



The Application of Nanocoating and Cold-Dip Galvanization on Mitigating Corrosion for Ship and Offshore Mooring Chains



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Article Info	Abstract
<p>Keywords: Mooring Chains, Corrosion, Nano coating, Seawater, Failure, Salinity, Cold-Dip Galvanization</p> <p>Article history: Received: 11/07/2024 Last revised: 14/03/2025 Accepted: 22/04/2025 Available online: 25/04/2025 Published: 25/04/2025</p> <p>DOI: https://doi.org/10.14710/kapal.v22i1.65061</p>	<p>Corrosion is a major challenge for marine vessels and offshore mooring systems due to the aggressive maritime environment characterized by high salinity, biological activity, and temperature variations. This study explores the effectiveness of nano-coatings derived from waste snail shells compared to traditional cold-dip galvanization in mitigating corrosion on ANSI A36 steel mooring chains. Three specimen groups—nano-epoxy composite coating, cold-dip galvanized, and bare metal—were tested in fresh and saltwater environments over a five-week period. Water composition, pH, and salinity were analyzed using Atomic Absorption Spectroscopy (AAS) to assess their influence on corrosion behavior. Weekly measurements of corrosion rates were taken to evaluate the protective performance of each treatment. The results demonstrated a significant reduction in corrosion rates for both nano-coated and galvanized samples compared to bare metal. Specifically, the nano-epoxy coating reduced corrosion from 0.13 mm/week to below 0.02 mm/week, while cold-dip galvanized samples showed a similar decline, converging around 0.02 mm/week. Bare metal, however, stabilized at approximately 0.05 mm/week. These findings suggest that nano-coatings are a promising, sustainable alternative to conventional galvanization, enhancing the durability and operational lifespan of mooring systems and offshore structures. This advancement supports the offshore industry's need to meet stringent classification guidelines and extend the design life of critical components. Further long-term exposure studies are recommended to confirm the sustained effectiveness of nano-epoxy coatings in marine environments.</p> <p>Copyright © 2021 KAPAL: Jurnal Ilmu Pengetahuan dan Teknologi Kelautan. This is an open access article under the CC BY-SA license (https://creativecommons.org/licenses/by-sa/4.0/).</p>

1. Introduction

Corrosions are natural processes by which metals and other materials deteriorate due to chemical reactions to their environment. The most common form of corrosion is the oxidation of metals, which typically occurs when exposed to moisture, oxygen, acids, or other reactive substances. This process leads to the formation of oxides or other compounds on the surface of the metal, which can weaken the material and lead to structural failure over time which fails mooring standards [1]. The marine environment is particularly harsh regarding corrosion due to its unique and aggressive conditions, like high salinity, moisture and humidity, oxygen availability, temperature variation, biological factors, and mechanical stresses [2]. Corrosion is a major concern for marine vessels due to their constant exposure to seawater, which is highly corrosive. Managing and mitigating corrosion on marine vessels is crucial for their safety, operational efficiency, and longevity. Mooring chains are critical components used to anchor vessels and floating structures securely in place. They are subjected to constant stress and harsh marine environments, making them highly susceptible to corrosion [3].

The pervasive and detrimental effects of corrosion on mooring chains require innovative and sustainable solutions to combat this global challenge. For station maintenance, floating structures in deep waters are anchored using mooring systems. Seawater can seriously erode a mooring line, which joins a floating construction to an anchor pile on the bottom. A portion of the mooring chain next to the anchor is frequently submerged in primary designs, making it particularly vulnerable to severe corrosion from microbiologically induced corrosion (MIC). Local corrosion is also found on chain links under the waterline, mainly occurring due to marine fouling and in the splash zone due to waves and tidal movements. Consequently, these chains are either designed with corrosion allowances or are fitted with different corrosion mitigation measures like anodic or cathodic protection (CP) systems, but over the years these mitigation measures have failed before the required design life of these structures. Also, maintaining corrosion mitigation measures poses a serious challenge to

offshore operators due to the harshness of the sea environment. Cathodic protection systems, for instance, are challenging to maintain because of the frequent wave motions that cause the anodes to become loose or displaced. Therefore, it is necessary to employ exact material loss parameters based on information from inspection agencies and literature, as well as to adjust corrosion allowance to site requirements. Furthermore, to create more effective and durable mitigation techniques for the mooring sector, new and creative coating concepts are required. The study aims to investigate the comparative effectiveness of the use of nano-coating from waste snail shell and cold-dip galvanization on ANSI A36 steel mooring chain. With a view to achieve the numerical application of corrosion rate equation for nano-coating, numerical application of corrosion rate equation of cold-dip galvanization, the application of nano-coating to metal steel plate lines, the application of cold-dip galvanization to metal steel plate line and compare study of the two methods: Nanocoating and Cold-Dip Galvanization on Mitigating Corrosion.

