Kathmandu University Journal of Science, Engineering and Technology, Vol. 18, No. 1, June 2024

Kathmandu University
Journal of Science, Engineering and Technology

Influence of corrosion on lifespan of reinforced concrete structures: A comprehensive review

Kameshwar Sahani*[a], Shyam Sundar Khadka[a], and Suresh Kumar Sahani[b]

[a]Department of Civil Engineering, Kathmandu University, Dhulikhel, Nepal.

[b]Department of Science and Technology, Rajarshi Janak University, Janakpurdham, Nepal.

Abstract

Carbonation-induced corrosion is a major concern for reinforced cement concrete (RCC) structures, impacting their long-term durability and structural integrity. This review synthesizes the findings on the deterioration mechanisms in concrete structures, focusing on carbonation, chloride-induced corrosion, and time-dependent deterioration. The analysis includes discussions on predictive likelihood methods for estimating bridge reliability, the impact of environmental factors on carbonation, and standardized testing methods for assessing concrete durability. The review highlights the importance of understanding material characteristics and environmental conditions in designing durable concrete structures, emphasizing the processes of carbonation, its impact on rebar corrosion, and strategies for mitigation. Sheltered concrete carbonation resistance in metropolitan tropical climates is 10-20% lower than open exposure. SCM concretes exhibit equivalent or greater long-term carbonation resistance to OPC concretes, as evidenced by the increase in carbonation depth (Δxd) at ages greater than 5 years. The paper concludes with recommendations for integrating advanced modeling techniques and empirical studies to develop robust maintenance strategies and improve concrete mix designs for enhanced durability.

Keywords: Corrosion; RCC structures; Service life; Carbonation depth; Carbonation; Reliability

1. Introduction

The majority of recently built structures anticipate deterioration in the near future, according to the substantial literature on corrosion in concrete. Corrosion affects the strength, stiffness, and stability of RC structures, and it also affects their serviceability and safety. In addition to its detrimental effects on structures and potential for fatalities, rust will raise related costs. Therefore, it is crucial to maintain reinforced concrete structures and extend their useful lives [3,5,11,12,41,51].

Due to the rising per capita demand for cement and concrete in nations like Nepal and India, the production of concrete is expected to generate between 5 and 8% of all man-made global CO_2emissions [11,12]. Furthermore, it is projected that by 2050, the world's cement output will have increased fourfold [11,12]. Cement contributes significantly to CO_2 emissions among the components of concrete. It is critical to select an alternate cementing material that may partially replace the clinker content in order to lessen the detrimental effects of concrete on the environment. Therefore, it is preferable to use locally accessible raw materials with a minimal carbon footprint and excellent durability to make concrete for reinforced concrete structures. One of the most significant challenges that reinforced concrete structures must contend with is deterioration brought on by corrosion, which has a negative impact on the structures' durability [3,4,5]. Carbonation-induced corrosion is more likely to occur in structures that are located away from coastal areas, such as tunnels, bridges, industrial buildings, and other structures. This type of corrosion has an impact on the structure's ability to withstand the consequences of corrosion over the long run. Carbonation is responsible for the deterioration of concrete structures and the induction of corrosion. It does this by making the pH of reinforced concrete structures lower, which in turn reduces the service life of the structures. According to Papadakis et al. [7], carbonation is given importance since there is a progressive increase in the concentration of carbon dioxide in the atmosphere [6-8]. This increase is caused by emissions from vehicles, effluents from factories, and the use of machines. If the minimum water-to-cement ratio and minimum grade of concrete that are defined in regulations are employed in the field for a variety of exposure situations, then concrete is considered to be one of the most durable materials. To check these parameters, however, there is no practical procedure that can be used in the field. As a result of the reaction between the relative humidity and atmospheric CO_2 hydration products, specifically $Ca(OH)_2$, the pH levels decrease, which in turn leads to the neutralization of the concrete and the beginning of the active corrosion process [6-8].

The corrosion of steel in concrete causes internal damage to reinforced concrete elements. This damage is caused by expanded corrosion products. There is a significant relationship between the qualities of oxide layers, which are results of corrosion, and the formation of corrosion cracks in concrete. One of the most important aspects to consider is the expansion ratio of the oxide, which is determined by the particular type of oxide that is generated. Depending on the degree of oxidation, the volume increase that occurs as a result of rebar corrosion is typically approximately 2.0, and it may be as much as 6.5 times greater than the volume of the original iron that is consumed by the corrosion process due

---

[*] Corresponding author. Email: kameshwar.sahani@ku.edu.np

to the development of a variety of corrosion products [4,6,8,42,32-35,61]. Reinforced concrete structures, particularly bridges, are integral to modern construction due to their strength and versatility. However, these structures are susceptible to various deterioration mechanisms over time, influenced by environmental factors and material properties, leading to significant maintenance and repair costs [36]. Carbonation and rebar corrosion are critical factors affecting their longevity. This paper reviews and synthesizes findings from three key studies to provide a comprehensive understanding of these degradation processes, discussing their underlying mechanisms, impact on durability, and strategies for mitigation. The review aims to offer a comprehensive approach to managing concrete structure durability, emphasizing the importance of predictive methods, environmental considerations, and advanced modeling techniques to develop robust maintenance strategies and improve concrete mix designs [5,7-15,34-40]. The compressive and tensile strength of concrete and steel reinforcement make reinforced concrete a popular building material. For strength and durability, steel bars or mesh are placed in the concrete. Concrete's pH is 12–13, making it alkaline. High pH forms a passivating coating on steel reinforcement, preventing corrosion. Alkaline surroundings limit corrosion cell development and produce the passive layer around steel. Carbonation happens when the atmospheric CO_2 combines with concrete's alkaline chemicals. This process progressively neutralizes concrete alkalinity by lowering pH. Carbon dioxide diffusion causes concrete carbonation to begin at the surface and advance within. As carbonation continues, the alkaline atmosphere neutralizes, lowering the pH of concrete to 8-9. In this pH range, the reinforcement's passive layer breaks away, exposing the steel to corrosion. Corrosion requires moisture, oxygen, and carbon dioxide, which promote it [30-33,43-50]. When carbonation reaches reinforcement depth, corrosion begins. Carbonic acid, formed from carbon dioxide and water in concrete, lowers the pH near the reinforcement. This acidic environment dissolves the passive layer, forming corrosion cells. Iron oxide (rust) forms as steel reinforcement corrodes, taking up more space than steel. Rust expansion presses on concrete, cracking, spalling, and letting moisture and oxygen in. Carbonation in concrete construction depends on several elements. These include concrete porosity and permeability, ambient carbon dioxide levels, relative humidity, temperature, and fractures or faults that let carbon dioxide and moisture in. On RCC construction, carbonation-induced corrosion causes several problems. Structures degrade due to reinforcing weakness and load-carrying capability. Expansive rust development can accelerate concrete cracking and spalling, reducing construction durability and service life [8-15, 33-35].

