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EFFECTS OF ENVIRONMENTS CONTAMINATED WITH CHLORIDES AND SULFATES ON RC COLUMNS

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Abstract

Introduction: Corrosion of steel reinforcement is a very complex process with clear differences in each geographical location. Many research models predicting the quality deterioration of reinforced concrete structures in areas contaminated with chlorides and sulfates are being developed around the world. However, these models still have a fairly wide application range and fail to accurately and fully reflect the reduction in structure quality in each specific condition. The **purpose of the study** was to survey the current status of reinforced concrete (RC) structures located in chloride- and sulfate-contaminated environments in coastal areas of Vietnam, analyze the result and compare it with previously researched proposals to clarify the impact of corroded steel reinforcement on the quality of RC columns. The following **methods** were used: Experimental Survey, Non-Destructive Testing, and Empirical Formula for determination of the deterioration of parameters including compressive strength of concrete, thickness of protective layer, diameter of reinforcement, and cross-sectional area of RC columns. In addition, this study was combined with the available recommendations on reinforcement corrosion to determine the residual physical and mechanical characteristics of concrete and reinforcement steel. As a **result**, the quality deterioration of RC columns with corroded reinforcement depends on the reinforcement location in the same longitudinal member. This indicates remarkable deterioration in the quality of structural sections that are regularly and directly affected by seawater.

Keywords: concrete; steel; reinforced concrete; corrosion; seawater; chloride.

Introduction

Reinforced concrete (RC) structures are common in civil construction, often used in saline areas with high concentrations of chloride and sulfate. These structures are often affected by the corrosion of steel reinforcement due to chlorides and sulfates in the environment.

Corrosion is a chemical or electrochemical process through which metals or other materials are destroyed by environmental influences (Nguyen et al., 2022). In the case of RC structures in coastal areas, corrosion is mainly caused by seawater components and salt-containing air (Viet Duc, 2021). Seawater contains a lot of salt, especially sodium chloride (NaCl). Chloride from the seawater environment can penetrate into concrete through voids and hollow structures, causing metal corrosion in reinforced concrete (Kumar, 1998).

During the process of corroding steel reinforcement, elemental Iron (Fe) converts to $Fe(OH)_2$ or hydroxide ions, known as common rust, which reacts with dissolved oxygen and produces hydrated iron oxide ($Fe_2O_3 \cdot H_2O$) in reddish brown color, Fe_3O_4 in black color and then hydrates into ($Fe_3O_4 \cdot H_2O$) in green color (Liu, 1996). Because the volume of rust is higher than that of iron, the process of rusting increases the volume of reinforcing steel, which leads to cracking and peeling of the protective layer (Liu, 1996).

To study the loss of RC strength with corroded reinforcement, Shayanfar et al. (2016) conducted experiments on various types of reinforcement, keeping all effective parameters on compressive strength constant except for the water-cement ratio (0.4, 0.45, and 0.5). Compressive strength tests were performed on corroded and non-corroded samples. The degree of reduction in compressive strength was measured at different corrosion levels. Other studies (Diamond, 1986; Enevoldsen et al., 1994; Ghods et al., 2009; Hussain et al., 1995; Moreno et al., 2004; Page and Vennesland, 1983) showed that the agents causing corrosion in steel reinforcement mainly come from chemical components containing sodium and potassium. This highlights the importance of considering cement composition and environmental exposure conditions when specifying allowable chloride limits to prevent reinforcement corrosion in concrete structures. The corrosion process is difficult to fully and accurately determine. However, some recent studies (Andrade and Alonso, 2001; Assouli et al., 2008; Schiegg et al., 2009; Suryavanshi et al., 1991) managed to

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partially quantify the reinforcement corrosion over the time. Corrosion behavior of steel reinforcement due to sulfates and chlorides was also investigated (Pradhan, 2014), the performance of corroded steel reinforcement in RC structures was evaluated through a comprehensive experiment in which the structures were exposed to mixed solutions of chloride and sulfate ions.

Chloride is the main agent that causes corrosion of steel reinforcement in concrete. It penetrates into the structure mainly in the process of mixing and pouring fresh concrete mixture into the structure from the outside environment (Arya and Xu, 1995; Dehwah et al., 2002; Saricimen et al., 2002). These studies highlight the complex interplay between chloride binding, pore solution chemistry, and transport properties in influencing reinforcement corrosion in chloride-contaminated concretes made with different cementitious materials. Especially in case of RC structures located in an environment with chloride content, chloride ions directly penetrate into the structure itself through voids and hollows, causing corrosion of the steel reinforcement (Shaheen and Pradhan, 2017; Vu and Stewart, 2000).

