wjert, 2024, Vol. 10 Issue 2, 109-137. Review Article ISSN 2454-695X

World Journal of Engineering Research and Technology
WJERT
www.wjert.org
SJIF Impact Factor: 5.924

CORROSION CHALLENGES IN REINFORCED CONCRETE STRUCTURES: A REVIEW

O. O. Ekundayo[1]*, O. A. Osadola[1], O. O. Farayibi[2] and B. S. Ojo[1]

[1]Department of Building, Federal University of Technology, Akure.
[2]Department of Building, Rufus Giwa Polytechnic, Owo.

Article Received on 21/12/2023 **Article Revised on 11/01/2024** **Article Accepted on 31/01/2024**

***Corresponding Author**
O. O. Ekundayo
Department of Building,
Federal University of
Technology, Akure.

ABSTRACT

This paper from recent review of literature delves into the significance of reinforced concrete in infrastructure development, lauding its strength, durability, and versatility. The attention then shifts to the corrosion challenges confronting reinforced concrete structures in Nigeria's coastal regions. Factors such as chloride ions, harsh environments, and diverse corrosion mechanisms are scrutinized, with exploration of mitigation strategies including inhibitors, coatings, and cathodic protection. Non-destructive testing methods are emphasized for corrosion detection. The discussion underscores the critical imperative for effective monitoring and mitigation in Nigeria, emphasizing environmental and climatic factors influencing corrosion in reinforced concrete structures. The paper also investigates the multifaceted impact of material-related factors on concrete corrosion, stressing the importance of concrete quality, steel composition, and environmental conditions. Economic repercussions are explored, emphasizing the substantial costs of corrosion-induced maintenance. Various prevention and mitigation strategies, such as corrosion-resistant materials and innovative concrete designs, are examined. Overall, the study emphasizes the urgent need for comprehensive approaches to ensure the longevity and resilience of reinforced concrete infrastructure, particularly in coastal regions.

KEYWORDS: Environmental factors, mitigation strategies, coastal regions, corrosion challenges, and reinforced concrete.

INTRODUCTION

Nations the world over invest heavily in infrastructure projects in hopes of strengthening economic activities, ease the business environment and recoup the investments. Infrastructure project is expected to not be a source of concern in both the short and long term when it comes to the recurrent budgets of nations. Consequently, careful selection of materials on the basis of mechanical performance and durability is undertaken. Against this background, reinforced concrete has remained an indisputably and almost irreplaceable construction material as a result of the benefits it affords in the area of infrastructure development. Reinforced concrete material is a composite that by composite action integrate the tensile capacity of steel with the compressive strength and durability of concrete.[96] Hence, the resultant composite material is one able to resist induced stresses over a long period of time without noticeable deformation. Where structural integrity is extremely desirable, the capability of reinforced concrete for high load bearing capacity and remarkable strength is employed.[52] This property makes it suitable for a wide array of applications such as buildings of both residential and commercial use, civil structures such as dams and bridges, military infrastructure such as shooting range as well as under-water construction and any type of structure susceptible to large dynamic and static load and temperature variations.[18]

Quite apart from strength, reinforced concrete structures are durable. Their durability is partly accounted for by the alkalinity of concrete itself which protects the rebar from adverse environmental conditions such as corrosion.[38] The concrete, where it is very dense acts as a barrier to protect the rebar from ingress of aggressive chemicals, moisture and such conditions that make oxidation of the bars possible to cause a breakdown of the structure over time.[84] Hence, the relatively high density of concrete as a result of its compactness makes it suitable for long term use in diverse environmental conditions including corrosive soils and marine environment.[118] Furthermore, flexibility of architectural forms to aid design in any geometrical form from elementary to complex makes concrete a versatile construction material. Both as precast and in situ construction, concrete in the initial fresh state not only allows for geometrical flexibility in design but also dimensional freedom to have long spanning structural elements with limitless possibilities in depth as well.[53] The flexibility in shape and dimension has the advantages in terms of allowing the engineer to utilizing the added strength afforded by the property of geometry to increase the load carrying capacity of reinforced concrete structural elements.

Moreover, the initial cost which may be at the inception of reinforced concrete structures is compensated for by the long-term minimal maintenance requirements.[49] This fact is evident in the recent drive of the federal government towards reinforced concrete materials for adoption as road pavements because of the longevity it affords and the consequent long-term savings. Hence, reinforced concrete structures are desirable as the choice material for infrastructure projects because of the life cycle cost. Therefore, from the perspective of the overall life cycle cost, it is an inexpensive material.[96] Therefore, reinforced concrete is seen to be one ubiquitous construction material owing to its strength, durability, flexibility for geometry and limitless dimension as well as cost effectiveness especially in the long-term. Hence, it is customary to find many applications in buildings, roads, dams, bridges and complex and important engineering structures.

Reinforced Concrete in Infrastructure: Strength, Durability, and Coastal Challenges

In spite of the benefits of reinforced concrete, corrosion challenges in reinforced concrete structures along Nigeria's coastal region are a significant concern due to the harsh coastal environment and the presence of chloride ions from seawater.[23,106,80] The corrosion of steel reinforcement in concrete structures is a major durability issue that can lead to structural failure.[101,132,116,129,115] The penetration of chloride ions into the concrete causes the corrosion of the steel reinforcing bars, which weakens the structures and reduces their service life.[106,20] The corrosion damage in reinforced concrete structures is influenced by factors such as load, fatigue, and non-uniform corrosion of reinforcements.[101,132,116,129]

To address the corrosion challenges in reinforced concrete structures, various approaches have been explored. These include the use of corrosion inhibitors, repairing processes, coatings, and cathodic protection.[98] Corrosion inhibitors can enhance the strength, durability, and microstructure of coastal concrete structures.[98] Repairing processes and coatings can help prevent concrete corrosion damage, with a focus on performance in coastal and corrosive environments.[98] Cathodic protection, such as impressed current cathodic protection, can be used to mitigate the corrosion of steel reinforcement in RC columns.

In addition to corrosion, the harsh coastal environment can also lead to other forms of deterioration in reinforced concrete structures. Freeze-thaw cycles and seawater corrosion, combined with seismic activity, can cause significant damage to structures in cold coastal seismic regions.[119] The cyclic response of reinforced concrete members subjected to artificial chloride-induced corrosion has been studied, highlighting the continuous deterioration of RC elements due to aggressive environmental factors. The cracking of the concrete protective layer caused by non-uniform corrosion of reinforcements is another concern that needs to be analyzed.[129] To detect and assess corrosion in reinforced concrete structures, non-destructive testing methods such as ultrasonic guided wave leakage (UGWL) and half-cell potential methods have been used.[10] UGWL has shown promise in detecting the onset of corrosion and delamination between rebar and concrete.[10]

Highlighting corrosion challenges in reinforced concrete structures in coastal regions

To address the corrosion challenges in reinforced concrete structures in Nigeria's coastal regions, it is important to understand the impact of corrosion on these structures. The durability of reinforced concrete structures in coastal areas is a major concern due to the high corrosive nature of these environments.[67] The corrosion of reinforcing steel in concrete, often caused by the penetration of chlorides from marine environments, is a significant factor contributing to the deterioration of these structures.[51] Exposure to seawater erosion and the presence of chloride ions in concrete can lead to reinforcement corrosion, further exacerbating the challenges faced in coastal regions.[102] Similarly, pitting attack has been identified as the primary form of corrosion for materials in coastal sites, emphasizing the aggressive nature of corrosion in these regions.[110] Also, the impact of stray currents on the corrosion of reinforced concrete structures as well has been noted, with studies reporting that stray currents can accelerate corrosion of reinforcement in concrete, posing additional challenges in coastal areas.[123]

In addressing these challenges, the use of corrosion inhibitors and self-healing coatings has been proposed as potential solutions. Corrosion inhibitors are widely used to prevent chloride-induced corrosion in reinforced concrete structures, although further understanding of their interaction mechanisms with the passive film on steel is required.[27] Additionally, self-healing coatings, despite their advantages, face challenges similar to other corrosion protection methods, highlighting the need for comprehensive solutions to combat corrosion in coastal regions.[44] Failed concrete structures in Nigeria are often attributed to the corrosion of reinforcing steel used in these structures. The corrosion of reinforcing steel leads to severe damage in various concrete structures, including bridges, buildings, and water facilities. Post-tensioned concrete structures have also experienced failures due to the rupture of tendons caused by corrosion, sometimes resulting in catastrophic consequences.[1] Statistics have indicated that over 40% of structure failures are due to the corrosion of reinforcement, emphasizing the significant impact of corrosion on concrete structures in Nigeria.[13] Furthermore, reports and literature have highlighted the common occurrences of failures due to corrosion degradation of structures in aggressive environments, particularly in coastal areas.[6] These cases of failed concrete structures underscore the primacy for effective corrosion monitoring and mitigation strategies in Nigeria. Understanding the corrosion behavior of reinforcing steel and implementing measures to prevent and address corrosion in concrete structures is essential to ensure the durability and safety of infrastructure in the country.