Corrosion is a pervasive and significant problem in various industries, including infrastructure, transportation, manufacturing, and marine applications, leading to the deterioration of materials and increased costs. The economic losses, safety hazards, and environmental implications of corrosion are discussed to highlight the significance of finding effective corrosion mitigation methods. The corrosion in mooring chains is largely influenced by environmental factors such as water temperature, salinity, and oxygen content [4]. High temperatures and salinity levels, as well as low oxygen levels, also increase the rate of mooring chain corrosion. Other causes of steel mooring chain corrosion generally depend on variables related to the alloy such as overall chemical composition and microstructure as well as the environment, such as the presence and concentration of dissolved metal ions which may initiate the corrosion reaction in the case of seawater as it is highly corrosive. Offshore mooring chains operate in this seawater characterized by high humidity, corrosive gases, and aggressive marine atmospheres [5].

Mooring chain corrosion in seawater is due to the interaction between the steel and the environment, caused by electrochemical reactions that occur at the metal surface which results from the dissolution of inorganic materials comprising almost all known elements, sometimes found in several ionic and molecular forms. Floating production unit mooring systems are subjected to constant corrosion due to site-specific harsh environmental conditions and loading resulting in the loss of strength and fatigue life as they near their design life. A huge consequence of this is the potential for premature mooring failure caused by pitting corrosion, which is sometimes reported within Floating Production Storage and Offloading (FPSO) design lives. Such mooring failures range from single to multiple line failures with damage requiring high costs for repairs or replacement [6].

On this note, effective corrosion mitigation measures on Floating Production System (FPS) mooring systems in seawater for the oil and gas industry are needed to ensure that such systems can fulfill their function since corrosion of mooring systems is significantly higher than design expectations. Despite the continuous advancements in mooring chain measurement and inspection techniques, adequate protection against mooring failures has only yielded limited progress, posing significant challenges to mooring integrity management, hence this comparative study on cold-dip galvanization and nano-coating as corrosion measures on steel mooring chains. The combination of seawater exposure, oxygen, and mechanical stress can accelerate these processes [7].

When mooring chains are exposed to the saltwater solution, the positively charged ions from the anode side of the metal atoms are made to bond with other groups of metal atoms that are negatively charged at the cathode site. The cathode and the anode are immersed in the salt solution, causing them to form their positive and negative charges. For iron and steel, the anodic reaction is:



After the metal atoms at the anode site release electrons, there are four common cathode reactions, which are:



Some forms of corrosion that attack mooring systems include:

1. Galvanic Corrosion

This corrosion, which happens when two distinct metals come into electrical contact with one another in the presence of an electrolyte, is also referred to as bimetallic corrosion or dissimilar metal corrosion. This electrochemical process leads to the deterioration of one of the metals. The process can be caused by either Electrochemical Potential Difference, Formation of a Galvanic Cell, Electrolyte Presence, or Corrosion at the Anode [8]. Prevention and control strategies for Galvanic corrosion will include material selection, insulation protective coatings, cathodic protection, corrosion inhibitors, and design considerations.

2. Crevice Corrosion

This type of corrosion is localized and happens in cracks or small areas where there is little access to the electrolyte, the working fluid. This kind of corrosion usually occurs in protected spaces or small openings where the electrolyte collects and forms a differential aeration cell, which produces a hostile corrosive environment. Here's a detailed explanation of crevice corrosion [9]. Prevention and control strategies for crevice corrosion will include design improvement, material selection, protective coatings, cathodic protection, and regular maintenance.

3. Microbiologically Induced Corrosion (MIC)

The presence and actions of microorganisms, including bacteria, fungi, and algae, are the cause of this corrosion, which is sometimes referred to as microbiological corrosion or biological corrosion. These microbes can alter the electrochemical conditions at the metal surface, which can result in localized assault and faster rates of corrosion [10]. Prevention and control strategies for MIC will include material selection, coating and linings, biocides and chemical treatments, design improvement and regular monitoring, and maintenance.

4. Stress Corrosion Cracking (SCC)

Tensile stress and a corrosive environment work together to cause this corrosion, which is a failure mechanism. This kind of corrosion is very confined and can cause materials that would otherwise seem to be in good condition to suddenly and catastrophically fail. Figure 1 shows the cause of failure in mooring chains while Figure 2 shows some examples of Severe Corrosion of Mooring Chains. Prevention and control strategies for SCC will include material selection, stress reduction, and environmental control, design improvement, regular inspection, and maintenance. From Figure 1, it can be deduced that fatigue and corrosion are the top two failure modes in mooring chains.

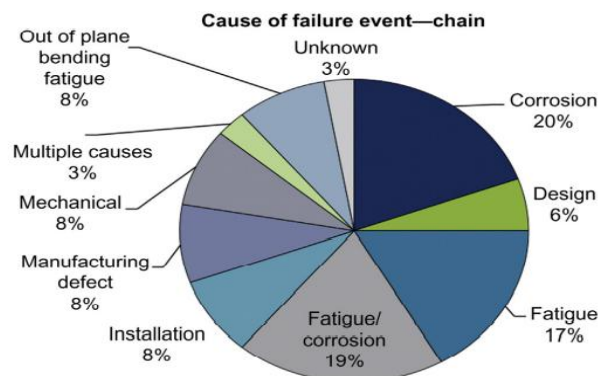


Figure 1. Causes of failure in mooring chains [11]



Figure 2. Examples of Severe Corrosion of Mooring Chains [11]

