

Journal of Materials and Engineering Structures

Research Paper

Comparative analysis of corrosion mass loss of SKK490 and Q345 steel pipe piles in marine conditions

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ARTICLE INFO

Article history :

Received : 14 November 2024

Revised : 26 December 2024

Accepted : 28 December 2024

Keywords:

Steel Pipe Piles

SKK490 Steel

Q345 Steel

Accelerated Corrosion Test

ABSTRACT

Vietnamese seawater, characterized by high chloride concentrations, presents unique challenges for corrosion in steel materials used in marine environments. This study conducts a comparative analysis of corrosion-induced mass loss in SKK490 and Q345 steels, commonly employed in steel pipe piles for coastal and offshore structures, under simulated Vietnamese seawater conditions. Accelerated corrosion tests were carefully designed with controlled factors, including temperature, humidity, and chloride concentration, using a simulated seawater solution containing 3.5% NaCl to replicate real-seawater conditions. Steel samples were partially immersed and connected to an external power source to accelerate the corrosion process over duration of 72 to 240 hours. The results show that Q345, containing protective elements like Nb, V, and Ti, exhibits better corrosion resistance, with a corrosion rate 1.32 times lower than SKK490. The findings underscore the need for material selection prioritizing corrosion-resistant steels or the application of protective measures such as coatings or cathodic protection. Additionally, the research provides valuable data for optimizing the design and durability of marine infrastructure in Vietnam. Future research should validate these results through long-term field studies and explore advanced anti-corrosion technologies.

1 General overview

Corrosion in marine environments is a major challenge for port and offshore structures in Vietnam, where seawater contains high chloride ion concentrations, coupled with high humidity and temperature [1]. The coastal waters of Vietnam typically have chloride concentrations ranging from 2.5% to 3.5%, contributing significantly to the aggressive corrosion of steel materials [2]. Additionally, the average seawater temperature varies between 24°C and 30°C, intensifying the corrosion processes.

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e-ISSN: 2170-127X, (cc) BY-SA

RESEARCH REVIEW of Sciences and Technologies

High relative humidity, often exceeding 80%, further exacerbates the degradation of materials by providing favorable conditions for electrochemical reactions [3].

Moreover, the Vietnamese coastline experiences significant seasonal weather variations, influenced by the tropical monsoon climate [2]. During the wet season (May to October), increased rainfall, fluctuating temperatures, and storm surges accelerate corrosion. The dry season (November to April) introduces slightly more stable conditions but still maintains high humidity levels, prolonging the corrosive impact on structures. In the long term, climate change poses additional challenges, with rising sea levels and increasing frequency of extreme weather events projected to intensify the impact of corrosion on coastal infrastructure [4]. Higher temperatures and elevated seawater salinity levels due to changing hydrological patterns could accelerate corrosion processes even further, emphasizing the urgent need for effective corrosion protection strategies.

Steel pipe piles in the foundations of these structures are greatly affected by corrosion, posing a high risk of structural failure [5]. SKK490 and Q345 steel are commonly used in marine and offshore structures, especially in steel pipe pile structures. The mechanical properties and load-bearing capacity of these two steels are suitable for structures that are strongly affected by the marine environment, such as bridge piers, foundations of oil and gas rigs, or ports. However, due to the difference in alloy composition, these two steels have different corrosion resistance, especially in the tropical marine environment of Vietnam. Q345 steel, with higher alloy content, can resist chloride ion attack better than SKK490 steel [6]. Evaluating the corrosion level of these two steels in Vietnam's seawater conditions is essential to determine the most suitable material for steel pile structures in the marine environment, ensuring sustainability and long-term service life.

This study conducted accelerated corrosion test in simulated seawater conditions, with controlled factors such as temperature, humidity, and chloride concentration, to compare the corrosion mass loss of SKK490 and Q345 steel. The results of the study will provide recommendations for the use of this steel pile material in coastal and offshore projects, helping to reduce maintenance costs and improve operational efficiency for marine infrastructure projects.

2 Testing method

2.1 Literature review andapplicable testing standards

Corrosion of steel in marine environments has been a subject of extensive research over the past few decades due to the critical need to protect infrastructure in coastal regions. Previous studies, such as those by Melchers (2003) [7] and Revie and Uhlig (2008) [8], have explored the mechanisms of corrosion in seawater, emphasizing the role of chloride ions as a primary aggressive agent that accelerates the breakdown of protective oxide layers on steel surfaces [7, 8]. These studies have shown that non-alloyed or low-alloyed steels, which lack protective elements such as chromium, nickel, or molybdenum, are particularly vulnerable to rapid corrosion in high-chloride environments.

