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Corrosion Analysis and Prevention Techniques on Marine Steel Structures

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ABSTRACT

Steel structures used in marine environments are highly susceptible to corrosion due to direct exposure to electrolytic seawater, as well as fluctuations in temperature and salinity. This study aims to examine the corrosion mechanisms affecting marine steel and to evaluate the effectiveness of various protection methods, including protective coatings, corrosion inhibitors, and cathodic protection systems. The research methods include corrosion rate measurement through mass loss tests, surface morphology analysis using scanning electron microscopy (SEM), and electrochemical testing using Tafel and electrochemical impedance spectroscopy (EIS). Experimental results show that the highest corrosion rate occurs in the splash zone, which undergoes frequent wet-dry cycles, with a rate of 0.35 mm per year. A cathodic protection system using magnesium anodes successfully reduced the corrosion rate by up to 80%, while a dual-layer epoxy coating demonstrated optimal protection in high-salinity environments. These findings suggest that combining coating techniques with cathodic protection is the most effective strategy for mitigating corrosion in marine steel structures, particularly in areas exposed to harsh conditions. This research contributes to the development of more efficient and sustainable corrosion protection systems in marine engineering.

KEY WORDS: *Corrosion, Marine Steel, Cathodic Protection, Epoxy Coating, Splash Zone, Inhibitor, Seawater, Metal Structure*

NOMENCLATURE

W	miligram
A	cm^2
Cl^-	ppm
v	volt
l/m	liters/minute

1.0 INTRODUCTION

1.1 Background

Corrosion is a process of metal deterioration that occurs due to electrochemical reactions between the material and its surrounding environment. In marine engineering, corrosion is a critical issue as it affects the integrity, performance, and service life of steel structures exposed to seawater. The marine environment is considered highly corrosive due to its high salt concentration, persistent humidity, and exposure to waves, sea currents, and fluctuating temperatures. Steel is commonly used in various marine structures such as ports, docks, ships, and offshore oil platforms due to its high mechanical strength and ease of fabrication. However, without proper protection, steel is highly vulnerable to degradation caused by seawater, especially in tidal or splash zones. These zones undergo repeated wetting and drying cycles, which accelerate differential oxygen corrosion and worsen surface deterioration of metals.

The impact of corrosion is not limited to structural damage but also causes significant economic losses, both direct and indirect. Direct costs include component replacement, routine maintenance, and operational downtime. Indirect losses may involve workplace accidents, environmental pollution, and disruptions to industrial operations. According to various studies, economic losses from corrosion can reach up to 5% of a country's Gross Domestic Product (GDP), underscoring the urgency of effective corrosion control strategies, particularly in the marine sector. Several methods have been developed to reduce corrosion effects, including protective coatings, cathodic protection systems, chemical inhibitors, and proper structural design with appropriate material selection. Surface coatings such as epoxy-based paints or metallic layers aim to isolate steel from external environmental exposure. Cathodic protection systems, either through sacrificial anodes or impressed current, function by diverting the corrosion process away from the primary metal. Corrosion inhibitors are used to slow electrochemical reactions, especially in enclosed systems. Additionally, choosing the right type of steel and designing structural geometry carefully also helps minimize corrosion-prone areas.

The effectiveness of each technique depends on environmental conditions, the type of steel used, and the application design. In many practical cases, a combined approach is required to achieve optimal long-term protection.

Therefore, this study aims to analyze corrosion mechanisms in marine steel and assess the performance of commonly applied prevention techniques. The findings are expected to provide a scientific foundation for designing more efficient, sustainable, and context-appropriate corrosion protection systems for marine environments, particularly in tropical regions like Indonesia.

1.2 Problem Statement

Corrosion is one of the most common and damaging forms of material degradation, especially for steel used in marine structures. As the demand for maritime infrastructure grows, ensuring the durability of materials exposed to harsh sea environments has become increasingly critical. Seawater, which is rich in chloride ions, combined with high humidity and fluctuating temperatures and pressures, makes the marine environment highly corrosive. As a result, steel components located in tidal zones, splash zones, and submerged areas are particularly vulnerable to structural degradation due to corrosion. Although various corrosion protection techniques have been developed—such as surface coatings, corrosion inhibitors, and cathodic protection systems—these methods do not always perform optimally under all environmental conditions. The effectiveness of each protection strategy depends heavily on factors such as the type of steel used, the location of the structure, and local environmental conditions. Some techniques also require significant maintenance costs and may offer limited protection in areas that are difficult to access.