1.1. Global impact of corrosion

The repair and rehabilitation of carbonation-induced corrosion in RCC structures can be costly and time-consuming. It often requires extensive remedial measures, including the removal of deteriorated concrete, the cleaning and treatment of reinforcement, and the application of protective coatings. In severe cases, it may even necessitate partial or complete replacement of structural elements, leading to significant financial burdens. The National Academy of Corrosion Engineers (NACE) has calculated that corrosion's worldwide expense reached an astonishing $2.5 trillion in 2016, which represents about 3-4% of the global GDP (NACE International, 2016) [1,2,3]. This huge sum includes the damage caused in areas like infrastructure and transportation, where reinforced concrete structures play a vital role. Corrosion in these structures is mainly triggered by carbonation and chloride getting in. The specific reason can vary based on where the building is and how it's affected by the environment.

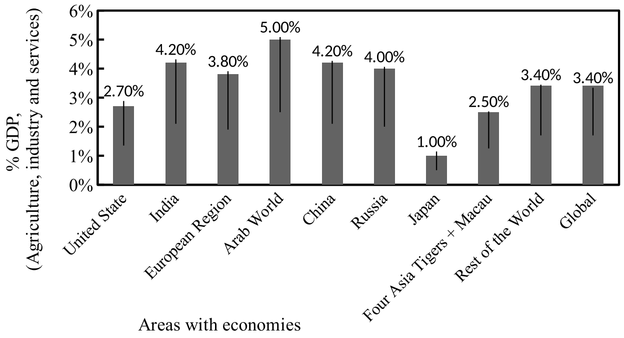

Figure 1: Global corrosion cost by sector and area.

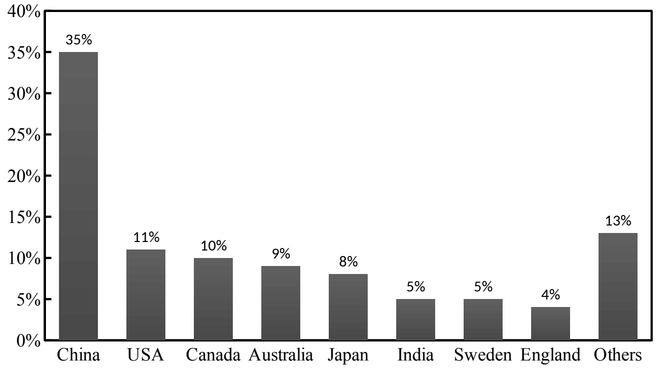

Figure 2: Distribution of publications by country.

To deal with different parts of the world's economy, the World Bank split it into areas with similar types of economies, as shown in Fig. 1 [41–44].

1.2. Research results

The writers of the chosen publications are distributed geographically across the various countries, as seen in Fig. 2. Having published up to half of all publications, China, the USA, and Canada may be able to facilitate researcher collaboration, joint venture investigations, and the interchange of cutting edge technology and concepts [66].

The study included in Fig. 3 shows the published articles from 2000 to 2024 (June). Using the search phrases "deterioration mechanisms in concrete structures," "carbonation," "chloride-induced corrosion," and "time-dependent" deterioration, the data for this graph was found on Google Scholar. Fig. 3 shows the specific publishing numbers by year. It shows that publications on this issue have consistently increased over the previous two decades. This implies an increasing interest in understanding and resolving concrete structure deterioration mechanisms. The study takes into account and presents the experimental data that have been published in the high impact research journals. Carbonation and chloride-induced corrosion are predominant causes of reinforced concrete deterioration. Carbonation reduces concrete's alkalinity

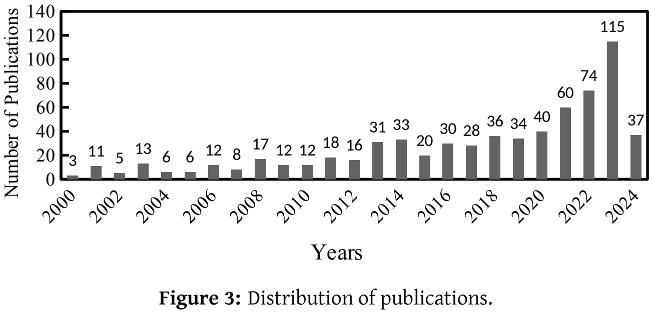

Figure 3: Distribution of publications.

by reacting atmospheric carbon dioxide with calcium hydroxide. This can cause concrete steel reinforcement corrosion. Chloride ions from seawater or de-icing solutions enter concrete and reach steel reinforcing, causing corrosion. Chlorides can rust steel. Time-dependent degradation is crucial to concrete durability. Concrete is complicated and can alter over time. Concrete can become more porous, allowing water and chloride ions to infiltrate. Environmental circumstances will also affect concrete deterioration. Designing and maintaining durable concrete structures requires understanding time-dependent degradation. Engineers can build long-lasting structures by understanding concrete degradation. They can also create methods for monitoring and repairing ageing concrete structures.

1.3. Motivation and aim of the study

Carbonation-induced corrosion significantly impacts the durability and service life of reinforced concrete (RC) structures. Understanding the underlying mechanisms and developing effective mitigation strategies are critical for maintaining structural integrity and reducing maintenance costs. This manuscript aims to provide a comprehensive review of the deterioration mechanisms in concrete structures, focusing on carbonation, chloride-induced corrosion, and time-dependent deterioration.

1.4. Novelty and organization of study

To improve the understanding of corrosion caused by carbonation, this study incorporates innovative modeling tools and presents the most recent research. Through an assessment of the effects of environmental conditions and Supplementary Cementitious Materials (SCMs), the manuscript provides novel views on the durability and lifespan of reinforced concrete structures. The inclusion of case studies and experimental data further highlights the real-world consequences of the research. An overview of earlier studies on corrosion caused by carbonation, corrosion produced by chloride, and time-dependent degradation is presented in this study. The Impact of Supplementary Cementitious Materials (SCMs) discusses the roles of SCMs and how they impact corrosion caused by carbonation. Advanced Modeling Techniques looks into a number of mathematical methods and how accurate they are at predicting corrosion rates and carbonation depth. An environmental factor investigates how estimations of carbonation depth are impacted by temperature, relative humidity, and carbon dioxide concentration. The study concludes with an interpretation of the earlier findings, recommendations for future research directions that take into account the findings from earlier sections, and a summary of the key findings and recommendations for enhancing the robustness of RC structures.

