



ACCELERATED CORROSION EFFECTS ON STEEL PIPE PILE MATERIALS IN SIMULATED NHA TRANG SEAWATER, VIETNAM

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Abstract. Steel pipe piles are widely used in coastal infrastructure due to their high strength and durability. However, in tropical marine environments like Nha Trang, Vietnam, the high chloride content, temperature, and humidity significantly accelerate the corrosion process. Despite their extensive application, no published studies have specifically addressed the corrosion behavior of steel pipe piles in Vietnam's marine environment. This study investigated the accelerated corrosion effects on steel pipe pile materials in a simulated Nha Trang seawater environment, representing typical coastal conditions in Vietnam. Using an accelerated corrosion testing method, steel pipe pile material samples were exposed to controlled Nha Trang seawater conditions with varying salinity and environmental factors such as temperature and pH. The objective of this experiment was to analyze the corrosion rate and determine the corrosion mechanisms within a short period, simulating long-term effects typically seen in real seawater environments. The experiment revealed mass loss and pitting corrosion morphology on SKK490 samples, highlighting the degradation caused by high chloride content and other conditions in the Nha Trang simulated seawater environment. The results provide critical insights into the corrosion behavior specific to Nha Trang seawater environment of Vietnam, particularly regarding the reduction in cross-sectional area of the steel pile materials. These findings offer valuable guidance for coastal infrastructure projects, especially in the selection of appropriate materials and the development of effective corrosion prevention strategies for long-term use in seawater environments.

Keywords: accelerated corrosion testing, steel piles, Nha Trang seawater, corrosion prevention, comparative analysis.

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1. INTRODUCTION

Vietnam, with over 3,260 (km) of coastline and a vast maritime area, has been vigorously developing marine-based industries, including maritime transportation, coastal infrastructure construction, and offshore oil and gas exploration projects [1]. Among these, Nha Trang City, located in Khanh Hoa Province, stands out as a strategic area with several important seaports and coastal structures. However, the tropical marine environment characteristic of Nha Trang presents significant challenges for the construction and maintenance of steel structures due to the effects of corrosion. Factors such as high temperatures, high humidity, and particularly high chloride content in seawater have been severely impacting the lifespan of steel structures, including steel piles, which are widely used in port foundation, underground structures, and other coastal infrastructure [2].

The issue of corrosion in the marine environment not only leads to structural degradation and safety concerns but also results in high maintenance, repair, and replacement costs [3]. Understanding the corrosion mechanisms and the extent of corrosion affecting steel piles in the Nha Trang seawater environment is crucial for developing optimal technical solutions to protect these piles. This study focuses on evaluating the impact of accelerated corrosion processes on steel pile materials in simulated Nha Trang seawater conditions in the laboratory. The study aims to recreate the actual conditions of Nha Trang seawater, and through accelerated corrosion experiments, analyze the degree and morphology of corrosion of the steel pile materials in Nha Trang seawater.

The goal of the study is to provide a comprehensive understanding of the corrosion levels of steel pile materials in the Nha Trang seawater environment, thereby offering practical recommendations to enhance the load-bearing capacity and lifespan of steel piles. This research is not only crucial for coastal infrastructure development projects in Vietnam but also contributes to the development of more sustainable design, maintenance, and repair strategies in harsh marine environments, helping to reduce operational costs and improve long-term safety.

2. EXPERIMENTS

2.1. Experimental method and applied standards

The corrosion experiment utilizes the Accelerated corrosion testing with impressed current method. This is an advanced experimental method designed to evaluate the corrosion rate of metal materials in a controlled environment, commonly used to simulate the harsh conditions that materials may face in reality [4, 5]. This method uses an impressed current to accelerate the corrosion reaction, allowing for a quick assessment of the durability and reliability of materials under various conditions [6].

The electrochemical accelerated corrosion test is conducted based on the following standards:

ASTM G31 - Standard Guide for Laboratory Immersion Corrosion Testing of Metals [7]: This standard is applied to determine the sample size, immersion procedure, and duration of the immersion test for steel samples in simulated Vietnamese seawater.