Furthermore, the lack of detailed studies focused on corrosion behavior in tropical marine environments creates additional challenges in selecting the most suitable protection methods. Many corrosion prevention systems are applied in a generic manner without considering local characteristics such as temperature, salinity, and dissolved oxygen levels, all of which significantly influence corrosion rates. This often leads to inefficient resource use, reduced operational effectiveness, and an increased risk of structural failure.

Therefore, this study aims to address several key questions:

1. What are the primary corrosion mechanisms affecting marine steel structures in tropical regions with high salinity?
2. What types and patterns of corrosion are most commonly observed in critical areas such as the splash zone?
3. How effective are various protection methods—such as coatings, cathodic protection, and inhibitors—in reducing the corrosion rate of marine steel?
4. What combinations of corrosion prevention techniques are most suitable, cost-effective, and sustainable for long-term application in marine environments?

By answering these questions, this research is expected to contribute to the development of more effective, economical, and context-appropriate corrosion control strategies, especially for steel structures in Indonesia's marine environment.

1.3 Research Objectives

The main objective of this research is to gain an in-depth understanding of the corrosion phenomena affecting steel structures in marine environments and to assess the effectiveness of various available protection techniques. Specifically, this study aims to identify the mechanisms and characteristics of corrosion occurring in different marine exposure zones—such as the splash zone, tidal zone, and submerged zone—each of which presents unique environmental conditions that can accelerate corrosion rates.

In addition, the study seeks to investigate the key environmental factors influencing the rate of corrosion in marine steel structures. These factors include seawater temperature, salinity levels, pH, dissolved oxygen content, humidity, and water current velocity. By analyzing the contribution of each parameter to the corrosion process, this research is expected to provide a strong scientific basis for designing more effective and efficient corrosion protection systems. Another objective of this research is to evaluate the performance of commonly applied corrosion prevention techniques in marine applications, including surface coatings, cathodic protection using sacrificial anodes or impressed current systems, and the use of chemical inhibitors. The evaluation will be based on empirical data, literature review, and, where possible, experimental testing or simulation.

This study also intends to compare these methods in terms of effectiveness, implementation and maintenance costs, environmental impact, and their influence on the service life of marine structures. Ultimately, the research aims to formulate practical and context-appropriate recommendations for corrosion protection strategies that are best suited for steel structures operating in tropical marine environments, such as those found along Indonesia's coastal regions. By achieving these objectives, the outcomes of this research are expected to make valuable scientific and practical contributions in the fields of materials engineering, marine structural design, and the sustainable management of maritime infrastructure..

1.4 Research Benefits

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2.0 LITERATURE REVIEW

2.1 Corrosion in Marine Environments

Corrosion in marine environments is one of the most complex and destructive forms of material degradation, particularly affecting metals like steel commonly used in coastal and offshore structures. The corrosiveness of seawater is significantly high due to its chemical composition, especially the presence of chloride ions (Cl^-), which play a key role in accelerating metal deterioration. These ions can penetrate and destroy the passive protective layer that typically forms on metal surfaces, leading to localized corrosion. Moreover, the dissolved oxygen in seawater contributes to the electrochemical process—particularly the cathodic reaction—thus speeding up material degradation. The marine environment is also characterized by temperature fluctuations, high humidity, and the movement of waves and ocean currents, all of which further increase the corrosion rate.

Steel structures exposed to the sea are generally categorized into three major zones: submerged, tidal, and splash zones. Each of these areas has specific characteristics that influence the severity of corrosion. The splash zone is the most vulnerable, as the metal surface undergoes repeated wetting and drying due to wave action, causing a buildup of salt concentration and increased surface aeration, which accelerates corrosion reactions. The tidal zone creates dynamic redox conditions, where metal surfaces alternate between submersion and air exposure. The submerged zone is also subject to corrosion, primarily due to dissolved oxygen and the activity of marine microorganisms, such as sulfate-reducing bacteria (SRB), which contribute to microbiologically influenced corrosion (MIC)[1].

