
Castor oil and nano-silica based multilayer coating system for improved corrosion protection of ASTM A36

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Abstract: This study aimed to evaluate the effectiveness of a castor oil and nano-silica based multilayer coating system in improving the corrosion protection of ASTM A36 in chloride-rich environments. ASTM A36 specimens were prepared and coated in four configurations: uncoated steel, epoxy-coated steel, castor oil/nano-silica-coated steel, and a multilayer system consisting of castor oil, nano-silica, and epoxy. The primer was formulated by dispersing 5 wt% nano-silica in castor oil with Triton X-100 as surfactant, followed by epoxy topcoat application and controlled curing. The coating systems were characterized using Fourier Transform Infrared Spectroscopy to identify functional group interactions, coating thickness measurements, potentiodynamic polarization for corrosion rate determination, immersion mass-loss testing for 21 days, and visual degradation observation. The results showed that the addition of nano-silica and epoxy altered the chemical structure of the coating and promoted a denser barrier network. Electrochemical testing indicated a substantial reduction in corrosion rate for coated specimens compared with uncoated steel, while thickness analysis showed that the multilayer coating produced the highest thickness and best uniformity. Immersion and physical degradation observations further confirmed that the integrated coating system improved barrier integrity and reduced corrosion damage. These findings indicate that combining castor oil, nano-silica, and epoxy is a promising strategy for developing durable and environmentally compatible anticorrosion coatings for structural steel.

Keywords: *castor oil; nano-silica; multilayer coating; corrosion protection; ASTM A36; epoxy coating*

How to Cite (APA 7th Style): Suryadi, B., Prasetya, R., & Andoko, A. (2026). Castor oil and nano-silica based multilayer coating system for improved corrosion protection of ASTM A36. *Jurnal Penelitian Saintek*, 31(2). <https://doi.org/10.21831/jps.v31i2.96941>

INTRODUCTION

Carbon-steel alloys such as ASTM A36 remain indispensable in structural, maritime, and industrial infrastructure; however, their operational reliability is critically undermined by corrosion processes triggered by moisture, dissolved oxygen, and chloride ions. In chloride-rich environments, ASTM A36 is particularly susceptible to passive film breakdown, where chloride penetration, oxygen availability, pH, temperature, and surface wettability collectively accelerate localized corrosion, especially pitting (Li et al., 2023; Salleh et al., 2024). Although two-component epoxy coatings are widely employed as protective barriers, their long-term effectiveness is limited by microdefects, moisture-induced plasticization, and insufficient resistance to chloride diffusion, often necessitating nanofiller or hybrid modifications to maintain durability (Hammouda & Belmokre, 2020). The initiation and growth of corrosion pits compromise the structural integrity of ASTM A36 steel by reducing its effective cross-sectional area, increasing local stress concentrations, and promoting crack initiation. As the pits grow, these effects can progressively reduce the material's tensile strength, yield strength, and ductility. (Songbo et al., 2021; Zhao

et al., 2020). These challenges highlight the need for advanced coating systems that can effectively inhibit chloride penetration, maintain coating integrity, and minimize corrosion-induced degradation of mechanical properties under aggressive service conditions. However, the effectiveness of such coating systems in simultaneously providing long-term corrosion protection and preserving the mechanical performance of ASTM A36 steel remains an important aspect to be investigated.

In response to these challenges, a wide spectrum of coating technologies has been investigated to enhance corrosion resistance in chloride-rich environments; however, each class of materials continues to exhibit intrinsic limitations that restrict long-term durability. Carbon-based nanomaterials, including graphene- and graphene-oxide-reinforced systems, initially provide low permeability but often suffer from nanoparticle agglomeration, microstructural defects, and instability during prolonged immersion. In some cases, graphene-containing coatings have even been reported to accelerate corrosion under extended chloride exposure due to localized galvanic effects (Dagdag et al., 2022; Madhusudhana et al., 2020; Saini et al., 2025). These dispersion-related deficiencies contrast with the more uniform segmental architecture of castor-oil-derived polymer networks, which exhibit higher crosslink densities (0.45-0.60 mol/L) than many vegetable-oil-based coatings. This molecular structure suppresses microvoid formation while providing elasticity and hydrolytic stability, making castor-oil systems more suitable as compliant foundational layers than brittle sol-gel or purely inorganic films.

