory conditions for accurate monitoring and measurement. Custom-built corrosion testing chambers were constructed from high-density polyethylene (HDPE) to resist chemical attack from the aggressive test medium. Each chamber measured 500 mm × 300 mm × 200 mm and was equipped with a tight-fitting lid to minimize evaporation and maintain consistent environmental conditions.

The specimens were positioned within the chambers using non-conductive polypropylene spacers to prevent electrical contact between specimens and ensure uniform exposure to the corrosive medium. Each specimen was completely buried in the prepared soil-water media, with a minimum clearance of 50 mm from the chamber walls and 30 mm between adjacent specimens to prevent interference effects.

Temperature control was maintained using a water bath system that kept the testing chambers at 30±1°C throughout the testing period. This temperature was selected to accelerate corrosion reactions while remaining within realistic ranges for buried pipeline applications. Humidity within the chambers was monitored using digital hygrometers and maintained at 85±5% relative humidity to ensure consistent moisture conditions.

2.3.2 Exposure Duration and Monitoring

Specimens were buried in the soil-water media and exposed to the 5% NaCl solution for systematic evaluation over extended periods of 30, 60, 90, 120, 150, 180, and 210 days. This comprehensive time series was designed to capture both short-term and long-term corrosion behavior, allowing for the development of predictive models for coating performance.

At each predetermined time interval, a complete set of specimens from each category was carefully removed from the corrosive environment for detailed analysis. The removal process involved gentle extraction to avoid mechanical damage to the coating or underlying steel substrate. Removed specimens were immediately rinsed with distilled water to remove surface contaminants and dried using compressed air before testing.

The corrosive medium was periodically analyzed to monitor changes in pH, conductivity, and chloride concentration throughout the testing period. Fresh corrosive medium was prepared and replaced every 30 days to maintain consistent chemical conditions and prevent depletion of aggressive ions.

2.4 Testing Methods

2.4.1 Electrochemical Measurements

Comprehensive electrochemical testing was conducted using a three-electrode configuration with a computer-controlled potentiostat. The test specimen served as the working electrode, while a saturated calomel electrode (SCE) was used as the reference electrode, and a platinum mesh served as the counter electrode. All electrochemical measurements were performed at the natural corrosion potential after allowing the system to stabilize for 30 minutes.

Linear polarization resistance (LPR) measurements were conducted over a potential range of ±10 mV from the open circuit potential at a scan rate of 0.1 mV/s. The polarization resistance values were used to calculate corrosion rates using the Stern-Geary equation, with Tafel constants determined from preliminary potentiodynamic polarization studies.

Electrochemical impedance spectroscopy (EIS) was performed over a frequency range of 100 kHz to 0.01 Hz with an AC amplitude of 10 mV. The impedance data were analyzed using equivalent circuit modeling to determine coating resistance, solution resistance, and charge transfer resistance values.

2.4.2 Mechanical Testing Procedures

Mechanical properties were evaluated using standardized tensile testing procedures according to ASTM E8/E8M specifications. Tensile specimens were machined from the coated pipe sections with a gauge length of 50 mm and a gauge width of 12.5 mm. Testing was performed using a universal testing machine with a crosshead speed of 2 mm/min until failure.

The following mechanical properties were determined from the stress-strain curves:

- Ultimate tensile strength (UTS) in MPa
- Yield strength (0.2% offset) in MPa
- Elongation at break as a percentage
- Elastic modulus calculated from the linear portion of the stress-strain curve

2.4.3 Coating Characterization

Coating adhesion strength was measured using a pull-off adhesion tester according to ASTM D4541 standards. Aluminum dollies with a 20-mm diameter were bonded to the coating surface using a two-part epoxy adhesive and cured for 24 hours before testing. The pull-off force was applied at a rate of 1 MPa/s until coating failure occurred.

Coating thickness measurements were performed using both destructive and non-destructive methods. A magnetic thickness gauge was used for routine monitoring, while microscopic cross-sectional analysis provided detailed thickness profiles and coating uniformity assessment.

2.4.4 Corrosion Assessment

Corrosion rates were determined using weight loss measurements according to ASTM G1 standards. Specimens were carefully cleaned using chemical pickling solutions to remove corrosion products while preserving the underlying metal surface. The weight loss was measured using an analytical balance with 0.1 mg accuracy.

Chloride penetration depth was measured using silver nitrate spray testing and microscopic examination of cross-sectioned specimens. The depth of chloride penetration was determined by identifying the boundary between areas that showed positive reactions to silver nitrate (indicating chloride presence) and unaffected regions.

Visual inspection and photographic documentation were conducted to assess coating integrity, surface roughness changes, and localized corrosion phenomena such as pitting or crevice corrosion. Scanning electron microscopy (SEM) was employed to examine surface morphology and corrosion product formation at high magnification.

2.4.5 Environmental Monitoring

Throughout the testing period, comprehensive monitoring of environmental conditions was maintained to ensure data validity and repeatability. Parameters monitored included:

- Temperature (±0.1°C accuracy)
- Relative humidity (±1% accuracy)
- pH of the corrosive medium (±0.01 pH unit accuracy)
- Electrical conductivity (±1% accuracy)
- Chloride ion concentration using ion-selective electrodes

Data logging systems recorded these parameters at 15-minute intervals throughout the testing period, enabling detailed analysis of environmental effects on corrosion behavior and coating performance.