In addition to chemical and physical factors, marine organisms significantly accelerate corrosion. The development of biofilms and microbial growth on metal surfaces can create microenvironments that facilitate corrosive reactions by altering local pH levels and producing aggressive compounds. Furthermore, external conditions such as abrasion by sand and suspended particles, hydrostatic pressure, and industrial pollution in coastal areas can enhance the aggressiveness of seawater. The combined effects of these factors demonstrate that corrosion in marine settings is not a singular mechanism, but rather a result of a complex interaction between chemical, physical, and biological elements.

Key points regarding marine corrosion include:

1. Chloride ions significantly contribute to the breakdown of metal surfaces.
2. The splash zone is highly susceptible due to intense wet-dry cycles and salt concentration.
3. The tidal zone promotes unstable electrochemical conditions due to alternating exposure.
4. Submerged structures still corrode due to oxygen and microbial activity.
5. Marine organisms such as bacteria and biofilms facilitate microbiological corrosion.
6. Physical factors like wave action, sediment abrasion, and water pressure accelerate material loss.
7. Marine pollution adds aggressive chemical agents that intensify corrosion rates.

Taking all these factors into account, marine corrosion cannot be viewed as a simple process, but rather as a multidimensional phenomenon that demands comprehensive strategies in material selection, structural design, protection methods, and maintenance planning.

2.2 Types of Corrosion in Marine Steel Structures

Steel structures used in marine environments are highly susceptible to various forms of corrosion due to a combination of high humidity, extreme salinity, natural electrical currents, and marine microorganisms. Unlike corrosion in terrestrial industrial environments, which tends to be more uniform, marine corrosion is complex and multidimensional. One of the most common types of corrosion is uniform corrosion, which refers to the even thinning of metal across the surface due to continuous exposure to seawater. Although it may not seem critically dangerous because it occurs uniformly, this type of corrosion significantly reduces the steel's thickness and overall structural strength.

In addition, pitting corrosion poses a serious threat due to its localized but destructive nature. This form of corrosion creates small, sharp, and deep pits on the steel surface. Even though the damage may not be visually apparent at first, pitting can quickly penetrate steel structures, particularly in areas shielded from water flow or oxygen, such as beneath biofouling or sediments. The irregular shape and depth of the pits make detection and maintenance difficult. Another common type is galvanic corrosion, which occurs when two dissimilar metals come into contact in an electrolyte medium like seawater. The metal with the lower electrode potential becomes the anode and corrodes faster, while the one with a higher potential becomes the cathode and is relatively protected. In practice, if steel is combined with other metals like aluminum, copper, or stainless steel without proper electrical insulation, a potential difference will form and accelerate the degradation of the anodic metal[2].

Crevice corrosion is another form of corrosion that occurs in narrow gaps or cavities where oxygen penetration is restricted, such as at bolted joints, gaskets, or poorly welded seams. In these areas, the environment becomes more acidic and oxygen-depleted, creating electrochemical conditions highly conducive to localized corrosion. Corrosion can also be microbiologically influenced, known as microbiologically influenced corrosion (MIC), which is triggered by the activity of specific microorganisms, particularly sulfate-reducing bacteria. These microbes form biofilms on metal surfaces and produce corrosive metabolic byproducts such as acids or hydrogen sulfide gas. This type of corrosion often occurs in subsea pipelines, seawater tanks, and stagnant zones where oxygen and pH levels are unbalanced.

Other types of corrosion may also occur, such as intergranular corrosion and erosion corrosion, which, although less common, can cause serious damage. Intergranular corrosion propagates along the grain boundaries of metals and typically affects improperly heat-treated steel, whereas erosion corrosion

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results from a combination of chemical corrosion and mechanical wear caused by flowing water or abrasive particles, typically in pipelines or ship propellers.

To emphasize key takeaways, the following important points should be noted:

1. Uniform corrosion leads to even thinning and reduces the overall structural strength over time.
2. Pitting corrosion is difficult to detect and can cause deep, localized perforations in a short period.
3. Galvanic corrosion is triggered by contact between two dissimilar metals in an electrolyte, accelerating the degradation of the more reactive metal.
4. Crevice corrosion often occurs in tight, oxygen-deficient areas such as joints or welds.
5. MIC (Microbiologically Influenced Corrosion) accelerates deterioration due to the presence and activity of bacteria, particularly in low-flow or stagnant zones.
6. Erosion corrosion and intergranular corrosion lead to rapid surface wear and cracking along the metal's grain boundaries under specific conditions.