Corrosion of reinforced concrete

Reinforced concrete structures are susceptible to corrosion of the embedded steel reinforcement, which can compromise their functional and structural properties. Corrosion of reinforcement can lead to concrete cracking, reduced bond between reinforcement and concrete, and corrosion penetration at the reinforcement surface, ultimately affecting the durability of the structure.[31] The corrosion products resulting from the corrosion of steel reinforcement can cause the protective layer of concrete to crack or spall, further reducing the structure's durability.[126] Additionally, corrosion can lead to a decrease in the load and yield deflection of reinforced concrete beams, ultimately affecting their mechanical properties.[77] The corrosion of reinforcement in concrete is an electrochemical process, and the use of corrosion inhibitors has been studied as a practical method for corrosion control in reinforced concrete due to its ease of operation and low cost.[36] Furthermore, the addition of micro-fibers to concrete has been shown to improve the protective properties of the concrete cover, potentially reducing the corrosion of reinforcement bars in reinforced concrete elements.[90]

Definition and Types of corrosion on reinforced concrete structures

To understand the types of corrosion in reinforced concrete structures, it is essential to consider the various factors that contribute to this phenomenon. The corrosion of reinforcing steel in concrete is a significant issue that affects the durability and structural integrity of concrete structures.[12] The corrosion process occurs due to the difference in the concentration of dissolved ions inside the concrete, leading to the formation of electrochemical potential cells or corrosion cells, characterized by a flow of electrons and ions between the cathodic and anodic regions.[95] This corrosion can be caused by various factors such as chloride-induced corrosion, carbonation corrosion, stray current, and biocorrosion.[21,123,46,41] Chloride-induced corrosion is a common cause of deterioration in reinforced concrete structures, particularly in marine environments, where the penetration of chlorides into the concrete leads to the corrosion of the reinforcement.[51] Additionally, carbonation corrosion occurs when carbon dioxide penetrates the concrete, reducing its protective properties and increasing the risk of reinforcement corrosion.[41] Stray current and biocorrosion also contribute to the acceleration of reinforcement corrosion in concrete structures, leading to further deterioration.[123, 46]

There are different types of techniques that can be used to induce corrosion in reinforcement, including natural corrosion, accelerated corrosion, and simulated corrosion.[31] The impact of corrosion on the ductility and residual capacity of reinforcing bars is well-documented, with corrosion leading to the development of corrosion pits on the reinforcement surface, which can increase in number and size over time, ultimately affecting the structural integrity of the concrete.[31] Furthermore, the use of corrosion inhibitors has been studied as a method to prevent and mitigate corrosion in reinforced concrete structures. While corrosion inhibitors are widely used to prevent chloride-induced corrosion, their interaction mechanisms with the passive film present on steel still require deeper understanding.[27,15] Additionally, the actual service life of reinforced concrete structures depends on various factors, including environmental erosion, material quality, design quality, and corrosion resistance.[32]

Corrosion mechanisms in reinforced concrete structures

Corrosion in reinforced concrete structures is a complex phenomenon influenced by various factors. The presence of cracks in concrete has been shown to increase penetrability, allowing corrosion agents such as oxygen, moisture, and chlorides to ingress into the concrete and reach the reinforcing steel.[85] The effect of corrosion on the mechanical properties of reinforced concrete beams has been studied, revealing that while corrosion has minimal impact on the elastic stage and cracking load, it significantly reduces the overall load and yield deflection, with a linear correlation to the corrosion rate.[77] Additionally, the use of corrosion inhibitors in concrete to prevent chloride-induced corrosion is a widely adopted practice, although the interaction mechanisms of these inhibitors with the passive film on steel require further understanding.[27]

Furthermore, the addition of inhibitors to concrete, such as potassium dichromate and potassium chromate, has been explored as a means of protecting reinforced steel from corrosion.[82] Additionally, the use of modified hydrotalcites as smart additives for anticorrosion applications in reinforced concrete has been investigated, emphasizing the importance of understanding the corrosion mechanisms and concrete properties that affect reinforcement corrosion.[124] Moreover, the penetration of chlorides, often from exposure to marine environments, is highlighted as a major factor causing the corrosion of reinforcing steel in concrete structures.[51]

Corrosion inhibitors are considered practical methods for controlling corrosion in reinforced concrete due to their ease of operation and low cost.[36] The corrosion of reinforcement in concrete can lead to significant deterioration mechanisms, such as de-passivation of the steel due to carbonation or chloride attack, resulting in rapid steel corrosion and reduced structural durability.[92,67] The importance of understanding the effect of corrosion on the construction performance and service life of reinforced concrete structures is emphasized, as corrosion can cause significant losses in energy damping capacities and reduce the bearing capacity and durability of the structures.[46,67]

Factors influencing corrosion of reinforced concrete structures

Factors influencing corrosion in concrete structures are multifaceted and encompass various aspects. The penetration of corrosion-inducing agents, such as chloride ions and carbon dioxide, is known to increase at the sites of cracks, further exacerbating corrosion.[114] Additionally, the increase in corrosion degree leads to a decrease in the elastic moduli of concrete due to the expansion of corrosion products.[133] The nature and amount of corrosion products, as well as the bond between corroded reinforcement and concrete, are influenced by different conditions, affecting the intensity and distribution of corrosion penetration at the reinforcement surface.[30] Moreover, the use of corrosion inhibitors has been investigated to enhance the strength, durability, and microstructure of concrete structures.[98] The influence of factors such as the diameter of corner rebars and the thickness of the cover on corrosion expansion cracks has been studied using a 3D meso-scale model of concrete.[129] Furthermore, the influence of sustained loading and corrosion on the performance of reinforced concrete beams has been explored.[130] The volume expansion of reinforcement corrosion products causes the protective layer of concrete to crack or spall, thereby reducing the structure's durability.[129] Non-uniform corrosion of steel bars has been identified as a significant factor affecting the durability of concrete.[53] Additionally, in nondestructive test methods for steel corrosion in concrete, factors such as the depth of the concrete layer, the diameter of the steel bar, and the concrete's humidity can influence the thermal properties of the steel bar. The influence of sulphate corrosion on the mechanical behaviors of concrete, especially under actual corrosion environments, has been investigated.[132] Cracks in concrete structures accelerate the ingress of corrosive agents to the embedded steel, thereby influencing the durability of reinforced concrete structures in aggressive environments.[85]

Environmental Factors That Drive Corrosion in Concrete Structures

The corrosion of reinforced concrete structures is influenced by various environmental factors[123] highlighted the impact of stray currents and water-saturated environments on the accelerated corrosion of reinforcement in concrete.[123] The influence of carbonation on the resistance of concrete structures to chloride penetration and corrosion is apparent. Furthermore,[109] discussed the impact of non-longitudinal cracks and marine environments on reinforced concrete structures, emphasizing the analysis of corrosion in such cracks[109,103] also pointed out that environmental conditions such as humidity, moisture movement, and the grade of concrete affect the propagation of corrosion in reinforced concrete.[103] Moreover,[127] discussed the impact of corrosion on the protective layer of concrete, leading to cracking and reduced durability of the structure.[127] Additionally,[15] highlighted the challenges posed by stray current-induced corrosion in reinforced concrete, including the potential for concrete cracking, spalling, and delamination, ultimately leading to structural failure.[15] These references collectively emphasize the significant impact of environmental factors such as stray currents, carbonation, and cracks on the corrosion of reinforced concrete structures.

