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Review Article

Corrosion Mechanisms in Reinforced Concrete: Causes, Effects, and Sustainable Mitigation Strategies

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Abstract

Corrosion in reinforced concrete (RC) structures is a serious concern in civil engineering, influencing durability, structural integrity, and maintenance costs. This research covers the principal corrosion processes, including carbonation-induced and chloride-induced corrosion, which erode reinforcement and impair the lifetime of RC structures. Carbonation lowers concrete alkalinity, weakening the passive layer on steel, while chloride penetration causes localized pitting corrosion, leading to fast degradation. Key environmental and material elements impacting corrosion advancement, such as concrete permeability, water-to-cement ratio, exposure circumstances, and cyclic wet-dry environments, are investigated. Corrosion-induced mechanical deterioration, including cracking, loss of reinforcement cross-section, and bond strength reduction, is also examined. The study analyzes mitigating measures, stressing the significance of supplemental cementitious materials (SCMs) such as silica fume, fly ash, and ground granulated blast furnace slag (GGBFS), which increase durability by lowering permeability and chloride diffusion. Additional preventive approaches, including corrosion inhibitors, epoxy-coated rebars, cathodic protection, and improved design codes, are explored. Advanced corrosion monitoring technologies, including non-destructive testing (NDT) methodologies and machine learning-based prediction models, offer new options for early corrosion identification and efficient maintenance planning. Findings reveal that combining corrosion-resistant materials with proactive maintenance procedures and real-time monitoring can greatly increase the service life of RC structures while lowering long-term repair costs. This work adds to creating sustainable and cost-effective corrosion mitigation technologies, giving significant information for researchers, engineers, and infrastructure managers.

Keywords: Corrosion, Carbonation, Chloride Penetration, Structural Degradation, Non-destructive Testing.

Introduction

Corrosion of reinforced concrete (RC) remains an issue in modern civil engineering as it severely affects durability, structural stability, and service life. Reinforced concrete finds significant application in the construction of important infrastructure such as bridges, buildings, tunnels, and seaports due to its favorable mechanical properties and cost-effectiveness. Despite the mechanical strength and longevity provided by steel reinforcement, corrosion of steel deteriorates structural integrity, which presents serious economic and safety problems [1]. Over time, the cumulative consequences of corrosion manifest as spalling, delamination, cracking, and loss of load-carrying capacity, necessitating costly maintenance and repair activities [2].

The two primary causes of corrosion in RC structures are carbonation-induced corrosion and chloride-induced corrosion. Carbonation-induced corrosion occurs due to the reaction of ambient carbon dioxide (CO_2) with calcium hydroxide in the concrete matrix, resulting in a loss of alkalinity and consequent depassivation of the reinforcing steel. The reduction in pH below the threshold value compromises the protective passive layer on the steel surface, initiating corrosion processes [3]. More localized and severe chloride-induced corrosion results from the ingress of chloride ions into the concrete, particularly in maritime environments and where de-icing solutions are applied. Chloride ions destroy the passive layer on the steel reinforcement, triggering pitting corrosion, which leads to substantial material degradation [4]. Both mechanisms significantly reduce the lifespan of RC structures and cause premature failures, especially in high-temperature and high-humidity conditions [5].

Aging infrastructure further exacerbates the corrosion problem, particularly in developed nations where a significant proportion of critical infrastructure has surpassed its intended service life. In the United States alone, over 617,000 bridges exist, with approximately 42% exceeding 50 years of age and 7.5% classified as structurally deficient [6]. The Federal Highway Administration (FHWA) estimates that an investment of $125 billion over the next decade is required to rehabilitate corroded bridges and address other structural deficiencies [7]. Similar challenges exist in Europe and Asia, where extensive RC infrastructure systems demand frequent rehabilitation and maintenance due to corrosion-related deterioration [8].

Beyond conventional infrastructure, corrosion poses a significant threat to high-risk structures such as nuclear containment facilities, offshore platforms, and maritime installations. Corrosion in containment liners of nuclear power plants has raised concerns about the long-term durability of RC components under harsh operational conditions. More than 40 cases of corrosion-induced failures in nuclear containment structures have been reported, underscoring the need for stringent durability standards and enhanced corrosion monitoring techniques [9]. Additionally, the economic impact of corrosion is substantial, with global annual repair and maintenance costs for RC infrastructure amounting to billions of dollars [7].

The extent and severity of corrosion in RC structures depend on various environmental and material factors. Concrete porosity and permeability play crucial roles in determining the ingress of aggressive agents such as CO_2 and chloride ions, which directly influence corrosion initiation and propagation [10]. The water-to-cement ratio (w/c) is equally important, as a lower w/c ratio minimizes porosity and enhances durability, delaying the onset of corrosion

[11]. Corrosive environments such as coastal and marine regions, industrial zones, and urban areas with high pollution levels further accelerate corrosion activity [8]. Moreover, cyclic wet-dry conditions and fluctuating temperatures significantly affect chloride diffusion rates, increasing corrosion susceptibility in regions undergoing climatic changes [4].