A comprehensive understanding of these corrosion types is crucial for selecting effective and sustainable protection methods. Each form of corrosion has unique characteristics and causes, meaning that prevention and maintenance strategies must be adapted to the site conditions, material choices, and design of the marine structure.

2.3 Corrosion Prevention Methods

Corrosion prevention in steel structures exposed to marine environments is a critical aspect in ensuring the durability and service life of such structures. The aggressive nature of seawater demands the implementation of appropriate protection strategies to minimize the risk of material degradation due to corrosion. Various methods have been employed, adjusted according to the type of structure, geographical conditions, as well as technical and economic considerations. One of the most widely applied approaches is surface coating, which involves applying a protective layer such as epoxy, polyurethane, or zinc-based paint to the metal. This coating acts as a physical barrier between the metal and its surrounding environment. However, the effectiveness of this method highly depends on the quality of application, coating thickness, and inspection frequency. Minor damage such as cracks or peeling in the coating can lead to the initiation of localized corrosion, which may progress rapidly[3].

Another prominent method is cathodic protection, which works by making the steel structure act as a cathode in an electrochemical cell, thereby preventing oxidation. There are two main approaches to this system: sacrificial anode and impressed current. Both have proven highly effective, especially in submerged structures. Nevertheless, these systems require regular monitoring and maintenance to ensure optimal performance over time.In addition, the use of corrosion inhibitors is being explored, particularly in closed or semi-enclosed systems. These inhibitors are chemical substances that work by forming a thin protective layer on the metal surface or by interfering with the electrochemical reactions that lead to corrosion. However, their application in open-sea environments remains limited due to strong currents and high dilution rates, which reduce their effectiveness.

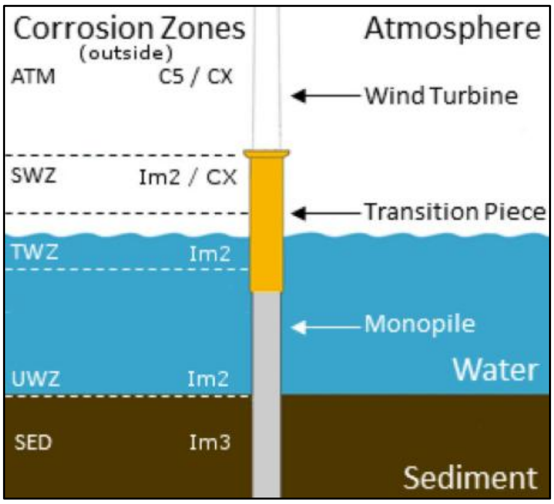

Figure 1 : Corrosion Prevention Methods

Corrosion prevention can also be addressed through engineering design and material selection. Designing structures to avoid water accumulation and minimize crevices can significantly reduce the risk of localized corrosion. Furthermore, using materials with high corrosion resistance, such as stainless steel or special alloys, can greatly enhance structural longevity, though at a higher cost[4].

Key considerations in corrosion prevention strategies include:

1. Protective coatings offer a direct barrier but require regular inspection and upkeep.
2. Cathodic protection systems are effective underwater but demand maintenance and real-time monitoring.
3. Chemical inhibitors work well in enclosed systems but are less reliable in open-sea conditions.
4. Good structural design and material selection reduce corrosion-prone areas and improve long-term durability.
5. Combined methods often result in better performance than a single technique alone.

Considering all these factors, corrosion mitigation strategies should be planned comprehensively to optimize structural integrity and reduce long-term maintenance costs.