The effects of chloride, sulfate and chloride-sulfate solutions on the corrosion of steel embedded in cement paste were studied. Reinforcement corrosion was evaluated by measuring the corrosion potential and corrosion current density using the linear polarization resistor technique. The results indicated that the corrosion of specimens immersed in pure sulfate solution is minimal (Al-Amoudi and Maslehuddin, 1993). However, Pradhan's study show that in the later stages of corrosion process, the formation of sulfate compounds increases the reacted product volume and breaks down the protective layer of the reinforcement. Then, the corrosion process of the reinforcement is increased due to chloride intrusion (Pradhan, 2014).

Corrosion of RC is the cause of a decrease in the bearing capacity and longevity of the structure (Rodriguez et al., 1997), reducing the cross-section and physical and mechanical properties of the reinforcement (Ballim and Reid, 2003). It causes the expansion of the protective concrete layer and cracking of the structure. Thereby, it keeps increasing the possibility of corrosion of the reinforcement (Cabrera, 1996), and the deterioration of the bond between the reinforcing steel and the concrete (Ahmad, 2003).

The main research method for RC corrosion involves surveying, evaluating current conditions, and using the corrosive acceleration method in experimental models. Osuji et al. (2020) assessed the level of deterioration of an existing 45-year-old concrete harbor structure in the Niger Delta zone of Nigeria. The applied methodology included a visual inspection of the structure to determine the current condition and the testing required. The results show that the corrosion rate and durability loss depend on the characteristics and exposure time. Structural elements exposed to tidal conditions have a higher degree of damage than the continuously submerged ones. The experimental survey method has proven to be reliable because it covers unique characteristics. The number of experimental studies on RC corrosion, as in these studies, has highly reliable conclusions (Ma et al., 2021; Medeiros et al., 2013; Nasser et al., 2021; Okada et al., 1988).

In experimental studies, the reduction in diameter and mechanical properties of reinforcement is quantified using a proposed formula (Du et al., 2005). As steel reinforcement corrodes, it creates oxides and increases the size of voids and cracks on the surface of the protective concrete layer. The expansion of steel reinforcement can cause concrete to crack and reduce its bearing capacity. This proves that the decrease in concrete strength depends on the level of reinforcement corrosion. This problem was raised by Shayanfar et al. (2016). An electrochemical corrosion experiment was conducted, and a formula to calculate the loss of concrete strength when reinforced steel is corroded was proposed. According to Tapan and Aboutaha (2011), the ratio between the protective concrete layer thickness and the longitudinal reinforcement diameter (c/d) is an important parameter that affects the remaining bearing capacity of the column structure after steel reinforcement is corroded. The destruction of the protective concrete layer occurs when the levels of longitudinal reinforcement corrosion are $Q_{corr} = 2.25$ % and 5.25 %, corresponding to the cases of c/d = 1 and c/d = 2.5. Gonzalez et al. (1995) as well as Andrade and Alonso (2001) proposed a formula to determine the reduction in reinforcement diameter as corrosion occurs. The rate of corrosion of steel reinforcement over time depends on many factors. However, according to Yokozeki et al. (1997), a formula to determine the rate of corrosion of steel reinforcement depends on the ratio of water/cement and protective layer thickness. Liu and Weyers (1998) developed a formula based on Yokozeki's research (Yokozeki et al., 1997) to determine the corrosion rate of steel reinforcement over time.

Corrosion of steel reinforcement is a very complex process with clear differences in each geographical location. Many research models predicting the quality deterioration of reinforced concrete structures in areas contaminated with chlorides and sulfates are being developed around the world. However, these models still have a fairly wide application range and fail to accurately and fully reflect the reduction in structure quality in each specific condition.

A survey was conducted on RC bridges in coastal areas of Vietnam. The visual and experimental results were combined to clarify the effects of chloride- and sulfate-contaminated environments on the decline in quality of RC bridges.

Methods

1. Experimental method

A survey of RC structures in chloride- and sulfate-contaminated areas was conducted by the research team. Visual inspection results show that damage commonly occurs in structures that are in close contact with seawater, such as bridge columns (Fig. 1).

Fig. 1a shows cracks along the concrete cover / protective layer of what appears to be a reinforced concrete column or a structural member. The cracks seem to be running parallel to the reinforcing bars within the concrete, suggesting that the cracking may be related to reinforcement corrosion and expansion.