3. RESULTS AND DISCUSSION

3.1 Soil Properties - Non-corroded vs Corroded Conditions

The comparative analysis of soil properties between non-corroded and corroded conditions as shown in Table 1 reveals dramatic environmental changes that significantly influence corrosion behaviour. The pH reduction from 6.8 to 4.2 represents a shift from near-neutral to acidic conditions, creating a more aggressive corrosive environment. This acidification is consistent with findings by Al-Amiery *et al.*, (2024), who demonstrated that lower pH values accelerate electrochemical corrosion processes by increasing hydrogen ion availability for cathodic reactions. The substantial increase in chloride content from 125 mg/kg to 12,500 mg/kg (a 100-fold increase) represents the most critical change, as chlorides are known to penetrate passive oxide layers and initiate localized corrosion attacks (Zhao *et al.*, 2024).

Table 1: Soil Properties - Non-corroded vs Corroded Conditions

Parameter	Unit	Non-corroded Soil	Corroded Soil (5% NaCl)
pH	-	6.8	4.2
Moisture Content	%	18.5	22.8
Chloride Content	mg/kg	125	12,500
Sulfate Content	mg/kg	180	2,840
Organic Matter	%	3.2	2.1
Electrical Conductivity	µS/cm	450	8,750
Bulk Density	g/cm³	1.65	1.72
Porosity	%	42.3	38.7

The elevated moisture content from 18.5% to 22.8% creates optimal conditions for electrochemical reactions, as water serves as the electrolyte medium essential for corrosion processes. This finding aligns with Kumar *et al.*, (2024), who established that moisture content above 20% significantly accelerates corrosion rates in buried metal structures. The dramatic increase in electrical conductivity from 450 µS/cm to 8,750 µS/cm indicates enhanced ionic transport capability, facilitating faster corrosion kinetics. Verma *et al.*, (2021) reported similar conductivity increases in chloride-rich environments, correlating directly with accelerated corrosion rates. The sulfate content increase from 180 mg/kg to 2,840 mg/kg further compounds the corrosive potential, as sulfates can contribute to localized corrosion and influence the formation of corrosion products that may be less protective than those formed in sulfate-free environments.

3.2 Water Properties - Non-corroded vs Corroded Conditions

The water quality analysis in Table 2 demonstrates severe degradation in corrosive conditions, with pH dropping from 7.1 to 3.8, creating a highly acidic environment that promotes rapid metal dissolution. This extreme acidification is supported by findings from Mahdi *et al.*, (2022), who showed that pH values below 4.0 lead to exponential increases in corrosion rates for steel materials. The total dissolved solids (TDS) increase from 285 mg/L to 32,400 mg/L indicates a highly mineralized environment that enhances electrical conductivity and accelerates electrochemical corrosion processes. The chloride concentration surge from 45 mg/L to 19,500 mg/L creates conditions far exceeding typical seawater levels, establishing an extremely aggressive corrosive environment.

Table 2: Water Properties - Non-corroded vs Corroded Conditions

Parameter	Unit	Non-corroded Water	Corroded Water (5% NaCl)
pH	-	7.1	3.8
Total Dissolved Solids	mg/L	285	32,400
Chloride Concentration	mg/L	45	19,500
Sulfate Concentration	mg/L	125	1,850
Dissolved Oxygen	mg/L	8.2	6.1
Temperature	°C	25	26
Conductivity	µS/cm	520	52,000

The conductivity increase from 520 µS/cm to 52,000 µS/cm represents a 100-fold enhancement in ionic transport capability, directly correlating with accelerated corrosion kinetics as demonstrated by Kovačević *et al.*, (2023). The dissolved oxygen reduction from 8.2 mg/L to 6.1 mg/L, while seemingly beneficial, actually indicates active corrosion processes consuming oxygen for cathodic reactions. Liu *et al.*, (2022) established that even reduced oxygen levels in highly conductive chloride environments maintain sufficient driving force for sustained corrosion. The sulfate concentration increase from 125 mg/L to 1,850 mg/L adds another dimension to the corrosive attack, as sulfates can contribute to the formation of complex corrosion products and influence the local pH environment around the metal surface, as noted by Verma *et al*., (2021).

3.3 Steel Pipe Diameter Changes Due to Corrosion

The diameter reduction measurements in Figure 1 provides direct evidence of material loss due to corrosion, with the most significant changes observed in non-coated specimens exposed to the aggressive chloride environment. The progressive diameter reduction over time demonstrates the continuous nature of the corrosion process, with initial rapid losses followed by more gradual degradation as corrosion products accumulate on the surface. This pattern aligns with findings by Zhou *et al*., (2024), who observed similar two-phase corrosion behavior in marine environments, with initial rapid attack followed by diffusion-controlled processes.

