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Monitoring corrosion progression and its structural consequences in reinforced concrete

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Abstract

Reinforced concrete is the most widely used material in construction due to its high compressive and tensile strength. However, it is often exposed to severe conditions that can damage it and subsequently reduce its durability. Corrosion is one of the major issues affecting reinforced concrete. It is a natural phenomenon that occurs when the potential of hydrogen (pH) of concrete decreases to between 8 and 9. This decrease is mainly caused by the presence of catalysts such as chloride ions (Cl^-) or carbon dioxide (CO_2). This initiates the corrosion process within the structure, causing changes in the physic-chemical properties of the concrete and its subsequent deterioration. From the appearance of micro-cracks to concrete spalling and the reduction in reinforcement diameter due to oxidation, the structure becomes more fragile. Consequently, it can no longer support the intended loads. This paper provides a comprehensive review of the corrosion mechanisms in reinforced concrete, along with the various forms of damage that arise from this phenomenon. Corrosion tests were conducted on reinforced concrete specimens. The results of these tests made it possible to monitor the evolution of various parameters during the corrosion process, more specifically pH, crack development, and the corrosion products released. The results indicate a progressive decrease in pH levels throughout the corrosion process in the specimens. The corrosion of the reinforcement bars produced expansive iron oxide formations, generating internal stresses. This buildup of internal pressure led to pronounced cracking within the specimens, ultimately compromising their structural integrity and resulting in complete failure.

Keywords

Corrosion, Reinforced concrete, Durability, Carbonation, Chloride ions, Crack development.

1.Introduction

Reinforced concrete is one of the most widely used materials in construction due to its high mechanical strength, durability, and fire resistance. It is a composite material consisting of concrete—a mixture of aggregates, sand, cement, water, and admixtures—and steel reinforcement, which enhances tensile strength [1]. The mechanical and durability properties of reinforced concrete depend on the characteristics and proportions of its constituents, which must comply with specific standards. Despite its advantages, reinforced concrete is vulnerable to environmental and mechanical degradation, particularly due to corrosion of the reinforcing steel [2, 3].

Corrosion in reinforced concrete is primarily driven by aggressive agents such as carbon dioxide (CO_2), chloride ions (Cl^-), and sulfates, which penetrate the concrete's porous structure, leading to a reduction in potential of hydrogen (pH) and the breakdown of the protective passivation layer on the reinforcement [4, 5]. This process generates expansive iron oxides, causing internal stresses, cracking, and a reduction in the structural integrity and service life of concrete structures [6]. Since many structures are difficult to access, early detection of corrosion is challenging, often leading to significant damage before intervention is possible [7–9].

The primary challenge in reinforced concrete structures is the early detection and mitigation of corrosion. Conventional methods often identify corrosion at an advanced stage when structural damage, such as cracking and spalling, is already visible [10, 6]. Additionally, the rate of corrosion

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varies depending on environmental conditions, concrete porosity, and reinforcement properties, making it difficult to establish universal preventive measures [11, 12]. Existing techniques for monitoring corrosion focus on electrochemical methods, but these require specialized equipment and may not be feasible for all structures [13]. Thus, there is a need for innovative, real-time monitoring approaches that can detect corrosion-related changes at an early stage [14, 15].

This study focuses on understanding and regulating the formation of corrosion products in reinforced concrete by analyzing physicochemical changes, particularly pH variations, and examining the relationship between corrosion and crack formation. The main contributions of this work include a comprehensive review of corrosion mechanisms and their impact on structural integrity, an experimental analysis of corrosion progression through pH monitoring, crack development assessment, and characterization of corrosion products, and insights into potential early detection strategies to improve the durability of reinforced concrete structures.

The rest of this paper is structured as follows: Section 2 provides an overview of corrosion mechanisms in reinforced concrete. Section 3 presents the experimental setup and testing procedures. Section 4 discusses the results, including pH monitoring, crack formation, and corrosion product characterization. Finally, section 5 concludes with key findings and future research directions.

2.Literature review

2.1Passivation process of steel in reinforced concrete

Reinforced concrete is a porous material often exposed to severe environmental conditions, such as high relative humidity, excessive levels of CO_2, acid rain, and seawater. These conditions are conducive to corrosion and structural deterioration. During concrete mix preparation, contact between cement and mixing water triggers the cement hydration process and reactions. During these reactions, cement components react with water, mainly silicates, to form hydrated calcium silicates ($(CaO)_x \cdot SiO_2 \cdot (H_2O)_y$), calcium hydroxides ($Ca(OH)_2$), hydrated aluminates, and anhydrous cement grains [16]. Due to their alkalinity, the concrete mix acquires a pH of between 12 and 13. Under these pH conditions, the steel reinforcement is coated with a protective layer known as the passivation layer. This mechanism remains stable until the introduction of corrosion catalysts, which destroy the passivation layer and initiate corrosion on the reinforcement.

The Pourbaix [17] potential-pH diagram helps explain this mechanism. The diagram shows the stability zones of each chemical form of any chemical element, based on the pH and potential of the medium. For iron, *Figure 1* shows the Pourbaix diagram for iron in an aqueous medium at normal temperature and pressure (T = 25°C, P = 1 atm) with a dissolved ferrous and ferric ion concentration of 10^{-6} mol/L.