Corrosion-related failures constitute a large percentage of the oil and gas industry failures. The cost of failure due to corrosion on offshore mooring facilities is associated with both capital and operational expenditures (CAPEX and OPEX), which also include health, safety, and the environment (HSE). To mitigate these costs, there is a need for topical research on corrosion mitigation measures. The integrity of the Floating Production System (FPS) mooring systems is essential to the safety and availability of deep-water field developments as they form part of the station-keeping systems used for the exploration of offshore resources and operations. Additionally, mooring systems generate the restoring force that counterbalances operational loads [11]. Recent developments in the creation of sustainable hybrid nanocomposite coatings for the corrosion inhibition of structural metals, driven primarily by the need to preserve structural integrity and function under extreme environments, were captured by Robert et al. [12] in Hybrid nanostructured coatings for corrosion protection of base metals: a sustainability perspective. The authors evaluated different corrosion inhibition mechanisms and the trend

toward multicomponent nanostructured coatings that combine several corrosion inhibition mechanisms in a single coating system.

In a review of recent advances made in nano-composite organic coatings for corrosion protection of metals, according to Mehdi et al. [13], organic coatings' intrinsic porosity, which creates channels for corrosive species or makes them vulnerable to mechanical damage, frequently affects how well they work. However, the authors confirmed that nanoparticles have been demonstrated to enhance coatings' resistance to corrosion and enhance engineering performance via a variety of methods. They concluded that bio- and carbon-based nanomaterials are highly effective, cost-effective, and the most promising nanofillers to enhance the barrier performance of organic coatings after reviewing the performance of polymer-based nano-coatings.

According to Shen et al. [14], stainless steel's corrosion resistance might be greatly increased by more than three orders of magnitude by applying a homogenous TiO₂ nanoparticle layer on its surface. When nano-TiO₂ is exposed to UV radiation, electrons and holes are created in the coating. These electrons are then transferred to the metal substrate, making its electrode potential more negative than its corrosion potential without consuming TiO₂. This is the protection mechanism of TiO₂-based nano coating. A coating based on nano-TiO₂ shows promise in providing anti-corrosion protection for metal. Normally, TiO₂ is hydrophobic. Nevertheless, it becomes both oleophilic and hydrophilic when exposed to UV light, which will reduce the angle of the water droplets until they are nearly flattened on the metal surface.

Devin et al. [15] stated that MIC has been linked to severe corrosion on offshore structures around the world. They maintained that MIC is responsible for the extensive deterioration of mooring equipment in regions with warm nutrient-rich waters. The authors summarized a study conducted at two different locations with differing water quality in West Africa using carbon steel coupons to understand mooring corrosion due to the influence of microbiological agents.

The mechanism of localized corrosion on mooring chain steel in seawater was covered by Zhang et al. [7], which is useful while looking for appropriate monitoring equipment and mitigation techniques. Using methods like potentiodynamic polarization, linear polarization resistance measurements, and electrochemical impedance spectroscopy, the study demonstrated the corrosion behavior of chain steel grade R4 in artificial seawater in the lab and artificial seawater containing microorganisms with corrosive organisms cultivated in the lab. The study's findings demonstrated that localized corrosion happens from the beginning of exposure and can occur both in the presence and absence of microorganisms. When bacteria were present in seawater, the steel's uniform corrosion rate was significantly lower than the localized corrosion rate.

Using ship-shaped FPSOs as a case study, Wang [16] reviewed the environmental conditions and water quality at offshore mooring locations and looks into the key elements influencing mooring line load and load-bearing capability (mooring line degradation). The study recommended that risk-based monitoring and inspection of mooring systems can be crucial in enhancing mooring reliability and operational efficiency. It also highlighted recent developments in the industry in mooring performance simulations, monitoring, and mooring incident identification techniques. However, the industry has also experienced several adverse events which indicate that there is room for improvement in mooring system reliability. Owing to uncertainties of mooring failure modes, a mooring risk management plan provides a potential framework to respond to a line failure, make operational decisions, and restore mooring integrity in an efficient manner.

In design considerations, the section of the mooring chain near the anchor is often buried, making it particularly susceptible to severe corrosion caused by MIC. According to the results of the life assessment of the FPSO Bonga and SPM mooring chains, sun corals and other types of MIC have accelerated the deterioration of the mooring system's top chain links, increasing corrosion rates just above the design specifications and causing pitting on the top portion of the chain links. The severe pitting of the top chains presented the largest integrity threat to the Bonga mooring system [17]. Local corrosion is also found on chain links under the waterline, mainly occurring due to marine fouling and in the splash zone due to waves and tidal movements. Consequently, these chains have corrosion allowances or are fitted with different corrosion mitigation measures like anodic or cathodic protection (CP) systems, but over the years these mitigation measures have failed before the required design life of these structures.

To respond to the wide range of corrosion protection, recent developments in coating technology have included the combination of different types of materials for mitigating corrosion in a synergetic manner to extend the lifespan of the offshore structure and the component to provide a shield against harsh stimulating corrosive environments. In this research, the authors assessed varying modes of corrosion inhibition and the drive toward multicomponent nanostructured coatings that synergistically unite multiple modes of corrosion inhibition within a single coating system [18]. On a general note, nanomaterials have been shown to increase the corrosion resistance of coatings and improve their engineering performance through various mechanisms. The performance of polymer-based nano-coatings and carbon-based nanomaterials are very efficient, economical and the most promising nanofillers to improve the barrier performance of organic coatings [13].