2. Literature review

Environmental stresses naturally have a negative impact on the durability of reinforced concrete (RC) constructions. Carbon dioxide (CO_2) is a rather frequent and significant stressor that can lead to carbonation, or the depassivation of the protective coating around steel reinforcement. The atmosphere contains carbon dioxide at all times, but it is concentrated more near its sources that is, in industrialized, highly populated areas that also happen to have the largest concentration of constructed infrastructure. Higher CO_2 concentrations can be expected to fluctuate with height above ground level since CO_2 is heavier than air.

Corrosion may happen when the carbonation depth reaches the reinforcement because the protecting film's passivity is destroyed by the fall in alkalinity. The term "initiation period" often refers to the time frame around this circumstance. The following time (propagation phase) sees a progressive reduction in the corroding steel sections, which causes concrete to fracture and eventually spall, decreasing the structural and serviceability reliability of structural parts. The period of noticeable corrosion-induced cracking and spalling would probably be a good way to define service life [3–4, 19–20, 31]. The time to corrosion initiation, a conservative measure of service life performance, will be the main focus of the current investigation. In order to monitor the background level of CO_2 concentrations required to help assess the magnitude of "global warming," CO_2 concentration measurements are more likely to be made in non-urban (remote) environments. They are also less likely to be reported or easily accessible.

Carbonation depth prediction models are briefly reviewed by the Structural Engineering Research Centre, CSIR Campus, Taramani, Chennai, India. Empirical, physical, probabilistic, and deterministic prediction models exist. This study investigated empirical and physical theories for natural carbonation depth prediction. Carbonation depths are estimated using empirical and physical models for CSIR-Structural Engineering Research Centre, Chennai campus buildings, as parametric research. In the parametric investigation, Fib model code, Ekolu's model, Kokubu's, and Hakkinen's models correlated well ($R^2 = 0.94$) with observed carbonation depths. Ekolu's model predicts carbonation depths for ordinary, standard, and high-strength concrete over 25, 50, and 100 years in rural, seacoast, urban, industrial, and tunnel environments. Tunnels have a higher carbonation depth than coastal areas due to CO_2 concentration and low humidity. Tunnels require a deeper cover depth for carbonation corrosion than industrial locations and urban areas [46,51].

Equations 1 to 4 show the mechanism of carbonation as well as the hydration process. Calcium silicate hydrate (C-S-H) and calcium hydroxide are the byproducts of the reaction between the tricalcium and dicalcium silicates found in cement and water. When calcium hydroxide in its aqueous condition combines with carbon dioxide during the carbonation reaction, calcium carbonate precipitate is created. Reactions with hydration

$$2\,(3CaO \cdot SiO_2) + 6H_2O \rightarrow (3CaO \cdot 2SiO_2 \cdot 3H_2O) + 3Ca(OH)_2 \quad (1)$$

$$(2CaO \cdot SiO_2) + 4H_2O \rightarrow (3CaO.2SiO_2 \cdot 3H_2O) + Ca(OH)_2 \quad (2)$$

Carbonation reaction

$$Ca(OH)_2(s) \leftrightarrow Ca^{2+}(aq) + 2OH^{-}(aq) \quad (3)$$

$$Ca^{2+}(aq) + 2OH^{-}(aq) + CO_2(g) \rightarrow CaCO_3(s) + H_2O \quad (4)$$

2.1. Corrosion mechanisms

Tuutti [62] divides the service life of reinforced concrete (RC) structures into two main phases: initiation and propagation. The initiation phase involves the penetration of CO_2 and chloride into the concrete, which gradually breaks down the passive film on the steel surface. The propagation phase is marked by active corrosion until it reaches the damage threshold defined by building standards. Generally, steel corrosion is passive if the current density is below 0.1 μA cm^{-2} and active if it exceeds 1 μA cm^{-2}. Other models also consider variations in corrosion rates over time or add stages for rust expansion, cover cracking, and spalling/delamination. The deterioration rate is non-linear, as cracking and spalling can accelerate corrosion, while corrosion products may fill pores and slow down the rate [62, 63].

Fig. 4 is used for estimating the service life of reinforced concrete necessitates understanding the two primary stages of steel

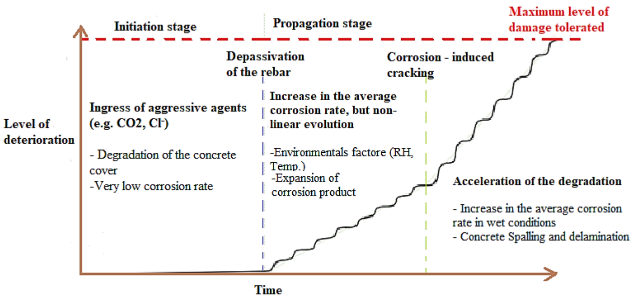

Figure 4: Schematic representation of the service life of RC structures [62,63].

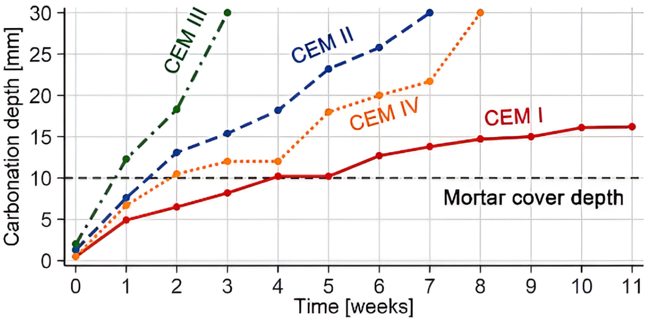

Figure 5: Accelerated carbonation depth of specimens determined with phenolphthalein [64].

corrosion in concrete. Improved predictions require models that couple transport and electrochemical processes.

Carbonation and chloride ions are the two main factors that can attack steel in concrete. Concrete absorbs carbon dioxide from the atmosphere gradually, and when it reacts with internal chemicals, the alkalinity of the material is reduced. This makes the protective layer on the steel weaker and invites corrosion. In addition to producing different chemicals such ferrous hydroxide carbonate, corrosion can cause the concrete itself to deteriorate and split.