Several strategies have been implemented worldwide to mitigate the adverse effects of corrosion. The incorporation of supplementary cementitious materials (SCMs) such as silica fume, fly ash, and ground granulated blast furnace slag (GGBFS) has been reported to enhance concrete durability by reducing permeability and increasing resistance to chloride penetration [5]. Additionally, corrosion prevention measures such as corrosion inhibitors, epoxy-coated reinforcement, cathodic protection systems, and advanced protective coatings have demonstrated effectiveness in extending the service life of RC structures [1]. Recent advancements in design codes and construction standards, including ACI 318-19 and the fib Model Code for Concrete Structures, emphasize stringent chloride content management, optimized concrete mix designs, and adequate reinforcement cover to improve corrosion resistance [8, 11].

Despite significant progress in corrosion research, challenges persist in accurately predicting and detecting early-stage corrosion in RC structures. Non-destructive testing (NDT) methods such as half-cell potential mapping, electrochemical impedance spectroscopy, and ground-penetrating radar have been developed for real-time corrosion monitoring; however, their large-scale application is limited by cost and technical constraints [4]. Furthermore, the integration of machine learning and artificial intelligence (AI) in corrosion prediction models has shown promise in forecasting corrosion onset and optimizing maintenance planning [2].

Given the complex and widespread nature of corrosion in reinforced concrete infrastructure, this study provides a comprehensive overview of fundamental corrosion mechanisms, environmental and material influences, and contemporary corrosion mitigation strategies. Additionally, it explores recent advancements in corrosion monitoring technologies and predictive modeling approaches to extend the longevity and durability of RC structures. By synthesizing knowledge from recent research, this study aims to contribute to existing literature on sustainable and cost-effective corrosion control solutions in civil engineering.

CORROSION MECHANISMS IN REINFORCED CONCRETE STRUCTURES

Reinforced concrete (RC) buildings rely on the passivation layer produced around embedded steel reinforcement to withstand corrosion. The inherent alkalinity of concrete (pH 12–13) affords a protective environment that resists the oxidation of reinforcing bars (rebar) [1]. However, this passivation layer is vulnerable to disintegration owing to chemical interactions with ambient pollutants, contributing to corrosion initiation and spread. The two primary processes responsible for corrosion in RC structures are carbonation-induced corrosion and chloride-induced corrosion, both of which lead to mechanical degradation, cracking, and structural collapse [2].

CARBONATION-INDUCED CORROSION

Carbonation is a slow but ongoing process in which ambient carbon dioxide (CO_2) diffuses into concrete and reacts with calcium hydroxide ($Ca(OH)_2$) in the cement matrix. The process forms calcium carbonate ($CaCO_3$), thereby reducing the alkalinity of the concrete. The protective passive layer surrounding the reinforcing steel destabilizes when the pH drops below 9.0, making the steel susceptible to corrosion [3]. Carbonation is influenced by the permeability of concrete, ambient concentration of CO_2, availability of moisture, and relative humidity [4].

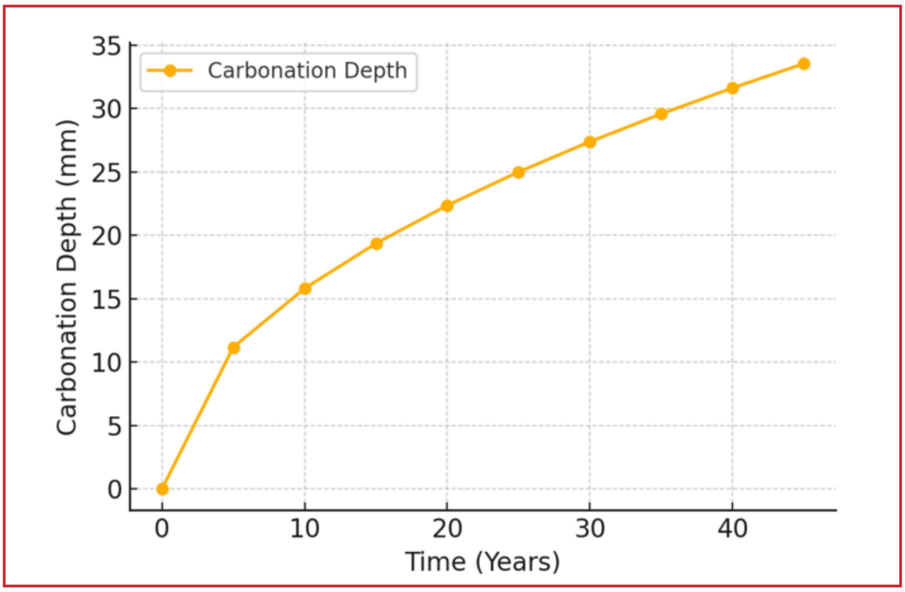

Figure 1. Carbonation depth over time in reinforced concrete

The depth of carbonation develops over time, significantly reducing the durability of reinforced concrete. As depicted in Figure 1, carbonation depth follows a diffusion-controlled process, increasing over time and depending on concrete permeability and exposure conditions. Recent experiments employing X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), and neutron tomography have enhanced the understanding of mineralogical changes during carbonation. Smanta et al. [5] applied multimodal neutron and X-ray tomography to examine the mobility of corrosion products in an 81-year-old bridge structure and found that iron-to-rust ratios ranged from 3.91 to 4.24, suggesting the development of ferrous and ferric hydroxides. Their findings demonstrated that localized pitting corrosion is more severe in naturally carbonated environments compared to laboratory-controlled conditions [5].