Alternative approaches such as rare-earth inhibitors (e.g., CeCl_3 and PrCl_3) can form temporary protective oxide layers, yet their effectiveness deteriorates as chloride ions penetrate and destabilize the passive film during extended exposure (Panaitescu et al., 2025). Nano-silica reinforcement offers a more durable barrier mechanism by increasing matrix compactness through microvoid sealing and tortuous diffusion pathways, reducing water uptake by approximately 30-60% at optimal loadings (0.5-2.0 wt%) and maintaining performance under prolonged immersion (Wang et al., 2025). While ceramic nanoparticles such as TiO_2 , ZnO , and Al_2O_3 enhance surface hardness and wear resistance, their incorporation into organic coating matrices often introduces brittleness, particle agglomeration, and interfacial compatibility challenges that can reduce coating flexibility and long-term stability (Zhang et al., 2025). In contrast, nano-silica exhibits superior compatibility with organic phases, enabling densification of castor-oil-based layers without compromising flexibility.

Hybrid nanocomposite coatings, such as graphene-NiO-polyaniline (Gr-NiO-PANI), demonstrate strong initial corrosion protection due to synergistic interactions between conductive polymers and inorganic nanoparticles. In these systems, graphene and NiO enhance barrier properties and charge-transfer resistance, while polyaniline contributes passivation via redox-mediated film formation at the steel interface. Although such combinations delay chloride ingress during early immersion, long-term durability is often limited by moisture uptake, polymer swelling, and interfacial debonding, which promote microcrack formation and, in some cases, accelerated under film corrosion through conductive pathways (Saini et al., 2025).

By contrast, barrier-based strategies that combine nano-silica with hydrolytically stable polymer matrices rely on physical densification rather than electroactivity. Nano-silica increases coating compactness and diffusion tortuosity, while castor-oil-derived polymers provide elasticity and moisture tolerance that suppress crack initiation (Wang et al., 2025). When protected by an epoxy overlayer, this silica-densified and flexible foundation further benefits from enhanced adhesion, mechanical toughness, and long-term impedance stability, outperforming single-layer polymer coatings under extended chloride exposure (Yu et al., 2025). Collectively, these findings indicate the potential of multilayer barrier architectures to overcome the brittleness and durability limitations of conductive hybrid nanocomposites and rigid sol-gel coatings.

Existing studies collectively suggest strong complementary interactions among castor-oil-derived polymers, nano-silica reinforcement, and epoxy coatings. Castor-oil polymers provide elasticity, hydrolytic stability, and resistance to microvoid formation, making them effective stress-accommodating underlayers, while nano-silica enhances barrier density by sealing microvoids and increasing diffusion tortuosity without inducing brittleness (Wang et al., 2025). Nano-silica-epoxy systems further improve adhesion and

electrochemical impedance; however, epoxy alone remains susceptible to moisture-induced plasticization and microdefect evolution during prolonged chloride exposure (Hussain et al., 2024; Yu et al., 2025). These observations imply that integrating all three components could yield synergistic protection through combined flexibility, densification, and interfacial sealing.

Despite these complementary indications, current literature has not translated these material-level advantages into a unified multilayer design strategy. Bio-based polymers are predominantly investigated for sustainability but frequently exhibit insufficient long-term chloride resistance (Selim et al., 2022; Wang et al., 2025; Yao et al., 2025), while nano-silica is typically studied as a dispersed filler rather than as a functional densifying layer (Wang et al., 2025). Epoxy coatings are commonly evaluated either alone or with single-phase nanofillers, without consideration of how their durability depends on the mechanical compliance and barrier integrity of underlying layers (Hussain et al., 2024; Yu et al., 2025). As a result, no studies systematically investigate a coordinated multilayer architecture in which a castor-oil-based underlayer provides flexibility and hydrolytic stability, a nano-silica-rich intermediate layer enhances barrier density and tortuosity, and an epoxy topcoat supplies adhesion and mechanical sealing under chloride-rich immersion or cyclic conditions. This unresolved lack of integrated evaluation defines the research need addressed in the present study.

To address this gap, the present work introduces a fully integrated multilayer coating composed of a castor-oil-based polymer underlayer, a nano-silica-reinforced intermediate layer, and an epoxy overlayer designed to act as a unified anticorrosion system. Although prior studies have independently demonstrated the advantages of bio-based polymers, nano-silica densification, and epoxy adhesion, no existing research has combined these functionalities within a structured multilayer architecture or evaluated their coordinated behavior under chloride immersion and wet-dry cyclic conditions. By strategically integrating organic flexibility, inorganic density, and polymeric sealing, this study aims to achieve superior early-stage immersion stability, enhanced chloride resistance, and significantly improved low-frequency impedance relative to conventional single-layer or dual-component coatings. Through this composite approach, the proposed system is positioned to overcome long-standing durability limitations and deliver improved protective performance for ASTM A36 in aggressive service environments.