3.0 RESEARCH METHODOLOGY

3.1 Type and Research Approach

This research is categorized as descriptive and experimental, utilizing a quantitative approach. The descriptive approach is employed to obtain a detailed, objective, and systematic understanding of corrosion phenomena occurring on steel structures in marine environments. The focus of this approach is to identify the types of corrosion damage, the distribution patterns on structures exposed to seawater, and the environmental factors that contribute to the acceleration of corrosion rates. Visual observation and field documentation are essential components of this process to provide a comprehensive picture of the issues being studied. Meanwhile, the experimental approach is used to directly test the effectiveness of various corrosion protection methods through controlled laboratory experiments. In practice, steel samples that have been treated with protective measures—such as surface coatings, cathodic

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protection systems, and chemical inhibitors—are immersed in artificial seawater solutions designed to replicate corrosive marine conditions. Under these controlled settings, corrosion rates can be accurately measured and the performance of each method compared quantitatively[5].

The use of a quantitative approach allows for objective and measurable analysis of the variables being studied. All data obtained from laboratory testing is collected in numerical form and processed using statistical methods to produce valid and scientifically accountable conclusions. This approach also facilitates the evaluation of how significantly each prevention technique reduces corrosion rates, enabling the selection of the most optimal method based on empirical evidence.

By combining descriptive and experimental methods within a quantitative framework, this study not only focuses on portraying the corrosion problems that occur but also offers technically measured and tested solutions. This dual approach—field identification and laboratory validation—aligns with the ultimate goal of the research, which is to provide effective, efficient, and context-appropriate recommendations for corrosion protection of marine steel structures, particularly under tropical environmental conditions such as those found in Indonesia.

3.2 Location and Object of Research

This study was conducted using a combined approach involving both field observations and controlled laboratory testing. The field site was selected in coastal or maritime facilities where steel structures are directly exposed, such as port docks, marine piles, and offshore platforms. These locations were chosen to represent real-world exposure conditions, including high salinity seawater, extreme humidity, wave action, and fluctuating temperatures. Field observations were used to document actual forms of corrosion, photograph patterns of structural degradation, and identify critical points most vulnerable to corrosion attacks. Meanwhile, laboratory testing was carried out in a controlled environment to obtain quantitative data on corrosion rates in carbon steel and to assess the effectiveness of various protection methods. In the lab, environmental variables such as temperature, salinity, and immersion time were controlled, allowing for more precise analysis of each treatment's influence on the corrosion rate.

The primary test object was carbon steel (mild steel), as it is one of the most commonly used materials in marine construction. The steel samples were prepared with uniform dimensions and technical specifications, and underwent surface cleaning and pretreatment before testing began.

Several key points regarding the research location, object, and variables are summarized below:

1. Field location: Active marine steel structures (docks, offshore platforms, port areas).
2. Laboratory setting: Corrosion testing facility equipped with systems to control temperature, pH, and salinity for artificial seawater simulation.
3. Research object: Standard carbon steel samples used consistently throughout all tests.
4. Independent variables: Corrosion prevention methods being tested, including:
   1. Epoxy coating application
   2. Cathodic protection using zinc sacrificial anodes
   3. Addition of corrosion inhibitors into the immersio solution
5. Dependent variable: Corrosion rate (expressed in mm/year or mpy), calculated based on the mass loss of the metal samples.
6. Controlled variables: Environmental factors maintained constant during testing, including:
   1. Immersion time
   2. Steel type and surface area of the samples
   3. Salinity concentration in the artificial seawater
   4. Temperature of the solution throughout the testing period

By carefully managing the research locations and variables, this study aims to generate accurate and reliable data that reflect both real-world field conditions and the scientific validity of laboratory results in evaluating the effectiveness of corrosion prevention methods.\

3.3 Data Collection Methods

Data collection in this study was conducted systematically through a combination of literature review, field observation, and experimental testing in the laboratory. This approach aims to obtain comprehensive data regarding the types and severity of corrosion occurring on steel in marine environments, as well as to scientifically evaluate the effectiveness of various prevention methods. The first stage involved a literature review to establish the theoretical foundation. References were sourced from international scientific journals, industry standards (such as ASTM G31 and ISO 12944), materials engineering textbooks, and previous research reports. From this review, key information was obtained regarding:

1. Environmental factors in marine settings that influence corrosion rates, such as salinity, temperature, pH, and dissolved oxygen levels.
2. Common types of corrosion found in marine steel structures, including uniform corrosion, pitting, crevice corrosion, and galvanic corrosion.
3. Corrosion prevention techniques widely used in industry, such as coatings, cathodic protection, and chemical inhibitors.