Research by Shifler and Aylor (2005) [9] further highlighted how factors like temperature, humidity, and salinity influence the corrosion rate of steel in marine conditions, providing a comprehensive understanding of environmental variables that exacerbate corrosion. In comparison, our study focuses on the accelerated corrosion of SKK490 and Q345 steel specifically in Vietnamese seawater conditions, which have unique characteristics, such as higher average salinity and temperature, due to the tropical climate. This local context sets our research apart, as it addresses corrosion challenges under the specific environmental conditions faced in Vietnam, thus contributing to more tailored solutions for coastal infrastructure.

Many existing studies around the world have focused on the general mechanisms of steel corrosion in marine environments, emphasizing factors such as chloride ion concentration, temperature, and humidity. However, there is a noticeable gap in research when it comes to region-specific analyses that account for unique environmental conditions, particularly in tropical coastal regions like Vietnam. Global studies often use standardized seawater simulations that may not accurately represent the highly variable and aggressive conditions of tropical seawater, such as fluctuations in salinity, seasonal temperature changes, and the impact of monsoonal humidity. Furthermore, there is limited research comparing the corrosion resistance of different steel types, such as SKK490 and Q345, specifically in environments with high chloride content and tropical climate factors. This gap can result in a lack of practical guidance for infrastructure projects in regions facing extreme marine corrosion challenges.

Therefore, the study titled "Comparative analysis of corrosion mass loss of SKK490 and Q345 steel pipe piles in marine conditions" is crucial. It aims to fill this research gap by providing localized data and insights, which can lead to more

effective material selection and corrosion protection strategies for coastal and offshore infrastructure in Vietnam and similar tropical environments worldwide.

The testing standards for steel corrosion in seawater environment applied in this study are:

- ASTM G31: Standard guide for laboratory immersion corrosion testing of metals [10].
- ASTM G102: Standard practice for calculation of corrosion rates and related information from electrochemical measurements [11].
- ASTM G5: Standard reference test method for making potentiodynamic anodic polarization measurements [12].

2.2 Accelerated corrosion test design

2.2.1 Preparation of test samples

The study selected two types of steel, SKK490 and Q345, for corrosion tests due to their wide application in steel pipe piles. SKK490 steel is a high-strength structural pipe steel in accordance with JIS A5525 standards, with tensile strength ranging from 490 to 610 (Mpa) [13]. Q345 steel is a low-alloy high-strength structural pipe steel in accordance with GB/T 1591-2008 standards, withtensile strength ranging from 470 to 630 MPa and contains alloying elements such as niobium (Nb), vanadium (V), and titanium (Ti) [14]. The chemical composition and mechanical strength test results of these steels are presented in Tables 1 and 2.

Table 1 – Test results of main chemical composition of SKK490 and Q345 steel

Information	SKK490 Steel *(%)*	Q345 Steel *(%)*
Carbon (C)	0.17	0.20
Silicon (Si)	0.30	0.50
Manganese (Mn)	1.40	1.35
Phosphorus (P)	0.03	0.03
Sulfur (S)	0.03	0.03
Niobium (Nb)	-	0.012
Vanadium (V)	-	0.08
Titanium (Ti)	-	0.02

Table 2 – Test results of mechanical strength of SKK490 and Q345 steel

Information	SKK490 Steel	Q345 Steel
Yield Strength *(MPa)*	325	345
Tensile Strength *(MPa)*	510	525
Elongation *(%)*	19%	22%

SKK490 and Q345 steel samples were cut into uniform sizes, 20mm x 200mm, ensure a standardized and easily manageable size for consistent testing. These dimensions are optimal for partial immersion tests, providing sufficient surface area to observe corrosion effects while maintaining ease of handling and weighing. The selected thicknesses of 12mm, 14mm, and 16mm reflect the common thicknesses used in large-diameter steel pipe piles in coastal constructions. The variation in thickness allows for a comprehensive assessment of how different material thicknesses influence corrosion rates, contributing to more accurate predictions of real-world performance.

For each thickness of SKK490 and Q345 steel, the study uses one set of samples consisting of three steel samples. To prepare the samples, each steel piece was cleaned using a mild acid solution or solvent to remove any surface contaminants, such as dust, grease, and impurities, then rinsed with distilled water and air-dried at room temperature. Accurate measurements of mass and size were taken before assigning the samples into corresponding groups.