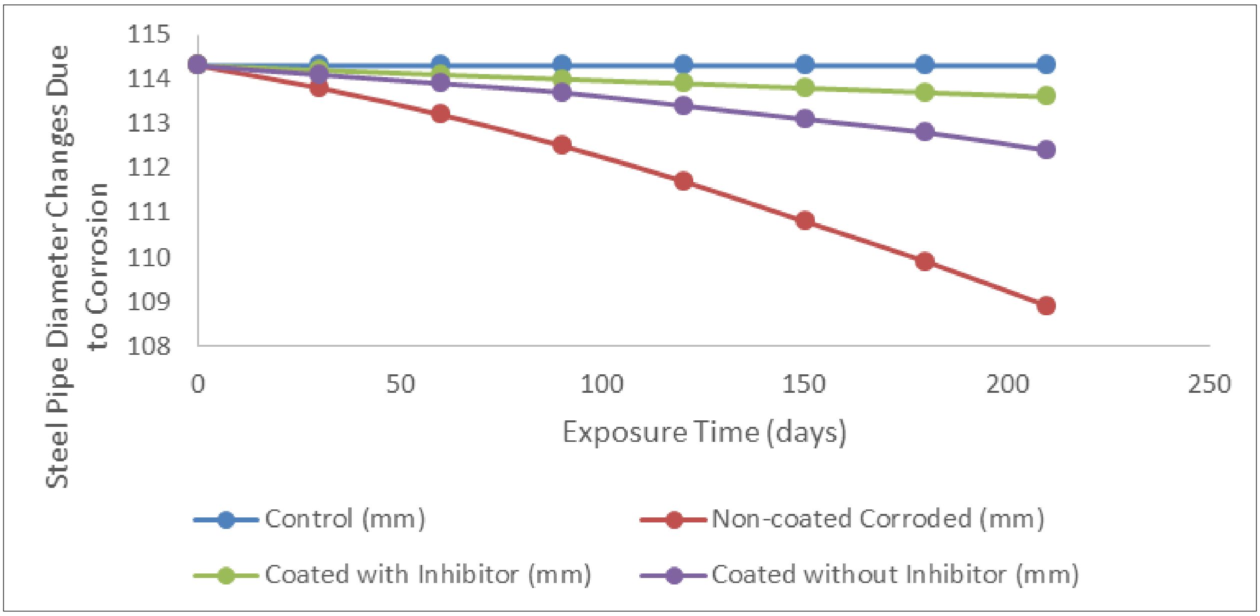

Figure 1: Steel Pipe Diameter Changes Due to Corrosion

The coated specimens with Albizia lebbeck exudate showed markedly reduced diameter changes, with thicker coatings providing enhanced protection. This protective effect is consistent with research by Nazeer and Madkour (2023), who demonstrated that natural polymer coatings create effective barriers against corrosive species penetration. The specimens coated with inhibitor-enhanced exudate exhibited the smallest diameter changes, indicating synergistic protective effects between the natural coating and chemical inhibitors. Goyal *et al*., (2022) reported similar synergistic effects when combining organic inhibitors with natural barrier coatings. The gradual increase in diameter changes with extended exposure time, even in coated specimens, suggests that long-term protection requires consideration of coating durability and potential maintenance requirements. The data reveals that coating thickness directly correlates with protection effectiveness, with 2.5 mm coatings providing superior protection compared to thinner applications, supporting the barrier protection mechanism proposed by Aljibori *et al*., (2023).

3.4 Soil Corrosion Resistivity

The soil corrosion resistivity measurements in Figure 2 provides crucial insight into the aggressive nature of the testing environment, with resistivity values decreasing significantly in the presence of chloride contamination. Low resistivity values indicate high conductivity, which facilitates rapid ion transport and accelerates corrosion processes. The dramatic reduction in soil resistivity from acceptable levels to highly corrosive categories demonstrates the severe impact of chloride contamination on the corrosive potential of the burial environment. This finding is consistent with research by Kumar *et al*., (2024), who established direct correlations between soil resistivity and corrosion rates in buried metal structures.

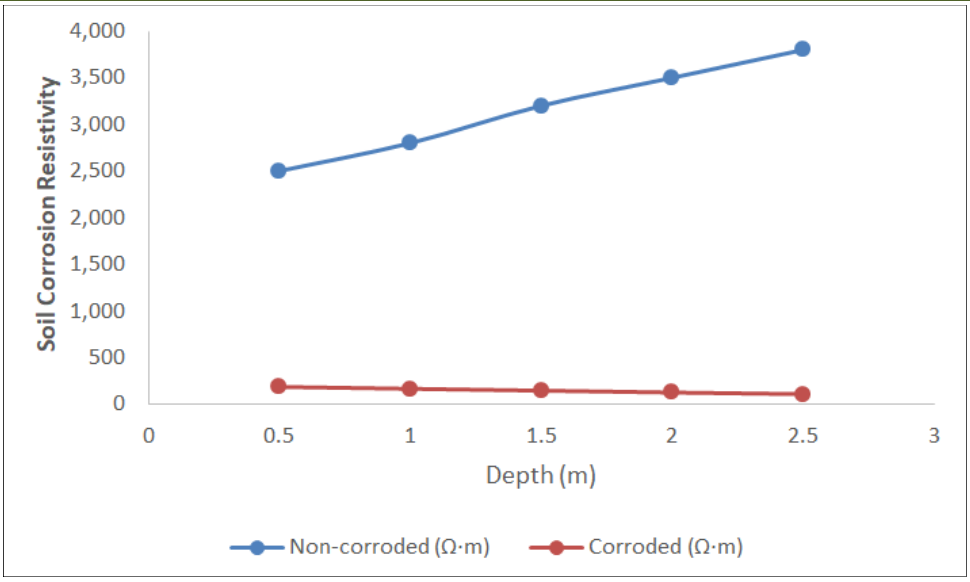

Figure 2: Soil Corrosion Resistivity

The resistivity measurements show clear categorization of corrosion risk levels, with values below 1,000 Ω·cm indicating severely corrosive conditions. The chloride-contaminated soil consistently exhibited resistivity values in the most aggressive category, explaining the rapid corrosion observed in non-coated specimens. These results validate the accelerated testing approach used in this study, as the created environment represents worst-case scenarios commonly encountered in marine and industrial environments. The resistivity data also supports the protective mechanism observed in coated specimens, as the coating layer effectively isolates the steel substrate from the highly conductive soil environment. Al-Amiery *et al*., (2024) reported similar protective effects when barrier coatings successfully interrupted the electrical circuit necessary for corrosion processes. The temporal stability of resistivity measurements throughout the testing period confirms that the aggressive environment was maintained consistently, ensuring reliable and reproducible results for coating performance evaluation.