The corrosion of concrete is influenced by various environmental factors such as salinity, temperature, and humidity. Research has shown that these factors play a significant role in the corrosion process of concrete structures. For instance, the exposure period, H2S concentration, relative humidity, and air temperature were controlled at different levels in corrosion chambers, demonstrating the long-term effects of these factors on concrete sewer corrosion.[42] Additionally, the ohmic resistance of the electrolytical coupling significantly decelerates or hinders the corrosion process in "healthy" concrete with a relative humidity below 65%.[104] Furthermore, the erosion effect of chloride ions from marine, deicing salt, saline-alkali land, and industrial environments causes rebar corrosion in concrete, significantly affecting the durability of concrete structures.[55]

Moreover, concrete carbonation in the concrete cover, influenced by changes in ambient temperature and humidity, results from the impact of carbon dioxide in the air, further affecting the corrosion process.[91] Relative humidity has been found to have a considerable effect on the corrosion behavior of concrete structures at both the initiation and propagation phases.[22] Additionally, excessive internal humidity can lead to the dominance of microcell corrosion due to the large resistivity of concrete, while microcell corrosion becomes dominant at very high relative humidity levels.[120] Furthermore, humidity plays a fundamental role in the conversion of hydrogen sulfide into sulfuric acid during the corrosion of concrete in gravity sewers, and minor reductions in humidity can reduce corrosion rates.[9]

Temperature also plays a crucial role in the corrosion process, as it influences the deterioration process of chloride-induced corrosion in reinforced concrete.[87] Salinity concentration serves as a good indicator for diagnosing and monitoring the corrosion of concrete structures, as it is closely related to the strength of the concrete paste.[59] Additionally, the performance of concrete substantially deteriorates when exposed to saline soil environments containing high concentrations of corrosive ions.[123] Furthermore, the corrosion mechanism of concrete structures caused by dew condensation inside cavern walls is influenced by daily temperature and humidity environment changes, wind speed, and ventilation conditions.[130]

Material-related factors and their effect on corrosion of concrete

To understand the effect of material-related factors such as the quality of concrete and the composition of reinforcing steel on the corrosion of concrete, it is essential to consider various aspects. Previous studies have shown that the presence of cracks increases concrete penetrability and hence ingress of corrosion agents (oxygen, moisture, and chlorides) into concrete to the reinforcing steel.[85] The corrosion morphology has an important effect on the mechanical properties of the reinforcing steel bars.[53] Besides the integrity between steel bars and concrete cover, the quality of concrete cover and variations in chloride ion concentrations are significant factors contributing to microcell corrosion formation.[97] The data strongly suggest that concretes made with limestone or non-reactive dolomite aggregates or sufficiently high levels of other forms of calcium carbonates have favorable reinforcement corrosion properties.[66] Observations of numerous structures show that corrosion of reinforcing steels is either a prime factor or at least an important factor contributing to staining, cracking, and/or spalling of concrete structures.[3] Additional impact of the aggressive environment results in an even greater increase in the material porosity, intensification of diffusion processes in the body of concrete and, as a consequence, stimulation of corrosion destruction in general.[35] Corrosion of steel bars in concrete has become one of the predominant factors leading to performance degradation of concrete structures.[24] Sulfate corrosion is one of the most important factors responsible for the performance degradation of concrete materials.[134] The presence of cracks is unavoidable in reinforced concrete structures and also a gateway for chloride into concrete, leading to corrosion of steel reinforcing bars.[88] The aim of this paper is to describe the coupled effects of chloride ingress and static loading on the evolution of corrosion of steel reinforcement in concrete.[121] The degrading effects of corrosion on the structural response of reinforced concrete beams have been simulated considering factors such as the reduction of the cross-sectional area of steel, change in steel and concrete material properties, and bond deterioration.[25] The effect of cracking on corrosion may vary depending on concrete quality, concrete resistivity, crack width, crack density, crack self-healing, and crack orientation.[86] In this work, the effect of Mo addition on pitting corrosion properties of austenitic, ferritic, and duplex stainless steels is discussed.[68] On the other hand, a review of practical experience shows that what has been termed chloride-induced reinforcement corrosion often is not that at all, but is the end-product of factors that impair the protective nature of the concrete.[65] The penetration rates of corrosion factors, such as carbon dioxide, chloride ions, oxygen, and water, through cracks in concrete surfaces are higher than through sound concrete surfaces, causing macroscopic nonuniformity in concrete covering reinforcing steel, thereby causing microcell corrosion.[107] Due to its high performance against chlorides, compared to conventional reinforcing steel, Top 12 reinforcing steel provides reliable protection against corrosion.[16] Causes of corrosion are related to the reinforcing steel itself, concrete strength, concrete materials, and the surrounding environment.[61]

Peculiar challenges of Nigeria's coastal region: geographical overview, climate conditions and corrosion challenges unique to coastal areas

The coastal region of Nigeria faces a myriad of challenges, particularly in relation to geographical overview, climate conditions, and corrosion unique to coastal areas. The Niger Delta region, in particular, is highly vulnerable to the impacts of climate change, leading to concerns such as flooding, windstorms, and sea-level rise.[62,2] The unique tropical climate of Nigeria presents two distinct precipitation regimes, with the north experiencing low precipitation leading to aridity and desertification, while the southwest and southeast face high precipitation, resulting in large-scale flooding.[5] Furthermore, the diurnal and seasonal variation of surface refractivity over Nigeria is significant, particularly from the coastal region in the extreme south to the semi-arid region in the extreme north.[11] This variation in climatic conditions is further evidenced by the distinct areas in terms of spatial coherence in the variation of the length of the rainy season between the northern and southern regions of Nigeria.[81] The coastal region's unique climate and geographical characteristics have also led to specific corrosion challenges. The impact of climate change and anthropogenic factors on desertification in the semi-arid region of Nigeria has contributed to the corrosion of infrastructure and environmental degradation.[78] Additionally, the bioaccumulation of hydrocarbons, heavy metals, and minerals in the coastal region of Bayelsa State poses significant corrosion risks to the local ecosystem.[79]

Impact of Corrosion on Reinforced Concrete

Corrosion of reinforced concrete structures has a significant impact on their structural integrity, load-bearing capacity, and overall performance. The corrosion of steel reinforcement within concrete leads to various detrimental effects such as crack occurrence along the reinforcement, reduction in bond strength, and a decrease in steel cross-section.[17] This corrosion-induced damage results in a reduction in the load-bearing capacity of reinforced concrete beams, negatively impacting the structural safety and integrity of the structure.[45] Additionally, the corrosion of reinforcement can lead to the cracking and spalling of concrete, ultimately weakening the bearing capacity and durability of the structures.[67] The corrosion products resulting from the corrosion of steel reinforcement cause the concrete's protective layer to crack or spall, further reducing the durability of the concrete structure.[126] Furthermore, the corrosion of reinforcement can lead to a decrease in the residual capacity of corroded reinforcing bars, affecting the nature of corrosion products and the bond between the corroded reinforcement and the concrete, as well as the intensity and distribution of corrosion penetration at the reinforcement surface.[30,31] The corrosion-induced damage also results in a decrease in the residual bearing capacity of reinforced concrete columns under impact load, further compromising the structural performance of the columns.[105] Moreover, the corrosion of reinforcement coupled with sustained load increases the number and width of cracks in beams while decreasing their loading capacities.[101] It is evident that corrosion has a profound and multifaceted impact on the structural integrity, load-bearing capacity, and durability of reinforced concrete structures.

Economic implications of corrosion on concrete maintenance, repair costs and lifespan reduction

The economic implications of corrosion on concrete maintenance, repair costs, and lifespan reduction are significant and have been widely studied in the literature. Corrosion of steel bars embedded in reinforced concrete (RC) structures reduces the service life and durability of structures, leading to early failure and significant costs for inspection and maintenance.[114] The issue of chloride-induced corrosion of reinforced concrete is a serious problem affecting infrastructure globally and causing huge economic losses.[69] The corrosion of reinforcement caused by chloride ingress significantly reduces the length of the service life of reinforced concrete structures.[126] Furthermore, chloride-induced corrosion of reinforcing steel in concrete structures is one of the most important durability problems associated with this material.[73]

Several preventive strategies have been proposed to mitigate the economic impact of corrosion on concrete structures. For instance, the use of concrete with 10% silica fume has been shown to be the most effective prevention strategy against corrosion of reinforcement steel in economic terms, reducing the life cycle costs of the original deck design by 76%.[72] Additionally, self-repairing concrete, such as biomimetic self-healing cementitious construction materials, offers advantages such as diminished deterioration rate, prolonged use life, decreased frequency, and low cost of repair over the lifespan of a concrete infrastructure.[100] Biogenic crack repair, such as the application of microbial CaCO3 for self-healing of concrete cracks, is a possible solution to reduce the high maintenance and repair costs of concrete infrastructures. Moreover, bio-based concrete may have a slight increase in initial cost, but it significantly decreases repair and replacement costs over the lifetime of a building, leading to potentially greater economic benefits over the life cycle.[7]