It is technically recommended that operators always have baseline measurements done on all chains before installation to quantify the wear and corrosion rate of mooring chains. Chain, connector, and wire rope are the three components that cause the most mishaps, according to an analysis of mooring systems' integrity [19], [20]. In the bid to improve the corrosion resistance of mooring chains, this study employs the numerical application of the corrosion rate equation to compare the effectiveness of the use of nano-epoxy coating and cold-dip galvanization as corrosion mitigation means. Locally sourced snail shell was pulverized, pyrolyzed, and used to produce the nano-epoxy coating for corrosion mitigation check, and a comparison of results obtained from both methods was assessed. Furthermore, there is a need for innovative and alternative coating ideas to develop better and long-lasting mitigation methods for the mooring and the marine industry [21].

2. Methods

The materials used in this study are readily available and the choice of selecting these materials was based on the durability and cost. In choosing metal steel plate for mooring applications, it is pertinent to note that strength, resistance to corrosion, and resistance to environmental challenges must be considered during the material selection stage. For this work, a 12mm thickness, 1 foot by 1 foot, R4 metal steel plate was adopted as a possible metal to be used in mooring chain applications. Locally sourced snail shell pulverized and characterized on a nano level was used. Saltwater and fresh water were used to carry out real-time practical experiments in a controlled environment to check and analyze the rate of corrosion on this metal plate. In addition to the snail shell and steel plate, other materials used in the tests were:

- Weight measuring scale: This was used for mass balance of each metal sample, calibration, and to estimate the weight loss of the metal steel substrate.
- Measuring cylinder: Used to quantify and hold both fresh water and saltwater for the duration of the experiment.
- Paint brush: This was used to stir and to apply the nanocoating and zinc-rich paint on the metal steel substrate.
- Epoxy resin: This served as a solvent for preparing the composite mixture.
- Epoxy catalyst and accelerator: Used to enhance and complete the reaction of the composite mixture.
- Pyrolysis heat reactor: This apparatus was used to heat the snail shell to soft flake-like form to ease pulverization.
- Nano sieve: Used to characterize the pulverized snail shell to the nano scale.

The test configurations were considered in three setups with the first setup as the Nano-epoxy coated metal immersed in fresh water and saltwater, while in the second setup, the Zinc-rich coated metal immersed in fresh water and saltwater, and the third setup, the bare metal steel plate immersed in fresh water and saltwater.



Plate 1. Experimental materials (a) Weight Measuring Scale (b) Washed and Dried Snail Shell ready for crushing and pyrolysis

2.1 Test methodology

2.1.1 Metal Preparation

The 12mm metal steel plate is cut and machined into pilot scales such that they fit into measuring cylinders containing salt water and fresh water. Holes drilled on the metal plates for suspending them in the cylinders. Proper surface cleaning was carried out for adequate adhesion of the coating. The prepared metal plates are then dried in the open air before coating application as shown in Plate 2.



Plate 2. ANSI A36 Metal steel plate machined for surface preparation

2.1.2 Pyrolysis of Snail Shell

The process involves the thermal decomposition of crushed snail shell into flake-like white substance, mainly calcium oxide (CaO). Subjecting the snail shell to elevated temperatures in the absence of oxygen prevents combustion and allows for the decomposition of the organic components present in the shells. The process typically involves drying at a lower temperature of around 100-200°C. This stage prepares the shells for further decomposition. As the temperature increases to

around 300-600°C, the organic components within the snail shells begin to break down. Plate 3 shows the crushed snail shell and the pyrolysis process of crushed snail shell.

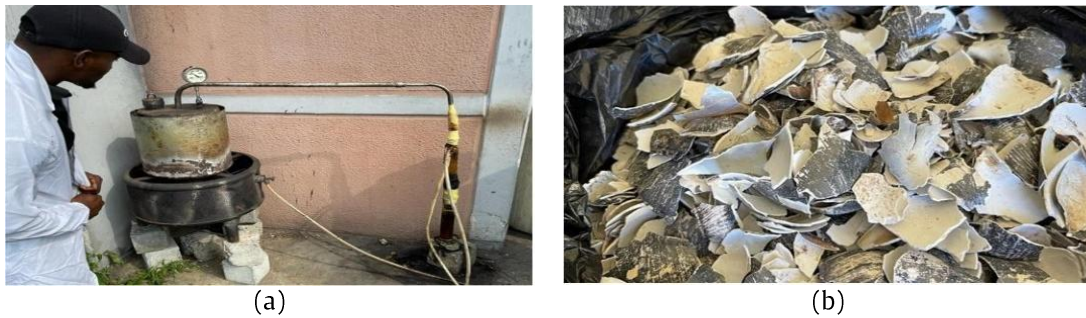


Plate 3. (a) Pyrolysis Process of Crushed Snail Shell (b) Crushed Snail Shell

2.1.3 Nanocoating Preparation

In harnessing the anti-corrosive potential of snail shell, it was processed into nanoscale particles using techniques such as grinding. This method breaks down the shells into fine particles of specific particle size range, increasing their surface area and enhancing their dispersibility in protective coatings and matrices. The nanocoating for this work is achieved by preparing an epoxy composite of epoxy resin with its chemical accelerator. The mixture is stirred continuously until color uniformity is attained. The pulverized snail shell is added as stirring continues. The mixture is then catalyzed by the addition of a binder to speed up the adhesion process to the metal substrate. Plate 4 shows the nanocoating preparation.