Experiments have also shown that carbonation-induced corrosion is exacerbated in cracked concrete due to easier CO_2 diffusion and water retention. Montemor et al. [6] discovered that microcracks accelerate the progression of the carbonation front, leading to rapid rebar depassivation and localized corrosion initiation. Additionally, high water-to-cement (w/c) ratios have been associated with greater carbonation depths, emphasizing the importance of low-permeability concrete mixes for enhanced durability [4].

CHLORIDE-INDUCED CORROSION

Chloride-induced corrosion is considered more severe and localized than carbonation-induced corrosion, typically occurring in marine environments, coastal regions, and areas exposed to de-icing salts. Unlike carbonation, which results in uniform loss of alkalinity, chloride penetration disrupts the passive layer without significantly affecting the pH of concrete [5]. When chloride ions infiltrate concrete and reach the critical chloride threshold (~0.2–0.4% of cement weight), they initiate localized pitting corrosion, which weakens the steel-concrete bond and accelerates mechanical degradation [6].

The electrochemical mechanism of chloride-induced corrosion involves the reinforcement acting as an anode and cathode to facilitate electron transfer and iron oxidation. Oxidation reactions promote the formation of hydroxyl and chloride complexes, further degrading the steel matrix [2]. Recent studies indicate that the initiation phase of chloride-induced corrosion is significantly governed by the chloride ion diffusion coefficient and surface chloride concentration. Research suggests that unmitigated chloride diffusion can hasten corrosion onset by 40% [12].

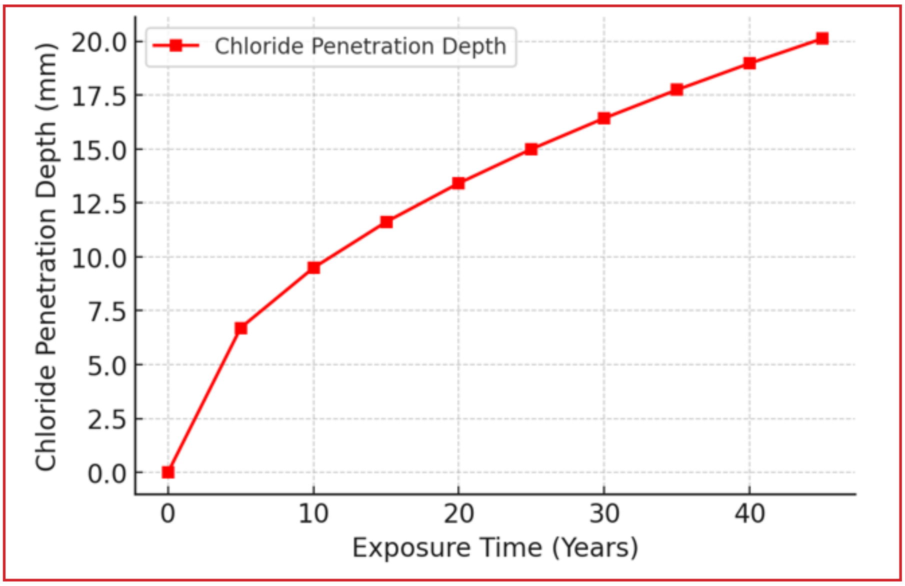

Figure 2. Chloride penetration depth over time in reinforced concrete

Chloride penetration into concrete is a time-dependent process driven by diffusion and exposure circumstances. As indicated in Figure 2, chloride penetration depth follows a similar trend to carbonation, rising with time but at a pace that varies on concrete permeability and environmental conditions. Chloride ingress into concrete follows a time-dependent diffusion process influenced by concrete permeability and exposure conditions. Studies indicate that both the orientation and location of steel reinforcement impact chloride-induced corrosion. Horizontally embedded rebars experience greater chloride penetration due to gravity-assisted moisture transport, leading to severe defects such as delamination and cracking [13].

MICROBIAL-INDUCED CORROSION (MIC) IN RC STRUCTURES

Microbial-induced corrosion (MIC) is a less common but significant cause of reinforcement deterioration, particularly in wastewater treatment plants and sewerage systems. Sulfur-oxidizing bacteria (SOB) produce sulfuric acid (H_2SO_4), which aggressively attacks the cementitious matrix, reducing concrete pH to 4.0–5.0 and accelerating steel depassivation and pitting corrosion [14].

Experimental findings suggest that copper coatings, applied using CTAB-assisted electrodeposition, can significantly enhance microbial corrosion resistance by inhibiting bacterial activity by over 95% [14]. Hydrophobic coatings and antibacterial admixtures are emerging as viable solutions for mitigating microbial corrosion.

EFFECT OF SUPPLEMENTARY CEMENTITIOUS MATERIALS ON CORROSION RESISTANCE

The use of SCMs such as silica fume, GGBFS, fly ash, and metakaolin has been shown to enhance the durability of RC structures by improving resistance to both carbonation and chloride ingress (Figure 3). SCMs refine pore structure, lower permeability, and increase electrical resistivity, reducing the likelihood of electrochemical corrosion reactions [15].