In Fig. 1b, the cross-section reveals a decrease in the effective area of the concrete due to cracking, spalling, and potential loss of concrete cover. This reduction in the cross-sectional area can lead to a loss of structural capacity and compromise the strength and durability of the member.

Fig. 1c shows the revealed and corroded reinforcing bars within the concrete member. The reinforcement appears to be heavily rusted and corroded, indicating advanced deterioration due to factors such as chloride ingress or carbonation. The loss of concrete cover has exposed the reinforcement, making it vulnerable to further corrosion and potentially leading to a loss of the bond between the steel and concrete.

In addition to the visual assessment, the research team conducted a numerical survey of 10 RC bridge columns with design data. Column cross section — 300×300mm. Concrete w/c ratio = 0.45. Compressive strength of concrete f_c' = 35 MPa. Reinforcement is arranged with eight φ20 main steel bars, each having a tensile strength of f_y = 300 MPa (Fig. 2).

This structure is located in the chloride- and sulfate-contaminated coastal region of Central Vietnam, with the indicators shown in Table 1 (Sample 2). The indicators of other samples from different coastal regions in Vietnam are also summarized in Table 1 for comparison purposes. It can be seen that the concentrations of chlorides and sulfates in samples from different coastal areas are not significantly different. Therefore, Sample 2 can be considered representative of the coastal region of Central Vietnam.

The survey was carried out on the basis of determining the thickness of the protective concrete layer, diameter of reinforcement, and compressive strength of concrete on RC bridge column components at different sections. The equipment used included a rebound hammer (Fig. 3a), a rebar detector PROCEQ PM-650 (Fig. 3b), and a concrete ultrasonic machine (Fig. 3c). The field investigation results are presented in Table 2.

Here, Ai is the survey cross-section condition; f_c' (MPa) is the compressive strength of concrete; c (mm) is the thickness of the protective layer; d (mm) is the diameter of the reinforcement; A_c (mm^2) is the survey cross-section area. Zone I was at the bottom of the column which is frequently submerged, Zone II was the middle of the column, and the top of the column was Zone III.

2. Basis for determining the reduction in the bearing capacity of RC columns as the reinforcement corrodes

a. Reduction in the cross-section area and tensile strength of longitudinal bars

Corrosion damage can reduce the stiffness and ductility of steel reinforcement. Cracks and rusts caused by corrosion on the reinforcement surface can reduce the load-bearing and bending capacity of the column. Corrosion of steel reinforcement can lead to loss of elastic properties, causing the structure to become less flexible and more susceptible to damage when subjected to force. The empirical formula proposed by Du et al. (2005) is used to determine the reduction of the tensile strength and cross-sectional area of reinforcement.

$$f_{y,corr} = (1 - 0.005Q_{corr}) f_{y,0}; \quad (1)$$

$$A_{y,corr} = (1 - 0.01Q_{corr}) A_{s,0}; \quad (2)$$

a) Cracks along the protective layer

b) Decreased cross-section area

c) Rusty reinforcement revealed

Fig. 1. Types of damage to RC structures caused by corroded reinforcement

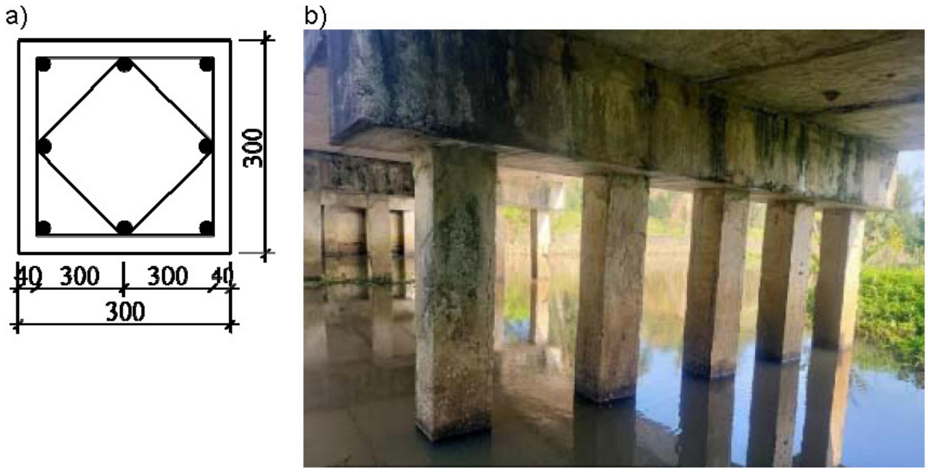


Fig. 2. a — column cross-section without corrosion; b — current status

a) using a rebound hammer b) using a rebar detector c) using an ultrasound machine