Plate 4. Nanocoating preparation showing: (a) Nano-pulverized snail shell; (b) Steel substrate in epoxy composite

2.1.4 Cold- dip Galvanizing Coating Preparation:

Cold-dip galvanizing involves the application of a zinc-rich coating to the surface of the metal at room temperature after adequate surface preparation. The process typically involves the use of zinc-rich paint or primer that contains a high concentration of zinc particles on a clean metal surface, using the method of brushing. The zinc particles form a protective layer on the metal surface through chemical reaction, thus providing galvanic protection to the underlying metal substrate. The coating is allowed to dry and cure, forming a protective layer on the metal surface as shown in Plate 5.



Plate 5. Cold-dip zinc galvanizing of metal steel plate

2.1.5 Heavy Metals Determination

Atomic Absorption Spectroscopy (AAS) was used to quantify the presence of metal ions in saltwater to determine the concentration of specific elements. This analytical technique relies on the principle that atoms absorb light at characteristic wavelengths when they transition from lower energy levels to higher energy levels. This indicates how the presence of heavy metals in a saltwater sample affects the corrosion of a metal steel plate. This method involves directly aspirating the sample

into an air/acetylene flame. A hollow cathode lamp emits a beam of light at a specific wavelength unique to the metal being analyzed. As this light passes through the flame, it is absorbed by the metal under investigation. The concentration of the metal ion in the saltwater sample is calculated based on the calibration curve.

2.1.6 Total Dissolved Solids (TDS) and Salinity

Electrical conductivity is often used as a proxy for salinity in water, as dissolved salts and other ions in water can increase its conductivity. It is measured in micro siemens per centimeter ($\mu\text{S}/\text{cm}$), which is a unit of electrical conductivity. The higher the conductivity, the higher the concentration of dissolved ions and salts in water and thus how this concentration will affect the corrosion of metal in fresh and saltwater. It was achieved after sample salinity value displayed on the meter screen attained stability and compared with salinity value in practical salinity unit (PSU) shown on the meter screen.

2.1.7 Potential of Hydrogen (pH)

pH quantifies the concentration of hydrogen ions (H^+) present in a solution. Corrosion is sensitive to pH, particularly in aqueous environments where metals are exposed. Here the pH meter was immersed in each fresh water and saltwater samples until a stable value was attained. However, it is important to note that the relationship between pH and corrosion is complex and depends on several factors, including the specific metal or alloy, the presence of other ions and chemicals in the environment, temperature, and the specific type of corrosion being considered.

2.2 The corrosion experiment

The corrosion experiment on the metal steel plate was conducted by creating a controlled environment that simulates the corrosive conditions of sea water where mooring chains find application. After metal plate preparation, initial measurement of the dimensions and weight of each metal sample was taken and recorded. The composition and temperature of the fresh water and saltwater were maintained at the start of the experiment to minimize errors. The samples were fully submerged but did not touch the walls of the measuring cylinder. An exposure period of five weeks was used for the experiment, and weight loss data measurement was collected weekly as regular observation and monitoring were done during the exposure period for any changes in appearance, color, or surface texture. The pH and salinity of both fresh water and saltwater were recorded weekly to learn the influence of these parameters on corrosion behavior. After the desired exposure period, the samples were removed from the solutions, gently cleaned to avoid altering the corroded surface. Final weight measurements were done, and any dimensional changes were recorded. [Plate 6](#) shows the Nano-epoxy coated metal immersed in fresh water and salt water while [Plate 7](#) shows the zinc-rich coated metal immersed in fresh water and salt water, and [Plate 8](#) shows the bare metal steel plate immersed in fresh water and salt water.



Plate 6. Setup A – Nano-epoxy coated metal immersed in fresh water and saltwater



Plate 7. Setup B – Zinc-rich coated metal immersed in fresh water and saltwater



Plate 8. Setup C – Bare metal steel plate immersed in fresh water and saltwater

2.3 Corrosion rate

Corrosion rate is an essential parameter for evaluating the effectiveness of corrosion protection measures and predicting the lifespan of metal structures in corrosive environments. The corrosion rate of a steel metal plate can be calculated using weight loss measurements. This method assumes uniform corrosion across the entire surface of the metal. It is worthy of note that corrosion rates can vary based on factors such as temperature, pH, exposure time, and the specific type of corrosive environment. The corrosion rate in this work is expressed in units of millimeters per week (mm/week). The metal surface is the area of metal plate that is exposed to the corrosive environment, and it is measured in square millimeters (mm²), while the exposure time is the duration for which the metal was exposed to the corrosive environment. The general expression for calculating corrosion rate using weight loss measurement is:

$$CR = \frac{\text{Weight loss}}{\text{Density} \times \text{Exposed area} \times \text{Exposure time}} \quad [17] \quad (6)$$

$$CR = \frac{WL}{\rho \times A \times T} \quad (\text{mm/wk.}) \quad (7)$$

CR = Corrosion Rate

WL = weight loss

$\rho = 0.00785 \text{ g/mm}^3$ or 7.85 g/cm^3 or 7850 kg/m^3 for metal steel plate