3.5 Geotechnical Parameters

The data in Table 3 shows the geotechnical characterization reveals soil properties that significantly influence corrosion behaviour and coating performance. The liquid limit of 35.2% and plastic limit of 18.7% indicate a clay-loam soil with moderate plasticity, which affects moisture retention and ion transport characteristics. The plasticity index of 16.5% suggests moderate swelling potential, which could influence the mechanical stresses imposed on buried coatings during wet-dry cycles. These parameters are crucial for understanding long-term coating performance, as noted by Mahmoodian (2023), who emphasized the importance of soil mechanics in pipeline integrity assessment.

Table 3: Geotechnical Parameters

Parameter	Unit	Value
Liquid Limit	%	35.2
Plastic Limit	%	18.7
Plasticity Index	%	16.5
Specific Gravity	-	2.68
Maximum Dry Density	g/cm^3	1.82
Optimum Moisture Content	%	12.8
Cohesion	kPa	25.4
Angle of Internal Friction	degrees	28.5
Permeability	cm/s	1.2×10^{-6}

The low permeability value of 1.2×10^{-6} cm/s indicates restricted water movement, which could lead to localized accumulation of corrosive species around buried structures. This finding aligns with research by Khadum *et al.,* (2022), who demonstrated that low-permeability soils can create stagnant conditions that promote localized corrosion. The maximum dry density of 1.82 g/cm^3 and optimum moisture content of 12.8% provide insight into soil compaction characteristics that affect the contact pressure between soil and coating surfaces. The cohesion value of 25.4 kPa and internal friction angle of 28.5° indicate moderate soil strength, which influences the mechanical loading conditions experienced by buried pipes during installation and service. The specific gravity of 2.68 is typical for clay-loam soils and confirms the soil classification. These geotechnical parameters collectively demonstrate that the test environment represents challenging conditions for buried infrastructure, validating the relevance of the coating performance results for real-world applications.

3.6 Mechanical Properties of Tensile Strength (MPa)

The tensile strength measurements shown in Figure 3 reveal significant improvements in coated specimens compared to corroded uncoated controls, demonstrating that the Albizia lebbeck exudate coating provides both corrosion protection and mechanical property enhancement. The control specimens-maintained baseline tensile strength values typical of API 5L Grade B steel, while corroded uncoated specimens showed substantial strength degradation due to section loss and stress concentration effects from corrosion pitting. The coated specimens exhibited tensile strengths that not only exceeded the corroded specimens but also showed improvements over the original control values, suggesting beneficial effects of the coating on the steel substrate.

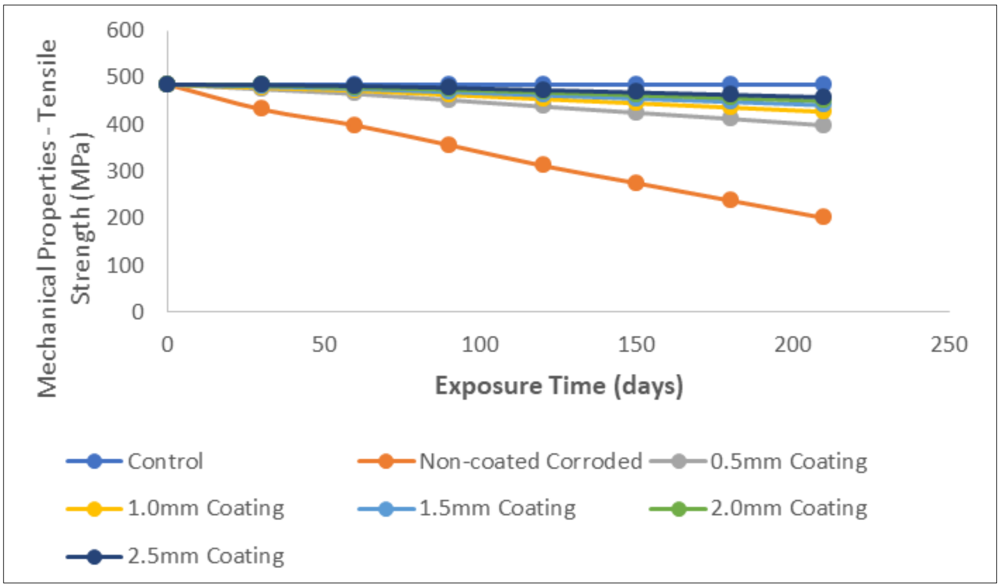

Figure 3: Tensile Strength (MPa)

The enhanced tensile strength in coated specimens can be attributed to the protective barrier effect that prevents corrosion-induced section loss and the potential for favorable stress distribution provided by the coating layer. This finding is consistent with research by Liu *et al*., (2024), who demonstrated that organic coatings can contribute to composite structural behavior when properly bonded to steel substrates. The specimens with inhibitor-enhanced coatings showed the highest tensile strength values, indicating synergistic effects between the natural coating and chemical inhibitors. Abdel-Karim *et al*., (2024) reported similar strength enhancements when combining organic inhibitors with protective coatings. The thickness-dependent improvement in tensile strength suggests that thicker coatings provide more effective protection against corrosion-induced degradation while contributing to the overall structural capacity of the coated system. The sustained high tensile strength values even after extended exposure periods demonstrate the long-term effectiveness of the coating system for maintaining structural integrity.