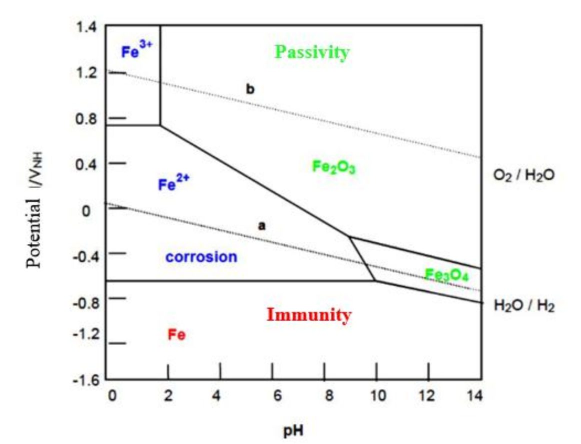

Figure 1 Pourbaix diagram of iron in an aqueous medium at 25°C and 1 atm, with a ferrous ion (Fe^{2+}) and **ferric ion (**Fe^{3+}) concentration of 10^{-6} mol/L

By analyzing this diagram, we can see that, as the concrete's interstitial solution has a basic pH, the most stable form of iron is found in the passivity zones. This leads to the precipitation of oxides in the form of a thin layer, which protects the steel from corrosion. However, when the reinforced concrete structure is exposed to corrosion catalysts such as CO_2 or Cl^-, the pH of the concrete's interstitial solution decreases, reaching values between 8 and 9 [4]. Under these conditions, the iron's stability zone shifts towards the corrosion zone, leading to the destruction of the protective layer and the initiation of corrosion in the reinforcement. The resulting corrosion products increase in volume, leading to cracking and subsequent spalling of the concrete.

2.2Corrosion mechanism in reinforced concrete

Corrosion of reinforced concrete is an electrochemical phenomenon that occurs when the physicochemical properties of the environment around the rebar change. According to the scientific literature, the corrosion process comprises two main stages: the first consists of the de-passivation of the steel, i.e., the destruction of the thin protective layer [18]. This is the primary trigger for corrosion. The second stage is corrosion propagation. The succession of oxidation reactions leads to the production of large-volume iron oxides, generating pressure forces within the structure, as shown in *Figure 2*. These pressure forces cause the concrete to swell, leading to the appearance of cracks that impair the structure's aesthetics and mechanical characteristics [19]. This degradation has a direct impact on the structure's durability, as reinforcement diameters are reduced and resistance to applied loads is weakened.

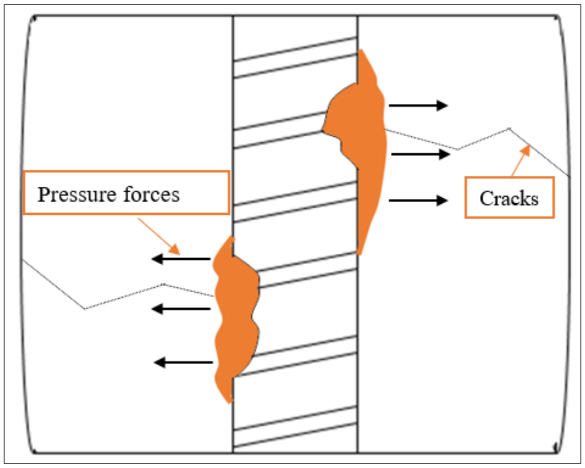

Figure 2 Internal pressure due to the formation of iron oxides

Corrosion of steel in reinforced concrete is an electrochemical mechanism. When steel comes into contact with water and oxygen, iron oxidation reactions take place, allowing it to return to its most stable chemical state under the given conditions. There are two main reactions:

In the first step of the corrosion process, iron undergoes oxidation, breaking down its atomic structure and forming Fe^{2+}**.** This reaction, represented by Equation 1, is fundamental to the corrosion mechanism and initiates the transformation of steel into corrosion products.

$$Fe \rightarrow Fe^{2+} + 2e^- \quad (1)$$

To ensure electrical neutrality, the electrons released during the anodic reaction are consumed by the oxygen reduction reaction, also known as the cathodic reaction, as described in Equation 2.

$$\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^- \quad (2)$$

Two main corrosion mechanisms affect reinforced concrete structures: carbonation and Cl^- integration.

2.2.1Carbonation

During concrete preparation, cement that comes into contact with mixing water primarily transforms into $Ca(OH)_2$, as described in Equation 3.

$$CaO + H_2O \rightarrow Ca(OH)_2 \quad (3)$$

The production of this chemical element gives concrete a basic pH of between 12 and 13 [16].

When a structure is put into service, it is frequently exposed to a variety of mechanical, chemical, biological, and other stresses. These stresses can modify the properties of the concrete, thereby affecting its long-term durability. In addition, degradation processes can be accelerated by other environmental factors such as temperature and humidity fluctuations. For example, the freeze-thaw process can lead to increased cracking and porosity, reducing the strength and longevity of concrete [6]. Carbonation is the chemical reaction between CO_2 in the air and $Ca(OH)_2$ in the concrete, leading to the formation of calcium carbonate ($CaCO_3$) [20], as shown in Equation 4.

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \quad (4)$$

The pH of concrete decreases during this reaction, from approximately 12–13 to about 9. By altering the pH, the passive protective layer that usually surrounds the steel bars in concrete is neutralized, making the steel more susceptible to corrosion.

The carbonation process occurs gradually. Several material and environmental conditions determine this process. Firstly, CO_2 is required, as it reacts with the calcium in concrete. The speed of the carbonation process is proportional to the concentration of CO_2 in the air [21]. Secondly, relative humidity is also crucial to carbonation. The optimum humidity range is generally 50-70%. When humidity is low, there isn't enough water to dissolve CO_2 and penetrate the concrete. On the other hand, when humidity is high, concrete is saturated, and CO_2 does not penetrate well [22].