However, corrosion can also be caused by chloride ions, which are frequently found in seawater or de-icing chemicals. These ions attack the steel locally, causing deeper damage in the vicinity of concrete air pockets. A self-sustaining cycle of corrosion begins as chlorides build up around the steel reinforcing. This entails the steel's protective layer repeatedly breaking down and reforming until a critical concentration of chloride is reached, which speeds up corrosion. Analogous to carbonation, corrosion generated by chloride can result in concrete cracking, spalling, and delamination. When there is both $CO_2$and chloride present, the situation gets significantly worse. When they cooperate, they have the potential to do greater harm than when they act separately. Under such circumstances, chlorides may interfere with the concrete's capacity to bind these ions, causing them to be released and hastening the steel reinforcement's corrosion [62, 63].

2.2. Role of blended cements and supplementary cementitious materials (SCMs)

It is well known that adding more cementitious ingredients to concrete can improve its pore structure and faster the carbonation process. When chlorides are also involved, the combination of the two processes can affect corrosion in both positive and negative ways. Hren et al. [64] assessed the corrosion properties of various blended cements in both carbonated and non-carbonated states, introducing chlorides through periodic ponding. Monitoring the propagation phase, figuring out cements' microstructural characteristics, and evaluating the ultimate corrosion damage were all part of the examination. As compared to the OPC, the steel in the mixed cements had a lower early corrosion activity, according to the data. The advantageous alterations to the pore structure are most likely what caused this stability. The corrosion was significantly affected by carbonation; carbonated mortars showed lesser damage over a wider surface area. For blended cements that showed a higher susceptibility to carbonation, this effect was more noticeable [64].

The CEM I cement exhibited the highest calcium oxide content and C/S ratio, indicating excellent mechanical characteristics and carbonation resistance. CEM II cement has similar silica, slightly higher alumina, and less calcium oxide, mostly replaced by amorphous fly ash. A moderate amount of limestone was found. CEM III cement had the maximum replacement of cement clinker, with a 75% amorphous phase and low clinker percentage. The cement has high alumina, magnesium oxide, and lower calcium oxide concentration, typical of slag cements. The CEM IV cement replaced clinker similarly to CEM II cement, however the higher amorphous phase suggests increased pozzolanic content. The cement exhibited alumina concentration similar to CEM III slag cement, an important factor in improving chloride binding [64].

Hren et al. [64] conducted a laboratory test in which accelerated carbonation was evaluated intermittently for 11 weeks using phenolphthalein. Fig. 5 shows carbonation depth measurements. The data represent the estimated average of carbonation depths measured at various positions around the middle circular crosssection, with just one specimen per cement examined weekly. The CEM I mortar had the slowest carbonation rate, with a depth of 16 mm after 11 weeks. The increased CaO percentage in cement clinker leads to more $Ca(OH)_2$ production, maintaining an alkaline environment and slowing carbonation compared to blended cements. In contrast, CEM III cement reached 30 mm carbonation depth after 3 weeks. Low CaO clinker content and high amorphous SiO_2 content in the chemical process led to quick pH reduction. Carbonation rate was quicker for CEM II cements compared to CEM IV cements. Despite having similar cement clinker amounts, CEM II may have had a higher carbonation rate due to its limestone content. The CEM II mortar achieved 30 mm depth in 7 weeks, while the CEM IV mortar required 8 weeks. Note that the CEM IV mortar results deviated significantly from expected values at weeks 4 and 8.

From Fig. 5 it is found that, in terms of carbonation depth following chloride exposure, the CEM I and CEM IV mortars had the lowest values at 0.5 mm, followed by the CEM II mortar at 1.5 mm and the CEM III mortar at 2.3 mm. After the 28-day curing period, only the CEM II and CEM III mortars' natural carbonation depths were found to have grown by 0.2 and 0.3 mm, respectively, in comparison.

2.3. Influence of SCMs on carbonation

Concrete carbonation resistance is influenced by binder type, SCM replacement amount, binder concentration, and water-to-binder ratio [46]. Fly ash and slag use reduces OPC clinker content, reducing carbonation resistance with higher replacement levels. Pozzolanic processes in concretes with SCMs consume $Ca(OH)_2$ and lower the initial pH of cured concrete to ≈12.5, compared to ≈13.5 in OPC, in addition to clinker reduction. Compared to fly ash, slag exhibits stronger carbonation resistance due to its higher CaO buffer. Many research evaluated carbonation in concretes with equal binder content and water-to-binder ratio, without addressing binder type. Comparing concrete carbonation with different CaO buffers challenges the long-term carbonation resistance of equal strength grade mixes. Many literature conclusions are based on short-term lab experiments, which may not accurately reflect the long-term carbonation resistance of concretes with SCMs. Lim-

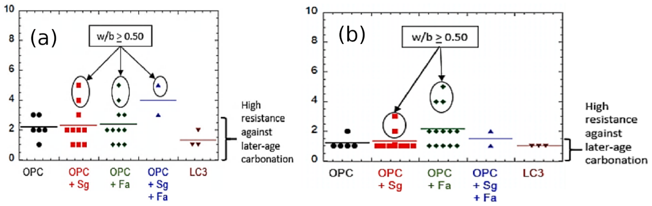

Figure 6: OPC SCM based concretes exhibiting similar later-age carbonation resistance [46]. (a) Natural sheltered (carbonation depth (Xd), natl); (b) accelerated 1% CO_2 (carbonation depth (Xd), accl).

ited global data exists on long-term natural carbonation in SCM-based concretes. Additional research on carbonation rate and corrosion mechanisms is necessary to assess the long-term performance of steel in SCM-based concretes at a certain depth [46,64-66].

2.4. Climatic conditions' impact on carbonation

Pillai et. al [46] used Ordinary Portland Cement (OPC) of 53 Grade from two sources (CmA, CmP) that met IS 269 (2015) and ASTM C150 Type I cement as the primary binder. Four SCMs were employed to partially substitute OPC: coarser slag (SgC), finer slag (SgF), Class C fly ash (FaC), and Class F fly ash. The study utilised blast furnace slag (SgC and SgF) from the steel manufacturing industry. This investigation utilised limestone calcined clay cement (LC3), a blend of clinker (50%), limestone (15%), and calcined clay (30%). Coarse aggregates were crushed granite with maximum particle sizes of 10-20 mm. The specific gravity values of fine river sand and crushed granite coarse aggregates were 2.53 and 2.76 at saturated surface dry (SSD) conditions, with water absorption capabilities of 0.43 and 0.71%, respectively. The carbonation rate differs between 'Open' and 'Sheltered' environments, depending on rain frequency and macropore/capillary saturation during alternate wet and dry exposure. Internal relative humidity, temperature, and moisture levels affect CO_2 diffusion and carbonation reactions. Open exposure can cause concrete macropores to become wet during seasonal rainfall, slowing carbonation. Sheltered exposure and 65-80% relative humidity can create partially saturated pores and promote carbonation. Carbonation of concrete structures in open exposure is influenced by the number of wet days per year, as well as the regional relative humidity and temperature [46, 64-65].