A = Exposed or projected area = *length x breadth* (mm²)

T = Exposure time in weeks

2.3.1 Calculation of Corrosion Rate for Nano-epoxy Composite Coated Metal (Setup A)

The results from this setup were recorded every week to evaluate the corrosion rate of the metal substrate and ascertain the performance of the nano-epoxy composite coating applied on the metal steel plate. The assumption here is that the metal plate is undergoing uniform corrosion, which will make for easy analysis of the corrosion rate. During this time, temperature and concentration of ions in both fresh water and saltwater were all assumed constant throughout the experiment. Using the corrosion rate expression based on weight loss measurement in Equation 6, the corrosion rate of the metal substrate is computed

2.3.2 Calculation of Corrosion Rate for Cold-dip Galvanizing (Setup B)

The results from this setup were also recorded every week to evaluate the corrosion rate of the metal substrate and learn the performance of the zinc-rich paint coating on the metal in comparison with the nano-epoxy composite coating in setup A. Uniform corrosion is still assumed for setup B in the same controlled environmental conditions. Using the corrosion rate expression based on weight loss measurement in Equation 6, the corrosion rate of the metal substrate is computed

2.3.3 Calculation of Corrosion Rate for Cold-dip Galvanizing (Setup C)

The results from this setup were also recorded every week to assess the corrosion rate of the bare metal plate in comparison with setups A and B in both fresh water and saltwater media. Uniform corrosion is maintained during this setup as well in a similar controlled environmental condition. Employing the same corrosion rate expression, the corrosion rate of the bare metal plate is computed as well.

3. Results and Discussion

The corrosion parameters considered in this work are the corrosion rate, salinity, potential of hydrogen (pH) and the total dissolved solids in both fresh water and salt water samples. The influence of these parameters on the corrosion rate on the test configurations during the exposure period is presented by the following figures below.

The corrosion rate of setup A, which involves nano-epoxy coated metal immersed in freshwater and saltwater, is illustrated in Figure 3. The graph depicts the variation of weekly corrosion rate of the metal substrate in fresh water and corrosive saltwater environment during the exposure period of this experiment. The corrosion rate for each of the specimens coated with nano-epoxy composite at the end of week 1 experienced the same corrosion rate of 0.116 mm/week irrespective of the medium the specimen was submerged under normal conditions of room temperature and pressure. This probably could have been due to uniform corrosion and the fact that there is no continuous flow of water as it is a controlled experiment. The rate of corrosion of the controlled specimen A_c in fresh water started just a few millimeters per week, above the specimen A₁ in saltwater, probably due to experimental errors in the setup and in taking weight loss measurement. The figure also shows that there was an overall decrease in the rate of corrosion throughout the five-week duration of the experiment, as depicted by the dotted trendline which serves as the average rate of corrosion during this period.

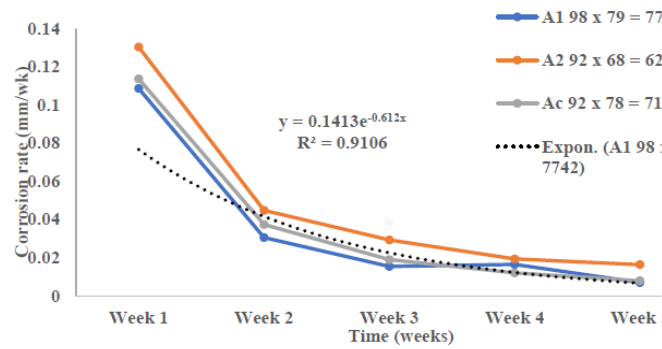


Figure 3. Weekly corrosion rate of specimens in the first setup

Figure 4 shows the plot for corrosion rate for setup B comprising zinc-rich paint coated metal steel plate in both fresh water and saltwater. The graph describes the variation of weekly rate of corrosion of the metal substrate in fresh water and corrosive saltwater environment during the exposure period of this experiment. From the plot, it can be seen that the corrosion rates were initially higher at the end of week 1 irrespective of the medium the coated metal was submerged and can be attributed to uniform corrosion. The rate of corrosion of the controlled specimen B_c in fresh water started just a few millimeters per week above the specimens B₁ and B₂ in saltwater, probably due to experimental errors in the setup and in taking weight loss measurement. The figure also shows that the rate of corrosion decreased throughout the five-week duration of the experiment as indicated by the dotted trendline which serves as the average rate of corrosion during this period.