Fig. 3. Equipment used in actual surveys

Table 1. **Results of water sample analysis from the coastal region of Central Vietnam**

No.	Indicator	Method	Unit	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
1	Chloride (Cl^-)	TCVN 6194:1996	mg/l	16.724	16.868	15.559	14.897	17.708	17.989
2	Sulfate (SO_4^{2-})	TCVN 6200:1996	mg/l	2.369	1.997	2.257	1.996	2.044	2.066

Table 2. **Results obtained from surveying the current status of RC columns**

No.	Design	Column 1			Column 2			Column 3			Column 4			Column 5		
A_i	–	Zone III	Zone II	Zone I	Zone III	Zone II	Zone I	Zone III	Zone II	Zone I	Zone III	Zone II	Zone I	Zone III	Zone II	Zone I
f_c'	35	32.0	28.8	26.4	30.1	27.8	25.0	30.0	27.1	24.3	31.7	28.8	24.9	31.8	27.5	25.8
c	30	28	24	20	28	27	24	28	27	23	28	26	22	27	27	22
d	20	20	19	18	19.8	19.7	18.6	20	19.2	18.3	19.9	19.5	18.6	19.6	19.7	18.4
A_b	300	296	288	280	296	294	288	296	294	286	296	292	284	294	294	284
No.	**Design**	**Column 6**			**Column 7**			**Column 8**			**Column 9**			**Column 10**		
A_i	–	Zone III	Zone II	Zone I	Zone III	Zone II	Zone I	Zone III	Zone II	Zone I	Zone III	Zone II	Zone I	Zone III	Zone II	Zone I
f_c'	35	30.2	27.9	25.8	30.2	28.5	25.7	29.7	28.0	24.8	30.9	28.6	25.0	31.7	27.4	24.8
c	30	28	26	22	28	26	23	27	27	23	29	26	24	28	25	24
d	20	19.6	18.7	18.3	19.8	18.8	18.3	19.7	19	18.4	19.7	19.4	18.2	19.7	19.4	18.4
A_c	300	296	292	284	296	292	286	294	294	286	298	292	288	296	290	288

$$Q_{corr} = 1 - \left(\frac{d_{corr}}{d_0} \right)^2. \quad (3)$$

Here, $f_{y,corr}$, $f_{y,0}$ are the post-corrosion and initial tensile strength of the reinforcement, respectively. $A_{s,0}$, $A_{y,corr}$ are the initial and post-corrosion reinforcement area. Q_{corr} is the degree of steel reinforcement being corroded. d_0, d_{corr} are the initial reinforcement diameter and the remaining reinforcement diameter after corrosion, respectively.

b. Decrease in the compressive strength of concrete

As steel reinforcement corrodes, it creates oxides, which expand in volume, leading to cracks on the surface of the protective concrete layer. The expansion of steel reinforcement can cause cracks in concrete and reduce its bearing capacity. This proves that the decrease in concrete strength depends on the level of reinforcement corrosion. Shayanfar et al. (2016) proposed a formula to calculate the loss of concrete strength by conducting electrochemical corrosion experiments on corroded RC as follows:

$$f'_{c,corr} = (1-\lambda) f'_{c,0}; \quad (4)$$

$$N/X = 0.40 \quad \lambda = 2.72 Q_{corr} - 1.98$$
$$N/X = 0.45 \quad \lambda = 2.288 Q_{corr} - 1.733 \quad (5)$$
$$N/X = 0.50 \quad \lambda = 2.576 Q_{corr} - 1.876.$$

Here, $f'_{c,corr}$, $f'_{c,0}$ are the post-corrosion and initial compressive strength of the concrete, respectively. λ is the percentage reduction in the compressive strength of concrete depending on the level of reinforcement corrosion and the water/cement ratio.

c. Reduction in rebar diameter over time

According to Gonzalez et al. (1995) as well as Andrade and Alonso (2001), when corrosion of reinforcement occurs, the reduction in reinforcement diameter can be determined according to the following formula:

$$D_{corr} = d_0 - 0.0232 I_{corr}(t) \cdot t_p. \quad (6)$$

Here, I_{corr} is the corrosion rate of reinforcement (μA/cm^2), t_p is the interval between the onset of reinforcement corrosion and the calculation time. According to Vu and Stewart (2000), the magnitude of I_{corr} depends on two parameters: water/cement ratio (N/X) and protective concrete layer thickness (c), determined by the following formula:

$$I_{corr}(t) = 32{,}1 \frac{(1 - \frac{N}{X})^{-1{,}64}}{C} t_p^{-0{,}29}. \quad (7)$$