METHOD

Materials

Table 1. Mechanical Properties of ASTM A36

Property	Value	Unit
Yield Strength (minimum)	250	MPa
Tensile Strength	400-550	MPa
Elongation (in 200 mm)	≥ 20	%
Elastic Modulus	200	GPa
Poisson's Ratio	0.26-0.30	-
Density	7.85	g/cm ³

ASTM A36 (Table 1) carbon steel was used as the substrate material with dimensions of $10 \times 10 \times 2$ mm. A36 is a low-carbon structural steel extensively applied in construction, marine, and industrial components due to its defined mechanical properties, including a minimum yield strength of 250 MPa, an ultimate tensile strength of 400-550 MPa, and elongation exceeding 20%. These properties provide sufficient load-bearing capacity and ductility; however, the low carbon content and moderate hardness of A36 Steel result in high susceptibility to localized corrosion, particularly pitting, in chloride-containing environments. This characteristic makes A36 Steel a relevant substrate for evaluating the protective effectiveness of anticorrosion coating systems.

Pure castor oil was used as the bio-based polymer matrix for the primer layer, while nano-silica (SiO₂) with an average particle size of approximately 20 nm served as an inorganic reinforcement to enhance coating compactness and barrier performance. A bisphenol-A-based epoxy resin (Epikote 828) and curing agent (Epikure 3402) were applied as the protective topcoat at a 2:1 (wt%) ratio. Triton X-100 was incorporated as a surfactant to improve nano-silica dispersion. Acetone and ethanol were used for surface cleaning, and a 3.5 wt% NaCl solution was employed as the corrosive medium to simulate chloride-rich exposure conditions.

Steel Surface Preparation

The surface of the steel specimens was mechanically abraded using silicon carbide (SiC) abrasive papers with grit sizes ranging from 400 to 600 to remove surface oxides and contaminants. Following abrasion, the specimens were sequentially cleaned with acetone to eliminate grease and organic residues and then rinsed with ethanol to ensure complete removal of solvent residues. The cleaned specimens were air-dried at room temperature and stored in a desiccator prior to coating application to prevent recontamination.

Primer Synthesis (Castor Oil-Nano-Silica Layer)

The primer formulation was prepared by dispersing nano-SiO₂ at 5 wt% relative to the weight of castor oil. Triton X-100 (0.2 wt%) was incorporated as a dispersing agent to enhance particle stability and ensure homogeneous distribution within the polymer matrix. The mixture was subjected to magnetic stirring at 500 rpm for 30 minutes at room temperature, resulting in a uniform castor oil-silica dispersion suitable for coating application.

Coating Application and Epoxy Topcoat Deposition

The castor oil-nano-silica primer was applied onto the pretreated A36 steel substrate using a brush coating technique to form a thin and uniform layer. The coated specimens were air-dried for 8 hours to allow solvent evaporation and initial film formation. After primer drying, the epoxy topcoat was prepared by mixing Epikote 828 resin and Epikure 3402 curing agent at a 2:1 weight ratio. The epoxy formulation was then applied over the primer layer by brush coating to achieve a dry film thickness of approximately 100-150 µm. The coated samples were cured at room temperature (25-28°C) for 24 hours, followed by post-curing at 60°C for 2 hours to ensure complete crosslinking and mechanical stabilization of the epoxy network. Design of experiment was shown in Table 2.

Table 2. Design Table of experiments

Code	Layer
S1	Steel
S2	Steel + Epoxy
S3	Steel + SiO ₂ + Castor oil
S4	Steel SiO ₂ +Castor Oil + Epoxy

Characterization

Fourier Transform Infrared Spectroscopy (FTIR).

FTIR analysis was conducted using a PerkinElmer Spectrum Two spectrometer (USA) in the range of 4000-400 cm⁻¹ with a resolution of 4 cm⁻¹. Functional group identification and interfacial interactions were interpreted in accordance with ASTM E1252.

Corrosion Rate.

Electrochemical corrosion behavior was evaluated using an Autolab PGStat 302N potentiostat/galvanostat. Corrosion rate values, expressed in millimeters per year, were determined from electrochemical parameters using the calculation procedures specified in ASTM G102.