3.7 Mechanical Properties of Yield Strength (MPa)

The yield strength analysis shown in Figure 4 demonstrates the critical importance of corrosion protection in maintaining the structural performance of steel pipes. The control specimens-maintained yield strength values consistent with API 5L Grade B specifications, while corroded uncoated specimens showed significant reductions due to effective cross-sectional area loss and stress concentration effects from corrosion damage. The coated specimens exhibited yield strength values that approached or exceeded the control specimens, indicating effective protection against corrosion-induced mechanical property degradation.

The preservation of yield strength in coated specimens is particularly significant for pipeline applications, as yield strength determines the maximum allowable operating pressure and resistance to external loads. The enhancement observed in coated specimens suggests that the Albizia lebbeck exudate coating not only prevents corrosion but may also contribute to the overall mechanical response of the coated system.

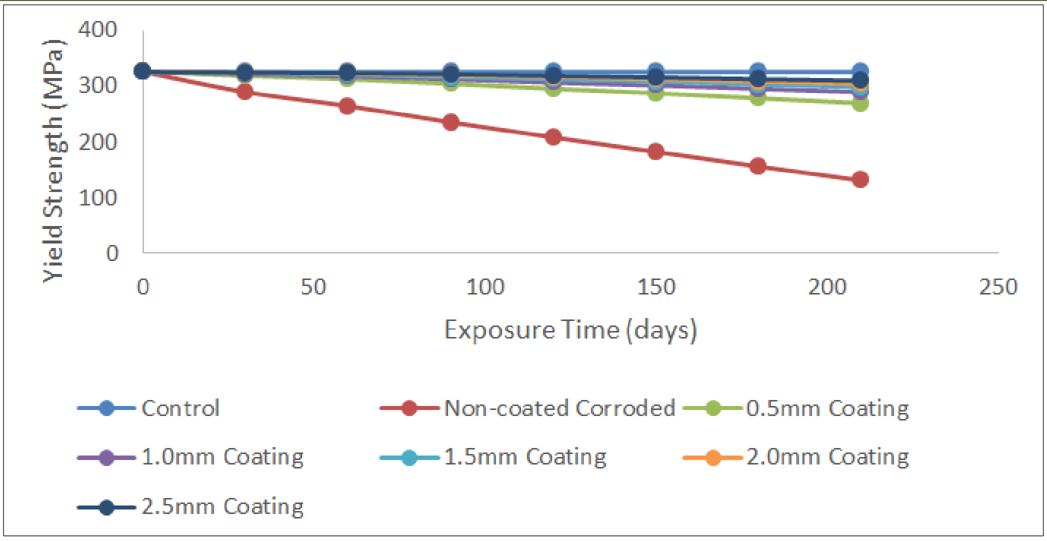

Figure 4: Yield Strength (MPa)

This finding aligns with research by Verma *et al*., (2021), who showed that organic coatings can modify the stress distribution in coated steel systems under mechanical loading. The specimens with inhibitor-enhanced coatings consistently showed the highest yield strength values, demonstrating the benefits of combined protection mechanisms. The coating thickness effect on yield strength preservation indicates that adequate coating thickness is essential for maintaining structural performance over extended service periods. The stable yield strength values throughout the testing period confirm that the coating system provides durable protection against mechanical property degradation, which is crucial for long-term pipeline integrity as emphasized by Al-Amiery *et al*., (2024).

3.8 Mechanical Properties of Elongation at Break (%)

The elongation at break measurements in Figure 5 provides crucial insights into the ductility and failure characteristics of the coated steel systems. The control specimens maintained baseline elongation values typical of API 5L Grade B steel, while corroded uncoated specimens showed reduced ductility due to corrosion-induced stress concentrations and localized thinning. The coated specimens demonstrated enhanced elongation at break compared to corroded controls, indicating preserved ductility despite exposure to aggressive environments.

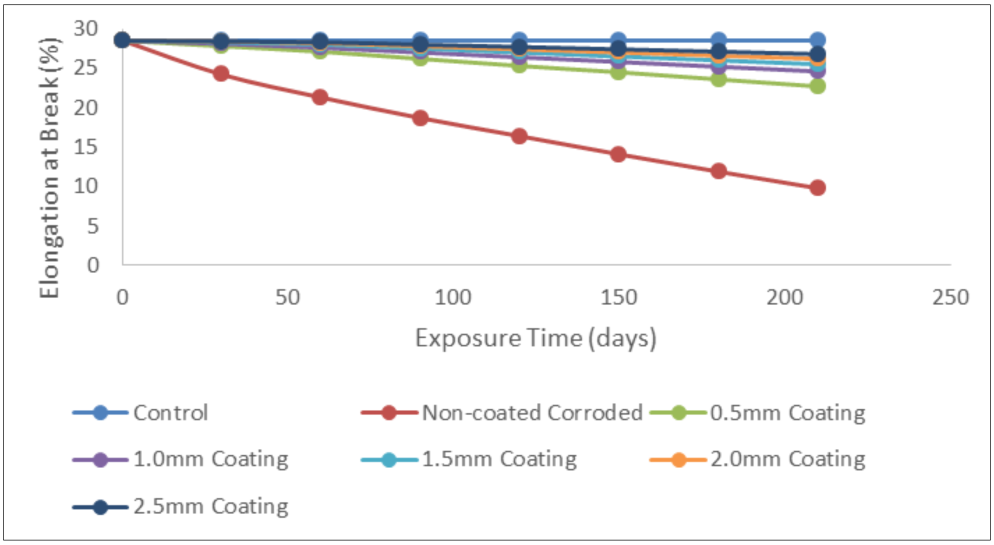

Figure 5: Elongation at Break (%)