Results

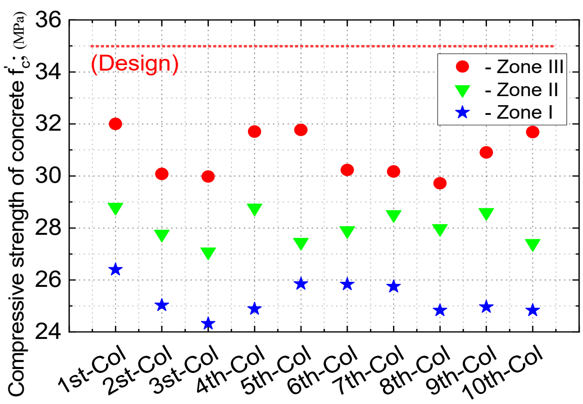
1. Results of the field survey

Fig. 4 shows the results of the field survey of 10 RC bridge columns on the compressive strength of concrete and the thickness of the protective concrete layer.

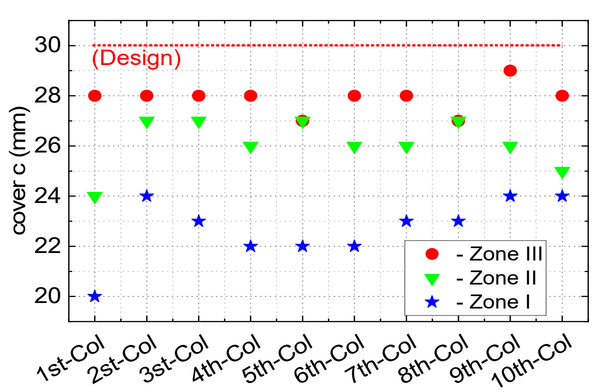
The chart in Fig. 4 shows that the compressive strength of concrete in Zone I reduced significantly compared to the design (26–31 %). The compressive strength reduction of concrete in Zone III compared to the design (8.5–15 %) is less than that in Zone I. In addition, the thickness of the protective concrete layer in Zone I decreased significantly compared to the design (20–33 %). The reduction in the thickness of the protective concrete layer in Zone III compared to the design (3–10 %) is less than that in Zone I. Thus, it is evident that the impact of frequent exposure to the water environment is significant.

2. Results based on the survey-theory combination

Based on the survey data and experimental formulas, the tensile strength of the reinforcement was determined. Data on the steel reinforcement strength of 10 RC columns at different zones are shown in Fig. 5. The X-axis represents the order of columns, and the Y-axis represents the tensile strength of the reinforcement in MPa. The data points show the measured tensile strength values for each column zone after the onset of corrosion. The graph allows for visualizing and comparing the remaining tensile strength values of the reinforcement in different column sections subject to corrosion.



a) Compressive strength of concrete



b) Cover

Fig. 4. Results of the survey on the compressive strength of concrete and the thickness of the protective layer