The coating thickness was measured using a digital micrometer (Mitutoyo, Japan). Thickness evaluation was referenced to ASTM D7091. Degradation resistance was assessed through mass loss measurements using an analytical balance (Mettler Toledo) after immersion exposure, with degradation expressed as percentage weight loss in accordance with ASTM G31. Macroscopic surface degradation, including rust formation, blistering, and coating deterioration, was evaluated visually following ASTM D610.

FINDINGS AND DISCUSSION

Fourier transform infrared spectroscopy (ftir)

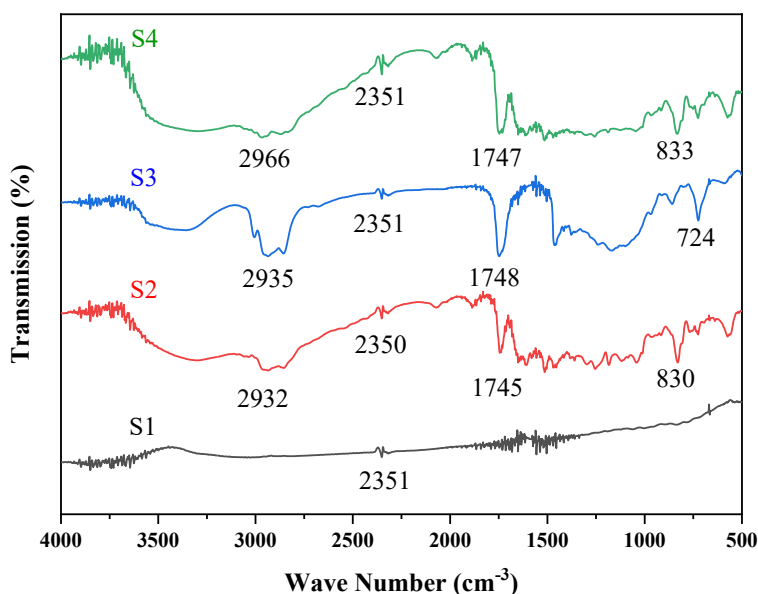


Figure 1. FTIR spectra of coating systems

The FTIR spectrum in Figure 1 shows systematic changes in chemical structure characteristics as the coating of the samples is modified from S1 to S4. Sample S1, which is based solely on castor oil without any inorganic reinforcing agents or overcoats, exhibits a dominant hydroxyl group (O-H) band at 3400-3500 cm^{-1} and a carbonyl ester (C=O) stretching band at 1730-1745 cm^{-1} , which are characteristic of castor oil triglycerides. In the modified samples (S2-S4), additional bands appear in the 700-850 cm^{-1} range, as well as a strong band at 1050-1100 cm^{-1} associated with Si-O-Si vibrations, indicating the presence and contribution of the nano-silica phase in the matrix. Furthermore, the aliphatic C-H stretching band at 2850-2950 cm^{-1} , clearly observed in S1, shows a decrease in intensity or becomes less defined in samples with more complex layered structures. These spectral changes indicate that the addition of nano-silica and epoxy layers progressively modifies the chemical environment of castor oil and the vibrational response of its functional groups.

The absence of absorption bands in the 700-850 cm^{-1} range in sample S1 is directly related

to the absence of a silica phase, as this range is generally associated with the bending or rocking vibrations of the Si-O bonds in the siloxane network. In samples S2-S4, the presence of nano-silica allows for the formation of interfacial interactions between silanol groups (Si-OH) and the polar groups of castor oil, particularly hydroxyl and carbonyl ester groups. Castor oil plays a crucial role as a reactive matrix due to its natural -OH group content, which facilitates the formation of hydrogen bonds and physical bonding points with nano-silica, thereby promoting the formation of a more interconnected and interfacially bonded structure (Han et al., 2025). The broadening of the aliphatic C-H stretching band at $2850\text{-}2950\text{ cm}^{-1}$ in the densified samples reflects reduced hydrocarbon chain mobility due to increased chain restriction by the silica network and additional crosslinking from the epoxy overcoat. The epoxy layer further acts as a secondary binder that reinforces the network through polar interactions and increased layer continuity. Overall, the evolution of the FTIR spectrum from S1 to S4 reflects a transition from a relatively loose castor oil matrix toward a more bound and interconnected organic-inorganic hybrid system, which directly implies an increase in barrier density and a reduction in electrolyte diffusion pathways in anticorrosion applications.