2.2.2 Preparation of seawater simulation solution and test parameters

Normally, the concentration of NaCl in seawater in coastal areas of Vietnam ranges from 2.5% to 3.5%. The seawater simulation solution was prepared by dissolving 35 grams of pure NaCl in one litter of distilled water to achieve a 3.5% concentration, which is the standard level equivalent to the average salinity of seawater globally [9].

The solution was carefully adjusted to maintain a pH range of 7.44 to 8.32, corresponding to the natural seawater conditions in Vietnam [2]. The pH value is set with an average value of 8.16, the value is adjusted using pH-modifying additives: $NaHCO_3$ and CH_3COOH at concentrations of 0.1 (M) or 0.01 (M) [15].

Temperature control was crucial, and the range of 24.5 to 29.7°C was selected to simulate the tropical seawater temperature of Vietnam [2].

Humidity was maintained at 75-80% to replicate the tropical monsoon climate, which is characteristic of the Vietnamese coastal environment [3].

2.2.3 Electrochemical stimulation setup

An external voltage was applied to the steel samples using a reference electrode to accelerate the corrosion process [15, 16] following the guidelines set by ASTM G102 and ASTM G5 [11, 12]. This setup enhances the charge exchange process, making it possible to observe significant corrosion effects within a shorter period [9, 17]. The current applied was calculated based on the sample properties, according to ASTM G102 standard, with adjustments made to simulate realistic conditions as closely as possible.

- Reference electrode: a silver/silver chloride (Ag/AgCl) electrode is placed in the simulation solution as the steel samples to accurately measure the electrochemical potential, following ASTM G5.

- Counter electrode: a stainless-steel plate is immersed in the simulation solution, positioned opposite the steel samples to complete the circuit, as guided by ASTM G5.

- Working electrode (steel sample): the steel sample is connected to an external power source, applying current to accelerate the corrosion process, in accordance with ASTM G102. Temperature, pH, and chloride ion concentration are strictly controlled per ASTM G31 to accurately simulate real-world corrosion conditions.

2.2.4 Testingprocedure

The SKK490 and Q345 steel samples are arranged according to the following standards:

- Steel samples were partially immersed (10cm depth) in the 3.5% NaCl solution at a controlled temperature range of 24.5 – 29.7 °C.

- The samples were connected to a voltage source, following the ASTM G102 standard, with a reference electrode completing the circuit as per ASTM G5.

- The immersion periods ranged from 72 to 240 hours, as recommended by ASTM G31. At the end of each cycle, samples were removed, and corrosion products were gently cleaned using a mild acid solution or a hard brush.

- Each sample was then reweighed using a high-precision balance to determine mass loss due to corrosion.

Figure 1 below illustrates the experimental setup, including the arrangement of steel samples partially immersed to a depth of 10cm in the 3.5% NaCl solution, the connection to the external voltage source, and the reference electrode positioning. The setup ensures consistent exposure of each sample to the corrosive medium.

Figure 2 shows the corrosion morphology observed on the surfaces of SKK490 and Q345 steel samples after each immersion cycle. The corrosion phenomenon occurs on all surfaces of the steel sample submerged in the simulated solution. This visual analysis helps compare the extent and nature of corrosion between the two types of steel.



Fig. 1 – Testing setup of the sample sets



Fig. 2 – Corrosion morphology of a sample set

2.2.5 Calculate the mass loss ratio and corrosion rate

The mass loss ratio after each testing period calculated using the formula (1) [18]:

$$c = \frac{\Delta m}{m_{before\ test}} \times 100 \quad (1)$$

where c : mass loss ratio (%); Δm: mass difference before and after test (g) and $m_{before\ test}$: mass of sample before testing (g), this value is calculated based on the mass of the sample immersed in the test solution (to a depth of 10 cm).

The mass loss after each testing period was measured and used to calculate the corrosion rate using the formula (2) [19]:

$$\rho = \frac{\Delta m}{S \times t} \quad (2)$$

where ρ : corrosion rate (g/cm^2 . hour); Δm: mass difference before and after test (g); S : contact surface area of the sample (cm^2) and t : sample immersion time (hours).

3 Analysis of testing results

The testing results, including the mass loss ratio calculated using formula (1) and the corrosion rate using formula (2), are summarized in Table 3, showing the mass loss due to corrosion for SKK490 and Q345 steel samples over different immersion times. The mass before test and mass after test in Table 3 represent the average mass of a sample set for each type of steel sample.