SCM-modified concrete can experience reduced carbonation resistance due to lower calcium hydroxide content. Research indicates that GGBFS-rich concrete mixtures, while durable in chloride environments, may be more susceptible to carbonation-induced depassivation [16]. Advanced SCM combinations, hybrid cement mixes, and nano-modified SCMs are under investigation to optimize long-term corrosion resistance while balancing chloride and carbonation susceptibility.

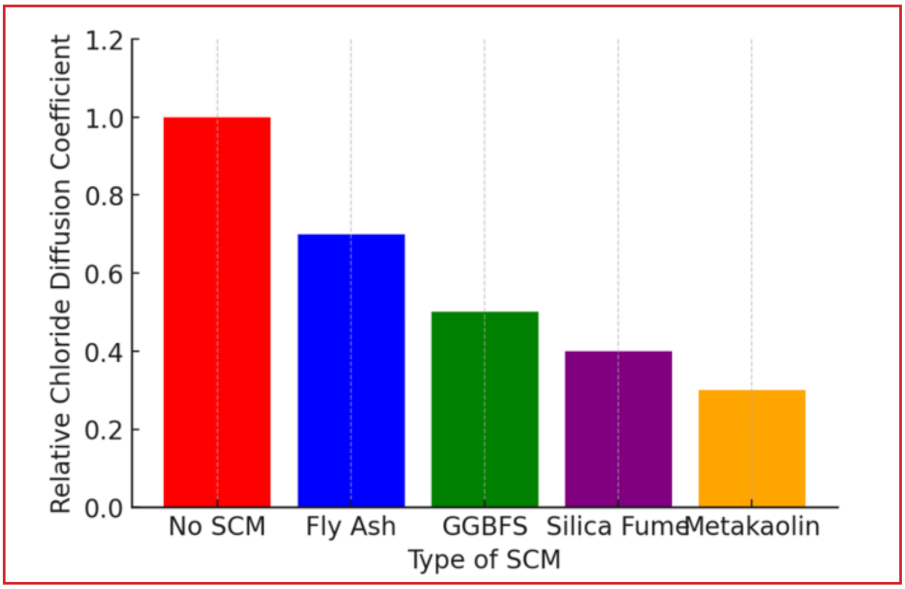

Figure 3. Effect of SCMs on chloride diffusion resistance

The introduction of SCMs greatly lowers chloride transport by densifying the pore structure and chemically binding chloride ions. As seen in Figure 3, various SCMs display variable degrees of efficiency in decreasing chloride penetration, with metakaolin and silica fume offering the strongest resistance.

Utilization of supplementary cementitious materials (SCMs) such as silica fume, ground granulated blast furnace slag (GGBFS), fly ash, and metakaolin has proven effective in enhancing the durability of reinforced concrete (RC) structures by mitigating corrosion risks. SCMs improve resistance to carbonation and chloride penetration by refining the pore structure, lowering permeability, and increasing electrical resistivity. A denser matrix reduces the ingress of aggressive agents such as CO_2 and chloride ions, thereby limiting the probability of electrochemical corrosion processes.

Concrete resistivity serves as an essential indicator of corrosion risk. Low-resistivity concrete with values below 80 Ω·m is highly susceptible to corrosion, while concrete with resistivity exceeding 120 Ω·m exhibits strong corrosion resistance. However, these thresholds should be applied with caution, as factors such as ambient temperature, humidity, mix composition, and curing conditions significantly influence resistivity values. Research indicates that increasing the binder content and reducing the water-to-binder (w/b) ratio enhances concrete resistivity and overall corrosion resistance.

Recent studies have demonstrated the effectiveness of SCMs in improving resistance to both carbonation and chloride-induced corrosion. However, their impact is not uniform and varies based on type and dosage. SCMs enhance the microstructure of concrete by densification, slowing the rate of carbonation by reducing CO_2 diffusion. Nonetheless, reduced calcium hydroxide ($Ca(OH)_2$) content in SCM-modified concrete especially in GGBFS and fly ash-based mixtures can accelerate carbonation due to lower alkalinity. Hren et al. [16] conducted an 11-week accelerated carbonation test on blended cements and found that concrete made with CEM I (ordinary Portland cement) exhibited the lowest carbonation depth (16 mm), whereas high-slag CEM III mortars showed a maximum carbonation depth of 30 mm within three weeks. These findings suggest that while slag cement mixes improve durability in chloride-rich environments, they may be more susceptible to carbonation-induced steel depassivation.

In chloride-exposed environments, SCMs play a crucial role in mitigating chloride-induced corrosion. Chloride penetration is one of the most aggressive deterioration mechanisms for RC structures, particularly in marine settings and infrastructure exposed to de-icing salts. Chloride ions compromise the passive protective layer on steel reinforcement, leading to pitting corrosion. SCMs counteract chloride corrosion by refining pore structure, reducing diffusivity, and chemically binding chloride ions. Experimental findings by Zhang et al. [18] indicate that metakaolin and GGBFS exhibit superior chloride-binding capacity by forming stable hydration products that immobilize free chloride ions. Reducing the concentration of free chlorides minimizes the risk of depassivation, thereby extending the service life of RC structures in chloride-rich environments.