Corrosion rate

Table 3. Corrosion Rates of A36 Samples with Different Coating Systems

Sample	Corrosion Rate (mm/year)
S1	0.257
S2	9.16×10^{-4}
S3	0.325
S4	3.72×10^{-3}

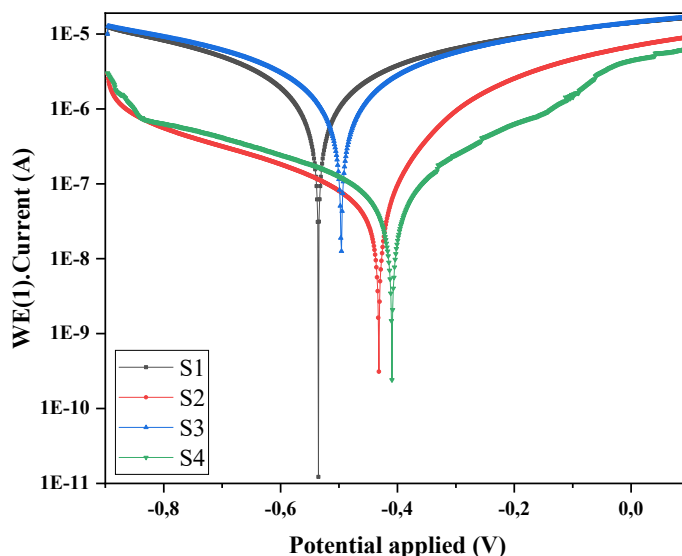


Figure 2. Polarization Behavior of A36 Steel

The potentiostatic polarization curves in Figure 2 and the corrosion rate data from Table 3 show clear differences in electrochemical degradation behavior among specimens S1 through S4. The order of

corrosion rates obtained is $S2 < S4 < S1 < S3$, with respective values of 9.16×10^{-4} , 3.72×10^{-3} , 0.257, and 0.325 mm/year. Specimens S1 and S3 exhibit relatively high corrosion current densities in both the anodic and cathodic branches, indicating that the electrolyte can easily reach the steel surface. This condition reflects low resistance to anodic iron dissolution and cathodic reduction reactions, resulting in active and continuous corrosion processes.

Conversely, specimens S2 and S4 showed a reduction in corrosion current density by several orders of magnitude compared to S1 and S3. The suppression of current in both reaction branches in the polarization curve indicates a decrease in the active electrochemical area and an increase in resistance to charge transfer. Although both specimens demonstrated significant protective performance, the reduction in corrosion current was greater for S2 than for S4. This indicates that the protective mechanisms at work in each system are not entirely identical and are influenced by different layer structures and configurations.

These differences in corrosion rates are directly related to the barrier-based protective mechanisms formed on each specimen. FTIR results indicate that the system containing nano-silica forms a Si-O-Si network that interacts with the -OH and C=O groups in the castor oil matrix, resulting in a denser and more homogeneous layer structure. In specimen S2, this organic-inorganic interaction produces a densified monolayer with a limited number of open pores, thereby making the diffusion paths for water and Cl^- ions longer and more tortuous. These conditions effectively suppress electrolyte transport toward the steel interface and explain the lowest corrosion rate value obtained for this specimen, consistent with studies showing that nano-silica densification increases barrier tortuosity and reduces ionic diffusion in protective coatings (Liu & Xu, 2025; Wang et al., 2025).

In specimen S4, the barrier protection mechanism is reinforced through the formation of a multilayer system with the addition of an epoxy overcoat. The epoxy layer acts as a sealing layer that enhances adhesion to the steel substrate and increases resistance to charge transfer. This multilayer structure increases the tortuosity of the diffusion path and suppresses both the diffusive mechanism and the kinetics of the electrochemical reaction, which has been widely reported for epoxy-based multilayer barrier coatings that improve charge-transfer resistance and corrosion protection in chloride environments (Yu et al., 2025). However, the presence of interlayer interfaces and the potential for microdefects in the multilayer system allow for residual ion transport, resulting in a slightly higher corrosion rate for S4 compared to S2.

Overall, these results indicate that the effectiveness of corrosion protection is determined not only by the presence of a protective layer, but by a combination of microstructural density, electrolyte diffusion path length, and layer interface integrity. The consistency between polarization data, corrosion rates, and chemical characterization confirms that a coating system with a structurally controlled barrier is capable of suppressing electrochemical activity and significantly improving the corrosion resistance of steel, consistent with recent studies highlighting the importance of dense barrier microstructures and diffusion-controlled protection mechanisms in anticorrosion coatings (Ramezanpour et al., 2024).