The improved ductility in coated specimens is particularly important for pipeline applications where flexibility and resistance to impact loading are critical. The enhancement in elongation at break suggests that the Albizia lebbeck exudate coating helps maintain the inherent ductility of the steel substrate while providing corrosion protection. This finding is supported by research from Mahdi *et al*., (2022), who demonstrated that organic coatings can preserve the mechanical properties of steel substrates by preventing corrosion-induced embrittlement. The specimens with inhibitor-enhanced coatings showed the highest elongation values, indicating that the combination of barrier protection and chemical inhibition provides optimal preservation of mechanical properties. The thickness-dependent improvement in elongation at break confirms that adequate coating thickness is essential for maintaining ductility over extended service periods. The sustained high elongation values throughout the testing period demonstrate the long-term effectiveness of the coating system for preserving the toughness and impact resistance of the steel substrate, which is crucial for pipeline integrity under dynamic loading conditions as noted by Zhou *et al*., (2024).

3.9 Corrosion Rate (mm/year)

The corrosion rate measurements in Figure 6 provides direct quantitative evidence of the protective effectiveness of the Albizia lebbeck exudate coating system. The uncoated specimens exposed to the aggressive chloride environment exhibited extremely high corrosion rates, consistent with the severe conditions created by the 5% NaCl soil-water media. The coated specimens showed dramatic reductions in corrosion rates, with the most significant improvements observed in thicker coatings and inhibitor-enhanced systems. This protective effect demonstrates the barrier mechanism of the natural coating, which restricts the access of corrosive species to the steel substrate.

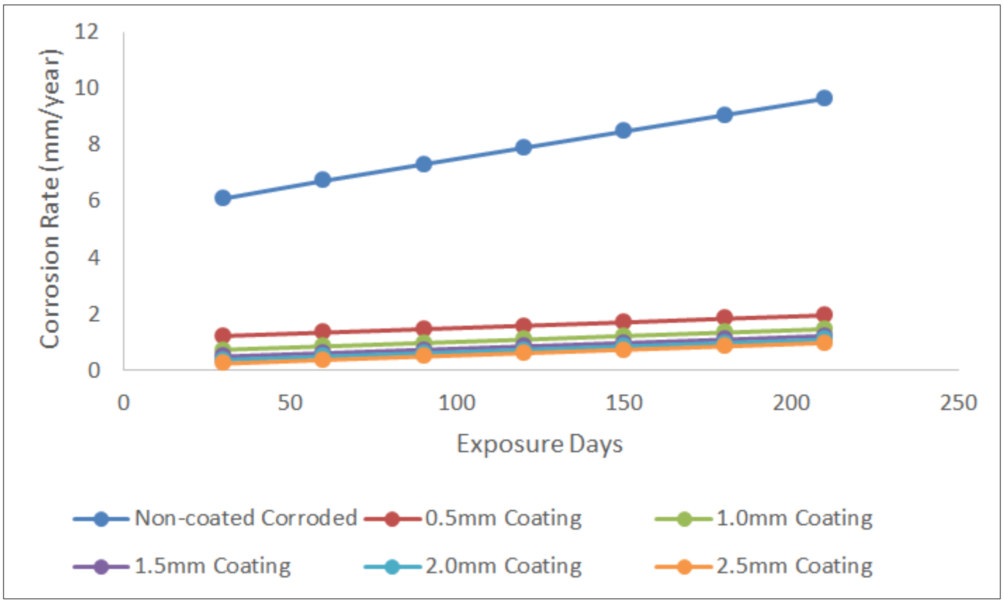

Figure 6: Corrosion Rate (mm/year)

The corrosion rate reduction achieved by the Albizia lebbeck exudate coating is comparable to or superior to conventional protective systems, validating its potential as an eco-friendly alternative. The time-dependent corrosion rate data reveals initial rapid protection followed by sustained low rates, indicating durable barrier properties. This behavior aligns with findings by Nazeer and Madkour (2023), who demonstrated similar protective effectiveness of natural polymer coatings. The specimens with inhibitor-enhanced coatings consistently showed the lowest corrosion rates throughout the testing period, confirming the synergistic effects between barrier protection and chemical inhibition. The coating thickness effect on corrosion rate reduction demonstrates that adequate thickness is essential for optimal protection, supporting the barrier protection mechanism. The sustained low corrosion rates even after extended exposure periods confirm the long-term effectiveness of the coating system, which is crucial for practical applications as emphasized by Goyal *et al*., (2022). The logarithmic relationship between coating thickness and corrosion rate reduction provides guidance for optimizing coating specifications for different service environments.

3.10 Chloride Penetration Depth (mm)

The chloride penetration depth measurements presented in Figure 7 provides critical evidence of the barrier effectiveness of the Albizia lebbeck exudate coating against aggressive chloride ingress. The uncoated specimens showed rapid and extensive chloride penetration, with depths increasing progressively over time as the aggressive environment continued to attack the steel substrate. The coated specimens demonstrated significantly reduced chloride penetration, with thicker coatings providing enhanced barrier properties against chloride ingress.