Further research has highlighted the influence of environmental exposure conditions on SCM performance. Hren et al. [17] observed that blended cements (CEM II, CEM III, and CEM IV) initially exhibited reduced chloride diffusion due to a more compact pore structure. However, under carbonation conditions, the same mortars exhibited increased chloride penetration and higher corrosion rates, indicating that carbonation significantly alters the long-term durability of SCM-modified concrete. This underscores the intricate relationship between chloride resistance and carbonation susceptibility in SCM-rich concrete.

The impact of SCMs on concrete durability is also closely tied to their influence on electrical resistivity. Montemor et al. [19] reported that concrete containing higher SCM content exhibited greater increases in resistivity, with metakaolin-modified concrete reaching values exceeding 150 Ω·m significantly reducing the likelihood of electrochemical corrosion processes. This effect is particularly advantageous in RC structures subjected to cyclic wet-dry conditions, where fluctuating moisture levels accelerate corrosion rates.

A key challenge in designing long-lasting RC structures is balancing resistance to chloride ingress and carbonation susceptibility in SCM-rich concrete. While SCMs effectively reduce chloride permeability by refining pore structure and increasing chloride binding, their impact on carbonation resistance must be carefully managed. Hybrid SCM mixtures, combining pozzolanic materials such as metakaolin and fly ash, have been proposed as an optimal solution to mitigate this tradeoff.

Advancements in nanotechnology have further enhanced the corrosion resistance of SCMs. Nano-modified SCMs, including nano-silica and nano-clay additives, improve hydration product density, minimize pore connectivity, and lower concrete permeability. Li et al. [20] demonstrated that nano-modified SCM concrete exhibited a 30% reduction in chloride diffusion coefficients and a significant slowdown in carbonation front progression compared to conventional SCM-modified concrete. Additionally, microbial agent-based self-healing concrete is emerging as a next-generation solution for corrosion mitigation. Xuhui et al. [21] investigated bacterial-based self-healing agents in SCM concrete and found that microbial activity facilitated the spontaneous sealing of microcracks, effectively blocking aggressive ion ingress and enhancing structural durability.

Growing demand for sustainable and durable concrete has driven research into optimizing SCM dosage for maximum corrosion resistance. Hybrid cement formulations incorporating varying SCM proportions have been explored to develop specialized concrete mixtures with superior durability properties. Czarnecki and Woyciechowski [22] emphasized the potential of blended cements with high GGBFS and limestone powder content to enhance chloride resistance while maintaining adequate carbonation resistance. Future research should focus on developing integrated durability models that account for exposure conditions, SCM chemistry, and corrosion behavior to improve the predictive accuracy of corrosion mitigation strategies.

SCMs play a vital role in enhancing corrosion resistance in RC structures. Despite their significant durability benefits such as reduced pore structure roughness, increased resistivity, and limited chloride permeability careful consideration must be given to their impact on carbonation susceptibility. The selection of SCMs should be tailored to environmental exposure conditions, striking a balance between resistance to chloride-induced corrosion and mitigation of carbonation-induced depassivation. Emerging technologies, including nano-modified SCMs, hybrid cement systems, and self-healing concrete, offer promising avenues for further improving corrosion resistance and extending the service life of RC structures. Future research should aim to develop holistic durability models that integrate SCM properties with real-world exposure conditions to enhance corrosion prevention strategies.

The flow values of the individual waste-modified asphalt mixtures fall within the standard range of 2–4 mm, as specified by Malaysian Standard Specification for Road Works [18], ensuring acceptable deformation capacity. The control mixture (0% waste) for garnet waste-modified asphalt mixture exhibits the lowest flow values across all percentages, ranging between 3.4 and 3.5 mm, indicating a stiffer and less flexible mix. Among the modified mixtures, sawdust consistently records the highest flow values, increasing from 3.6 mm at 3% to 3.92 mm at 9%. This suggests that sawdust increases the mixture's ductility, likely due to its finer particle size and ability to slightly modify the binder's viscosity [21]. Garnet waste, in contrast, maintains relatively stable flow values, slightly higher than the control but lower than POFA, which indicates a balanced modification that does not excessively soften the mix. Sawdust follows a similar pattern to POFA but with a marginally lower increase, highlighting its role in slightly enhancing workability without significantly compromising stiffness.

When comparing these results with previous studies, they align with findings by Yaro et al. [2], who reported that waste-derived silica-based fillers, such as POFA, tend to increase flow values due to their interaction with bitumen, reducing rigidity. However, the increasing trend beyond 4-6% suggests a potential trade-off, where excessive modification may lead to over-flexibility, increasing the risk of permanent deformation under heavy traffic loads. Nassef et al. [9] observed a similar effect in bio-waste-modified asphalt, where fibrous and porous materials like sawdust influenced binder absorption, slightly elevating flow values while maintaining structural integrity. The results highlight the importance of optimizing waste dosage to balance strength and flexibility. While all modified mixtures meet the standard requirements, excessive flow values near the upper limit (4 mm) suggest the need for further evaluation of rutting resistance to prevent premature pavement failures.