ASTM G102 - Standard Practice for Calculation of Corrosion Rates and Related Information from Electrochemical Measurements [8]: This standard is applied to calculate parameters such as the impressed current applied to the test samples in the experiment.

ASTM G5 - Standard Reference Test Method for Making Potentiostatic and Potentiodynamic Anodic Polarization Measurements [9] : This standard is applied to set up the applied electrode system and reference electrodes in the experimental setup for the study.

2.2. Sample design

SKK490 is a commonly used steel type for many coastal constructions in Vietnam due to its advantages in structure and technical characteristics, such as at Dung Quat Port (Quang Ngai), Son Duong Port (Ha Tinh), and others. Therefore, the study selects SKK490 steel for corrosion experiment. SKK490 is a high-strength structural pipe steel according to JIS A5525 standards, with good mechanical properties and a tensile strength of approximately 490 - 610 (Mpa) [10]. The test results of the main chemical composition and mechanical strength of SKK490 steel are presented in Table 1 and Table 2.

Table 1. Test results of the main chemical composition of SKK490 steel.

Composition	SKK490 steel
Carbon (C)	0.17 (%)
Silicon (Si)	0.30 (%)
Manganese (Mn)	1.40 (%)
Phosphorus (P)	0.035 (%)
Sulfur (S)	0.03 (%)
Niobium (Nb)	-
Vanadium (V)	-
Titanium (Ti)	-

Table 2. Test results of the mechanical strength of SKK490 steel.

Composition	SKK490 steel
Yield strength (MPa)	325
Tensile strength (MPa)	510
Elongation (%)	17 (%)

The typical thickness of large-diameter steel pipe piles in coastal structures ranges from 12 (mm) to 16 (mm) to ensure load-bearing capacity. Therefore, this study selects three sample thicknesses: 12 (mm), 14 (mm), and 16 (mm), with uniform dimensions (20×200 (mm)). The test samples are cleaned with a solvent to remove dust, grease, and other contaminants, then rinsed with distilled water and dried at room temperature.

Table 3. Sample labeling for the experiment

Composition	Dimensions (mm)	Thickness (mm)	Sample Code
SKK490 bare steel	20×200	12	SKK490 - 12
	20×200	14	SKK490 - 14
	20×200	16	SKK490 - 16

2.3. Design of the simulated solution according to Nha Trang seawater conditions

According to data collected by a group of scientists from the Vietnam Institute of Marine Resources and Environment, the seawater temperature measured in Nha Trang Bay ranges

from 24.7 (°C) to 32.9 (°C). Meanwhile, the seawater pH fluctuates significantly, ranging from 7.82 to 8.36, with an average of 8.1. The average salinity across the observations is 30‰, indicating the characteristics of salty seawater. The turbidity of seawater in Nha Trang Bay is relatively low, ranging from 1.0 to 3.3 (NTU), with an average value of 1.40 (NTU), which is considered favorable for coral reef development [11]. To ensure the simulation of the Nha Trang seawater environment, the pH of the experimental solution is set at 8.18, corresponding to the average value.

The seawater in the Nha Trang area has characteristics as shown in Table 4.

Table 4. Seawater characteristics of the Nha Trang are [12].

Chemical composition	Unit	Range	Concentration
Cl ⁻	mg/l	Max	19702
		Min	19525
SO ₄ ²⁻	mg/l	Max	25147
		Min	2501
Na ⁺	mg/l	Max	9957
		Min	9926
Mg ²⁺	mg/l	Max	1200
		Min	1000
Ca ²⁺	mg/l	Max	65.6
		Min	24.4
K ⁺	mg/l	Max	680
		Min	-

The high concentration of Cl⁻ ions in seawater is a key factor driving the corrosion process of metals. Cl⁻ ions participate in the mechanism of breaking down the protective oxide layer on the metal surface, leading to electrochemical attack and localized corrosion, especially in metals like stainless steel. In the case of Nha Trang seawater, the measured Cl⁻ ion concentration is 19702 (mg/L), corresponding to a molar concentration of approximately 0.556 (mol/L). This concentration reflects the high Cl⁻ ion content in seawater, which plays a crucial role in determining salinity and other physicochemical properties.