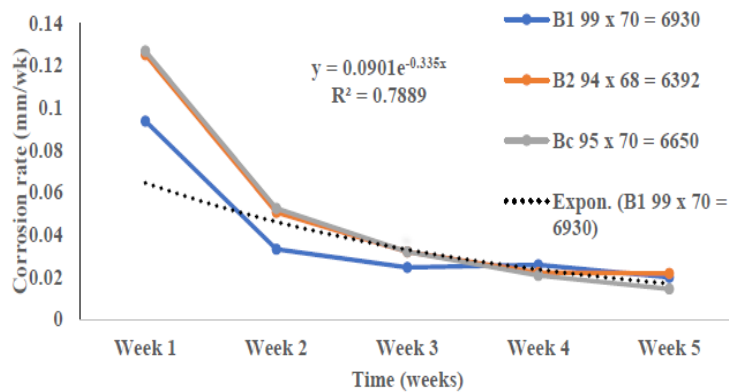


Figure 4. Weekly corrosion rate of specimens in the second setup

Figure 5 shows the plot of the corrosion rate for the experimental setup C involving the bare metal steel plate submerged in both fresh water and saltwater during the exposure period of this experiment. The graph portrays that the corrosion rate for each of the specimens experienced different outcomes at the end of week 1 in both water media under normal conditions of room temperature and pressure. This probably could have been since uniform corrosion on these plates took different rates as there was no means of mitigation on the plates. Despite an overall decrease in the rate of corrosion throughout the five weeks depicted by the trendline, the rate of corrosion of the controlled specimen C_c in fresh water started above the specimens A₁ and below A₂ in saltwater, probably due to experimental errors.

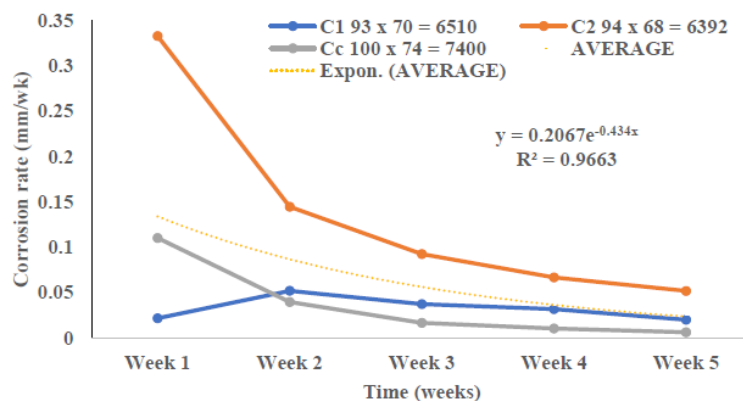


Figure 5. Weekly corrosion rate of specimens in the third setup

Figures 6-11 present the plots of pH and salinity against the rate of corrosion in the water media for the test configurations. The plots illustrate the variation of corrosion rate as the result of the effect of pH and salinity of the fresh water and the saltwater.

The results, as demonstrated in Figure 7, for the freshwater medium show the salinity was almost constant at zero, which is expected, the pH on the other hand averaged a starting point of 4 on the vertical axis, and for each test configuration. For the saltwater medium, from Figure 6, both the pH and salinity started above the zero mark on the vertical axis and increased at some weeks during the experiment period. This suggests that an increase in the alkalinity of the fresh water can lead to the formation of protective metal oxide layers on the surface of the metal substrate through passivation in such a situation where the zinc-rich coating fails in the long term. The trends show that by comparing the effect of these corrosion parameters on the rate of corrosion, the rate of corrosion remained constant throughout the exposure period of the experiment. This implies that the increase in pH and salinity of saltwater had little or no effect on the rate of corrosion on the metal steel substrate.

Figures 6-11 present the plots of pH and salinity against the rate of corrosion in the water media for the test configurations. The plot illustrates the variation of corrosion rate as the result of the effect of pH and salinity of freshwater and saltwater.

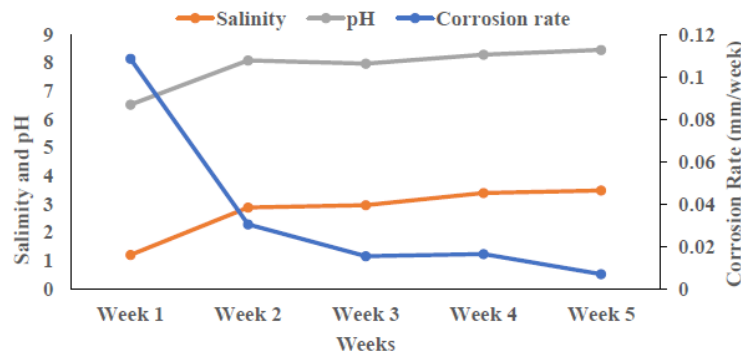


Figure 6. Effect of salinity and pH on corrosion rate in saltwater (First setup)

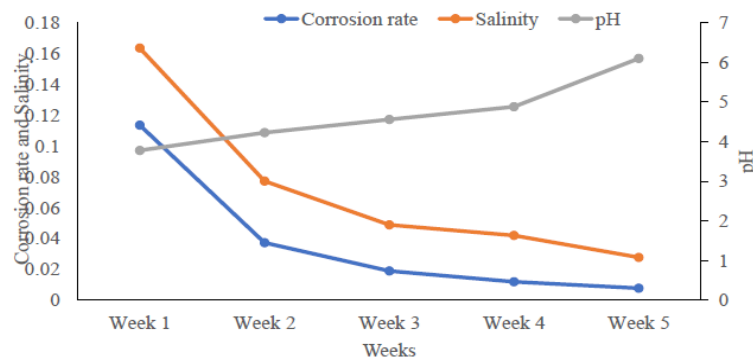


Figure 7. Effect of salinity and pH on corrosion rate in freshwater (First setup)