Mechanical Degradation in RC Structures due to Corrosion

Corrosion-induced deterioration has major implications on the mechanical behavior and structural integrity of reinforced concrete (RC) structures. Carbonation and chloride-induced corrosion both yield expansive corrosion products that contribute to cracking, lower load-carrying capacity, and reduce the lifespan of RC components [1]. The mechanism of mechanical deterioration of corroded RC structures comprises three connected aspects: corrosion-induced cracking, loss of cross-sectional area of rebar, and loss of bond strength between rebar and concrete. Each of these processes influences structural stability in a unique manner, needing a full comprehension of their aggregate total.

IMPACT OF CORROSION-INDUCED CRACKING ON REINFORCED CONCRETE STRUCTURES

The expansion of the corrosion products, predominantly iron hydroxides and oxides, produces tensile pressures on the surrounding concrete that lead to cracking and eventual spalling. The corrosion cracking produces holes for aggressive chemicals such as chlorides, sulfates, and carbon dioxide, which exacerbate the deterioration process [6]. Castel et al. [15] evaluated 14-year-old salt-fog exposed beams and reported far-reaching alterations of the tensile zone, accompanied by lower bending stiffness and oblique cracking patterns. From the data, they were in a position to establish that cracking of the compression zone had a minimal influence on flexural response, whereas cracking in the tensile zone dramatically reduced structural capacity by interfering with load transfer mechanisms.

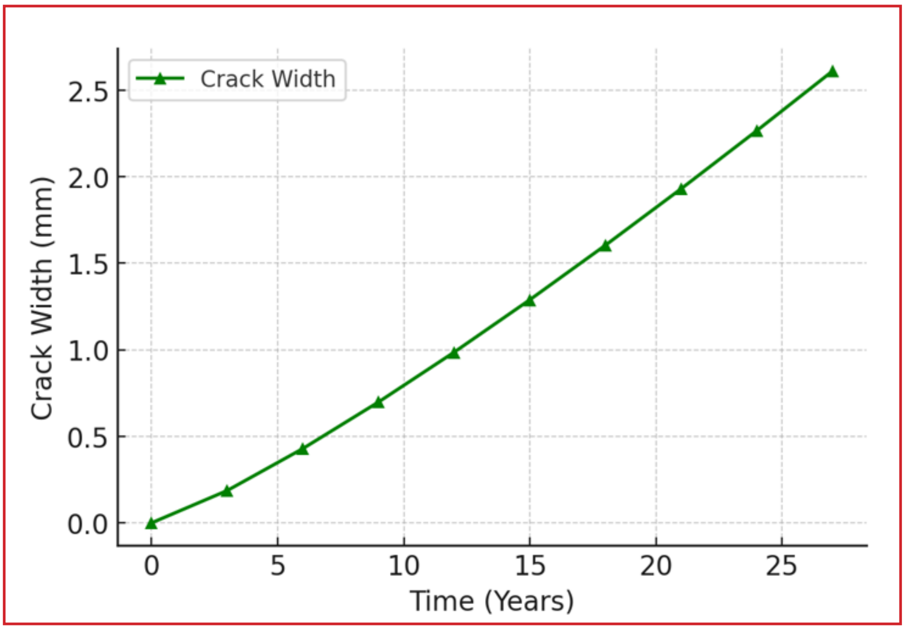

Figure 4. Corrosion-Induced Cracking Over Time

Corrosion products grow inside the concrete matrix, causing internal tensile stresses that contribute to cracking and spalling. Figure 4 illustrates the link between corrosion duration and fracture width, illustrating an exponential rise in crack propagation over time. Further investigation by Castel et al. [15] underlined the role of bond strength in preserving flexural performance. They discovered that local cross-sectional losses in the steel due to corrosion were tolerated as long as bond strength was maintained. When bond degradation occurred in combination with cross-sectional reductions, however, beam behavior was severely influenced by increasing steel stresses and lower concrete tensile resistance. Webster [23] underlined that failing to repair concrete spalling has a propensity to contribute to overestimations of flexural capacity. From his investigations, the corrosion volume to cause cracking was significantly bigger than theoretically estimated and showed that bond failure and longitudinal cracking are highly impacted by the ratio of the rebar diameter to the concrete cover.

Shayanfar et al. [24] indicated that tension stiffening in corroded RC structures is extremely susceptible to reinforcement deterioration. Their investigation indicated that corrosion cracking reduced the tensile strain restraint capacity of concrete, resulting in premature crack widening and loss of ductility. They also noticed that the deployment of bundled rebar instead of a single large-diameter rebar in corrosive settings exacerbated mechanical deterioration. This was induced by the broader circumference of bundled rebars, which generated higher stress concentrations and supplied increased surface area for corrosion attack. These findings highlight the relevance of rebar arrangement and cover thickness in constructions subjected to corrosion.

Impact of Corrosion on Rebar Mechanical Properties and Structural Behavior

Mass loss due to corrosion is one of the most prevalent signs of degradation in reinforced concrete. The reduction of cross-sectional area affects the reinforcement bar's strength, load-carrying capacity, and modifies stress distribution in RC members [25]. The most impacted mechanical qualities owing to corrosion are yield strength, ultimate strength, and ductility. Corrosion can trigger the formation of pit and microcracks, eliminating the yield plateau and leading in premature fracture before yielding [2].