2.2.2Cl^- integration

Chloride-induced corrosion in reinforced concrete is a complex phenomenon that can compromise the structural integrity of constructions. These ions can infiltrate the concrete from various sources and initiate corrosion of the embedded steel. In marine environments, structures located near the coast or in direct contact with seawater are particularly vulnerable due to high chloride concentrations. In cold climates, de-icing salts used to melt ice on roads and sidewalks also contribute to chloride ingress. These compounds are frequently present in run-off water that permeates concrete structures [23].

Some sources of chlorides come from the building materials themselves. For example, poorly controlled additives or cements may contain Cl^- from when concrete is manufactured. Industrial environments can also contribute to concrete contamination, as particles or gases containing chlorides can settle on surfaces and penetrate over time. Concrete in contact with chloride-contaminated soils, such as those near salt storage sites or industrial facilities, can absorb these ions by capillary action or diffusion. Moreover, in some regions, rainwater can be contaminated by chlorides from natural sources or industrial pollution, contributing to their penetration into concrete [24, 25].

Once chlorides reach the steel reinforcement, they accumulate at its surface. These ions compromise the protective passive layer by lowering the local pH, leading to its breakdown. As this layer deteriorates, the underlying steel becomes increasingly vulnerable to corrosion.

The corrosion of steel rebars in reinforced concrete initiated by chloride ingress involves several complex chemical reactions. Initially, these ions penetrate the concrete matrix and migrate toward the steel reinforcement [26]. The passive iron oxide layer, which typically protects the steel from corrosion, is disrupted by chloride attack. This leads to localized acidification, lowering the pH and promoting the formation of complexes with Fe^{2+}, as shown in Equation 5.

$$Fe_2O_3 + 6Cl^- + 6H^+ \rightarrow 2FeCl_3 + 3H_2O \quad (5)$$

2.3Impact of corrosion on reinforced concrete

The pH of concrete plays a key role in protecting reinforcing steel from corrosion, as a high pH (above 12.5) maintains a passive protective layer on the steel, reducing the risk of corrosion [27]. However, the presence of chloride and sulfate ions can lower the pH, compromising this layer and accelerating corrosion. A pH range between 12.4 and 13.5, typical of concrete, promotes corrosion resistance by limiting the adsorption of these ions onto the passivation film [28]. During hydration, the pH of the interstitial solution of concrete fluctuates between 13.1 and 13.8 due to the concentration of alkali hydroxides and calcium, but various factors, such as carbonation, alkali leaching, and continuous exposure to water, can cause the pH to fall below critical levels, triggering corrosion [29]. The accumulation of corrosion products causes pressure on the surrounding concrete, leading to cracking and further degradation of the structure.

Corrosion in reinforced concrete depends mainly on the environment to which it is exposed and is particularly intense in marine environments, where corrosion activity is higher than elsewhere [30]. In these environments, reinforced concrete structures are exposed to high concentrations of corrosive agents, which have an impact on the critical chloride concentration required to initiate corrosion of the reinforcement. This critical concentration is influenced by the total and free chloride content, the binding capacity of chlorides, as well as the effect of external loading and erosion caused by seawater [12]. In addition, marine structures can be colonized by microbial organisms, which cause a pH imbalance, facilitating the corrosion process [31]. Reinforced concrete structures are also subject to severe environmental conditions, such as exposure to acidic solutions, which can cause critical damage, including loss of material mass. These acid solutions attack the mineral components of cement, threatening the durability of concrete [32].

Various parameters influence the rate of corrosion in reinforced concrete, including temperature and CO_2 pressure. For example, a high temperature over 50°C leads to a 10-45% increase in porosity, which intensifies the corrosion process. On the other hand, under pressures ranging from 0 to 10 MPa, the solubility of CO_2 increases, which contributes to the acceleration of the corrosion rate [33]. It is also important to note that the more severe environmental conditions combine, the worse the corrosion rate becomes: in a study conducted by Peng et al. [34], samples exposed to a combined corrosion environment of aggressive CO_2 and sodium sulfate experienced more intense degradation.

The composition of concrete has a direct influence on its resistance to corrosion, which makes it crucial to choose constituents according to the service environment [30]. To improve this resistance, the addition of fibers, particularly steel fibers, increases the cohesion and watertightness of the concrete cover, thereby reducing the penetration of Cl^- and corrosion activity [35]. Fibers limit the diffusion of chlorides, improving the resistance of concrete to chloride-induced corrosion by reducing its permeability [27]. In addition, the presence of fibers increases the tensile strength of concrete, which reduces crack width and prolongs crack formation time, thereby increasing its durability [27]. However, in a severely corrosive environment, even fiber-reinforced concrete is vulnerable: in a study of ultra-high-performance fiber-reinforced concrete, it was observed that corrosion often starts at the surface of fibers exposed to an erosive solution, which degrades their integrity and their ability to transfer loads, thus weakening the concrete matrix [27]. The pH of concrete also influences steel fiber corrosion, particularly in the presence of Cl^-; a pH lowered by chloride ingress and carbonation accelerates the dissolution of protective passive films on steel fibers, thereby increasing corrosion rates [36]. In a separate study carried out by [37], it was found that chromium-modified rebars exhibit improved passivation due to the rapid formation of a passive film and low activation energy. The presence of chromium oxide or hydroxide in the passive film forms a more effective barrier against ion migration, thus increasing corrosion resistance in hostile environments.

In addition to the composition of the concrete, the thickness of the concrete cover is also crucial in limiting corrosion in the structure [38]. Furthermore, Xia et al. [39] confirm that this thickness has a significant influence on the length and angles of crack propagation. His study shows that increasing the thickness of the protective layer significantly reduces crack length. What's more, with increased thickness, the angle between the cracks and the surface of the protective layer also decreases, contributing to greater mechanical strength and durability of the structure.