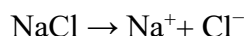
To prepare the experimental solution with a pH of 8.18 and a Cl⁻ ion concentration of 19702 (mg/L), specific adjustments need to be made for both pH and Cl⁻ ion concentration

2.3.1. Adjustment of Cl⁻ ion concentration

Calculating the required amount of NaCl: The concentration of Cl⁻ ions is provided by sodium chloride (NaCl), where 1 mol of NaCl yields 1 mol of Cl⁻ ions. The molecular weight of NaCl is 58.44 (g/mol), and Cl⁻ accounts for 35.45 (g/mol) of this. The formula to calculate the required amount of NaCl to achieve the desired Cl⁻ ion concentration in the solution is based on the basic principles of quantitative chemistry and concentration calculations. The steps to perform the calculation are as follows:

- Basic principle:

The relationship between concentration and mass: For a simple salt like sodium chloride (NaCl), when dissolved in water, it fully dissociates into ions:



Using molecular weight (mol): The molecular weight of NaCl is 58.44 (g/mol), meaning 1 (mol) of NaCl contains 58.44 (g) of NaCl. Out of this, Cl⁻ accounts for 35.45 (g/mol) of the total mass. This means that in 1 (mol) of NaCl, there are 35.45 (g) of Cl⁻ ions.

Mass ratio between NaCl and Cl⁻: From the molecular weight of NaCl and Cl⁻, the amount of NaCl needed to achieve the desired concentration of Cl⁻ ions can be calculated.

This ratio is calculated as follows:

$$\frac{\text{Molecular weight of NaCl}}{\text{Molecular weight of Cl}^-} = \frac{58.44}{35.45} = 1.647 \quad (1)$$

- Calculating the required mass of NaCl:

Given that the desired Cl⁻ ion concentration is 19702 (mg/L), the necessary NaCl concentration for the test solution can be calculated using the formula:

$$\text{NaCl concentration} = \text{Cl}^- \text{ concentration} \times 1.647 = 19.702 \times 1.647 = 32.48 \text{ (g/l)} \quad (2)$$

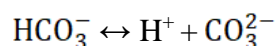
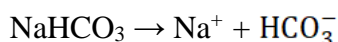
Therefore, to achieve a Cl⁻ ion concentration of 19702 (mg/L), 32.48 (g) of NaCl needs to be dissolved per liter of water.

2.3.2. Preparation of the test solution

To prepare the test solution with a pH of 8.18 and a Cl⁻ ion concentration of 19702 (mg/L), the test solution is made by mixing 1 (litter) of purified water, 32.48 (g) of NaCl, and a necessary amount of buffering additive to neutralize the solution as follows:

- Basic principle:

Sodium bicarbonate (NaHCO₃) is a commonly used buffering additive in the preparation of test solutions in Vietnam. When dissolved in water, it dissociates into the following ions:



To determine the required amount of NaHCO₃ for the test solution, the Henderson-Hasselbalch equation is used. This equation is applied to calculate the pH of buffer solutions in particular, and weak acid solutions in general, based on the concentration ratio of their components [13]:

$$\text{pH} = \text{pK}_a + \log \left(\frac{[\text{Base}]}{[\text{Acid}]} \right) \quad (3)$$

Where:

K_a is the acid dissociation constant.

[Base] is the concentration of the conjugate base (the remaining part after the acid has donated its H⁺ ion).

[Acid] is the concentration of the weak acid.