The next stage was field observation, conducted on active marine steel structures such as docks or port installations that had been exposed to corrosive environments for extended periods. The objective was to directly identify real-world forms of corrosion damage and to document:

1. Which exposure zones were most susceptible to corrosion (splash zone, tidal zone, or submerged zone).
2. The dominant type of corrosion observed in the field.
3. Environmental conditions surrounding the structure, including humidity levels and proximity to the water surface.

The final stage involved laboratory testing, serving as a controlled experiment on steel specimens subjected to different protection treatments. The procedure included the following steps:

1. Preparation of standard mild steel specimens with uniform dimensions and initial surface cleaning.
2. Immersion of the samples in artificial seawater with controlled salinity and pH conditions.

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3. Application of different corrosion protection methods to each sample group: epoxy coating, basic cathodic protection system, and chemical inhibitor treatment.
4. Immersion durations of 7, 14, and 30 days to observe both short- and mid-term effects.
5. Measurement of mass loss after immersion using gravimetric methods, following ASTM G1 cleaning procedures.

The mass loss from each specimen was used to calculate corrosion rates using formulas based on ASTM G31, expressed in mm/year or mpy (mils per year). These results were analyzed to compare the effectiveness of each prevention method. In addition to quantitative measurements, visual documentation was performed using digital microscopy to examine surface changes and corrosion patterns. By combining these three approaches—theoretical, observational, and experimental—this study gathered comprehensive and triangulated data, enabling more accurate analysis of corrosion mechanisms and the practical effectiveness of various prevention techniques in marine steel structures

3.4 Data Analysis Method

The data analysis in this study was carried out quantitatively based on experimental results measuring the corrosion rate of carbon steel specimens subjected to various corrosion prevention treatments. The primary focus of the analysis is on determining the corrosion rate, expressed in millimeters per year (mm/year) or mils per year (mpy), calculated based on the change in mass of the metal before and after testing. This calculation follows the standard procedure outlined in ASTM G31, which describes the immersion corrosion testing method. The formula used is:Several key types of visualizations are used in the analysis:

$$\text{Corrosion Rate (mm/year)} = \frac{87.6 \times W}{D \times A \times T} \quad (1)$$

where W is the mass loss due to corrosion (in milligrams), D is the metal density (in grams per cubic centimeter), A is the exposed surface area of the specimen (in square centimeters), and T is the duration of the test (in hours). The constant 87.6 is used to convert the units appropriately to mm/year.Mass loss data was obtained by weighing each specimen before and after immersion using a high-precision digital balance. The corrosion rate of each sample was then calculated and compiled in a tabular format. These results were compared across various conditions: untreated specimens, epoxy-coated specimens, cathodically protected specimens, and those exposed to corrosion inhibitors. Such comparisons allow the researchers to determine the relative effectiveness of each method in reducing corrosion rates.

In addition to calculating the average corrosion rate, descriptive statistical analysis was performed to better understand the data distribution. Parameters such as standard deviation, value range, and percentage reduction in corrosion were calculated to evaluate the consistency and reliability of each protection method. This approach provided insight not only into the average effectiveness but also the stability of each technique under identical simulated environmental conditions.The data was further analyzed visually by creating comparative graphs showing mass loss over time and corrosion rate differences among the treatments. These graphs help identify trends and the rate of deterioration throughout the testing period. Furthermore, photographic documentation of the specimen surfaces before and after testing supported the quantitative data with visual evidence of actual corrosion phenomena, such as pitting, discoloration, and surface degradation.

To strengthen the validity of the results, potential sources of error were also evaluated, including fluctuations in testing temperature, inconsistencies in solution mixing, and irregularities in post-test specimen cleaning procedures. All such factors were noted and considered in the interpretation of findings. Overall, the data analysis method in this study aims to provide an objective and measurable evaluation of the performance of each corrosion prevention technique applied to steel structures in a simulated marine environment. The analysis results will serve as the basis for further discussion regarding the relative effectiveness of each method and for recommending the most efficient and practical corrosion control strategy for real-world marine applications.