3.1 Mass loss after testing of SKK490 and Q345 bare steel

The testing results in Table 3 show that both SKK490 and Q345 bare steel samples experienced corrosion and mass loss over time (72 hours, 120 hours, and 240 hours). The mass loss of these samples ranged from 6.15 to 31.74 (g), depending on the steel type and immersion time. The mass loss ratio of SKK490 steel fluctuated between 5.34% and 16.29%, while that of Q345 steel ranged from 3.38% to 14.1%. These findings indicate that Q345 steel demonstrates better corrosion resistance compared to SKK490 steel in a simulated Vietnamese seawater environment.

The observed difference in corrosion behaviour between SKK490 and Q345 steels can be attributed to the alloy composition. The presence of alloying elements such as niobium (Nb), vanadium (V), and titanium (Ti) in Q345 steel contributes to forming a stable and protective oxide layer on the surface. This oxide layer acts as a barrier that prevents chloride ions from directly attacking the steel, thereby reducing the corrosion rate. In contrast, SKK490 steel, lacking these protective elements, is more susceptible to chloride-induced corrosion, leading to a higher rate of mass loss.

Table 3 – Summary of corrosion test results of SKK490 and Q345 bare steel samples

Sample type	Test time *(hours)*	Mass before test m_0*(g)*	Mass after test m *(g)*	Mass loss Δm *(g)*	Mass loss ratioc *(%)*	Corrosion rateρ *(g/cm². hour)*
SKK490 - 12	72	313.08	303.9	.18	5.86	0.00192
	120	312.67	302.51	).16	6.50	0.00128
	240	312.5	287.05	5.45	16.29	0.00160
SKK490 - 14	72	351.3	339.71	..59	6.60	0.00227
	120	352.1	337.17	4.93	8.48	0.00176
	240	351.7	327.53	4.17	13.74	0.00142
SKK490 - 16	72	396.7	386.1	0.6	5.34	0.00196
	120	401.96	387.12	4.84	7.38	0.00164
	240	398.85	367.11	..74	15.92	0.00176
Q345 - 12	72	314.26	308.11	.15	3.91	0.00129
	120	312.33	303.17	.16	5.87	0.00115
	240	313.79	291.66	'.13	14.10	0.00139
Q345 - 14	72	357.71	349.67	.04	4.50	0.00158
	120	358.5	347.63	).87	6.06	0.00128
	240	357.12	333.66	5.46	13.14	0.00138
Q345 - 16	72	398.41	391.67	.74	3.38	0.00124
	120	402.23	393.15	.08	4.51	0.00101
	240	401.61	374.3	'.31	13.60	0.00151

3.2 Comparison of corrosion rate between two types of SKK490 and Q345 bare steel

The results in Table 3 indicate that the corrosion rate of SKK490 bare steel ranges from 0.00128 to 0.00196(g/cm²·hour), while Q345 bare steel exhibits a lower corrosion rate, ranging from 0.00101 to 0.00158(g/cm²·hour). Therefore, SKK490 steel corrodes approximately 1.32 times faster than Q345 steel under the same testing conditions.

Figure 3 was constructed using the mass loss data from Table 3. The mass loss rates for both SKK490 and Q345 steel were plotted over time (72, 120, and 240 hours) to visually compare the differences in corrosion rates between the two types of steel. The graph clearly shows that SKK490 steel experiences a greater rate of mass loss over time compared to Q345, illustrating that Q345 steel has better corrosion resistance in the seawater environment of Vietnam.

Our findings align with the research by Robert E. Melchers (2003) [7], who demonstrated that low-alloy steels without protective elements like Nb, V, and Ti are highly susceptible to accelerated corrosion when exposed to chloride-rich seawater. This explains why SKK490 steel, which lacks these protective alloying elements, has a significantly higher corrosion rate than Q345 steel.

The study by R. Winston Revie and Herbert Henry Uhlig (2008) [8] also emphasized the crucial role of alloying elements such as Nb, V, and Ti in forming protective oxide layers that reduce corrosion rates in marine environments. Our results are consistent with this, as Q345 steel, which contains these alloying elements, exhibits superior corrosion resistance.

Research by Phan Thi Thu Hang and Nguyen Xuan Hung (2019) [20] highlighted the significant challenges faced by low-carbon steels in the coastal seawater conditions of Vietnam, which have high chloride content. This study confirmed that alloy steels, like Q345, offer better corrosion resistance, particularly for coastal structures. Our findings are in agreement with this conclusion, as Q345 steel, enhanced with alloying elements, effectively withstands chloride ion attacks compared to SKK490 steel.