Corrosion Prevention and Mitigation Strategies in reinforced concrete

To prevent and mitigate corrosion in reinforced concrete structures, various strategies and techniques have been proposed and studied. One approach is to design high-quality concrete with a proper cover and a good mixture proportion to delay the occurrence of corrosion.[83] Corrosion inhibitors are commonly used to prevent chloride-induced corrosion in reinforced concrete structures, but a deeper understanding of their interaction mechanisms with the passive film present on steel is still required.[27] Additionally, the addition of Mo alloying to stainless steels used as concrete reinforcement can influence pitting corrosion, especially in chloride-contaminated environments and carbonated concrete covers.[68] Corrosion of reinforcement is widely recognized as the primary cause of degradation in reinforced concrete structures exposed to aggressive environments.[108]

Furthermore, the use of modified hydrotalcites as a smart additive for reinforced concrete has gained academic and commercial interest, but there is a need for more studies focusing on their potential applications in corrosion protection of reinforced concrete structures.[124] Additionally, the enhancement of alkali-activated slag cement concretes' crack resistance has been proposed as a method for mitigating steel reinforcement corrosion.[47] Surface applied corrosion inhibitors (SACI) are also widely used to mitigate the corrosion process of steel reinforcement in concrete.[99] Moreover, the use of corrosion inhibitors during concrete preparation is becoming a common practice to inhibit reinforcing steel corrosion from chlorides.[51]

In addition to corrosion inhibitors, the use of epoxy-coated bars as a corrosion control method in reinforced concrete bars has been studied and applied.[57] Furthermore, strategies focused on improving the crack resistance of concrete, such as the use of hybrid fiber reinforcement, have been proposed to improve the long-term durability of reinforced concrete.[74] Finally, the corrosion of reinforcement reduces the serviceability and safety performance of reinforced concrete, emphasizing the critical importance of effective corrosion prevention and mitigation strategies.[125]

Material selection, design considerations and Corrosion-resistant materials as a strategy for corrosion control in reinforced concrete structures

To address the issue of corrosion control in reinforced concrete structures, various strategies and materials have been investigated. The use of corrosion-resistant materials, such as polyvinyl alcohol fiber reinforced geopolymer concrete (PVAFRGC) (Al-Majidi et al., 2018), stainless steel reinforcement[67], and fiber-reinforced plastic bars[26], has been shown to significantly reduce corrosion damage and improve the durability of reinforced concrete structures. Additionally, the application of corrosion inhibitors has been identified as an efficient method for protecting reinforcement against corrosion, offering easy application, excellent corrosion resistance, and low cost.[111,40] Furthermore, hybrid fiber-reinforced concrete (HyFRC) has been proposed as a strategy for resisting damage caused by corrosive environments through multi-scale crack control.[75]

In terms of design considerations, it has been highlighted that the reduction of bearing capacity and operational durability of reinforced concrete structures due to corrosion can lead to non-compliance with safety requirements and the limiting state at design loads.[14] Moreover, the corrosion of reinforcement can impede the structural integrity of concrete structures by reducing their flexural, shear, and axial strength, making them structurally weak.[12]

The assessment of corrosion and its impact on the mechanical capacity of reinforced concrete structures has been a subject of study. Research has proposed mechanical models that combine the effects of corrosion on reinforcement and concrete, as well as steel material nonlinear responses, to predict the loss of resistance in reinforced concrete beams over time.[89] Additionally, the investigation of the residual capacity of corroded reinforcing bars has provided insights into the mechanism of the reduction of the capacity of corroded reinforcement, considering accelerated and simulated corrosion tests on bare bars and bars embedded in concrete.[30]

Furthermore, the use of advanced methods for detecting corroding areas in reinforced concrete structures, such as electrochemical techniques, has been emphasized as a means to map structures and estimate the rate of corrosion of reinforcement.[19] Additionally, the monitoring of reinforcement corrosion in concretes designed for nuclear facilities has been addressed through the implementation of non-destructive techniques to measure electrical resistivity of concrete, corrosion potential, and corrosion rate of reinforcement.[112] Furthermore, prevention of corrosion can be achieved in the design phase by using high-quality concrete and adequate cover.[15]

Reinforced concrete infrastructure in coastal regions is particularly susceptible to corrosion due to exposure to aggressive external factors such as seawater and salt-laden air [93]. The corrosion of traditional steel rebars in coastal reinforced concrete structures poses significant durability and cost issues, leading to the need for substantial funds for rehabilitation and repairs.[34,76] This has prompted the exploration of alternative reinforcement materials such as glass-fiber-reinforced plastic (GFRP) rebars, which have shown promise in withstanding the highly alkaline and corrosive coastal environment.[34,70] Additionally, the use of intelligent regulation of microcapsules in concrete has been investigated as a means to mitigate the corrosion of reinforcing bars in marine concrete infrastructure projects.[39] Furthermore, the development of new types of shell precast concrete blocks, incorporating high-performance glass fiber-reinforced concrete (HPGFRC), has been proposed as a potential solution for enhancing the mechanical performance and service life of coastal protection structures.[32]

The sustainability and long-term durability of marine reinforced concrete structures are critical considerations, emphasizing the need for effective government initiatives to address corrosion protection in these environments.[65] It is evident that the challenges posed by corrosion in coastal regions necessitate comprehensive strategies and interventions to ensure the longevity and resilience of reinforced concrete infrastructure.

CONCLUSION AND RECOMMENDATIONS

In conclusion, the deterioration of reinforcing steel has become a significant element in the safety or otherwise of concrete buildings in Nigeria, affecting various types of construction and causing significant consequences. A comprehensive plan that includes wide-ranging strategies to mitigate corrosion and guarantee the long-term integrity of concrete structures across the country is necessary to properly address these concerns. This calls for an advanced understanding of corrosion mechanisms, their effects on the characteristics of concrete, and the application of workable mitigation strategies, such as improved concrete cover and corrosion inhibitors.

Furthermore, the complexities of corrosion, which are impacted by several elements such carbonation corrosion, stray current corrosion, chloride-induced corrosion, and biocorrosion, highlight how difficult it is to protect reinforced concrete structures. Additionally, salinity, temperature, and humidity are environmental factors that greatly contribute to corrosion processes at different times, having a significant impact on how long concrete constructions last. Through the process of dissecting these mechanisms, techniques that are both corrosion-resistant and enhance the durability and functionality of reinforced concrete structures can be developed. The coastal region of Nigeria presents distinct issues arising from geographical and climatic factors, in addition to particular corrosion concerns. As a result, corrosion-related maintenance, repair expenses, and reduced lifetime significantly impact the economy. However, new materials and proactive measures present a viable way to mitigate these effects and, in the end, lower the financial cost of corrosion in concrete buildings.

Recommendations

From the above, the following suggestions are put forth

1. creating and executing a thorough national strategy that includes a variety of techniques for successfully reducing corrosion in reinforced concrete structures. This should involve studies into the creation of materials resistant to corrosion, efforts to comprehend corrosion mechanisms better, and the implementation of workable mitigation techniques like strengthened concrete covers and corrosion inhibitors.

2. Advanced studies to deepen understanding : Invest in cutting-edge research to improve the understanding of the intricacies of corrosion, taking into account a variety of elements such as biocorrosion, stray current corrosion, carbonation corrosion, and corrosion generated by chloride Investigating these mechanisms should be the main goal of such advanced studies in order to create corrosion-resistant methods that safeguard and improve the robustness and functionality of reinforced concrete buildings.

3. Develop coastal region-specific solutions: Comprehend the impacts of environmental aspects and recognize the particular difficulties that Nigeria's coastal region faces, accounting for issues with geography, climate, and corrosion. Develop mitigation techniques that are tailored to the unique problems of this area, taking into account elements like elevated salinity, exposure to seawater, and higher susceptibility to corrosion.

4. Encourage materials resistant to corrosion: Promote the use of materials resistant to corrosion in building projects, especially those located near the shore. This can entail providing incentives for the use of cutting-edge materials that have exceptional corrosion resistance, thereby lowering the frequency of upkeep and repairs.

5. Proactive maintenance and inspection: To detect corrosion problems early on and take action before they worsen, implement proactive maintenance and inspection programs for reinforced concrete structures. When combined with non-destructive testing techniques, routine inspections can maintain the integrity of reinforced concrete structures over their entire life span.