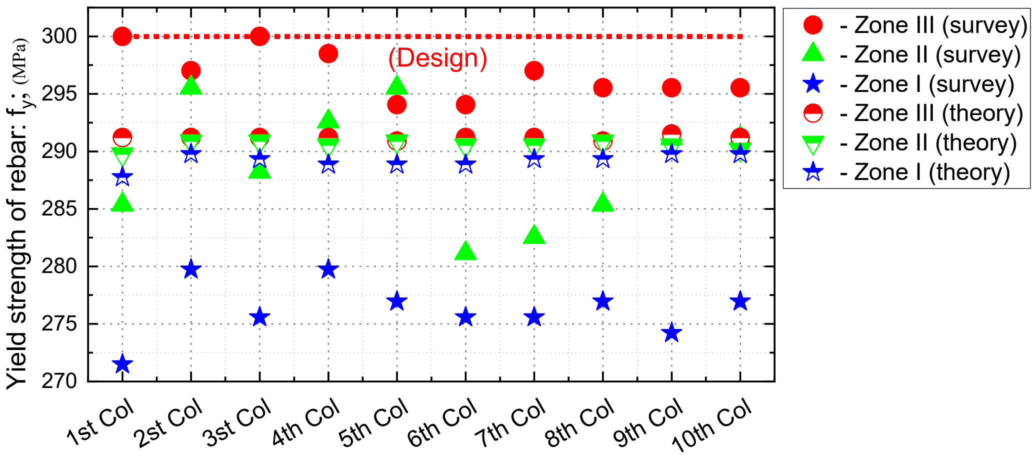


Fig. 5. Decrease in the reinforcement tensile strength after corrosion

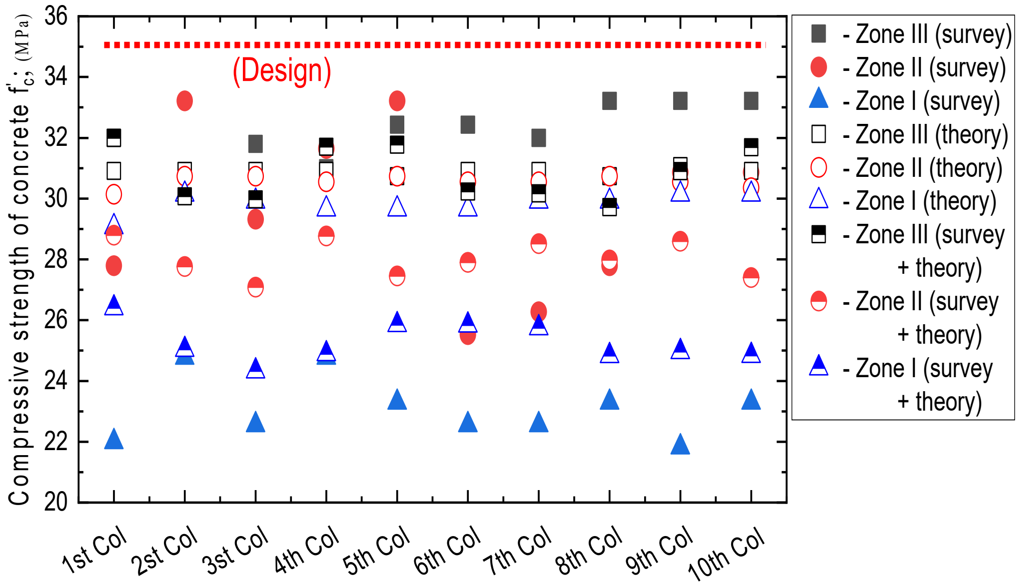


Fig. 6. Decrease in concrete strength after corrosion

The chart shows that the tensile strength of the reinforcement was greatly reduced after corrosion compared to the design specifications. According to the field survey, the tensile strength reduction in Zone I (6.5–8.6 %) is higher than that in Zone III (0–2 %). According to the proposed empirical formula, the tensile strength reduction in Zone I (3.4–4.1 %) is slightly higher than that in Zone III (2.9–3.1 %). The results show a clear difference in the reduction of reinforcement tensile strength at different zones of the same structure. The bottom zone of the column frequently exposed to seawater (Zone I) has a significant reduction compared to the column top area (Zone III). In addition, the results also show that calculations based entirely on the proposed theoretical formulas only approximate a specific cross-section in Zone II.

Fig. 6 shows the compressive strength of concrete after reinforcement corrosion. The results were obtained based on calculating survey data and combining it with the empirical formulas.

It can be seen that the decrease in the compressive strength of the protective concrete layer was actually significant (8.5–30 %). The decrease in the compressive strength of concrete columns, according to the survey combined with the experimental formulas (5–37 %) is higher than that of the theoretical calculation (11.7–15 %). Besides, the reduction of the compressive strength of concrete in different zones of the same structure has a remarkable difference in case of the survey alone (23 %), in case of the theory only (4.5 %), and in case of the theory combined with experimental data (37.2 %).

3. Predicting the loss of material strength over time after corrosion

In addition, by applying the theory of Gonzalez et al. (1995), Andrade and Alonso (2001), and Vu and Stewart (2000), along with the field survey data, a predictive curve is presented, showing the reduction in steel tensile strength (Fig. 7), concrete compressive strength (Fig. 8), and the remaining diameter of steel rebars over 80 years from the onset of corrosion.

Figs. 7, 8, and 9 collectively illustrate the detrimental effects of the steel reinforcement corrosion on the material properties and structural performance of reinforced concrete components over time.

In Fig. 7, the curve represents the reduction in the strength of reinforcement steel over time. This curve was determined using empirical formulas proposed by Du et al. (2005), Gonzalez et al. (1995), and Vu and Stewart (2000). The points shown in Fig. 7 at the 20-year mark represent the strength of the reinforcement steel as experimentally determined by the authors. It should be noted that the surveyed structures have different ages. However, data on the bridge columns of a specific structure were collected to obtain a sufficient dataset for analysis and evaluation. According to local investigations, this structure was 20 years old at the time of the survey.