- Calculating the required amount of NaHCO₃:

Considering the dissociation of NaHCO₃ in water as mentioned, we have:

$$\text{pH} = \text{pK}_a + \log \left(\frac{[\text{CO}_3^{2-}]}{[\text{HCO}_3^-]} \right) \quad (4)$$

Where:

pH is the desired pH of the test solution, set to 8.18.

pK_a is the dissociation constant of HCO₃⁻ into CO₃²⁻, approximately 10.33.

[CO₃²⁻] is the expected concentration of carbonate ions used in the test solution.

[HCO₃⁻] is the expected concentration of bicarbonate ions used in the test solution.

Thus, the concentration ratio between CO₃²⁻ and HCO₃⁻ is:

$$\frac{[\text{CO}_3^{2-}]}{[\text{HCO}_3^-]} = 10^{(\text{pH}-\text{pK}_a)} = 10^{(8.18-10.33)} = 10^{-2.15} \quad (5)$$

With the concentration of [CO₃²⁻] is 0.001(mol/L), the necessary concentration of [HCO₃⁻] is:

$$[\text{HCO}_3^-] = 0.001 \times 10^{-2.15} = 0.141 \text{ (mol/L)} \quad (6)$$

The molar mass of NaHCO₃ is approximately 84 (g/mol), meaning that 1 mol of NaHCO₃ contains 84 (g) of NaHCO₃. The required mass of NaHCO₃ is:

$$m \text{ NaHCO}_3 = 0.141 \times 84 \approx 11.87 \text{ (g)} \quad (7)$$

Through these calculations, the components of the test solution are determined as follows:

Table 5. Components of the test solution.

Component	Mass / Volume	Unit
Purified Water	1	l
NaCl	32.48	g
NaHCO ₃	11.87	g

2.3.3. pH checking and adjustment

Measuring the initial pH of the solution: After preparing the solution with NaCl, use a pH meter to measure the actual pH value of the solution.

- Adjusting pH:

- + If the pH is lower than 8.18 (too acidic): Increase the pH by adding a diluted NaOH solution. It is recommended to use NaOH solution with a low concentration (0.1 (M) or 0.01 (M)) to gradually and accurately raise the pH.
- + If the pH is higher than 8.18 (too alkaline): Lower the pH by adding acetic acid solution (CH₃COOH) (0.1 (M) or 0.01 (M)), using a similar method as above, slowly adding drop by drop and checking the pH.
- Checking pH: After adding small amounts of NaOH or CH₃COOH, stir well and use the pH meter to recheck the pH until the value reaches 8.18.

2.4. Design of experimental parameters

2.4.1. Experimental current

The test current is calculated based on the characteristics of the test specimen and according to ASTM G102 Standard [8], specifically as follows:

With the bare steel sample SKK490 with dimensions of 20 × 200 × 12 (mm), the applied current can be calculated as follows:

The corrosion current density is calculated by the formula:

$$i_{\text{cor}} = \frac{I_{\text{cor}}}{A} \quad (8)$$

Where:

i_{cor} is the corrosion current density ($\mu\text{A}/\text{cm}^2$)

I_{cor} is the applied current to the sample (μA)

A is the area of the test specimen exposed to the corrosive environment (cm^2)

Consider a test specimen with dimensions of 20 × 200 × 12 (mm), immersed 100 (mm) in the test solution according to the experimental method setup, calculate the contact area in the corrosive solution environment as follows:

The area of the upper and lower surfaces in contact with the solution is:

$$S_1 = 2 \times 10 \times 2 = 40 \text{ (cm}^2\text{)}$$

The area of the front and back surfaces in contact with the solution is:

$$S_2 = 2 \times 10 \times 1,2 = 24 \text{ (cm}^2\text{)}$$

The area of 01 bottom surface in contact with the solution is:

$$S_3 = 2 \times 1,2 = 2,4 \text{ (cm}^2\text{)}$$

So the contact area of the sample with the experimental solution is:

$$A = S_1 + S_2 + S_3 = 66,4 \text{ (cm}^2\text{)}$$

From formula (8), the current applied to the test sample is calculated according to the formula:

$$I_{cor} = i_{cor} \times A \tag{9}$$

Consider Faraday's formula in calculating corrosion rate:

$$CR = K_1 \times \frac{i_{cor}}{\rho} \times EW \tag{10}$$

Where:

CR is the expected corrosion rate (mm/year)

K_1 is the constant value used in Faraday equation, with CR (mm/year); i_{cor} ($\mu A/cm^2$); ρ (g/cm^3), take the value $K_1 = 3.27 \times 10^{-3}$ (mm g/ μA cm year) according to the regulations in ASTM G102.

ρ is the Material density, with SKK490 steel, take the value ~ 7.85 (g/cm^3)

EW is the Equivalent weight of material is calculated by the following formula:

$$EW = \frac{W}{n} \tag{11}$$

Where:

W is the atomic weight of the material, with bare steel SKK490, take the value $W = 55.85$

n is the valence of the material, with bare steel SKK490 in Nha Trang sea area, the value is $n = 2$

Considering the expected average corrosion rate of steel materials in Nha Trang sea area is 0.0523 (mm/year) [14], to suit the scale of the accelerated experimental research and experimental equipment, the desired corrosion rate is taken as 25 (mm/year), which means that 10 days of accelerated experiment is equivalent to 15 years of actual corrosion . From formulas (9), (10) and (11), the formula for calculating the applied current ofv the SKK490 sample is as follows:

$$I_{cor} = \frac{CR \times A \times \rho \times n}{K_1 \times W} = \frac{25 \times 66.4 \times 7.85 \times 2}{3.27 \times 10^{-3} \times 55.85} \approx 142704 (\mu A) \approx 140 (mA) \tag{12}$$

Similar calculations for the steel samples in the experiment, the current results applied to the test samples are as Table 6.

Table 6: Calculated current applied to the test specimen

Steel sample	Width (mm)	Long (mm)	Thickness (mm)	I_{cor} (mA)
Bare steel SKK490	20	200	12	140
	20	200	14	160
	20	200	16	180

2.4.2. Experiment time

According to ASTM G31 Standard [7] and to suit the scale of laboratory testing, the test time points are divided as follows:

- Milestone 01: 72 (hours)
- Milestone 02: 120 (hours)
- Milestone 03: 240 (hours)

2.5. Experimental layout model

Based on the applied current value I_{cor} and the characteristics of the experimental samples, the study divided the samples into 03 groups of samples, each group of samples includes 03 samples of the same size. The sample groups will be arranged as follows:



Figure 1. Experimental setup.

Table 7. Experimental setup of electrochemical acceleration.

Group	Number of samples	Sample symbol	Experimental time (hours)	Estimated Real-time equivalent (years)	Applicable current (mA)
01	03	SKK490 – 12	72	4.5	140
	03	SKK490 – 12	120	7.5	
	03	SKK490 – 12	240	15	
02	03	SKK490 - 14	72	4.5	160
	03	SKK490 - 14	120	7.5	
	03	SKK490 - 14	240	15	
03	03	SKK490 - 16	72	4.5	180
	03	SKK490 - 16	120	7.5	
	03	SKK490 - 16	240	15	

3. RESULTS AND DISCUSSION

3.1. The degree of mass loss and surface morphology of steel samples due to corrosion after the experimental period

Based on the results in Table 2, calculate and construct a graph of mass loss over time of bare steel SKK490 (Figure 2). Based on the experimental results in Table 2 and the graph in Figure 2, the following comments can be made:

- Mass loss:

Bare steel SKK490 when exposed to simulated seawater in Nha Trang in the accelerated test showed a large mass loss, ranging from 0.2-0.6 (g/m²/year) under accelerated test

conditions. This corrosion rate is a testament to the ability of steel to deteriorate rapidly in harsh tropical marine conditions such as in Nha Trang.