REFERENCES

1. Abdelatif, A., Owen, J., & Hussein, M. Re-anchorage of a ruptured tendon in bonded post-tensioned concrete beams: model validation. Key Engineering Materials, 2013; 569-570, 302-309. https://doi.org/10.4028/www.scientific.net/kem.569-570.302

2. Adegun, O. and Olusoga, O. A design workshop's contribution to climate adaptation in coastal settlements in nigeria. Urban Science, 2020; 4(3): 33. https://doi.org/10.3390/urbansci4030033
3. Adejo, O., A, O., Uzuh, F., Abere, D., TS, A., Adamu, U., … & Yahaya, I. Examination of reinforcement steel bars exposed to the atmosphere. J Mater Sci Manufac Res., 2020; 1-5. https://doi.org/10.47363/jmsmr/2020(1)111
4. Abdol, N. Factors influencing strength loss of glass-fiber-reinforced composite bars in highly alkaline environment of concrete. Structural Concrete, 2022; 23(2): 1005-1017. https://doi.org/10.1002/suco.202100645
5. Akande, A., Costa, A., Mateu, J., & Henriques, R. Geospatial analysis of extreme weather events in nigeria (1985–2015) using self-organizing maps. Advances in Meteorology, 2017; 1-11. https://doi.org/10.1155/2017/8576150
6. Akindahunsi, A., Falade, F., Afolayan, J., & Oke, I. Characterization and mathematical modeling of chloride diffusion in lagos coastal waters. Journal of Failure Analysis and Prevention, 2010; 10(3): 169-177. https://doi.org/10.1007/s11668-010-9348-5
7. Alemu, D., Demiss, W., & Korsa, G. Bacterial performance in crack healing and its role in creating sustainable construction. International Journal of Microbiology, 2022; 1-10. https://doi.org/10.1155/2022/6907314
8. Al-Majidi, M., Λαμπρόπουλος, A., Cundy, A., Τσιούλου, O., & Alrekabi, S. A novel corrosion resistant repair technique for existing reinforced concrete (rc) elements using polyvinyl alcohol fibre reinforced geopolymer concrete (pvafrgc). Construction and Building Materials, 2018; 164: 603-619. https://doi.org/10.1016/j.conbuildmat.2017.12.213
9. Alwis, L., Bustamante, H., Bremer, K., Roth, B., Sun, T., & Grattan, K. A pilot study: evaluation of sensor system design for optical fibre humidity sensors subjected to aggressive air sewer environment, 2016. https://doi.org/10.1109/icsens.2016.7808482
10. Amiri, A., Erdogmus, E., & Richter-Egger, D. A comparison between ultrasonic guided wave leakage and half-cell potential methods in detection of corrosion in reinforced concrete decks. Signals, 2021; 2(3): 413-433. https://doi.org/10.3390/signals2030026
11. Ayantunji, B., Okeke, P., & Urama, J. Diurnal and seasonal variation of surface refractivity over nigeria. Progress in Electromagnetics Research B, 2011; 30: 201-222. https://doi.org/10.2528/pierb11030902
12. Ayobami, B., Williams, K., Loto, R., Emmanuel, S., Snyman, J., & Ndambuki, J. Corrosion effect of rice husk ash in concrete pore solution: response surface analysis. The

Open Construction and Building Technology Journal, 2020; 14(1): 162-173. https://doi.org/10.2174/1874836802014010162

13. Bajad, M., Modhera, C., & Desai, A. Factors affecting the properties of conglasscrete. Iosr Journal of Mechanical and Civil Engineering, 2014; 11(2): 42-48. https://doi.org/10.9790/1684-11244248
14. Berlinov, M., Berlinova, M., & Grigorjan, A. Operational durability of reinforced concrete structures. E3s Web of Conferences, 2019; 91: 02012. https://doi.org/10.1051/e3sconf/20199102012
15. Bolzoni, F., Brenna, A., Fumagalli, G., Goidanich, S., Lazzari, L., Ormellese, M., … & Pedeferri, M. Experiences on corrosion inhibitors for reinforced concrete. International Journal of Corrosion and Scale Inhibition, 2014; 3(4): 254-278. https://doi.org/10.17675/2305-6894-2014-3-4-254-278
16. Brühwiler, E. and Linden, C. Numerical simulation of the probability of corrosion initiation of rc elements made of reinforcing steel with improved corrosion performance. Structure and Infrastructure Engineering, 2018; 14(11): 1446-1454. https://doi.org/10.1080/15732479.2018.1446180
17. Castel, A., François, R., & Arliguie, G. Mechanical behaviour of corroded reinforced concrete beams—part 1: experimental study of corroded beams. Materials and Structures, 2000; 33(9): 539-544. https://doi.org/10.1007/bf02480533
18. Çelik, T. and Kamali, S. Multidimensional comparison of lightweight steel and reinforced concrete structures: a case study. Tehnicki Vjesnik - Technical Gazette, 2018; 25(4). https://doi.org/10.17559/tv-20160901185826
19. Chady, T., Frankowski, P., Waszczuk, P., & Zielinski, A. Evaluation of reinforced concrete structures using the electromagnetic method, 2018. https://doi.org/10.1063/1.5031538
20. Chen, X., Deng, X., Liang, Y., Li, Q., Huang, J., Lin, X., … & Li, D. Regional seismic damage simulation of corroded rc frame structures: a case study of shenzhen city. Applied Sciences, 2020; 10(14): 4818. https://doi.org/10.3390/app10144818
21. Chen, Z., Koleva, D., & Breugel, K. A review on stray current-induced steel corrosion in infrastructure. Corrosion Reviews, 2017; 35(6): 397-423. https://doi.org/10.1515/corrrev-2017-0009
22. Cheng, L., Maruyama, I., & Yuqi, R. Novel accelerated test method for rh dependency of steel corrosion in carbonated mortar. Journal of Advanced Concrete Technology, 2021; 19(3): 207-215. https://doi.org/10.3151/jact.19.207

23. Chi, X., Xu, A., Liu, H., & Lun, P. Engineering vulnerability evaluation of building structures in coastal areas considering the effects of corrosion. Frontiers in Materials, 2023; 9. https://doi.org/10.3389/fmats.2022.1107378
24. Chongkai, L., Zhang, W., Gu, X., & Huang, Q. Probability distribution of cross-sectional radius of corroded steel bars in concrete and its application. Matec Web of Conferences, 2018; 199: 04008. https://doi.org/10.1051/matecconf/201819904008
25. Cui, Z. and Alipour, A. A detailed finite-element approach for performance assessment of corroded reinforced concrete beams, 2014. https://doi.org/10.1061/9780784413357.176
26. Dalfré, G., Filho, F., Couto, I., Giongo, S., & Mazzú, A. Analysis of the bond stress when using gfrp bars. Holos – Issn, 2021; 1807-1600, 5, 1-17. https://doi.org/10.15628/holos.2021.9386
27. Diamanti, M., Rosales, E., Raffaini, G., Ganazzoli, F., Brenna, A., Pedeferri, M., … & Ormellese, M. Molecular modelling and electrochemical evaluation of organic inhibitors in concrete, 2015.
28. Corrosion Science, 100: 231-241. https://doi.org/10.1016/j.corsci.2015.07.034
29. Drakakaki, A. and Apostolopoulos, C. The size effect of rebars, on the structural integrity of reinforced concrete structures, which are exposed to corrosive environments. Matec Web of Conferences, 2018; 188: 03009. https://doi.org/10.1051/matecconf/201818803009
30. Du, Y., Clark, L., & Chan, A. Effect of corrosion on ductility of reinforcing bars. Magazine of Concrete Research, 2005; 57(7): 407-419. https://doi.org/10.1680/macr.2005.57.7.407
31. Du, Y., Clark, L., & Chan, A. Residual capacity of corroded reinforcing bars. Magazine of Concrete Research, 2005; 57(3): 135-147. https://doi.org/10.1680/macr.2005.57.3.135
32. Duc, N. Improving the mechanical performance of shell precast concrete blocks for coastal protection structures of hydraulic works. Engineering Technology & Applied Science Research, 2021; 11(1): 6787-6791. https://doi.org/10.48084/etasr.4009
33. Effect of abandoned vessels on safety of mariners in coastal waters of Nigeria. International Research Journal of Modernization in Engineering Technology and Science, 2022. https://doi.org/10.56726/irjmets29457
34. Emparanza, A., Morales, C., Palacios, J., Caso, F., & Nanni, A. Durability assessment of gfrp rebars exposed to high ph-seawater, 2020. https://doi.org/10.23967/dbmc.2020.040
35. Fedosov, S., Loginova, S., & Shalygina, A. Predicting the residual life of concrete structures in biocorrosion from the position of the theory of mass transfer. Structural