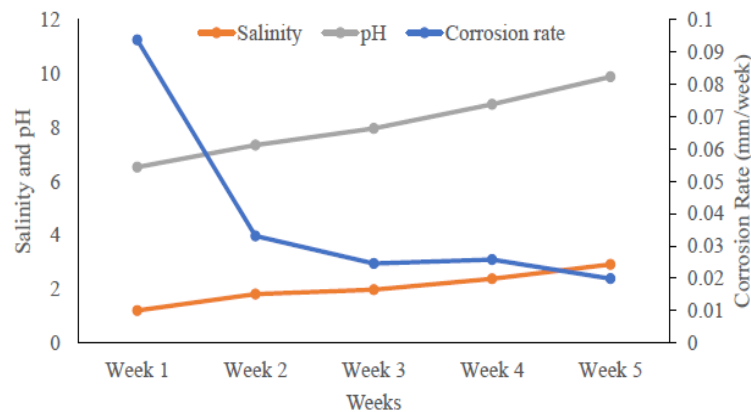


Figure 8. Effect of salinity and pH on corrosion rate in saltwater (Second setup)

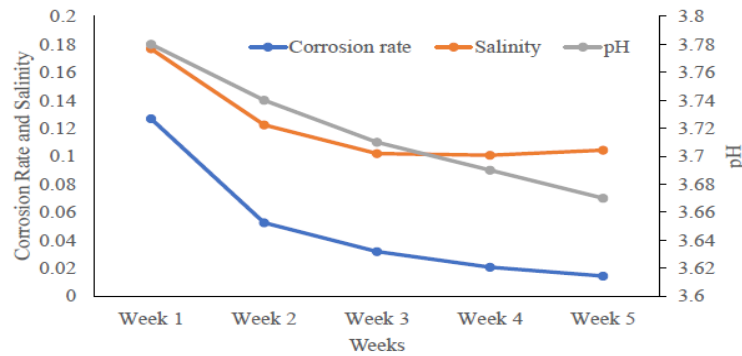


Figure 9. Effect of salinity and pH on corrosion rate in freshwater (Second setup)

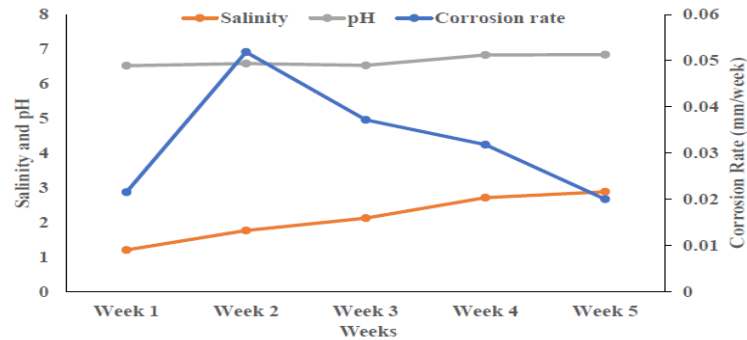


Figure 10. Effect of salinity and pH on corrosion rate in saltwater (Third setup)

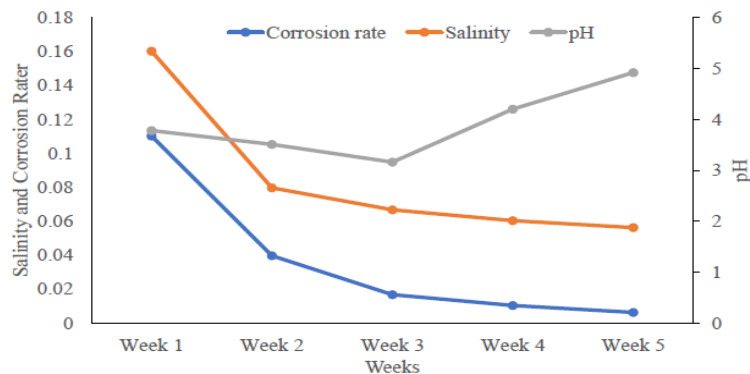


Figure 11. Plot of the effect of salinity and pH on corrosion rate in freshwater (Third setup)

4. Conclusion

With each experimental setup, it was observed that there were changes in appearance, color, or surface texture of the coated metal plates during the exposure period of the experiment. In comparing the performance of the effectiveness of the nano-epoxy composite coating in the first setup to the effectiveness of the zinc-rich paint coating in the second setup on the metal substrates, it can be seen that both coatings performed equally considering the controlled environmental conditions that the experiment was carried out. A closer look shows that the nano-epoxy composite coating performed a little better compared to the zinc-rich paint coating at the end of the experiment since the corrosion rates were below 0.02 mm for the weeks on the vertical cartesian coordinate. This is also demonstrated by the trendline. The trendline for nano-epoxy coating is steeper than that of zinc-rich paint coating. Hence, the decreasing trend in the corrosion rate suggests a reduction in the corrosion process or improvement in the corrosion mitigation measures applied on metal steel used in mooring chain applications.

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