Cracking in cementitious materials often results from the degradation of $(CaO)_x{\cdot}SiO_2{\cdot}(H_2O)_y$ in two main phases. In the first phase, the removal of the outer layer of calcium oxide(CaO) lowers the calcium-to-silicon ratio without causing displacement; in the second phase, the removal of calcium from the inner layer produces a partial lamellar structure that can lead to cracking and spalling, weakening the cement matrix [33]. This phenomenon is amplified by carbonation, which releases bound chlorides, increasing the concentration of free Cl^- and promoting corrosion and crack propagation [40]. At the same time, carbonation induces volumetric changes due to chemical reactions, causing shrinkage that can crack concrete, especially if it is stressed. It also refines the pore structure, increasing porosity and making concrete more susceptible to cracking under stress or environmental variations. Reducing moisture content post-carbonation can further increase internal stresses and cause cracking. Finally, the addition of certain cementitious components can affect the concrete's resistance to cracking, depending on their chemical composition and their interaction with the cementitious matrix [41].

Corrosion, with its destructive effects, makes inspection and maintenance tools essential for preserving large structures. Today, several techniques are used, such as half-cell potential, linear polarization resistance (LPR), electrochemical impedance spectroscopy (EIS), and integrated sensors, which make it possible to closely monitor the evolution of corrosion [42]. A recent advance has even shown that a high alternating current (AC) can slow down the corrosion caused by a direct current (DC) by increasing the pH around the steel, opening up new prospects for protecting metal infrastructures from the parasitic currents of modern electrical systems [43].

Although laboratory tests help to better understand corrosion, they cannot fully reproduce real-life conditions. In the field, corrosion rates generally decrease over time due to the formation of protective rust layers, but cracks due to uneven corrosion products persist. Advances in modeling, protective coatings, and electrochemical methods show that it is crucial to refine testing and predictive tools to better address the challenges of corrosion and ensure the durability and safety of structures [44].

The current literature provides extensive insights into the physicochemical factors that drive corrosion in reinforced concrete, such as pH fluctuations, chloride ingress, and carbonation effects. Studies also emphasize the role of concrete composition, protective strategies, and monitoring techniques in enhancing structural durability. However, important gaps remain. In particular, while the influence of pH changes on corrosion initiation is well recognized, few experimental studies have systematically tracked real-time pH evolution alongside crack development and corrosion product formation. Moreover, the interplay between chemical degradation processes and mechanical damage has not been thoroughly explored under controlled laboratory conditions. Although emerging detection methods are promising, there is still a need for integrated approaches that combine chemical monitoring, mechanical assessment, and material characterization. This study aims to address these gaps by experimentally investigating the relationship between pH variation, corrosion progression, and crack formation. Through detailed characterization of corrosion products and identifying early indicators of degradation, this work seeks to support the development of more effective strategies for improving the long-term durability of reinforced concrete structures.

3.Materials and methods

3.1Material description

Reinforced concrete specimens were prepared for this investigation. The specimens are 100 mm cubes with a 10 mm diameter reinforcement placed in the center (*Figure 3*).

Figure 3 The reinforced concrete specimens used

The concrete mix design is obtained using the Dreux-Gorisse method [45]. The specimens were prepared using regular portland cement of class portland limestone cement (CPJ) 55. At 28 days, the compressive strength was set at 25 MPa with a 15% safety margin. The crushed sand utilized has a 70% purity level. Lastly, 9 cm is the chosen concrete subsidence. The initial mix has a maximum aggregate diameter of 25 mm and a water-to-cement ratio of 65%. The concrete mix design is given in *Table 1*.

Table 1 Concrete mix composition

Element	**Quantity (Kg/m^3)**
Crushed sand	912
Type GI gravel	509
Type GII gravel	411
Cement	330
Water	214

In a controlled setting with 20°C±2 and 95% humidity, the concrete was allowed to cure. To ensure ideal strength growth, specimens were also continuously hydrated in a water bath. To ensure constant conditions, they were moved right away to the curing chamber after demolding. No extra surface treatments or curing chemicals were used.

3.2Test description

Once hardened, the specimens are subjected to a corrosion test. The test involves immersing the specimens in a solution containing 30g/L of sodium chloride (NaCl), simulating seawater, and applying a constant voltage of 15 V between the reinforcement and a reference electrode. In this study, a stainless-steel bar serves as the reference electrode. 10g/L of potassium chloride (KCl) is added to the solution to accelerate the corrosion process further. The distance between the reinforcement bar and the reference electrode is fixed to ensure accurate measurements. Voltage monitoring is performed using the electrochemical potential measurement technique, which records the potential difference between the reinforcement and the reference electrode. The applied 15V remains constant throughout the test.

By completing the circuit, the reference electrode functions as the cathode, while the reinforcement acts as the anode, leading to iron oxidation and corrosion of the specimen. *Figure 4* illustrates the setup for the corrosion test.