Table 8. Experimental results on corrosion level and surface morphology of bare steel SKK490.

Sample type	Experiment time (hour)	Mass before experiment* (g)	Mass after experiment* (g)	Mass loss* (g)	Surface morphology
SKK490 - 12	72	312.07	303.91	8.16	Smooth surface, slight corrosion
	120	313.66	304.55	9.11	Uneven corrosion, signs of oxidation
	240	310.55	287.04	23.51	Obvious corrosion, gray patches, slightly rough surface
SKK490 - 14	72	352.53	343.72	8.81	Rough surface with signs of oxidation
	120	351.00	338.89	12.11	Uneven corrosion, obvious tarnish
	240	351.65	328.63	23.02	Obvious corrosion, white streaks, rough surface.
SKK490 - 16	72	392.82	385.30	7.52	Relatively smooth surface, with slight signs of corrosion
	120	402.64	391.10	11.54	Different corrosion spots appear
	240	394.58	367.04	27.54	Obvious corrosion, rough surface

* The mass before and after the test is the average mass of a sample set.

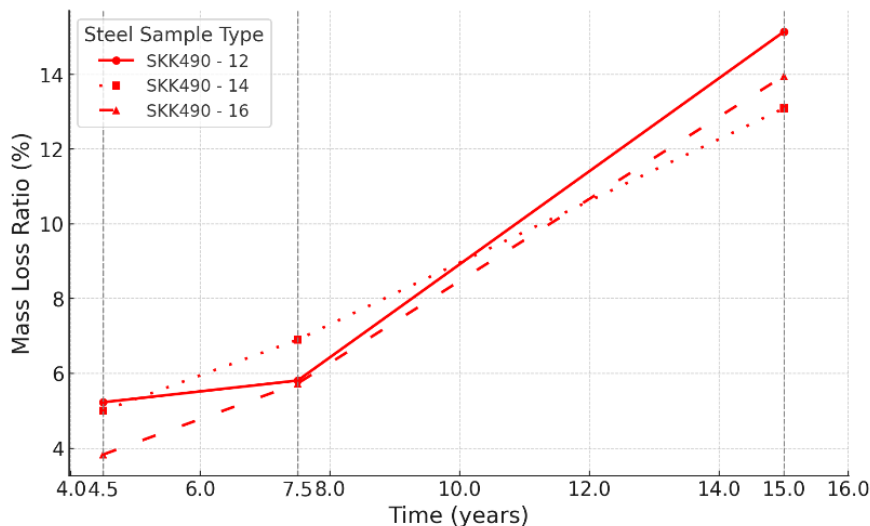


Figure 2. Chart of mass loss due to corrosion over time for SKK490 bare steel.

- Corrosion morphology:

Figure 3 shows that the bare SKK490 steel in the experiment shows a clear tendency to form localized corrosion and spot corrosion. In addition, the typical corrosion morphology

found in the SKK490 steel sample in Nha Trang seawater environment is pitting corrosion. Corrosion does not occur evenly on the entire steel surface but is concentrated in local areas.



Figure 3. Morphology of steel samples after 240 hours of corrosion.

3.2. Comparison with previous corrosion experiments in other marine areas and evaluation

The experimental results show that the SKK490 bare steel when exposed to Nha Trang simulated seawater in the acceleration experiment has a fairly large mass loss. It can be explained that, due to the strong influence of tropical marine environmental factors in Nha Trang, including high chloride content, high temperature and humidity [15]. Compared with temperate seas such as the Mediterranean and the North Sea, SKK490 bare steel in Nha Trang has a faster corrosion rate, with the amount of steel lost ranging from 0.2-0.6 (g/m²/year), while temperate seas are only about 0.1-0.4 (g/m²/year) [16]. This is because Nha Trang seawater has high temperature (26-30(°C)), high humidity (>80%) and high chloride ion content (>20,000 (ppm)), creating favourable conditions for the electrochemical corrosion process to take place strongly [17].