In Fig. 8, the curve represents the reduction in concrete strength over time. This curve was determined using empirical formulas proposed by Du et al. (2005), Shayanfar et al. (2016), Gonzalez et al. (1995), and Vu and Stewart (2000). The points shown in Fig. 8 at the 20-year mark represent the concrete strength as experimentally determined by the authors. The reduction in steel tensile strength, concrete compressive strength, and steel rebar diameter can significantly affect the durability, serviceability, and safety of the affected structures. When comparing the predicted degradation results

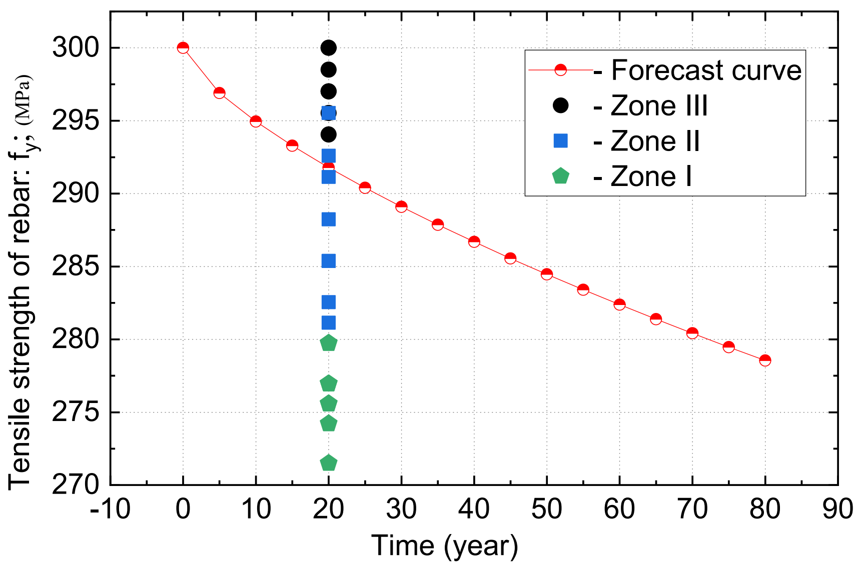


Fig. 7. Decrease of reinforcement tensile strength over time

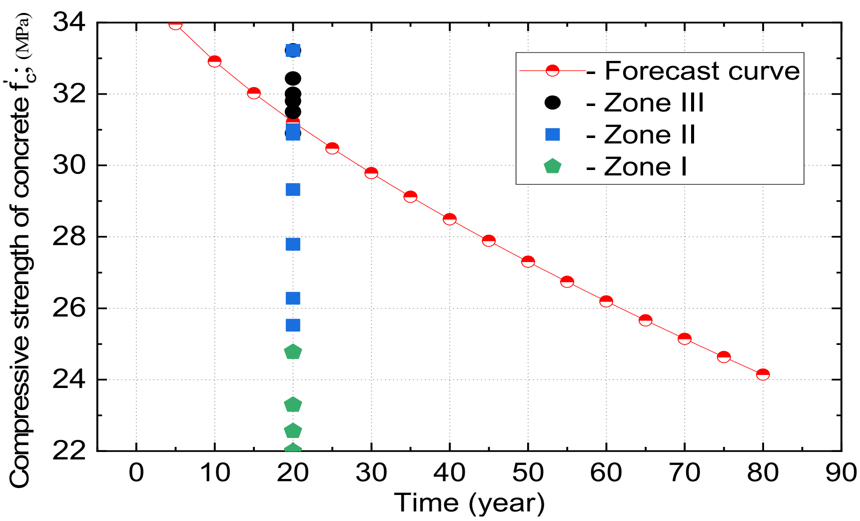


Fig. 8. Decrease of concrete compressive strength over time

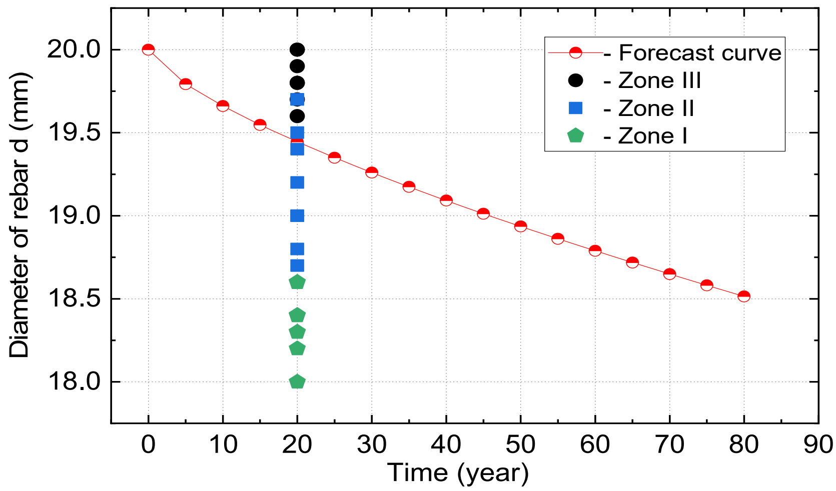


Fig. 9. Decrease of reinforcement diameter over time

with the current survey data (for the 20-year-old structure), the reduction rates of material strength and remaining rebar diameter over time closely approximate the empirical formula predictions only in Zone II (approximately –2 % to 4 %). However, significant discrepancies were observed between the measured values and the predicted results based on proposed empirical formulas in both Zone I and Zone III. This suggests that the existing empirical models have limited applicability across different structural zones and may require zone-specific calibration for accurate long-term performance assessment. The reduction in mechanical properties in Zone I is greater (4 % to 7 %) than that in Zone II, while the reduction in Zone III (–1 % to –3 %) is less than in Zone II.

In Fig. 9, the curve represents the reduction in the diameter of reinforcement steel over time. This curve was determined using empirical formulas proposed by Gonzalez et al. (1995) and Vu and Stewart (2000). The points shown in Fig. 9 at the 20-year mark represent the diameter of the reinforcement steel as experimentally determined by the authors.

This again reflects that the corrosion rate of the structure, or the reduction in the bearing capacity of the column components when corroded, depends not only on the general environmental conditions but also on the specific cross-sections within the structure. This should be taken into serious consideration when calculating the residual bearing capacity of the components after steel reinforcement corrosion.

Discussion

A survey was carried out on RC bridges in the coastal regions of Vietnam. We compared the survey results with the estimates obtained using a formula to calculate the loss of concrete strength, the reduction of tensile strength and cross-sectional area of reinforcement. We managed to draw the following conclusions:

1. Corrosion of reinforced concrete columns in zones contaminated with chlorides and sulfates in coastal areas of Vietnam occurs unevenly depending on the height of the structure.

2. The most corroded is the area at the column foot frequently submerged by flooding (Zone I). This can be attributed to the water level rising and falling regularly in this region, leading to the highest rate of corrosion.

3. Analysis of the survey results indicated that the bearing capacity of reinforced concrete columns affected by steel reinforcement corrosion in the study area must be assessed in Zone I.

4. These conclusions are based on the structural and environmental conditions of the study area (coastal regions of Vietnam). However, they offer a different perspective compared to some of the conclusions from previous studies.

5. While this study included some field survey experiments, the authors propose expanding the research to a larger scale, involving more structures and additional corrosive agents, to obtain more reliable results.

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ВЛИЯНИЕ ЗАГРЯЗНЕННЫХ ХЛОРИДАМИ И СУЛЬФАТАМИ СРЕД НА ЖЕЛЕЗОБЕТОННЫЕ КОЛОННЫ

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Аннотация

Введение. Коррозия стальной арматуры — сложный процесс, имеющий явные различия в разных географических регионах. Во всем мире разрабатываются многочисленные модели для прогнозирования ухудшения качества железобетонных конструкций в районах, загрязненных хлоридами и сульфатами. Тем не менее из-за слишком широкой сферы применения эти модели не способны полно и точно отразить снижение качества структуры в каждом конкретном случае. **Целью исследования** было изучение текущего состояния железобетонных (ЖБ) конструкций, расположенных в средах, загрязненных хлоридами и сульфатами, в прибрежных районах Вьетнама. Мы также проанализировали результаты и сравнили их с ранее исследованными предложениями, чтобы уточнить влияние коррозии стальной арматуры на качество ЖБ колонн. Были использованы следующие **методы**: экспериментальное исследования, неразрушающий контроль для определения снижения таких характеристик, как прочность бетона на сжатие, толщина защитного слоя, диаметр арматуры и площадь поперечного сечения ЖБ колонн. Кроме того, данное исследование было объединено с имеющимися рекомендациями по коррозии арматуры для определения остаточных физико-механических характеристик бетона и арматурной стали. В **результате** ухудшение качества ЖБ колонны с подвергшейся коррозии арматурой зависит от местоположения арматуры в одном и том же продольном элементе. Это указывает на значительное ухудшение качества конструктивных элементов, регулярно подвергающихся непосредственному воздействию морской воды.

Ключевые слова: бетон; сталь; железобетон; коррозия; морская вода; хлорид.