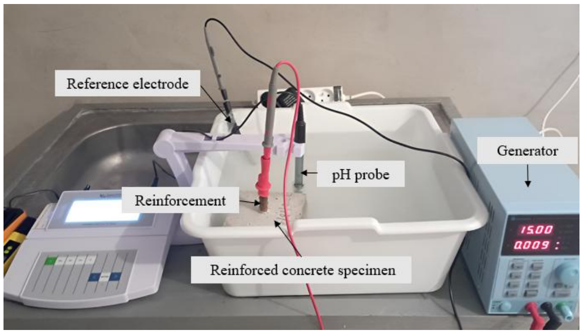

Figure 4 Corrosion test devices

The immersion corrosion test was conducted by submerging the specimen to its upper surface to ensure proper ion transfer during the corrosion process. After adding NaCl and KCl, the solution was initially stirred to ensure homogeneity but remained static throughout the test. The experiments were carried out in a controlled chamber maintained at 23°C. pH measurements were performed using a fixed probe near the external surface of the specimens and a mobile probe to verify pH variations around the specimen. Electrochemical potential measurements were recorded using a multimeter, while mass loss was determined by comparing the weight of the specimens and reinforcement bars before and after the test.

4.Results and discussion

The tests continued until the specimens failed due to corrosion. On average, the process took 15 days for each sample. During the test, pH and potential were measured twice daily. Crack propagation and corrosion product evolution were also monitored.

4.1Electrochemical potential and pH evolution

When reinforced concrete corrodes, electrochemical cells form between the anodic and cathodic zones. The porous, moist nature of concrete facilitates the transfer of ions between the two zones. As a result, iron corrodes by oxidation, lowering the electrochemical potential. According to the American society for testing and materials standard (ASTM) C876 [46], the lower the potential, the more severe the corrosion. *Figure 5* shows the variation in potential measured during the corrosion tests performed on the 3 specimens.

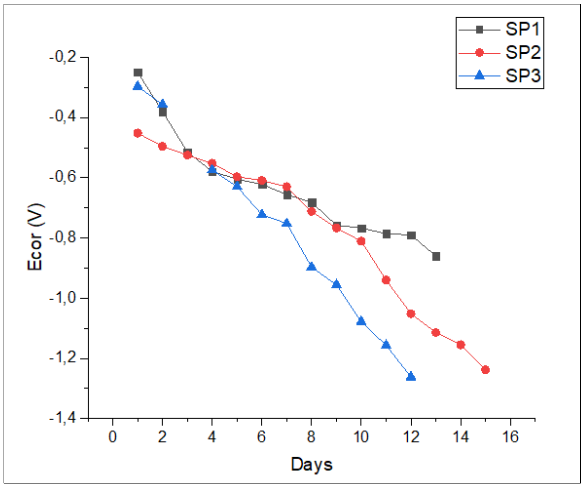

Figure 5 Variation of electrochemical potential during corrosion test

On the other hand, corrosion of reinforced concrete also affects its pH. Since it is difficult to determine the pH of the concrete directly during testing, pH measurements were taken near the exterior surfaces of the specimens using a pH meter. *Figure 6* shows the average pH change over the 15-day test period for each specimen.

The test results confirm the decrease in pH during rebar corrosion. For the three tests conducted, the pH dropped from 13 to approximately 10 over the 15 days.

Due to the chemical reactions caused by the corrosion process, the resulting corrosion products lead to a decrease in pH, dropping from 13 to around 8. This change in chemical composition affects the pH of the environment, further promoting the spread of corrosion within the concrete.

After removal from the initial solution tank, the test specimens were carefully rinsed to remove solid corrosion products and deposits from the components of the basic solution used in the test. They were then immersed in a tank of distilled water according to the leaching method. After 24 hours, the pH was measured to be 8.14 (*Figure 7*).

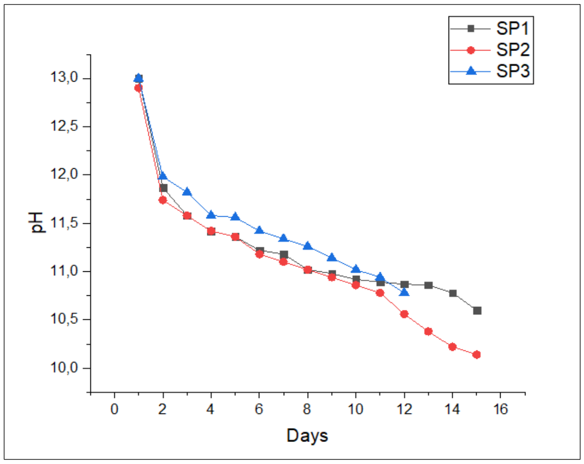

Figure 6 pH variation

Figure 7 pH measurement after the corrosion test

4.2Crack propagation and associated effects

At the start of the test, air bubbles were observed near the reinforcement, indicating hydrogen (H_2) formation as a result of the water reduction reaction. After 24 hours, liquid corrosion products appeared on the surface, accompanied by the first visible crack, which began propagating along the top surface of the specimen.

The accumulation of corrosion products generated internal compressive forces, promoting the expansion of the initial crack and the formation of new ones. By the sixth day, the crack had extended along the lateral surface, reaching a width of approximately 2 mm. This cracking facilitated the penetration of corrosive agents to the reinforcement, further accelerating the corrosion process.

By the tenth day, the cracks became more pronounced and numerous, signaling advanced deterioration of the specimen. *Figures 8*, *9*, and *10* illustrate the crack progression for specimens 1, 2, and 3, respectively.