Similar studies in temperate seas such as the Mediterranean and the North Sea have shown that steel tends to corrode more slowly, mainly in the form of uniform surface corrosion. For example, the study by Yunze Xu et al. (2021) [18], Flow accelerated corrosion and erosion – corrosion behaviour of marine carbon steel in natural seawater, which examined the corrosion of steel in natural marine environments, found that corrosion rates were typically 0.1–0.3 (mm/year) in the North Sea, much lower than in the tropics. The study focused on how factors such as flow and chemical composition affect the rate of corrosion in temperate marine environments. Or the study by Senka Gudić et al. (2023) [19], Corrosion Behavior of Stainless Steel in Seawater in the Presence of Sulphide, indicates that in the Mediterranean, corrosion mainly occurs in the form of uniform surface corrosion with lower levels, unless affected by pollutants such as sulphide ions. Under moderate temperature and low chloride conditions, corrosion rates are only about 0.1 - 0.4 (g/m²/year). These studies are in marked contrast to tropical environments such as Nha Trang, where factors such as high temperature and high chloride content promote rapid and localized corrosion.

Accelerated corrosion test also showed that bare steel SKK490 has a tendency to form localized corrosion and spot corrosion. It can be explained that chloride ions in Nha Trang seawater concentrate on uneven areas on the steel surface, causing spot corrosion. Initially, small rust spots can develop into deep holes, weakening the steel structure and increasing the risk of affecting the resistance of the steel pipe pile structure. The typical corrosion morphology of bare steel SKK490 in this tropical marine environment is pitting corrosion, concentrated in local areas and can reduce the bearing strength of the steel pipe pile over time. Different from the report of Nour Eldeen MAAbo Nassar et al. (2022) [20], Corrosion in marine and offshore steel structures: Classification and overview, the study showed that in the North Sea, the corrosion rate of steel ranges from 0.1-0.154 (mm/year), which is typical for

temperate marine environments with low temperatures and less chloride, causing corrosion to occur mainly in a uniform and less localized form. In temperate seas such as the Mediterranean and the North Sea, SKK490 steel often exhibits more uniform surface corrosion and less localized corrosion. Due to the lower temperature and humidity conditions, corrosion occurs slowly and uniformly over the entire surface, minimizing the risk of spot corrosion. This results in a lower corrosion rate and the steel structure can maintain its durability for a longer period of time compared to tropical marine environments such as Nha Trang.

4. CONCLUSIONS

The study designed a simulation of Nha Trang seawater, Vietnam and conducted accelerated corrosion experiments for steel pile materials in that seawater environment. Through the initial study, it can be concluded that SKK490 steel for manufacturing steel pipe piles when exposed to Nha Trang seawater environment has a higher corrosion rate than temperate seas such as the Mediterranean and the North Sea. Factors such as high temperature (26-30(°C)), high humidity (>80(%)), and high chloride content (>20,000 (ppm)) create a favourable environment for electrochemical corrosion. As a result, the corrosion rate of steel in Nha Trang reached 0.2-0.6 (g/m²/year), significantly higher than the level of 0.1-0.4 (g/m²/year) in temperate seas. In addition, in the tropical marine environment, SKK490 steel showed obvious localized corrosion and spot corrosion. This is the result of the concentration of chloride ions in uneven surface areas, causing deep corrosion pits that weaken the steel structure and increase the risk of affecting the resistance of the steel pipe pile structure, unlike the uniform corrosion phenomenon in temperate seas.

Based on the research results, it is recommended that for projects using SKK490 steel piles in tropical marine areas, additional protection methods such as anti-corrosion coating, waterproof coating or cathodic protection should be implemented to minimize the impact of corrosion. In addition, a periodic inspection process is required to promptly detect corrosion holes and signs of steel strength loss. Regular reinforcement and maintenance measures are required to help extend the life and support the improvement of the durability of SKK490 steel piles in tropical marine environments, meeting the long-term requirements for structure and safety of the project.

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