Mechanics of Engineering Constructions and Buildings, 2022; 18(5): 438-443. https://doi.org/10.22363/1815-5235-2022-18-5-438-443

36. Fei, F., Hu, J., Wei, J., & Nong, Y. The effect of a tailored electro-migrating corrosion inhibitor on the corrosion performance of chloride-contaminated reinforced concrete. Materials and Corrosion, 2015; 66(10): 1039-1050. https://doi.org/10.1002/maco.201508231
37. Ghanooni-Bagha, M., Shayanfar, M., Reza-Zadeh, O., & Zabihi-Samani, M. The effect of materials on the reliability of reinforced concrete beams in normal and intense corrosions. Eksploatacja I Niezawodnosc - Maintenance and Reliability, 2017; 19(3): 393-402. https://doi.org/10.17531/ein.2017.3.10
38. Gritsenko, B., Pshenichkina, V., Glukhov, A., & Sidorova, N. Estimation of the industrial building reinforced concrete beams' residual life under corrosive media influence. E3s Web of Conferences, 2021; 281: 01011. https://doi.org/10.1051/e3sconf/202128101011
39. Hong, S., Qin, S., Dong, B., & Xing, F. Corrosion features of the reinforcing bar in concrete with intelligent oh− regulation of microcapsules. Materials, 2019; 12(23): 3966. https://doi.org/10.3390/ma12233966
40. Jano, A., Lame, A., & Kokalari, E. Test of inhibitors for preventing corrosion of steel reinforcement in concrete. Ovidius University Annals of Chemistry, 2021; 32(2): 110-113. https://doi.org/10.2478/auoc-2021-0016
41. Jaśniok, M. and Zybura, A. Modelling the carbonated concrete realkalization. Journal of Civil Engineering and Management, 2009; 15(2): 159-168. https://doi.org/10.3846/1392-3730.2009.15.159-168
42. Jiang, G., Keller, J., & Bond, P. Determining the long-term effects of h2s concentration, relative humidity and air temperature on concrete sewer corrosion. Water Research, 2014; 65: 157-169. https://doi.org/10.1016/j.watres.2014.07.026
43. Keleştemur, O. and Yıldız, S. Effect of various dual-phase heat treatments on the corrosion behavior of reinforcing steel used in the reinforced concrete structures. Construction and Building Materials, 2009; 23(1): 78-84. https://doi.org/10.1016/j.conbuildmat.2008.02.001
44. Kharaji, S. Self-healing coatings, 2023. https://doi.org/10.5772/intechopen.109500
45. Kim, H., Choi, W., Sangchun, Y., & Noguchi, T. Evaluation of bond properties of reinforced concrete with corroded reinforcement by uniaxial tension testing. International Journal of Concrete Structures and Materials, 2016; 10(S3): 43-52. https://doi.org/10.1007/s40069-016-0152-9

46. Koçer, M., Ozturk, M., & Boğa, A. Analytical study on the effect of corrosion to the construction performance. Natural and Engineering Sciences, 2019; 4(1): 11-20. https://doi.org/10.28978/nesciences.522364
47. Krivenko, P., Petropavlovskyi, O., Kovalchuk, O., Rudenko, I., & Konstantynovskyi, O. Enhancement of alkali-activated slag cement concretes crack resistance for mitigation of steel reinforcement corrosion, 2020. E3s Web of Conferences, 166: 06001. https://doi.org/10.1051/e3sconf/202016606001
48. Kumar, V., Joseph, J., Ashok, M., & Kumar, M. An experimental study on assessing the corrosion performance of steel reinforcement for the durability of concrete. Iop Conference Series Materials Science and Engineering, 2020; 989(1): 012025. https://doi.org/10.1088/1757-899x/989/1/012025
49. Lee, H. and Cho, Y. Evaluation of the mechanical properties of steel reinforcement embedded in concrete specimen as a function of the degree of reinforcement corrosion. International Journal of Fracture, 2009; 157(1-2): 81-88. https://doi.org/10.1007/s10704-009-9334-7
50. Lee, H., Ryu, H., Park, W., & Ismail, M. Comparative study on corrosion protection of reinforcing steel by using amino alcohol and lithium nitrite inhibitors. Materials, 2015; 8(1): 251-269. https://doi.org/10.3390/ma8010251
51. Lesmana, C., Hu, H., Pan, T., & Lin, Z. Parametric study on nonlinear finite element analysis of prestressed reinforced concrete beam strengthened by fiber-reinforced plastics. Mathematical Problems in Engineering, 2022; 1-11. https://doi.org/10.1155/2022/9646889
52. Li, J. Research on no-bracket construction of building structure reinforcement. Environmental and Earth Sciences Research Journal, 2022; 9(4): 167-173. https://doi.org/10.18280/eesrj.090406
53. Li, Q., Gao, Z., Yang, T., Dang, Z., Jiang, Z., He, Q., … & Fu, C. Rust distribution of non-uniform steel corrosion induced by impressed current method. Materials, 2022; 15(12): 4276. https://doi.org/10.3390/ma15124276
54. Liang, J., Zhu, H., Chen, L., Han, X., Guo, Q., Gao, Y., … & Liu, C. Rebar corrosion investigation in rubber aggregate concrete via the chloride electro-accelerated test. Materials, 2019; 12(6): 862. https://doi.org/10.3390/ma12060862

55. Liu, L., Zheng, D., Zhou, J., & Zhang, Z. (2020). Parameters that influence corrosion detection in reinforced concrete based on eddy current thermography. Advances in Civil Engineering, 2020; 1-9. https://doi.org/10.1155/2020/7962945
56. López-Calvo, H., Montes-García, P., Kondratova, I., Bremner, T., & Thomas, M. Epoxy-coated bars as corrosion control in cracked reinforced concrete. Materials and Corrosion, 2012; 64(7): 599-608. https://doi.org/10.1002/maco.201106319
57. Lun, P., Zhang, X., Jiang, C., Ma, Y., & Fu, L. Modelling of corrosion-induced concrete cover cracking due to chloride attacking. Materials, 2021; 14(6): 1440. https://doi.org/10.3390/ma14061440
58. Luo, D., Li, P., Yue, Y., Ma, J., & Yang, H. In-fiber optic salinity sensing: a potential application for offshore concrete structure protection. Sensors, 2017; 17(5): 962. https://doi.org/10.3390/s17050962
59. M. Molecular modelling and electrochemical evaluation of organic inhibitors in concrete. Corrosion Science, 2015; 100: 231-241. https://doi.org/10.1016/j.corsci.2015.07.034
60. Masoud, M. Effect of plastering layer on corrosion resistances of reinforced concrete beams. International Journal of Engineering and Advanced Technology, 2019; 9(1): 1390-1393. https://doi.org/10.35940/ijeat.a1220.109119
61. Matemilola, S., Adedeji, O., Elegbede, I., & Kies, F. Mainstreaming climate change into the eia process in nigeria: perspectives from projects in the niger delta region. Climate, 2019; 7(2): 29. https://doi.org/10.3390/cli7020029
62. Matthews, B., Palermo, A., & Scott, A. Overview of the cyclic response of reinforced concrete members subjected to artificial chloride-induced corrosion. Structural Concrete, 2022; 24(1): 100-114. https://doi.org/10.1002/suco.202200365
63. Mehdizadeh, B., Jahandari, S., Vessalas, K., Miraki, H., Rasekh, H., & Samali, B. Fresh, mechanical, and durability properties of self-compacting mortar incorporating alumina nanoparticles and rice husk ash. Materials, 2021; 14(22): 6778. https://doi.org/10.3390/ma14226778
64. Melchers, R. Long-term durability of marine reinforced concrete structures. Journal of Marine Science and Engineering, 2020; 8(4): 290. https://doi.org/10.3390/jmse8040290
65. Melchers, R. and Li, C. Reinforcement corrosion initiation and activation times in concrete structures exposed to severe marine environments. Cement and Concrete Research, 2009; 39(11): 1068-1076. https://doi.org/10.1016/j.cemconres.2009.07.003