2.5. Experimental results

The study was done on 68 concrete prism specimens from the same batch as used in accelerated carbonation experiments were subjected to 'Natural – Open' and 'Natural – Sheltered' exposure on a rooftop in Chennai, India. EN 206 (2000) defines XC3 (moderate humidity) and XC4 (cyclic wet and dry) exposure classes for carbonation and accelerated carbonation chamber [46,65]. Specimens were spaced at least 5 cm apart to promote airflow and prevent shadowing. The monthly average of ambient temperature (T: 27-34 °C), relative humidity (RH: 65-80%), precipitation days (P), and CO_2 concentration at the exposure location (Chennai, India) throughout the year is shown. Samples were fractured transversely at 1, 2, 3, and 5 years of natural exposure, sprayed with phenolphthalein indicator, and quantified for carbonation depth $(xd, natl)$ per RILEM CPC 18 recommendations [46,65]. The carbonation depth under naturally protected environments is shown in Fig. 6a, while the carbonation depth obtained in artificially controlled conditions from the accelerated carbonation chamber is shown in Fig. 6b.

Five-year natural and four-month accelerated carbonation tests were done on 34 concretes containing OPC, fly ash, slag, and LC3.

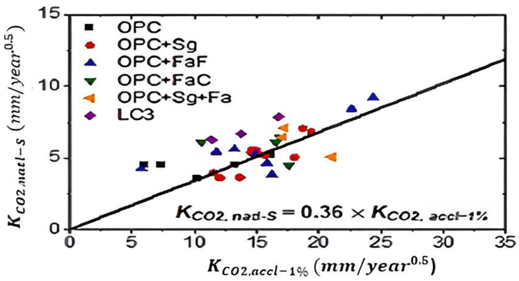

Figure 7: Relationship between sheltered and accelerated carbonation [46].

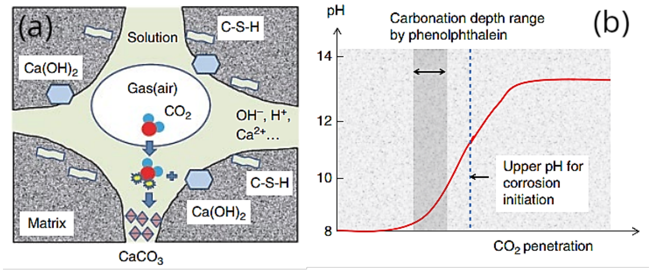

Figure 8: Pore-level carbonation mechanism (a) and CO_2 infiltration pH profile (b).

The data was used to construct a model to estimate carbonation coefficient (KCO_2) levels in tropical concretes, estimating carbonation depth at 50 years for 34 concretes [46, 65]. The relation between accelerated and sheltered carbonation is illustrated in Fig. 7.

The concrete carbonation resistance in urban tropical climates is 10-20% lower in sheltered exposure than in open exposure. The rise in carbonation depth (Δxd) at older ages (>5 years) shows that concretes with SCMs can achieve comparable or superior long-term carbonation resistance than OPC concretes. SCM-based concretes may have similar long-term carbonation depth to OPC concretes due to improved pore refinement and changes in moisture conditions. SCMs use affects the linear relationship between accelerated and natural carbonation coefficients, with material composition significantly affecting the relationship [46,65].

3. Carbonation of concrete

The incoming CO_2 gas and the liquid interstitial solution in the pores must react chemically to carbonate concrete. After the binder materials hydrate, solidified concrete's pore solution is alkaline (pH =13.0) and primarily K^+, Na^+, Ca^{2+}, and OH ions. Fig. 8 shows pore solution carbonation between dissolved CO_2 and aqueous ions. This CO_2, OH^-, and Ca^{2+} interaction dominates [8], [11-12].

This claim obscures the fact that CO_2 is soluble in the pore solution, where it ionises to form HCO_3^- and CO_3^{2-} and creates carbonic acid (H_2CO_3). By using this method, OH^- ions in the pore solution are reduced and calcite $(CaCO_3)$ is precipitated. While the latter fills the initial pore space and strengthens concrete, the former lowers the pH of the pore solution from 13.0 to less than 9.0. OPC-containing carbonated cement pastes increased compressive strength by 30% (Lea, 1970) while reducing porosity by 10% to 15% [8]. Using rapid carbonation or CO_2 mixing, this idea was used to increase the compactness of cured concrete (Estoup, 1987). CH carbonation improves porosity and has little influence on compactness in concretes with high SCM content, such as FA or GGBS. Thus, the influence of carbonation on increasing compactness should be taken into account.

The impact of CSH carbonation on pore solution pH is thought to be minimal since CSH is so poorly soluble in the pore solution. Because CSH forms the bulk of cement pastes, carbonation's effect on CSH's characteristics can have far-reaching effects on concrete's performance. Unhydrated tricalcium silicates (C_3S) and dicalcium silicates (C_2S) and aluminates hydrates are also present in hardened cement paste and can react with dissolved CO_2, in the pore solution, in addition to calcium hydroxide ($Ca(OH)_2$ or CH) and CSH [8,33].

3.1. Influence of temperature, humidity, and CO_2 concentration on corrosion rate

The impact of CO_2 concentration, temperature, and humidity on corrosion is significant and can be quantified through specific chemical reactions and empirical data.

3.1.1. CO_2 level

Carbonation is influenced by the amount of CO_2, in the air around concrete structures. The depth of carbonation is related to the square root of the ambient CO_2, concentration when the kinetics of carbonation are governed by CO_2, diffusion [67]. The carbonation depth increases by 12% with a 25% rise in CO_2 concentration. The typical range of atmospheric CO_2, concentrations is 350–380 ppm (0.57–0.62 g/m3). CO_2, levels rose from 280 parts per million in 1750 to 380 parts per million in 2005 as a result of greenhouse gas emissions [49]. The local CO_2, concentration near structural components can be up to twice the average ambient level in poorly ventilated locations and polluted cities [13-22,49].