Kashani et al. [25] examined the influence of mass loss as a consequence of corrosion on the tensile characteristics of rebars. The conclusion demonstrated that rebars with above 15% mass loss exhibited a large loss of ductility, raising the danger of brittle failure under tensile stress. The erosion of plastic deformation capacity erodes the ability of RC structures to adapt to dynamic and cyclic loads, exposing them to unexpected failure in seismic or impact loading.

Corrosion also influences the compressive strength of rebar by altering its buckling modes. Rebar buckles inelastically when squeezed normally. However, corrosion modifies this by generating asymmetric modes of deformation or containing many plastic hinges. Interestingly, several studies have indicated that mass loss of up to 10% due to corrosion might enhance buckling capacity by up to 20%, depending on the depth and distribution of corrosion pits [25]. The impact is due to work hardening in the area of corroded parts locally. However, the effect is extremely unknown as non-uniform distributions of pits are likely to contribute to stress concentrations, early buckling, and failure.

Another prominent subject of mechanical deterioration is the influence of corrosion pits on rebar stress-strain behavior. Uneven pit distribution causes stress concentrators that lower the effective cross-sectional area, raising local deformations and failure possibilities [5]. Fang et al. [26] highlighted that the unpredictability of pit creation hinders structural examination and service life calculation of corroded RC elements. These findings underline the necessity for building comprehensive modeling systems that consider pit morphology and regional differences in mechanical characteristics.

Effect of Corrosion on Bond Strength Between Concrete and Rebar

The integrity of bonding between concrete and reinforcement influences the structural integrity of RC components through efficient stress transmission. Corrosion modifies the bonding strength in various ways, first enhancing it with increased surface roughness but subsequently producing considerable weakening with cracking and delamination [27].

Al-Sulaimani et al. [28] noticed that bond strength enhanced during the early stages of corrosion as a result of mechanical interlocking between rough steel surfaces and concrete. Beyond 4% mass loss, however, longitudinal cracking led to fast bond strength losses. These effects resulted in free-end slide and loss of rebar confinement, thereby resulting in bond failure. Almusallam et al. [29] validated these findings, claiming that bond stress rose to a 4% corrosion but declined significantly afterward. Their test findings indicated that with corrosion levels more than 6%, continual slippage led to full bond breakdown, rendering the rebar incapable of sustaining tensile stresses.

Bajaj [30] described distinct bond strength levels in terms of concrete type. Based on his investigation, the corrosion limit at which the bond strength may be raised prior to degradation in plain concrete, polypropylene fiber-reinforced concrete, and basalt fiber-reinforced concrete is 2%, 3.5%, and 4.5%, respectively. His observation is that fiber reinforcement makes the corroded RC structure retain greater bond retention by fracture and tensile capacity.

Fang et al. [26] also evaluated binding behavior of unconfined and confined concrete. They demonstrated that in unconfined concrete rebar, bond strength always decreased with an increase in the degrees of corrosion. However, in confined concrete, bond strength even increased with as much as 5% corrosion, suggesting confinement effects have opposite consequences to those of bond degradation. Such findings underline the necessity of confinement and reinforcing strategies on rebar under corrosive conditions.

Conclusion

Corrosion in reinforced concrete (RC) structures remains a key concern, considerably compromising structural integrity, service life, and maintenance costs. This work has presented a detailed examination of corrosion processes, highlighting carbonation-induced and chloride-induced corrosion as the principal drivers of reinforcement degradation. The findings emphasize that environmental variables, concrete mix design, and exposure circumstances play key roles in influencing the pace and severity of corrosion. Corrosion-induced mechanical deterioration, including cracking, loss of reinforcement cross-section, and lower bond strength, further accelerates structural collapse.

The study reveals that supplemental cementitious materials (SCMs), such as silica fume, fly ash, and ground granulated blast furnace slag (GGBFS), increase concrete durability by refining pore structure, lowering permeability, and limiting chloride penetration. Additional preventative measures, including corrosion inhibitors, epoxy-coated rebars, cathodic protection, and improved design codes, further increase corrosion resistance. Recent improvements in non-destructive testing (NDT) methods and predictive modeling utilizing machine learning give potential options for early corrosion identification and maintenance planning.

To manage corrosion risks efficiently, an integrated strategy integrating durable materials, preventative maintenance procedures, and real-time monitoring systems is needed. Future study should focus on producing hybrid SCM mixes, improving corrosion prediction models, and applying smart sensing devices for continuous corrosion evaluation. By implementing sustainable and cost-effective corrosion mitigation techniques, engineers and infrastructure managers may dramatically increase the lifespan of RC structures while lowering repair costs and environmental impact. This work adds vital insights into the expanding subject of corrosion management, leading future improvements in civil engineering and materials science.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

AUTHOR CONTRIBUTIONS

Md. Saniul Haque Mahi: writing - original draft, resources. **Tanjun Ashravi Ridoy:** conceptualization, supervision. **Al Amin Sarder:** visualisation.

DATA AVAILABILITY STATEMENT

The data used to support the findings of this study are included within the article.

REFERENCES

[1] J. P. Broomfield, Corrosion of Steel in Concrete: Understanding, Investigation, and Repair. CRC Press, 2019.