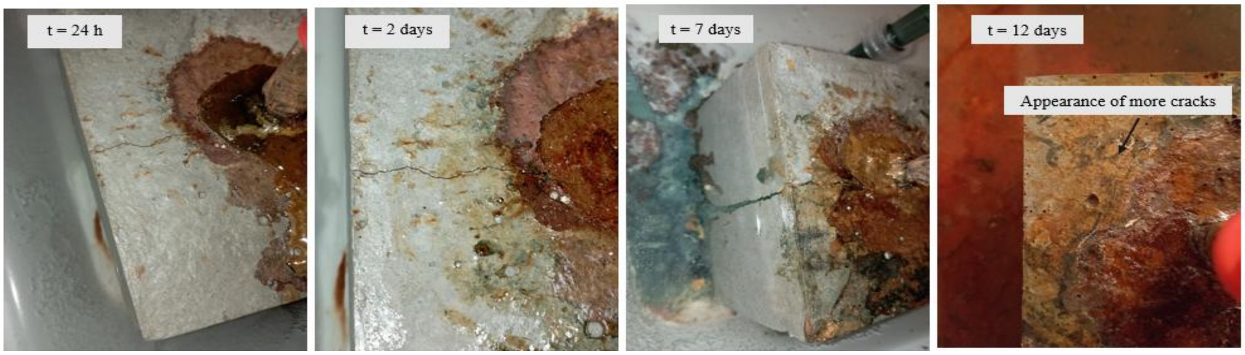

Figure 8 Crack development on specimen 1

Figure 9 Crack development on specimen 2

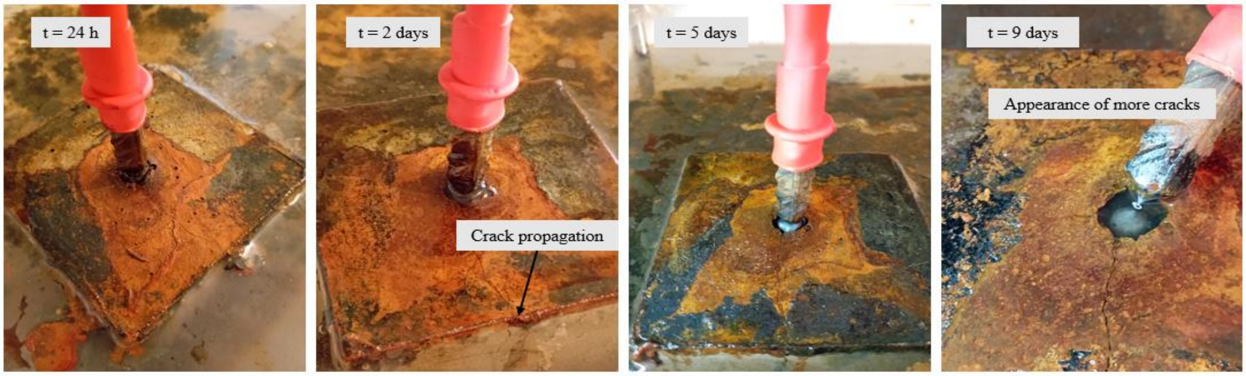

Figure 10 Crack development on specimen 3

At the end of the tests, specimen weights and deformations were checked. To do this, the specimens were removed and placed in an oven to remove as much water as possible. The masses of the specimens before and after the corrosion test are shown in *Table 2*.

Table 2 Specimen weight measurements before and after the corrosion test

Specimen	weight before (g)	Weight after (g)
SP1	2380,40	2470,50
SP2	2379,20	2478,25
SP3	2377,40	2410,25

As the results indicate, the mass of the test specimens increased by an average of 74 g. This gain is directly linked to the formation of corrosion products on the reinforcement surface [47]. During the corrosion process, iron reacts with oxygen and Cl^- in the solution, leading to the development of iron oxides and hydroxides. These byproducts adhere to the steel surface and progressively accumulate, contributing to the observed weight increase. Additionally, the composition and density of these corrosion products can vary depending on exposure conditions, influencing the overall mass gain. This phenomenon provides a quantitative indicator of corrosion progression, complementing the deformation measurements discussed earlier. Corrosion strain was measured on each lateral surface of the specimens at three different points: top (T), middle (M), and bottom (B), as shown in *Figure 11*. These measurements are summarized in *Table 3*.

Table 3 Deformations generated on each specimen side face

Specimen	Face 1 (cm)	Face 1' (cm)	Face 2 (cm)	Face 2' (cm)
SP1	T: 10,20	T: 10,15	T: 10,04	T: 10,12
	M: 10,25	M: 10,17	M: 10,05	M: 10,05
	B: 10,18	B: 10,14	B: 10,02	B: 10,12
SP2	T: 10,25	T: 10,12	T: 10,11	T: 10,12
	M: 10,25	M: 10,06	M: 10,16	M: 10,15
	B: 10,2	B; 10,02	B; 10,10	B: 10,00
SP3	T: 10,23	T: 10,14	T: 10,06	T: 10,12
	M: 10,26	M: 10,14	M: 10,06	M: 10,08
	B: 10,25	B: 10,13	B: 10,05	B: 10,02