The presence of CO_2, in the atmosphere contributes to corrosion by forming carbonic acid (H_2CO_3) when it dissolves in water, as shown by the equation:

$$CO_2 + H_2O \to H_2CO_3$$

This carbonic acid can further dissociate into hydrogen ions (H^+) and bicarbonate ions ($HCO3^-$), lowering the pH of the solution and enhancing corrosion:

$$H_2CO_3 \to H^+ + HCO_3^-$$

In reinforced concrete structures, CO_2 from the atmosphere penetrates the concrete and reacts with water to form carbonic acid, which then lowers the pH of the concrete. When the pH drops below a critical level (~9.5), the protective passive oxide layer on the steel rebar breaks down, initiating corrosion. Studies have shown that the rate of carbonation of concrete is about 1-3 mm per year under typical conditions [10]. In an environment with a CO_2concentration of 0.03% and a relative humidity of 65%, the corrosion rate of steel in concrete can increase significantly [10,13-14].

3.1.2. Temperature

In nature, temperature has an impact on the carbonation of concrete. In the past 100 years, the greenhouse emission process has raised the average global temperature by 0.074 °C per decade to 0.177 °C per decade.

Temperature also plays a crucial role in corrosion. The Arrhenius equation,

$$k = A \ \exp\left(\frac{-E_a}{RT}\right)$$

In the above equation, The pre-exponential factor is A, the activation energy is E_a, the gas constant is R, the temperature in kelvins is T, and the rate constant is k.

For steel in an acidic environment, increasing the temperature from 20°C to 30°C can double the corrosion rate due to the exponential dependence of reaction rates on temperature. In a study on the corrosion of carbon steel in a 3.5% NaCl solution, the corrosion rate increased from 0.5 mm/year at 20°C to 1.1 mm/year at 30°C, illustrating the temperature effect [15-17].

3.1.3. Humidity

In order to enable the electrochemical processes that are essential for corrosion, the presence of a thin electrolyte coating on the surface of the metal is necessary.

Atmospheric corrosion of steel is significantly influenced by relative humidity. At relative humidity levels above 60%, a continuous thin water layer forms on the metal surface, enhancing the electrochemical corrosion processes. Experiments have shown that the corrosion rate of steel can increase from negligible levels at 40% relative humidity to over 0.02 mm/year at 80% relative humidity [14].

3.2. Combined effects

In a marine environment with a CO_2 concentration of 0.04%, a temperature of 25°C, and relative humidity of 75%, the combined effects of these factors can lead to significantly higher corrosion rates for steel structures. A study on the corrosion of mild steel in a coastal environment showed that the corrosion rate increased from 0.05 mm/year at 50% humidity and 20°C to 0.15 mm/year at 80% humidity and 30°C, demonstrating the synergistic effect of temperature and humidity [13].

4. Prediction of concrete carbonation depth

There are several different kinds of models available that may be used to estimate the carbonation depth. These models fall into several categories, including simulation, statistical, numerical, and empirical models.

The empirical models that are offered are based on the exposure of structures to their natural environment. Furthermore, the empirical model's composition, strength, diffusion, and permeability were combined. A statistical model is only concerned with producing data by means of multiple variable regression and standard mathematical procedures. The foundation of numerical models is computational methodology, which uses software applications that use hybrid physico-chemical equations and concrete transport mechanisms. Artificial neural network methods with input and output parameters provide the basis of simulation models, which train on a data set to produce reliable results. Without the requirement for actual measurements, prediction models may be used to estimate the depth of carbonation in reinforced concrete structures. Five models are selected from among the many models available in the literature based on the input parameters' accessibility. These models are briefly described in the following sections [3-5] and [42-49].

Concrete carbonation is a chemical process in which atmospheric CO_2 reacts with calcium hydroxide in concrete to form calcium carbonate, reducing the pH and potentially compromising the steel reinforcement. Accurate prediction of carbonation depth is essential for assessing the durability and service life of concrete structures.

The most widely used empirical formula to predict carbonation depth (x_c) is

$$x_c = k\sqrt{t}$$

Where,

x_c = carbonation depth left (mm right) ,
k = carbonation coefficient (mm/year$^{0.5}$)
t = time (years)

DuraCrete [67]: Dependent on the surrounding CO_2 concentration, the carbonation depth is precisely proportional to the square root of time in this fundamental equation. According to DuraCrete (2000), there is a 12% increase in carbonation depth for every 25% increase in CO_2 concentration [13-15, 51-52, 67].

Papadakis et al. [53] proposed a model that considers the concrete's water-to-cement ratio and the presence of pozzolanic materials, which affect the carbonation resistance [7, 13-15, 53]:

$$x_c = k\sqrt{\frac{t}{\alpha}}$$

Where, α,represents the concrete's resistance to carbonation, influenced by composition and porosity [7, 13-15, 53].

Parrott (1992): Parrott introduced a model that includes environmental exposure classes, acknowledging that carbonation rates vary significantly with environmental conditions [54].

$$x_c = k_c\sqrt{t}$$

Where, k_c is an exposure-dependent coefficient. This model is particularly useful for structures exposed to varying climates (Parrott, 1992).

Fick's Second Law Model: Fick's second law of diffusion describes the diffusion process of CO_2 into concrete. This model assumes that the diffusion coefficient is constant and that the carbonation front moves as a function of time [55]:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2}$$

Applying this to the carbonation process, the depth x_c can be expressed as:

$$x_c = k\sqrt{\frac{2D_{eff}C_{co_2}}{C_{OH^-}}t}$$

Where,
D_{eff}= effective diffusion coefficient of CO_2 in concrete
C_{CO_2}= concentration of CO_2
C_{OH^-} = concentration of hydroxide ions in the pore solution

BRE Model (Building Research Establishment): The BRE model accounts for environmental exposure and concrete quality. It uses the following form [56] and [13-15]:

$$x_c = k_1\sqrt{t}$$

Where, k_1 is a carbonation coefficient influenced by environmental and material factors [68].

The various models for carbonation depth are summarized in Table 1.

Kokubu and Nagataki's Model: This strength-based empirical model from regression analysis predicts carbonation depth using minimal parameters. This model works for fly-ash and portland cement. If compressive strength and curing period are known, this model can forecast carbonation depth for new and existing buildings. The model accounts for slump, cement content, and fly ash replacement ratios based on concrete compressive strength [11]. In this model, CO_2 concentrations, relative humidity, and temperature are ignored.