The results obtained indicate that the design of an effective anticorrosion coating system cannot rely on a single parameter, such as the presence of a coating or an increase in thickness alone, but rather on the integrated control of microstructure and interlayer interactions. The performance difference between S2 and S4 confirms that a well-densified single layer (S2) can provide very high electrochemical protection through a diffusion barrier mechanism, while the multilayer system (S4) adds mechanical benefits and interface stability through epoxy sealing, although it still leaves residual ion transport potential at the interlayer interface. Thus, anticorrosion performance is determined by the balance between microstructural densification, electrolyte diffusion path length, and the quality of interlayer interface bonding. Integration of corrosion rate data, polarization curves, FTIR, and coating thickness indicates that coating systems capable of limiting the active electrochemical area and suppressing reaction kinetics through a homogeneous structural barrier will yield more stable and controlled corrosion resistance in chloride

environments, as similarly reported in recent multilayer and nanocomposite coating studies (Ramezanpour et al., 2024). This coating structure design-based approach provides a scientific basis for understanding how coating configurations fundamentally influence the electrochemical response of steel, rather than merely empirically.

Coating thickness

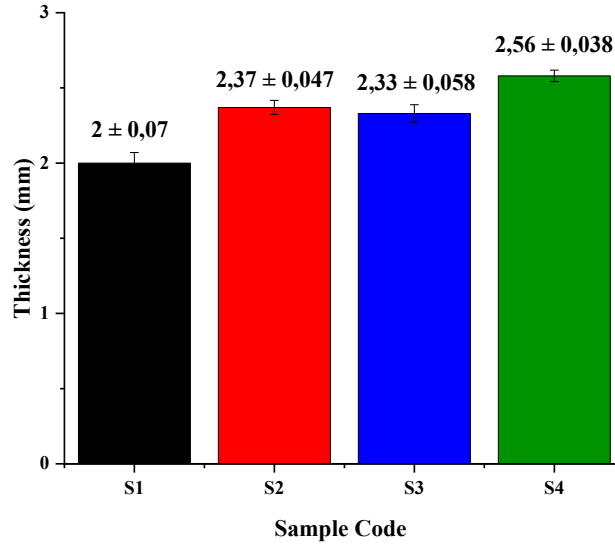


Figure 3. Comparison of Coating Thickness Samples

The thickness graph in Figure 3 shows a systematic difference between the control specimen (S1) and the coated specimens (S2-S4), which directly reflects the presence and configuration of the coating system. Specimen S1 has an average thickness of 2.00 ± 0.07 mm, which fully represents the thickness of the A36 carbon steel substrate without an additional protective coating. In specimens S2 and S3, the total thickness increased to 2.37 ± 0.047 mm and 2.33 ± 0.058 mm, respectively, indicating the formation of a coating layer with an effective thickness of approximately 370 μ m on S2 and 330 μ m on S3 over the steel substrate. The highest thickness was obtained in specimen S4, namely 2.56 ± 0.038 mm, indicating the formation of a multilayer coating system with an effective coating thickness of approximately 560 μ m. The consistent increase in total thickness from S1 to S4 demonstrates the cumulative contribution of the protective material as well as improved layer continuity in the multilayer system.

The thickness deviation value provides important information regarding the homogeneity and uniformity of the coating. Control specimen S1 exhibited a deviation of ± 0.07 mm, which stemmed from manufacturing tolerances of the steel plate and minor irregularities in the substrate surface. In the coated specimens, the thickness deviation is relatively smaller, particularly in S4, which has the lowest deviation (± 0.038 mm), indicating that the multilayer system produces a more uniform and geometrically stable coating. Conversely, S2 and S3 exhibit slightly larger deviations (± 0.047 - 0.058 mm), indicating local variations in thickness due to the coating material's distribution not being fully homogeneous, as well as the possible presence of micro-pores or discontinuities in the single-layer coating. This difference in deviation confirms that increasing the complexity of the layer structure (multilayer) not only increases

thickness but also improves coating uniformity, which has been reported for multilayer protective coatings where successive layers help stabilize surface morphology and reduce thickness variability (Ramezanpour et al., 2024).