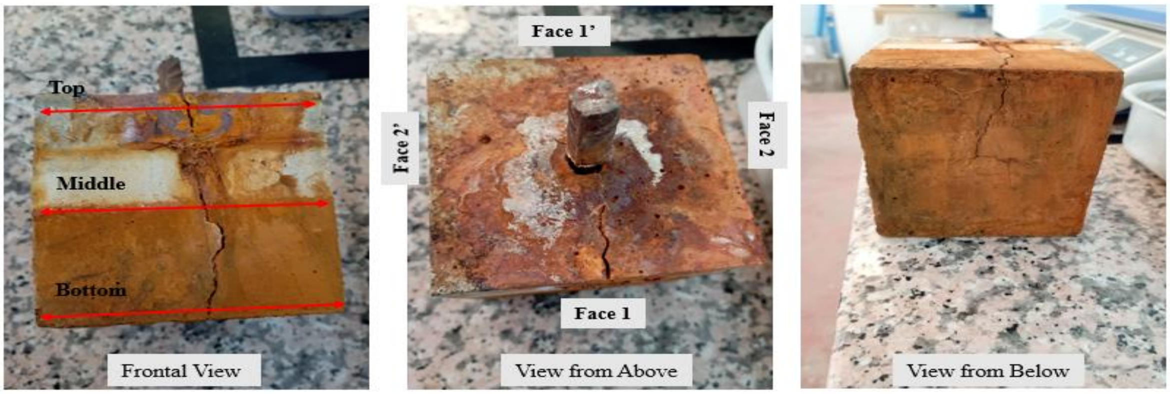

Figure 11 Specimen state after corrosion test

As mentioned earlier, the accumulation of corrosion products, which have a greater volume than the original steel, generates internal pressures within the concrete matrix. These pressures induce tensile stresses that progressively build up around the reinforcement bars. As the corrosion process advances, these stresses lead to microcracking and eventual deformation of the specimen. This phenomenon explains the deformation values presented in *Table 3*, as the expansive forces exerted by the corrosion products compromise the structural integrity of the concrete over time.

4.3Reinforcement damage

As the corrosion process progresses, the steel in the reinforcement bars reacts with oxygen and water, forming different types of iron oxides like rust. These corrosion products accumulate on the surface of the reinforcement bars, contributing to surface roughness and altering their mechanical properties. As oxidation progresses, metal loss occurs, leading to a reduction in the effective cross-sectional area of the steel, which weakens the rebar structurally [48]. The reduction in diameter observed during testing is a direct consequence of this metal loss. Measurements revealed that the diameter of the rebars decreased by approximately 50%, significantly compromising their load-bearing capacity.

Moreover, iron oxide deposits were visibly accumulated on the surface of the rebars, as illustrated in *Figure 12*. These deposits indicate localized corrosion activity, suggesting that the protective passive layer initially present on the steel surface had broken down, exposing the underlying metal to aggressive environmental factors. Due to the expansive nature of the corrosion products, this degradation not only causes the rebar to thin but also increases the probability that cracks will appear in the surrounding concrete.

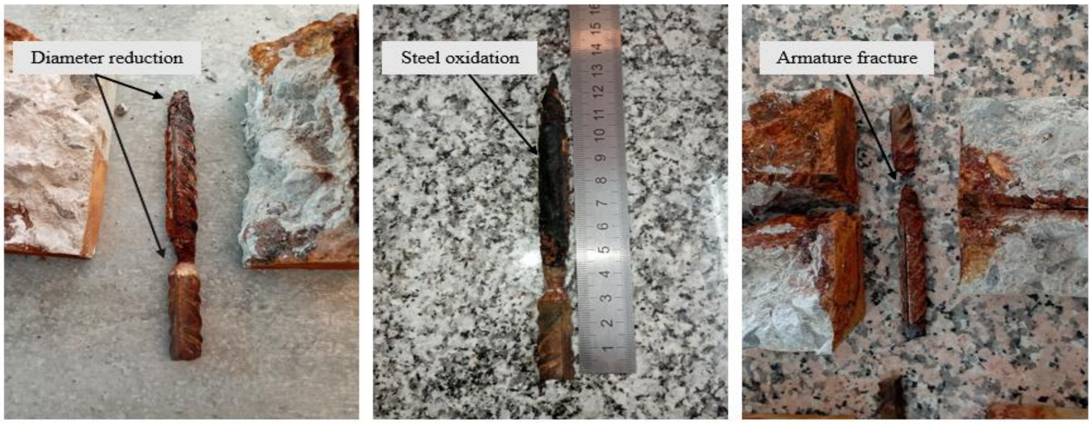

Figure 12 Corroded reinforcement

On average, the rebars' weight decreased by 24 g during the corrosion tests. *Table 4* shows reinforcement weight measurements before and after the test.

Table 4 Reinforcement weights before and after the test

Reinforcement number	Weight before (g)	Weight after (g)
1	108,60	88,80
2	109,35	72,60
3	110,57	94,45

4.4Discussion and interpretation

The primary objective of this study was to analyze the effects of corrosion on reinforced concrete specimens and assess its impact on the material's structural integrity. The experimental results demonstrated a strong correlation between corrosion severity and a reduction in pH levels within the concrete matrix. Initially, the pH electrode recorded highly alkaline value of approximately 13, providing a stable environment for the steel reinforcement due to forming a passive iron oxide layer [28]. However, as corrosive agents such as Cl- and CO2 penetrated the concrete, this protective layer deteriorated, triggering corrosion. The pH value gradually dropped to around 9, indicating an increase in acidity and a reduction in hydroxide ion (OH^-) concentration, which ultimately led to the active corrosion of the steel reinforcement [41].

A key observation from the study was the direct link between corrosion and crack propagation. Iron oxide byproducts accumulated around the steel reinforcement as corrosion progressed, causing expansion and generating internal tensile stresses within the concrete. This stress led to crack initiation and widening, facilitating further penetration of corrosive agents and exacerbating the deterioration process. Additionally, mass variations in both the concrete specimens and the reinforcing steel were recorded before and after corrosion tests. While the concrete specimens exhibited an increase in mass due to the accumulation of corrosion byproducts, the steel reinforcement experienced mass loss due to oxidation. This reduction in the reinforcement's diameter compromised its load-bearing capacity, highlighting the detrimental impact of corrosion on the overall durability of reinforced concrete structures [49].

To contextualize these findings, a comparative analysis with previous studies was conducted. Similar trends were observed in research conducted by Natkunarajah et al. [29] and Ramirez et al. [41], where pH reduction was identified as a key indicator of corrosion progression in reinforced concrete.