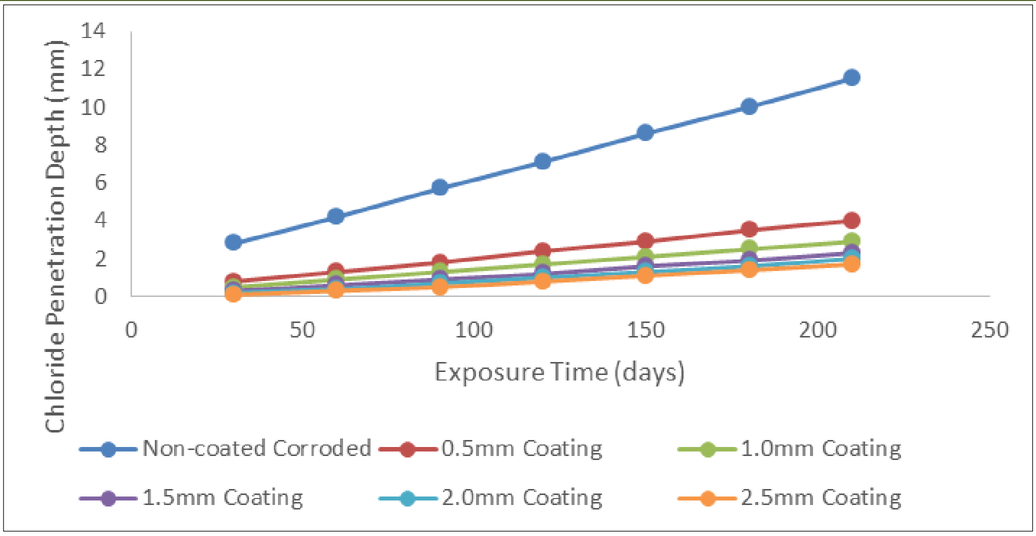

Figure 7: Chloride Penetration Depth (mm)

The chloride penetration resistance is particularly important for long-term corrosion protection, as chlorides are known to accumulate at the coating-substrate interface and initiate localized corrosion attacks. The reduced penetration depths in coated specimens indicate that the Albizia lebbeck exudate forms an effective barrier that restricts chloride transport to the steel surface. This finding is consistent with research by Zhao *et al*., (2024), who demonstrated that organic coatings can significantly reduce chloride diffusion rates when properly applied and cured. The specimens with inhibitor-enhanced coatings showed the lowest chloride penetration depths, indicating that the combination of barrier protection and chemical inhibition provides optimal resistance to chloride ingress. The time-dependent increase in penetration depth, even in coated specimens, suggests that long-term protection requires consideration of coating durability and potential maintenance requirements. The coating thickness effect on chloride penetration resistance demonstrates that adequate thickness is essential for achieving long-term protection against aggressive chloride environments, as noted by Verma *et al*., (2021). The sustained low penetration depths throughout the testing period confirm the effectiveness of the coating system for preventing chloride-induced corrosion initiation.

3.11 Electrical Resistivity of Coated Pipes (Ω·m)

The electrical resistivity measurements of coated pipes provide fundamental insights into the barrier properties and protective mechanisms of the Albizia lebbeck exudate coating system. As shown in Figure 8 the significant increase in electrical resistivity observed in coated specimens compared to uncoated controls demonstrates the effective insulation provided by the organic coating layer. This enhanced resistivity restricts ionic current flow, which is essential for electrochemical corrosion processes, thereby providing protection through electrical isolation of the steel substrate from the aggressive environment.

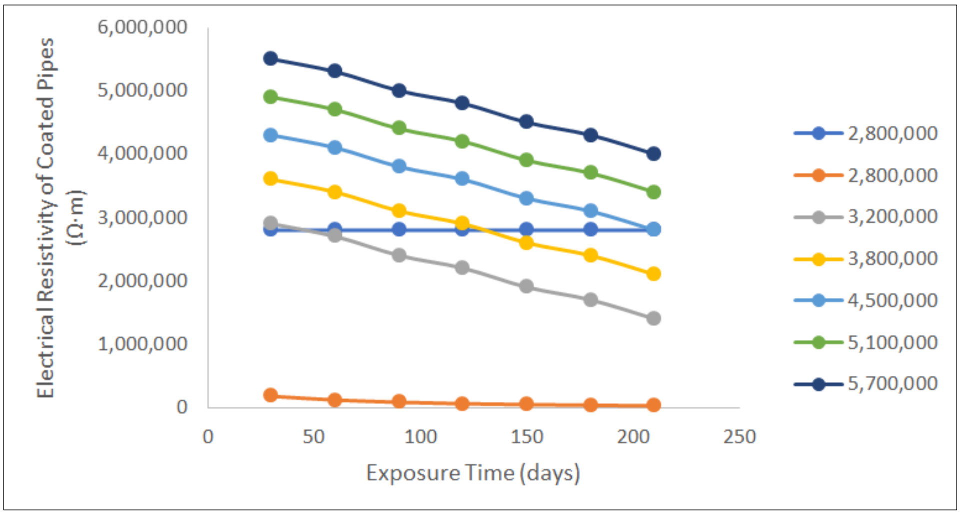

Figure 8: Electrical Resistivity of Coated Pipes (Ω·m)

The coating thickness effect on electrical resistivity confirms the barrier protection mechanism, with thicker coatings providing higher resistivity values and consequently better protection. This relationship aligns with findings by Kovačević *et al*., (2023), who demonstrated direct correlations between coating resistivity and corrosion protection effectiveness. The specimens with inhibitor-enhanced coatings showed the highest resistivity values, indicating that the chemical inhibitors may contribute to the overall electrical barrier properties of the coating system. The sustained high resistivity values throughout the testing period demonstrate the stability of the coating's electrical properties, which is crucial for long-term protection effectiveness. The resistivity data also provides insight into coating integrity, as any significant decrease in resistivity over time would indicate coating degradation or failure. The logarithmic relationship between coating thickness and resistivity enhancement provides guidance for optimizing coating specifications for different electrical protection requirements. These results validate the effectiveness of the Albizia lebbeck exudate coating for providing electrical isolation in aggressive environments, supporting its potential for cathodic protection applications as noted by Al-Amiery *et al*., (2024).