Physically, the increase in coating thickness from approximately 330-370 μm (S2-S3) to ± 560 μm (S4) significantly extends the diffusion path length that water molecules and aggressive ions such as Cl^- must travel before reaching the steel surface. In S2 and S3, the relatively thinner coating thickness still allows for the formation of short diffusion paths, especially if there are micro-pores or local defects. Conversely, in S4, the combination of greater thickness and a multilayer structure increases the tortuosity of the diffusion path, thereby reducing the likelihood of a continuous electrolyte transport path forming toward the metal interface, consistent with barrier-based corrosion protection mechanisms reported for thick and multilayer polymer-nanocomposite coatings (Yu et al., 2025). Greater thickness also reflects a higher degree of surface coverage and a reduction in the area of the steel substrate exposed to the corrosive environment.

Differences in coating thickness and homogeneity correlate directly with the anticorrosion performance observed in electrochemical testing. Specimen S4, with the highest coating thickness (± 560 μm) and lowest deviation, exhibited the most stable barrier performance, as evidenced by a lower corrosion current density and corrosion rate compared to S2 and S3. This indicates that coating thickness not only functions as a geometric barrier but also represents microstructural densification and improved coating continuity. Thus, coating thickness acts as a primary structural parameter that simultaneously controls both physical and electrochemical barrier mechanisms, thereby significantly enhancing the corrosion protection stability of A36 steel compared to uncoated control specimens.