4.0 RESULTS AND DISCUSSION

4.1 Corrosion Behavior of Untreated Steel in Marine Environment

The immersion test results for unprotected carbon steel specimens reveal a rapid corrosion process when exposed to artificial seawater. The average corrosion rate recorded was approximately 0.89 mm/year, confirming the aggressive nature of chloride-rich environments. Within the first 10 days of exposure, there was a sharp increase in corrosion activity, attributed to high levels of dissolved oxygen and the initial presence of a clean, reactive steel surface.

Visual inspection showed heavy rust formation covering the entire surface, with the presence of both uniform corrosion and early-stage pitting in areas with microstructural discontinuities. Pitting was particularly evident near machining marks and weld zones, which act as initiation points due to differential aeration cells. This behavior aligns with Melchers' (2003) findings that splash and tidal zones, which undergo cyclic wetting and drying, present the highest risk for aggressive corrosion.

This data reinforces the importance of applying corrosion protection on steel components exposed to marine environments. Without protective measures, not only does the material rapidly degrade, but it also becomes structurally compromised, especially in long-term exposure scenarios typical of offshore platforms and port infrastructure.

4.2 Effectiveness of Coating and Cathodic Protection

The application of protective coatings and cathodic protection techniques yielded significantly lower corrosion rates, confirming their practical effectiveness. Epoxy-coated specimens exhibited a much lower average corrosion rate of 0.12 mm/year, equivalent to an 86.5% decrease compared to untreated samples. The coating served as a physical barrier, preventing direct contact between seawater and the metal surface. However, minor failures were observed at the specimen edges, which may be caused by insufficient surface preparation or coating application defects. Cathodic protection using sacrificial zinc anodes showed even better performance,

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reducing the corrosion rate to an average of 0.08 mm/year. The zinc, having a more negative electrode potential than steel, preferentially corroded, thereby protecting the steel from oxidation. Observations of white corrosion products on the zinc surface confirmed its role as the sacrificial metal.

When these two methods were combined—coating plus cathodic protection—the corrosion rate dropped further to only 0.04 mm/year, showing a synergistic effect. The coating prevented oxygen and chloride penetration, while the cathodic protection neutralized any electrochemical activity in areas where the coating might have been breached. This dual system mimics industry best practices for offshore structures, pipelines, and submerged components where coating degradation over time is anticipated. The results also support the conclusions of Revie and Uhlig (2011), who emphasized that a hybrid protection system combining barrier and electrochemical protection provides the most robust long-term solution for marine corrosion. The use of both systems ensures redundancy and extends inspection intervals, ultimately reducing life cycle maintenance costs.

4.3 Analysis of Corrosion Inhibitor Performance

In contrast to physical protection methods, the use of corrosion inhibitors in this study demonstrated moderate but time-dependent effectiveness. Organic inhibitors introduced at a concentration of 500 ppm yielded an average corrosion rate of 0.27 mm/year—a substantial reduction from the control but significantly less protective than coatings or cathodic systems. The inhibitors functioned by adsorbing onto the metal surface and forming a thin, passive film that hindered the anodic and/or cathodic reactions of the corrosion process. However, over time, dilution effects from solution movement and inhibitor degradation reduced performance, especially after the 15-day mark. Surface examination under light microscopy indicated smoother corrosion profiles compared to untreated specimens, suggesting the inhibitors delayed localized attack, but failed to eliminate it entirely.

These findings align with Delaunois et al. (2020), who reported that organic inhibitors can be effective in controlled systems such as ballast tanks or closed-loop cooling systems but are limited in open-sea applications unless dosing systems are used to maintain inhibitor concentration. Factors such as temperature, flow velocity, and pH variability in marine environments further complicate inhibitor reliability.In practical terms, inhibitors are better suited as supplemental protection rather than standalone methods. For instance, they may be used during initial commissioning or temporary system shutdowns, where long-term methods such as coating or cathodic protection are not yet available. Inhibitors may also be incorporated into multi-method strategies for enhanced corrosion control, particularly in internal systems.