$D = \left(10 - 1.6\sqrt{f_{ck}}\right)\sqrt{t}$ (Outdoor exposure)
$D = \left(17 - 2.2\sqrt{f_{ck}}\right)\sqrt{t}$ (Indoor exposure)

Where, D = carbonation depth (mm); f_{ck} = characteristic compressive strength of concrete at 28 days (MPa); t =time of exposure (years).

Hakkinen's Model: This strength-based empirical model can be utilized for new and existing structures with air entrainment data. The Hakkinen model predicts carbonation depth using equations developed. The model's key input is the concrete's air content coefficient. ASTM C 173 measures concrete air content. This model replaces fly ash, silica fume, and slag to a certain amount.

$D = K\sqrt{t}$
Carbonation rate factor (mm/year0.5), $K = C_{env}C_{air}a$

Where, C_{env} = environmental coefficient; C_{air} = air content coefficient; a and b are constants depending on the type of cement and can be calculated from [11]; f_{ck} = characteristic compressive strength of concrete (MPa).

4.1. Practical considerations

Real-world predictions must account for varying environmental conditions, concrete quality, and protective measures such as coatings. In poorly ventilated or polluted areas, local CO_2concentration can be significantly higher, potentially doubling the predicted carbonation depth [49].

Key findings include that concrete carbonation is influenced by factors such as the water-cement ratio, aggregate-cement ratio, ambient CO_2concentration, temperature, and relative humidity. The study underscores the importance of accurately predicting carbonation depths to assess the damage and durability of reinforced concrete structures, providing a basis for necessary repairs, reinforcement, or demolition. The authors tested their model on ten RC bridges in Taiwan, confirming its predictive capability and practical applicability.

In summary, this paper presents a valuable methodological approach for predicting concrete carbonation, with significant implications for maintaining and extending the service life of concrete structures. The results offer critical insights for civil engineering practices aimed at enhancing the longevity and safety of infrastructure

The time to corrosion initiation (carbonation) depends on many parameters: concrete quality, concrete cover, relative humidity, ambient carbon dioxide concentration and others. The impact of carbonation has been studied by several researchers and various mathematical models have been developed with the purpose of predicting carbonation depths. Most models predict that carbonation depths increase as a function of the square root of time.

The Papadakis et al. [53] model is the only one to explicitly include CO_2concentration as an input parameter and considers several affecting parameters. This mathematical model uses differential mass-balances for gaseous CO_2, solid and dissolved Ca(OH)2, CSH, and unhydrated silicates. According to [7, 21, 31, 33, 53], these mass-balances account for production, diffusion, and consumption of the chemicals. Thus, these processes determine the carbonation depth, X_c, in metres.

$$X_c = \left(\frac{2\left[CO_2\right]^0 D_{e,CO_2}}{\left[CH\right] + 3\left[CSH\right]}t\right)^{\frac{1}{2}} \quad RH \geq 50\% \tag{5}$$

$$\left[CO_2\right]^0 = 42y_{CO_2 10^{-6}} \tag{6}$$

$$D_{e,CO_2}\left(\mathrm{m}^2\mathrm{yr}^{-1}\right) = 51.8\,\varepsilon_p^{1.8}\left[1 - \left(\frac{RH}{100}\right)\right]^{22} \tag{7}$$

$$\varepsilon_p \approx \left(\frac{\rho_c}{\rho_w}\right)\frac{\left(\frac{w}{c} - 0.3\right)}{1 + \left(\frac{\rho_c}{\rho_w}\right)\left(\frac{w}{c}\right)} \tag{8}$$

Table 1: Comparison of different models.

Model	Equation	Factors considered	Strength	Limitation
DuraCrete [67]	$x_c = k\sqrt{t}$	concentration, time	Simple, widely accepted	Does not consider detailed material properties
Papadakis et al. [53]	$x_c = k\sqrt{\frac{t}{\alpha}}$	Water-to-cement ratio, pozzolanic materials	Incorporates material properties	Requires detailed material data
Parrott [54]	$x_c = k_c\sqrt{t}$	Environmental exposure classes	Accounts for environmental variability	Requires exposure classification
Fick's Second Law Model	$x_c = k\sqrt{\frac{2D_{eff}C_{co_2}}{C_{OH^-}}t}$	Diffusion coefficient CO_2 and OH^- concentration	Theoretically robust, details	Complex, requires precise data
BRE Model [68]	$x_c = k_1\sqrt{t}$	Environmental exposure, concrete quality	Practical, consider exposure and quality	Generalized coefficients, lack of precision

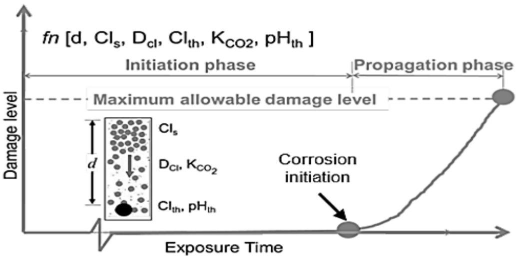

Figure 9: Parameters influencing the corrosion initiation phase [46,57].

$$[CH] + 3\,[CSH] \approx \frac{33000}{1 + \left(\frac{\rho_c}{\rho_w}\right)\left(\frac{w}{c}\right) + \left(\frac{\rho_c}{\rho_a}\right)\frac{a}{c}} \tag{9}$$

$$X_c \approx 350\left(\frac{\rho_c}{\rho_w}\right)\frac{\left(\frac{w}{c}\right) - 0.3}{1 + \left(\frac{\rho_c}{\rho_w}\right)\left(\frac{w}{c}\right)}$$
$$f(RH)\sqrt{1 + \left(\frac{\rho_c}{\rho_w}\right)\left(\frac{w}{c}\right) + \left(\frac{p_c}{p_a}\right)\left(\frac{a}{c}\right)\left(y_{CO_2}10^{-6}\right) \times t} \tag{10}$$

While $[CO_2]^\circ$ (mol/m^3) represents atmospheric CO_2 molar content. The effective CO_2diffusivity in concrete is De_{CO_2}. [CH]+3[CSH] is the total molar concentration of concrete's carbonable ingredients is expressed as [CSH] (mol/m^3); y_{CO_2} is volumetric ambient CO_2 (ppmv); RH is the relative humidity percentage; A, w, and c are the cement, water, and aggregate contents (kg); ε_p is the porosity of fully hydrated and carbonated cement paste; and ρ_c, ρ_w and p_a are the densities (kg/m^3). Aggregate is gravel and sand combined. Ambient CO_2 and relative humidity are clearly long-term averages.