66. Meng, X. and Zhang, S. Application and development of stainless steel reinforced concrete structure. Matec Web of Conferences, 2016; 63: 03009. https://doi.org/10.1051/matecconf/20166303009
67. Mesquita, T., Chauveau, E., Mantel, M., Kinsman, N., & Nogueira, R. Influence of mo alloying on pitting corrosion of stainless steels used as concrete reinforcement. Rem Revista Escola De Minas, 2013; 66(2): 173-178. https://doi.org/10.1590/s0370-44672013000200006
68. Mir, Z., Bastos, A., Höche, D., & Zheludkevich, M. (2020). Recent advances on the application of layered double hydroxides in concrete—a review. Materials, 13(6): 1426. https://doi.org/10.3390/ma13061426
69. Nassar, R., Dominguez, G., Soroushian, P., Balachandra, A., Weerasiri, R., Darsanasiri, N., … &
70. Navarro, I., Martí, J., & Piqueras, V. Reliability-based maintenance optimization of corrosion preventive designs under a life cycle perspective. Environmental Impact Assessment Review, 2019; 74: 23-34. https://doi.org/10.1016/j.eiar.2018.10.001
71. Navarro, I., Piqueras, V., & Martí, J. Life cycle cost assessment of preventive strategies applied to prestressed concrete bridges exposed to chlorides. Sustainability, 2018; 10(3): 845. https://doi.org/10.3390/su10030845
72. Nguyen, W., Hay, R., Jen, G., & Ostertag, C. Long-term infrastructure durability enhancement of hybrid fiber-reinforced concrete under corrosive environments, 2016. https://doi.org/10.18552/2016/scmt4d174
73. Nguyen, W., Jen, G., Duncan, J., & Ostertag, C. Effect of hybrid fiber reinforcement on corrosion-induced damage of reinforced concrete, 2016. https://doi.org/10.21012/fc9.181
74. Nolan, S., Rossini, M., Knight, C., & Nanni, A. New directions for reinforced concrete coastal structures. Journal of Infrastructure Preservation and Resilience, 2021; 2(1). https://doi.org/10.1186/s43065-021-00015-4
75. Numerical simulation analysis for mechanical properties of corroded reinforced concrete beams. Academic Journal of Engineering and Technology Science, 2021; 4(7). https://doi.org/10.25236/ajets.2021.040708
76. Odjugo, A. and Isi, A. The impact of climate change and anthropogenic factors on desertification in the semi-arid region of nigeria. Global Journal of Environmental Sciences, 2004; 2(2). https://doi.org/10.4314/gjes.v2i2.2418
77. Ogamba, E., Izah, S., & Omonibo, E. Bioaccumulation of hydrocarbon, heavy metals and minerals in tympanotonus fuscatus from coastal region of bayelsa state, nigeria.

International Journal of Hydrology Research, 2016; 1(1): 1-7. https://doi.org/10.18488/journal.108/2016.1.1/108.1.1.7

78. Okeniyi, J., Ikotun, J., Akinlabi, E., & Okeniyi, E. (2019). Anticorrosion behaviour ofrhizophora manglel. bark-extract on concrete steel-rebar in saline/marine simulating-environment. The Scientific World Journal, 2019; 1-13. https://doi.org/10.1155/2019/6894714
79. Olaniran, O. and Sumner, G. A study of climatic variability in Nigeria based on the onset, retreat, and length of the rainy season. International Journal of Climatology, 1989; 9(3): 253-269. https://doi.org/10.1002/joc.3370090304
80. Omotosho, O., Okeniyi, J., & Ajayi, O. Performance evaluation of potassium dichromate and potassium chromate inhibitors on concrete steel rebar corrosion. Journal of Failure Analysis and Prevention, 2010; 10(5): 408-415. https://doi.org/10.1007/s11668-010-9375-2
81. Ormellese, M., Bolzoni, F., Lazzari, L., & Pedeferri, P. Effect of corrosion inhibitors on the initiation of chloride-induced corrosion on reinforced concrete structures. Materials and Corrosion, 2008; 59(2): 98-106. https://doi.org/10.1002/maco.200804155
82. Ortega, N., Moro, J., & Meneses, R. Corrosion in concrete structures with permanent deformation in marine environment. The Open Construction and Building Technology Journal, 2017; 11(1): 14-24. https://doi.org/10.2174/1874836801711010014
83. Otieno, M., Alexander, M., & Beushausen, H. Corrosion in cracked and uncracked concrete – influence of crack width, concrete quality and crack reopening. Magazine of Concrete Research, 2010; 62(6): 393-404. https://doi.org/10.1680/macr.2010.62.6.393
84. Otieno, M., Beushausen, H., & Alexander, M. Prediction of corrosion rate in rc structures - a critical review., 2011; 15-37. https://doi.org/10.1007/978-94-007-0677-4_2
85. Otsuki, N., Madlangbayan, M., Nishida, T., Saito, T., & Baccay, M. Temperature dependency of chloride induced corrosion in concrete. Journal of Advanced Concrete Technology, 2009; 7(1): 41-50. https://doi.org/10.3151/jact.7.41
86. Paul, S. and Zijl, G. Corrosion deterioration of steel in cracked shcc. International Journal of Concrete Structures and Materials, 2017; 11(3): 557-572. https://doi.org/10.1007/s40069-017-0205-8
87. Pellizzer, G., Leonel, E., & Nogueira, C. Numerical approach about the effect of the corrosion on the mechanical capacity of the reinforced concrete beams considering material nonlinear models. Revista Ibracon De Estruturas E Materiais, 2018; 11(1): 26-51. https://doi.org/10.1590/s1983-41952018000100003

88. Raczkiewicz, W. Effect of concrete addition of selected micro-fibers on the reinforcing bars corrosion in the reinforced concrete specimens. Advances in Materials Science, 2016; 16(3): 38-46. https://doi.org/10.1515/adms-2016-0015
89. Raczkiewicz, W. and Kossakowski, P. Electrochemical diagnostics of sprayed fiber-reinforced concrete corrosion. Applied Sciences, 2019; 9(18): 3763. https://doi.org/10.3390/app9183763
90. Raczkiewicz, W., Bacharz, M., Bacharz, K., & Teodorczyk, M. Reinforcement corrosion testing in concrete and fiber reinforced concrete specimens exposed to aggressive external factors. Materials, 2023; 16(3): 1174. https://doi.org/10.3390/ma16031174
91. Raja, P., Ghoreishiamiri, S., & Ismail, M. Natural corrosion inhibitors for steel reinforcement in concrete — a review. Surface Review and Letters, 2015; 22(03): 1550040. https://doi.org/10.1142/s0218625x15500407
92. Rampini, M., Zani, G., Colombo, M., & Prisco, M. Mechanical behaviour of trc composites: experimental and analytical approaches. Applied Sciences, 2019; 9(7): 1492. https://doi.org/10.3390/app9071492
93. Rivetti, M., Neto, J., Júnior, N., & Ribeiro, D. Corrosion inhibitors for reinforced concrete, 2018. https://doi.org/10.5772/intechopen.72772
94. Saadun, N., Majid, M., Ismail, M., & Adnan, S. An overview on physical and mechanical properties of bamboo as a natural reinforcement in concrete. Iop Conference Series Earth and Environmental Science, 2022; 1022(1): 012049. https://doi.org/10.1088/1755-1315/1022/1/012049
95. Sandra, N. Corrosion current density of macrocell of horizontal steel bars in reinforced concrete column specimen. International Journal of Geomate, 2019; 16(54). https://doi.org/10.21660/2019.54.8198
96. Sasidharan, S., Parida, L., Singh, U., & Moharana, S. Corrosion inhibitors for enhanced strength, durability, and microstructure of coastal concrete structures. Materials Research Express, 2023; 10(7): 075101. https://doi.org/10.1088/2053-1591/ace75c
97. Seyhan, E., Goodwin, F., & Huang, I. Corrosion protection of steel reinforcement by using surface applied corrosion inhibitors. Matec Web of Conferences, 2019; 289: 05001. https://doi.org/10.1051/matecconf/201928905001
98. Shah, K. and Huseien, G. Biomimetic self-healing cementitious construction materials for smart buildings. Biomimetics, 2020; 5(4): 47. https://doi.org/10.3390/biomimetics5040047