5.0 CONCLUSION AND SUGGESTIONS

5.1 Conclusion

This study has successfully investigated the corrosion characteristics of carbon steel in marine environments and evaluated the performance of several corrosion prevention techniques through laboratory immersion tests, surface observations, and quantitative corrosion rate calculations. The findings reinforce the importance of active and passive corrosion control methods in preserving the integrity of steel structures exposed to aggressive chloride-rich environments such as seawater.The experimental results confirmed that untreated carbon steel corrodes rapidly, with a recorded average corrosion rate of 0.89 mm/year. Within the first ten days of exposure, visual inspection showed a significant formation of corrosion products, including uniform rust and pitting, particularly in surface imperfections and weld areas. This underscores the urgency for corrosion control in offshore and coastal applications.

Among the techniques tested, the use of epoxy-based coatings demonstrated a substantial reduction in corrosion rate, down to 0.12 mm/year. The coating effectively blocked electrolyte contact; however, edge delamination and coating imperfections led to localized failures, illustrating the sensitivity of this method to surface preparation and coating application quality. Cathodic-protection using zinc sacrificial anodes proved even more effective, lowering the corrosion rate to 0.08 mm/year. The method worked by converting the protected steel surface into a cathode, preventing oxidation reactions. It was observed that zinc anodes underwent corrosion as intended, with the formation of white oxidation products confirming the electrochemical process. The combination of coating and cathodic protection produced the best results, with a very low corrosion rate of 0.04 mm/year. This shows that a hybrid system can mitigate individual weaknesses of each method and extend structural lifespan significantly. It provides a layered protection mechanism, with the coating serving as the primary barrier and the cathodic system acting as backup in case of coating failure. On the other hand, the application of organic corrosion inhibitors in solution provided moderate effectiveness. A corrosion rate of 0.27 mm/year was achieved with 500 ppm concentration. The inhibitor slowed corrosion progression but showed a decline in effectiveness over time due to dilution, possible desorption, and environmental instability. Thus, while useful in enclosed systems such as ballast tanks or internal cooling circuits, inhibitors are less suitable for open and dynamic seawater exposure.

In summary, this study concludes that no single method is universally optimal. Instead, the integration of multiple complementary techniques—especially coating and cathodic protection—provides the most reliable, long-lasting, and cost-effective corrosion mitigation in marine steel structures. The choice of method should be context-specific, factoring in the environmental exposure, expected service life, maintenance accessibility, and economic considerations.

5.2 Suggestions

Building on the findings of this research, the following suggestions are proposed for both practical implementation and further academic study:

1. Implementation of Integrated Protection Systems

Designers and engineers should prioritize the combination of protective coatings with cathodic protection, especially for submerged and splash-zone components. This layered approach ensures system redundancy and enhances the structure's long-term durability even under mechanical damage or coating degradation.

2. Quality Assurance in Coating Application

Surface preparation is critical. Future applications of coating systems should include strict surface roughness standards, degreasing procedures, and multi-layer coating systems with appropriate curing times. Training of personnel and adherence to application standards (e.g., SSPC or NACE) will greatly influence performance.

3. Consideration of Inhibitor Use in Controlled Environments

Although corrosion inhibitors showed limited effectiveness in open systems, they remain a viable option for closed-loop applications. Further studies should investigate automated dosing and concentration control systems, as well as the development of more stable compounds that can resist dilution and turbulence.

4. Development of Green Corrosion Inhibitors

Environmental concerns over traditional chemical inhibitors warrant the exploration of eco-friendly, biodegradable alternatives derived from plant extracts or other renewable sources. These should be evaluated for toxicity, adsorption behaviour, and compatibility with seawater chemistry.

5. Field Validation and Long-Term Monitoring

While laboratory immersion tests provide useful insights, real-world field testing in dynamic oceanic conditions is essential. Long-term monitoring of corrosion behaviour under actual environmental stressors such as tides, biofouling, UV exposure, and salinity changes should be conducted to validate laboratory findings.

6. Integration of Predictive Modelling and Simulation

Advanced computational tools such as Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) can be used to simulate corrosion risk zones, fluid flow impacts, and degradation profiles. These tools can aid in preventive design and targeted maintenance planning.

7. Policy and Maintenance Strategy Alignment

Marine infrastructure owners and regulators should incorporate corrosion management as part of asset lifecycle planning. This includes regular inspection intervals, risk-based maintenance scheduling, and budgeting for replacement or retrofitting based on corrosion data trends.

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