Degradation test

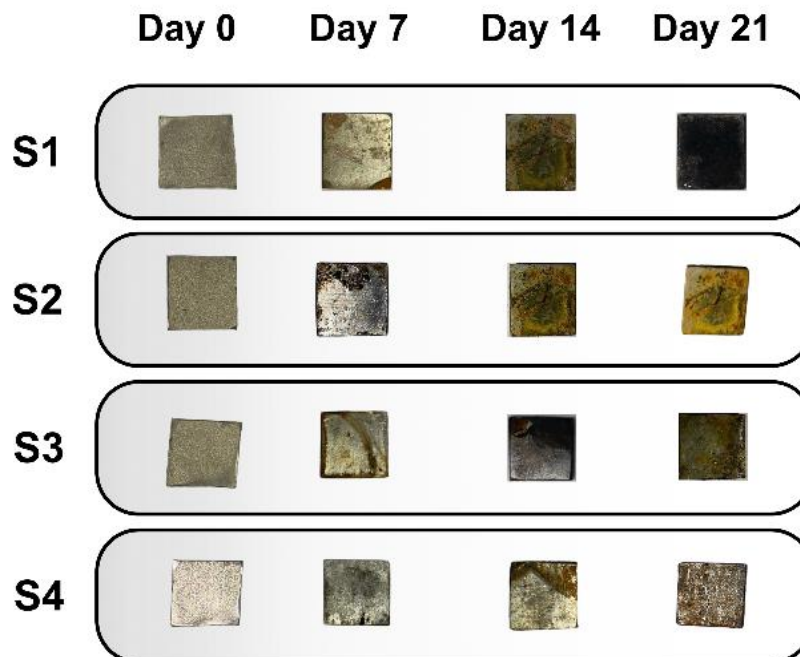


Figure 4. Physical Appearance of A36 Samples During 21-Day Immersion Test

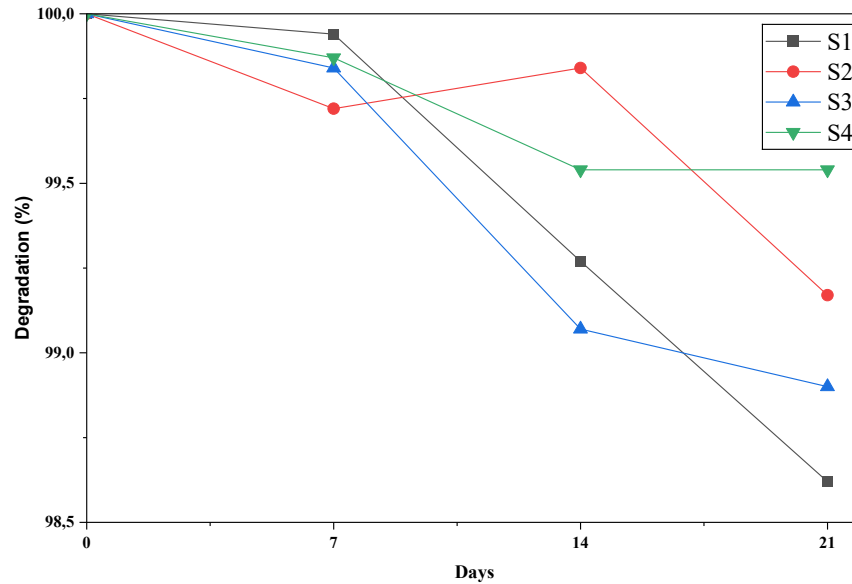


Figure 5. Mass Loss Degradation of A36 Steel Samples (S1-S4) During Immersion

The degradation behavior of the coated A36 steel samples, evaluated through combined visual observation shown in Figure 4 and 5 showing mass-loss measurements during 21 days of immersion, reflects fundamental differences in electrochemical stability and barrier performance among the coating systems. Specimen S1 exhibited the most pronounced surface degradation and the highest mass loss, which is consistent with its elevated corrosion rate obtained from potentiodynamic polarization measurements. The extensive formation of corrosion products indicates that electrolyte transport to the steel surface was not effectively impeded, allowing sustained anodic iron dissolution and cathodic reactions to proceed with minimal resistance.

Specimen S3 displayed the lowest degree of visible surface degradation and the smallest mass-loss percentage throughout the immersion period. This behavior indicates that the coating structure on S3 significantly limited electrochemical activity at the metal-electrolyte interface. The reduced mass loss can be attributed to suppressed anodic dissolution, as supported by the lower corrosion current density observed in the polarization data. The relatively intact surface morphology suggests that the coating maintained its barrier integrity, delaying electrolyte ingress and inhibiting the development of underfilm corrosion processes (Verma et al., 2023).

Specimens S2 and S4 exhibited intermediate degradation behavior, characterized by moderate mass loss and localized surface deterioration. The degradation trends of these samples correspond to their respective corrosion rates, indicating partial suppression of electrochemical reactions. In S2, the lower mass loss is associated with a reduced corrosion rate, suggesting that the coating effectively increased resistance to ionic transport and charge transfer. In contrast, S4 showed slightly higher mass loss despite the presence of a multilayer system, indicating that although electrolyte diffusion was significantly restricted, localized pathways for ionic transport remained available, enabling limited corrosion activity over extended immersion.

The correlation between physical degradation patterns and electrochemical corrosion parameters

confirms that mass loss and surface deterioration are governed by electrochemical degradation pathways. Coatings that reduce corrosion current density and limit electrochemical reaction kinetics exhibit lower rates of metal dissolution, resulting in reduced physical degradation. Conversely, higher electrochemical activity accelerates material loss and surface damage, as observed in S1. These findings demonstrate that degradation under immersion conditions is controlled primarily by the ability of the coating system to restrict electrolyte transport and suppress charge-transfer processes at the steel surface rather than by exposure time alone, as widely reported in modern anticorrosion coating studies (Najm Obaid & Al-Bermany, 2024)

CONCLUSION

The present study demonstrates that integrating a bio-based castor-oil polymer underlayer, a nano-silica-reinforced intermediate barrier, and an epoxy topcoat can significantly improve the corrosion protection performance of ASTM A36 in chloride-rich environments. The multilayer configuration effectively addresses the key limitations of conventional single-layer coatings by combining the flexibility and hydrolytic stability of castor-oil polymers with the densification capability of nano-silica and the strong adhesion and sealing properties of epoxy. The nano-silica layer contributes to increased coating compactness and tortuous diffusion pathways, thereby suppressing the penetration of aggressive chloride ions, while the castor-oil-based foundation accommodates mechanical stresses and minimizes microcrack formation. The epoxy outer layer further enhances mechanical durability and interfacial stability, preventing rapid moisture ingress and coating delamination during exposure. As a result, the integrated multilayer system exhibits improved barrier integrity, reduced corrosion degradation, and better preservation of the mechanical reliability of ASTM A36 compared with conventional coating approaches. These findings confirm that the synergistic interaction between bio-based polymers, inorganic nano-fillers, and synthetic sealing layers provides a promising strategy for developing durable and environmentally compatible anticorrosion coatings for structural steel applications operating in aggressive service environments

ACKNOWLEDGMENT

The author would like to thank Prof. Dr. Ir. Andoko S.T., M.T., the research advisor who has provided guidance, advice, and insights, and Riduwan Praseta S.T., M.T., served as scientific advisors who provided directions so that the author could complete the research.

DISCLOSURE STATEMENT

“The author(s) do(es) not have any potential conflict of interest to disclose.”

FUNDING STATEMENT

“This work does not receive funding.”

ETHICS APPROVAL

“There is no ethics approval needed because *REASON*.”

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