These studies also confirmed that a pH threshold of around 9 marked the onset of active corrosion, aligning with our experimental findings. Additionally, research reported that the expansion of corrosion products increased internal tensile stress, leading to crack formation, a phenomenon consistent with the results obtained in our study [39].

However, some discrepancies were noted when comparing corrosion rates across different studies. While our results indicated a steady progression of corrosion, some studies reported accelerated deterioration due to variations in concrete porosity, exposure conditions, and environmental factors such as humidity and temperature [32,33,44]. Differences in reinforcement materials and protective coatings also influenced corrosion resistance, suggesting that material selection plays a crucial role in mitigating corrosion-related damage.

While this study provides valuable insights into the effects of corrosion on reinforced concrete, certain aspects of corrosion progression could be further explored to enhance the depth of the findings. The experimental setup was designed to closely simulate real-world conditions; however, in actual structures, factors such as fluctuating humidity, temperature variations, and dynamic loading may influence corrosion progression over extended periods. Although these variables were not the primary focus of this study, the controlled environment enabled a clear and precise evaluation of the key corrosion mechanisms.

Additionally, the study duration was sufficient to capture significant trends in corrosion behavior, particularly the relationship between pH reduction, crack formation, and reinforcement mass loss. However, long-term studies could provide further insights into the later stages of corrosion development and its impact on structural integrity over time. The concrete mix and reinforcement materials used in this study were selected based on standard industry practices, ensuring relevance to real-world applications. Future work could expand on this by exploring different concrete compositions or protective coatings to assess their effectiveness in corrosion prevention. Despite these considerations, the findings of this study are robust and align well with existing research. The results provide a solid foundation for understanding corrosion progression and its consequences on reinforced concrete, reinforcing the importance of early detection and monitoring systems. Further research can build upon these results by incorporating real-time monitoring techniques and testing alternative mitigation strategies to enhance the long-term durability of reinforced concrete structures.

A complete list of abbreviations is listed in *Appendix I*.

5.Conclusion

The corrosion of reinforced concrete is a complex phenomenon. It has a negative impact on reinforced concrete structures, deteriorating the strength of the concrete and posing a major risk of structural collapse. Reinforced concrete is a composite material consisting of a concrete mix and reinforcement, often used for its high resistance to simultaneous compressive and tensile forces. The nature of this material creates an environment conducive to the passivation of reinforcement. Concrete has an alkaline pH of between 12 and 13, which causes the reinforcing steel to passivate and form a protective oxide layer around the reinforcement. When exposed to conditions conducive to corrosion, aggressive agents enter the reinforced concrete structure, causing an imbalance in the concrete's physicochemical properties and thus facilitating corrosion initiation by destroying the passivation layer. The work presented in this article aims to validate and deepen our understanding of the damage sustained by reinforced concrete during the corrosion process. When exposed to aggressive conditions, reinforcement corrosion is accelerated. It has been observed that a progressive decrease in the pH of the concrete accompanies the increase in the rate of corrosion. This drop in pH destroys the passivation layer that initially protects the steel, allowing corrosion products to form and accumulate. These products create internal pressure stresses within the structure, leading to the appearance of cracks. As corrosion progresses, cracks widen and multiply, facilitating the infiltration of aggressive agents deep into the structure. This penetration accelerates the process of reinforcement degradation. Steel oxidation leads to a progressive reduction in the diameter of the reinforcing bars, weakening them mechanically and compromising the structure's ability to withstand normal loads.

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Conflicts of interest

The authors have no conflicts of interest to declare.

Data availability

The data for this study were developed as part of a collaboration between the LABNORVIDA laboratory and the MEGCE research team at ESTO - Laboratory of Materials, Wave, Energy and Environment (LaMOn2E). The data are not publicly available. However, the data may be provided by the corresponding author upon reasonable request.

Author's contribution statement

Sadeq Hajar: Conceptualization, investigation, methodology, data collection, data curation, analysis and interpretation of results, investigation on challenges and draft manuscript preparation, writing – original draft, writing – review and editing. **Abdelkader Nasser:** Conceptualization, investigation, methodology, supervision, validation, investigation on challenges and draft manuscript preparation. **Abdelhamid Kerkour El Miad:** Conceptualization, investigation, methodology, supervision, validation, investigation on challenges and draft manuscript preparation. **Najib Amar:** Conceptualization, investigation, data curation, analysis and interpretation of results, investigation on challenges and draft manuscript preparation, validation.

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Appendix I

S. NO.	Abbreviation	Description
1	AC	Alternating Current
2	ASTM	American Society for Testing and Materials
3	$Ca(OH)_2$	Calcium Hydroxide
4	$CaCO_3$	Calcium Carbonate
5	CaO	Calcium Oxide
6	$(CaO)_x\cdot SiO_2\cdot (H_2O)_y$	Calcium-Silicate-Hydrate
7	Cl^-	Chloride Ions
8	CO_2	Carbon Dioxide
9	CPJ	Portland Limestone Cement
10	DC	Direct Current
11	EIS	Electrochemical Impedance Spectroscopy
12	Fe^{2+}	Ferrous Ion
13	Fe^{3+}	Ferric Ion
14	$FeCl_3$	Iron (III) Chloride (ferric chloride)
15	$Fe_2(OH)_2$	Iron (II) Hydroxide
16	Fe_2O_3	Iron (III) Oxide (hematite)
17	H_2	Hydrogen
18	KCl	Potassium Chloride
19	LPR	Linear Polarization Resistance
20	NaCl	Sodium Chloride
21	OH^-	Hydroxide Ion
22	pH	Potential of Hydrogen