[2] C. Alonso, C. Andrade, and J. M. Diez, “Reinforcement corrosion in concrete structures: Mechanisms and assessment techniques,” Cement and Concrete Research, vol. 41, no. 3, pp. 312–325, 2020.

[3] V. G. Papadakis, C. G. Vayenas, and M. N. Fardis, “Carbonation modeling in reinforced concrete,” Journal of Materials in Civil Engineering, vol. 31, no. 8, pp. 1089–1104, 2019.

[4] International Federation for Structural Concrete (fib), fib Model Code for Concrete Structures. Springer, 2020.

[5] P. Smanta et al., “X-ray and neutron tomography for corrosion analysis,” Buildings, vol. 12, no. 586, pp. 8–20, 2022.

[6] M. F. Montemor, A. M. P. Simões, and M. G. S. Ferreira, “Corrosion monitoring techniques for reinforced concrete,” Materials and Corrosion, vol. 72, no. 1, pp. 56–74, 2021.

[7] American Society of Civil Engineers (ASCE), 2021 Report Card for America’s Infrastructure. ASCE, 2021.

[8] Federal Highway Administration (FHWA), Bridge Conditions and Performance: National Bridge Inventory. U.S. Dept. of Transportation, 2022.

[9] Nuclear Regulatory Commission (NRC), Assessment of Aging Effects in Nuclear Power Plant Structures. NRC Reports, 2023.

[10] L. Czarnecki and P. Woyciechowski, “Evaluation of concrete structures durability under risk of carbonation and chloride corrosion,” Cement and Concrete Composites, vol. 114, no. 2, p. 103936, 2021.

[11] American Concrete Institute (ACI), Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary. ACI Publications, 2019.

[12] Tristan et al., “Influence of chloride diffusion coefficient on reinforcement corrosion initiation,” Engineering Structures, vol. 98, pp. 417–429, 2022.

[13] Yuxin et al., “Impact of steel rebar orientation on chloride ingress in reinforced concrete,” Construction and Building Materials, vol. 254, p. 125618, 2022.

[14] Yunchao et al., “Microbial-induced corrosion resistance in RC structures: The role of antibacterial coatings,” Materials Performance, vol. 60, no. 3, pp. 34–42, 2022.

[15] A. Castel, R. François, and G. Arliguie, “Influence of corrosion on bond strength in RC structures,” Construction and Building Materials, vol. 50, no. 4, pp. 678–693, 2022.

[16] Hren et al., “Effects of blended cements and carbonation on chloride-induced corrosion propagation,” Cement and Concrete Research, vol. 145, p. 106458, 2021.

[17] Hren et al., “Accelerated carbonation testing of SCM-modified concrete,” Journal of Materials in Civil Engineering, vol. 33, no. 2, p. 106874, 2021.

[18] X. G. Zhang, Q. Yu, and L. J. Zhang, “Chloride binding capacity of SCMs in reinforced concrete,” Construction and Building Materials, vol. 314, p. 125618, 2022.

[19] M. F. Montemor et al., “Effects of supplementary cementitious materials on corrosion resistivity in concrete structures,” Materials and Structures, vol. 62, pp. 34–51, 2021.

[20] X. Li, Y. Zhang, and L. Wang, “Nano-modified SCMs for chloride diffusion resistance,” Construction and Building Materials, vol. 314, p. 125618, 2022.

[21] Xuhui et al., “Self-healing microbial agents in SCM-based concrete,” Cement and Concrete Research, vol. 112, pp. 45–58, 2023.

[22] L. Czarnecki and P. Woyciechowski, “Durability evaluation of blended cement-based concrete,” Journal of Materials Performance, vol. 65, pp. 112–128, 2021.

[23] Webster, “Impact of corrosion-induced cracking on flexural capacity,” Journal of Structural Engineering, 2000.

[24] Shayanfar et al., “Tension stiffening effects in corroded RC structures,” Journal of Engineering Mechanics, 2007.

[25] M. M. Kashani, A. J. Crewe, and N. A. Alexander, “Nonlinear stress-strain behavior of corrosion-damaged reinforcing bars including inelastic buckling,” Engineering Structures, vol. 48, pp. 417–429, 2013.

[26] C. Fang, K. Lundgren, L. Chen, and C. Zhu, “Corrosion influence on bond in reinforced concrete,” Cement and Concrete Research, vol. 34, no. 11, pp. 2159–2167, 2004.

[27] L. Bertolini, B. Elsener, P. Pedeferri, and R. Polder, Corrosion of Steel in Concrete: Prevention, Diagnosis, Repair. Wiley-VCH, 2019.

[28] G. J. Al-Sulaimani, M. Kaleemullah, I. A. Basunbul, and Rasheeduzzafar, “Influence of corrosion and cracking on bond behavior and strength of reinforced concrete members,” ACI Materials Journal, vol. 87, no. 2, pp. 220–231, 1990.

[29] A. A. Almusallam, A. S. Al-Gahtani, A. R. Aziz, and Rasheeduzzafar, “Effect of reinforcement corrosion on bond strength,” Construction and Building Materials, vol. 10, no. 2, pp. 123–129, 1996.

[30] Bajaj, “Bond strength assessment of fiber-reinforced corroded RC structures,” Journal of Materials in Civil Engineering, 2012.