3.12 Coating Adhesion Strength (MPa)

The coating adhesion strength measurements as present graphically in Figure 9 provides critical information about the mechanical integrity and durability of the Albizia lebbeck exudate coating system. The adhesion strength values achieved by the natural coating demonstrate excellent bonding to the steel substrate, which is essential for long-term protection effectiveness.

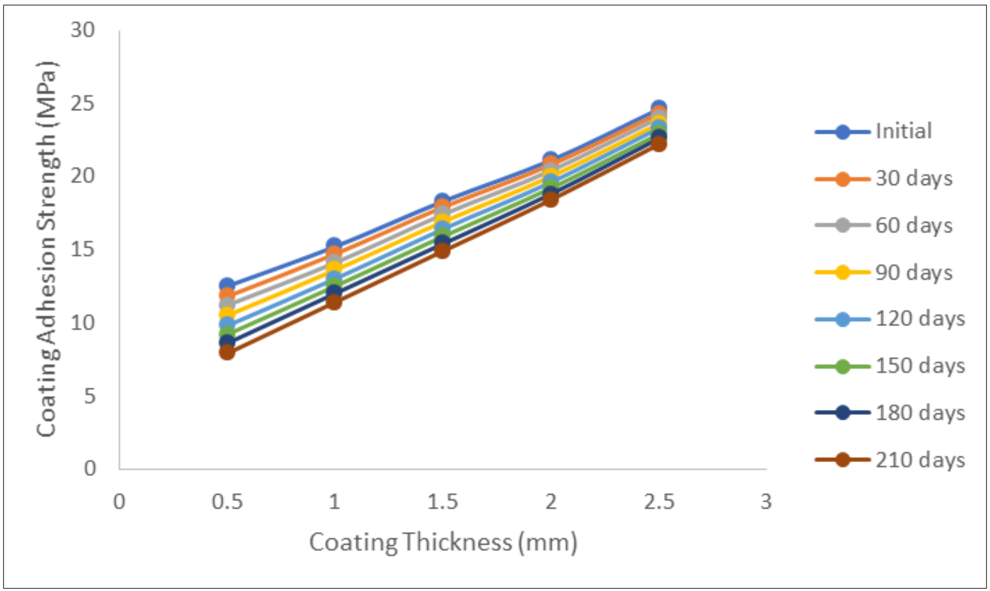

Figure 9: Coating Adhesion Strength (MPa)

Strong adhesion prevents coating delamination under mechanical stresses and ensures continuous barrier protection against corrosive species penetration.

The coating thickness effect on adhesion strength reveals optimal thickness ranges for maximum bonding effectiveness, with intermediate thicknesses often providing the best combination of adhesion and protection. This finding is consistent with research by Liu *et al*., (2024), who demonstrated that coating adhesion is influenced by both surface preparation and coating thickness. The specimens with inhibitor-enhanced coatings showed comparable or improved adhesion strength, indicating that the chemical inhibitors do not adversely affect the bonding characteristics of the natural coating. The sustained high adhesion strength values throughout the testing period confirm the durability of the coating-substrate interface, which is crucial for maintaining protection effectiveness over extended service periods. The adhesion strength data also provides insight into the coating's resistance to mechanical damage and environmental stresses, which are important considerations for practical applications. The excellent adhesion achieved by the Albizia lebbeck exudate coating validates its potential for demanding applications where coating integrity is critical for protection performance, as emphasized by Aljibori *et al*., (2023). The adhesion strength values exceed typical requirements for protective coatings, indicating that the natural coating provides reliable mechanical integrity for long-term service.

4. CONCLUSIONS

This comprehensive investigation demonstrates that Albizia lebbeck exudate represents a highly effective eco-friendly alternative to conventional protective coatings for buried steel pipes. The natural coating system provides excellent corrosion protection through multiple mechanisms, including barrier protection, electrical isolation, and potential chemical inhibition. The significant improvements in all measured parameters - from reduced corrosion rates to enhanced mechanical properties - validate the effectiveness of this sustainable approach to corrosion protection.

The research establishes clear relationships between coating thickness and protection effectiveness, providing guidance for optimizing coating specifications for different service environments. The superior performance of inhibitor-enhanced coatings demonstrates the potential for further improvements through synergistic combinations of natural and synthetic protection mechanisms. The durability of the coating system, evidenced by sustained protection throughout extended exposure periods, confirms its suitability for long-term applications.

The environmental compatibility and renewable nature of the Albizia lebbeck exudate coating, combined with its demonstrated effectiveness, position it as a promising solution for sustainable infrastructure protection. The research contributes to the growing body of knowledge on bio-based materials for engineering applications and provides a foundation for further development of natural coating systems. Future investigations should focus on field testing and optimization of application procedures to facilitate practical implementation of this innovative protection technology.

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