These differences have important practical implications, suggesting that using Q345 steel for coastal infrastructure in Vietnam can extend the lifespan of structures and reduce maintenance costs. On the other hand, if SKK490 steel is used, additional protective measures such as anti-corrosion coatings or cathodic protection would be necessary to ensure long-term durability.

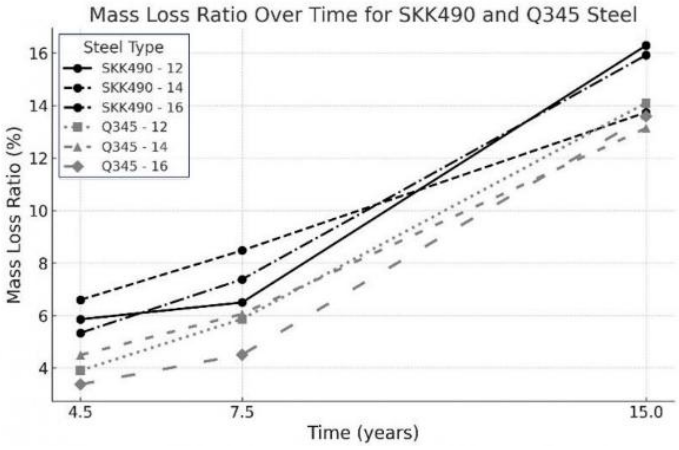


Fig. 3 – Corrosion loss rate graph over time of bare steel SKK490 and Q345

4 Conclude

Research on accelerated corrosion test for two types of steel for steel piles, SKK490 and Q345, in an environment simulating Vietnam's seawater, shows that the corrosion rate of SKK490 bare steel ranges from 0.00128 to 0.00196 (g/cm2.hour) with the average rate is 0.00173 (g/cm2.hour) and that of Q345 steel is from 0.00101 to 0.00158 (g/cm2.hour) with the average rate is 0.00131 (g/cm2.hour). The corrosion rates of the two types of steel are quite distinct, SKK490bare steel has a corrosion rate that is on average about 1.32 times higher than that of Q345 bare steel. The findings of this study are consistent with those of previous studies worldwide. This can be explained by the fact that seawater in Vietnam has a high chloride ion content, which is a strong corrosive agent. Chloride ions easily penetrate the oxide layer of steel, destroying the protective layer and promoting the electrochemical corrosion process. For SKK490, the lack of alloying elements makes chloride ions more susceptible to attack on the steel surface, while Q345 has better resistance due to the alloying elements.

From the research results, it can be recommended that when using steel piles in the seawater environment of Vietnam, where there is a high chloride content and high humidity, to protect steel piles from corrosion, prolong their service life and increase their durability, steel with enhanced alloy content, containing simple anti-corrosion elements such as Nb, V, and Ti can be used to help increase the corrosion resistance of steel. In addition, anti-corrosion measures such as epoxy paint, bitumen paint, or marine anti-corrosion paint should be applied to the surface of steel piles before installation, this coating creates a barrier between the steel surface and the corrosive environment, preventing the penetration of seawater and chloride ions; Or cathodic protection with a sacrificial anode, allowing this sacrificial metal to corrode first, protecting steel piles from corrosion.

Future studies should involve long-term field investigations to validate the results obtained from these accelerated simulation tests. Measuring and recording the real-time corrosion of SKK490 and Q345 steel in various marine environments across Vietnam will provide accurate data to improve predictive models for steel durability. These field studies should consider specific local environmental factors, including chloride ion concentration, temperature variations, humidity levels, and the presence of microorganisms, to tailor anti-corrosion strategies effectively for each sea area.

Additionally, further research should explore alternative protective coatings and technologies that may offer better or more cost-effective solutions for corrosion protection. Comparative studies with other types of steel commonly used in marine construction could also be valuable to establish a comprehensive database for material selection. Such research could inform the development of more robust guidelines and policies for coastal infrastructure design and maintenance, ensuring safer and more sustainable engineering practices in Vietnam and similar coastal regions.

This research emphasizes the need for regular inspection and maintenance strategies for existing steel infrastructure in marine environments. Strategies may include periodic re-application of protective coatings, monitoring the effectiveness of cathodic protection systems, and implementing real-time corrosion monitoring technologies. The insights from this study

could significantly influence engineering practices, encouraging the adoption of more resilient and sustainable materials for Vietnam's growing coastal infrastructure.

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