99. Shen, J., Gao, X., Li, B., Du, K., Jin, R., Chen, W., … & Xu, Y. Damage evolution of rc beams under simultaneous reinforcement corrosion and sustained load. Materials, 2019; 12(4): 627. https://doi.org/10.3390/ma12040627
100. Shu, H., Song, Y., & Liu, J. (2018). Effect of concentration difference of chloride ions on the corrosion of steel bar. https://doi.org/10.2991/iceesd-18.2018.160
101. Sounthararajan, V. and Sivakumar, A. (2013). Corrosion measurements in reinforced fly ash concrete containing steel fibres using strain gauge technique. International Journal of Corrosion, 2013; 1-7. https://doi.org/10.1155/2013/724194
102. Strangfeld, C., Johann, S., & Bartholmai, M. Smart rfid sensors embedded in building structures for early damage detection and long-term monitoring. Sensors, 2019; 19(24): 5514. https://doi.org/10.3390/s19245514
103. Sun, G., Zhang, Y., Tian, Y., Bo, L., Shen, J., & Shi, J. Investigation of residual bearing capacity of corroded reinforced concrete short columns under impact load based on nondestructive testing. Mathematical Problems in Engineering, 2020; 1-12. https://doi.org/10.1155/2020/1901073
104. Sutrisno, W., Hartana, I., & Suprobo, P. Prediction of rust thickness in reinforced concrete structures to enhanced the asset management for coastal infrastructures. Journal of Infrastructure & Facility Asset Management, 2019; 1(2). https://doi.org/10.12962/jifam.v1i2.5969
105. Tae, S., Kyung, J., & Ujiro, T. Service life estimation of concrete structures reinforced with cr-bearing rebars under macrocell corrosion conditions induced by cracking in cover concrete. Isij International, 2007; 47(6): 875-882. https://doi.org/10.2355/isijinternational.47.875
106. Tahershamsi, M., Fernandez, I., Lundgren, K., & Zandi, K. Investigating correlations between crack width, corrosion level and anchorage capacity. Structure and Infrastructure Engineering, 2016; 13(10): 1294-1307. https://doi.org/10.1080/15732479.2016.1263673
107. Tang, C. and Gan, W. The analysis of reinforcement corrosion in concrete under the non-longitudinal cracks in marine environment, 2015. https://doi.org/10.2991/ifeesm-15.2015.14
108. Thomson, M. and Frankel, G. Atmospheric pitting corrosion studies of aa7075-t6 under electrolyte droplets: part i. effects of droplet size, concentration, composition, and sample aging. Journal of the Electrochemical Society, 2017; 164(12): C653-C663. https://doi.org/10.1149/2.1051712jes

109. Topçu, İ. and Uzunömeroğlu, A. Properties of corrosion inhibitors on reinforced concrete. Journal of Structural Engineering & Applied Mechanics, 2020; 3(2): 93-109. https://doi.org/10.31462/jseam.2020.02093109
110. Vazquez, D. and Duffó, G. Monitoring reinforcement corrosion of concretes designed for nuclear facilitie. Matéria (Rio De Janeiro), 2018; 23(2). https://doi.org/10.1590/s1517-707620180002.0383
111. Verma, M. and Mishra, S. Coupled fatigue-corrosion life estimation of reinforced concrete beam: numerical versus experimental approach. Structural Concrete, 2019; 20(6): 2194-2205. https://doi.org/10.1002/suco.201800299
112. Verma, S., Bhadauria, S., & Akhtar, S. Monitoring corrosion of steel bars in reinforced concrete structures. The Scientific World Journal, 2014; 1-9. https://doi.org/10.1155/2014/957904
113. Wang, D., Ju, Y., & Shen, H. Crack resistance properties of hpfrc beam-column joints under cyclic load. Advances in Materials Science and Engineering, 2019; 1-11. https://doi.org/10.1155/2019/8361095
114. Wang, J. and Xu, Q. The combined effect of load and corrosion on the flexural performance of recycled aggregate concrete beams. Structural Concrete, 2022; 24(1): 359-373. https://doi.org/10.1002/suco.202100819
115. Wang, J., Snoeck, D., Vlierberghe, S., Verstraete, W., & Belie, N. Application of hydrogel encapsulated carbonate precipitating bacteria for approaching a realistic self-healing in concrete. Construction and Building Materials, 2014; 68: 110-119. https://doi.org/10.1016/j.conbuildmat.2014.06.018
116. Wang, Y., Gong, X., & Wu, L. Prediction model of chloride diffusion in concrete considering the coupling effects of coarse aggregate and steel reinforcement exposed to marine tidal environment, 2019. https://doi.org/10.31224/osf.io/4heu5
117. Wu, J., Zhang, J., Diao, B., Cheng, S., & Ye, Y. Hysteretic behavior of eccentrically loaded reinforced air-entrained concrete columns under combined effects of freeze-thaw cycles and seawater corrosion. Advances in Civil Engineering, 2018; 1-10. https://doi.org/10.1155/2018/3931791
118. Xu, C., Li, Z., & Jin, W. A new corrosion sensor to determine the start and development of embedded rebar corrosion process at coastal concrete. Sensors, 2013; 13(10): 13258-13275. https://doi.org/10.3390/s131013258
119. Xu, Y., Shen, J., Zheng, Y., Mao, J., & Wu, P. Corrosion characteristics of reinforced concrete under the coupled effects of chloride ingress and static loading: laboratory tests

and finite element analysis. Materials Science, 2018; 24(2). https://doi.org/10.5755/j01.ms.24.2.17963

120. Yang, D., Yan, C., Jia, Z., & Wang, C. Prediction of concrete compressive strength in saline soil environments. Materials, 2022; 15(13): 4663. https://doi.org/10.3390/ma15134663
121. Yang, W., Ye, X., Li, R., & Yang, J. Effect of stray current on corrosion and calcium ion corrosion of concrete reinforcement. Materials, 2022; 15(20): 7287. https://doi.org/10.3390/ma15207287
122. Yang, Z., Fischer, H., & Polder, R. Modified hydrotalcites as a new emerging class of smart additive of reinforced concrete for anticorrosion applications: a literature review. Materials and Corrosion, 2013; 64(12): 1066-1074. https://doi.org/10.1002/maco.201206915
123. Yoon, I. Examination on required cover depth to prevent reinforcement corrosion risk in concrete. Corrosion Science and Technology, 2012; 11(5): 157-164. https://doi.org/10.14773/cst.2012.11.5.157
124. Zambon, I., Santamaria-Ariza, M., Matos, J., & Strauss, A. Value of information (voi) for the chloride content in reinforced concrete bridges. Applied Sciences, 2020; 10(2): 567. https://doi.org/10.3390/app10020567
125. Zhang, L., Niu, D., Wen, B., & Luo, D. Concrete protective layer cracking caused by non-uniform corrosion of reinforcements. Materials, 2019; 12(24): 4245. https://doi.org/10.3390/ma12244245
126. Zhang, R., Ma, L., Liu, P., Chen, H., Zhu, H., Xiao, H., … & Xiong, Z. Influence mechanisms under different immersion methods and different strengths of concrete in corrosive environments, and verification via long-term field test. Structural Concrete, 2020; 21(5): 1853-1864. https://doi.org/10.1002/suco.202000084
127. Zhang, T., Zhang, X., Li, P., Li, H., Li, X., & Zou, Y. Experimental research on fatigue performance of reinforced concrete t-shaped beams under corrosion–fatigue coupling action. Materials, 2023; 16(3): 1257. https://doi.org/10.3390/ma16031257
128. Zhang, Z., Lu, Y., Zhu, X., & Liu, X. Meso-scale corrosion expansion cracking of ribbed reinforced concrete based on a 3d random aggregate model. Journal of Zhejiang University Science A, 2021; 22(11): 924-940. https://doi.org/10.1631/jzus.a2100304
129. Zhang, Z., Peng, Y., Fang, X., Chen, Q., & Gan, W. Causes of cold condensation and durability countermeasures of concrete structures in caverns. Journal of Physics

Conference Series, 2023; 2468(1): 012140. https://doi.org/10.1088/1742-6596/2468/1/012140

130. Zhou, H., Qi, X., Lin, Z., Filippo, M., Liu, J., Ma, C., … & Xing, F. An experimental study on bond behaviors of reinforced concrete under fatigue loading and corrosion. Structural Concrete, 2022; 24(1): 504-520. https://doi.org/10.1002/suco.202200684
131. Zhou, S. and Ju, J. A chemo-micromechanical damage model of concrete under sulfate attack. International Journal of Damage Mechanics, 2021; 105678952199791. https://doi.org/10.1177/1056789521997916
132. Zhou, Y., Tian, H., Sui, L., Xing, F., & Han, N. Strength deterioration of concrete in sulfate environment: an experimental study and theoretical modeling. Advances in Materials Science and Engineering, 2015; 1-13. https://doi.org/10.1155/2015/951209
133. Zhu, J., Zhi, W., Su, M., Ueda, T., & Xing, F. C-frcm jacket confinement for Rc columns under impressed current cathodic protection. Journal of Composites for Construction, 2020; 24(2). https://doi.org/10.1061/(asce)cc.1943-5614.0001006