The function $f(RH)$ is defined as $1 - \left(\frac{RH}{100}\right)$, where RH is the relative humidity. But using data from a cooling tower in Bohemia, researchers [31,33] have suggested a step-wise linear connection for $f(RH)$. Equation (10) is not very conservative since it underestimates carbonation depths by around 5-10%. This is why the most used formulas for determining carbonation depths are eqns. (5-9) [31,33].

5. Service life prediction model

Concrete structures exposed to chloride intrusion or carbonation often go through two distinct phases during their service life: initiation and propagation (Fig. 9). Since the propagation phase's duration can be drastically affected by factors like cracking and may be much shorter than the initiation phase's, it is generally safe to assume that the service life is equal to the initiation phase's duration [25-27, 35, 38, 46-51].

The carbonation coefficient (K_{CO_2}) and the pH threshold (pH_{th}) are the primary material parameters that regulate the initiation of carbonation-induced corrosion. K_{CO_2} is a function of the concrete mix proportions and the microclimate or internal relative humidity [54]. It is important to acknowledge that the external relative humidity and the pore structure of the concrete cover can affect the internal relative humidity (RH) at different depths. In particular, the carbonation rate can be substantial when the RH is between 65 and 80% [7,53]. Various concretes have been calculated to have a pH between 9 and 10 [58].

The literature contains a variety of perspectives regarding the correlation between the advent of reinforcement corrosion and the location of the carbonation front. In theory, corrosion commences upon the carbonation front's arrival at the reinforcement; however, certain authors have documented an apparent earlier onset of corrosion. In the current investigation, mortar samples with and without reinforcement were subjected to a temperature of 20°C, a relative humidity of 60%, and a carbon dioxide concentration of 1.5% for a maximum of 22 weeks. Potential measurements were employed to monitor the reinforcement's condition. To find the carbonation of the bulk and the mortar-steel interface, the pH indicator was spritzed over a recently split or sliced surface. When compared to reinforcement in its passive condition, the low potential values observed at the mortar-steel contact were in excellent agreement with carbonation. There was a difference in the spatial variation of the carbonation profundity between the normal and reinforced samples. Inconsistencies in where the carbonation front and corrosion begin have been reported in the literature, which is most likely due to the fact that the carbonation depth varies spatially near the reinforcement [59]. Due to carbonation, the pore solution's pH drops to levels below 7. Because the oxide layer becomes unstable at such a low pH, carbonated concrete's embedded reinforcement may erode under certain conditions. There are differing opinions in the literature on when reinforcing corrosion first appears and where the carbonation front is located. Even before the carbonation depth reaches the concrete cover, reinforcement corrosion can start, according to some writers. When the ”un-neutralized remainder,” or the gap between the average carbonation depth of regular concrete and the concrete cover (in reinforced samples), was 10-15 mm, Parrott noted corrosion. To rephrase, he noticed corrosion prior to the reinforcement being reached by the apparent carbonation front. Gravimetric examination of the reinforcing and the unneutralized residual from carbonation depth measurements in plain samples [49-59] revealed the persistent corrosion.

5.1. Probability of failure

An estimate of the likelihood of a prerequisite structural element's failure may be obtained from the structural reliability. For any given resistance and load, the concrete probability is the total of the failure possibilities for each occasion when the burden effect (S) is greater than the structural capability to endure this impact (R).The structural element is considered to have failed if (R< S) acts on it. Relative failure frequency is calculated as the number of failures divided by the total number of outcomes [27,28,37]. ”Structural reliability provides an estimate of the likelihood that a structural element might fail”. The probability of failure in concrete structures is determined by summing up the chances for all instances where the applied load (S) exceeds the structure's capacity to withstand it (R). If $(R < S)$ for any given structural element, that element is considered to have failed. The relative frequency of failure is then calculated by dividing the number of failures by the total number of outcomes [27,28,37].

$$P_f = P(R - S \leq 0) = \int_{-\infty}^{\infty} \int_{-\infty}^{s \geq r} f_R(r) f_s(s) dr ds = P(Z \leq 0) \tag{11}$$

Integrating equation (11), then above equation becomes

$$P_f = P(R - S \leq 0) = \int_{-\infty}^{\infty} F_R(r) f_s(s) ds = P(Z \leq 0) \tag{12}$$

In equation (11) $f_s(s)$ is the density function of probability of the loading and $F_R(r)$ represents the probability density functions of the capacity. Where as in equation (12) the Cumulative Distribution Function of the capacity is $F_R(r)$.

It interprets a reasonable compromise between time integration methods that underestimate reliability. Therefore, the approach involves highly demanding algorithms with respect to computational time. The lifetime is divided into different intervals, when the combination of a significant value distribution for load and durability is evaluated.

5.2. Selection of stochastic variables

For assessing the resistance of concrete bridges, selecting random or simple factors is rather simple. However, in order to incorporate these elements into a reliability study, different scholars have chosen to use very diverse statistical models and approaches [28]. The fundamental material and strength parameters used for the concrete bridges under investigation in the ongoing Highways Agency study [28]. The stochastic variable used to assess the resistance of concrete bridges is presented in Table 2.

5.3. Deterioration model

Concrete structures subject to service conditions are inevitable for processes where time can affect their ability to meet structural requirements. The progress is required in existing structural assessment method to meet the future needs in associate environmentally friendly and economical approach without unnecessary reconstruction. Reinforcement in structural concrete is initially covered by the excitation layer because of the alkalinity of the surrounding concrete [30]. Corrosion reinforcement affects concrete structures in a number of ways, which are racking and spalling of the concrete cover, loss of stiffness and strength, loss of bond between reinforcement and surrounding concrete. For the reinforced concrete bridges, initiation of corrosion in reinforcement is generally due the immersion of chloride ion. The chloride ingress can be modeled by using equation (13) given by (Fick's Second Law of diffusion) [25] under diffusion-controlled process.

$$\frac{\partial C}{\partial t} = D_c \frac{\partial^2 C}{\partial x^2} \tag{13}$$

In which,D_c is the chloride diffusion coefficient in (cm^2/year) and C *is* evaluated by % of the weight of cement which denotes the concentration of chloride ion after (*t*) years of exposure to the chloride source at a distance of (*x*) cm from the concrete surface.

5.4. Time for initiation of corrosion

The corrosion initiation time is given by [35].

$$T_i = \frac{X^2}{4D_c} \left[erf^{-1} \left(\frac{C_0 - C_{cr}}{C_0} \right) \right]^{-2} \tag{14}$$

In this context, (*Ti)* denotes the initiation time for corrosion, measured in years. The concrete cover is represented by (X), measured in centimeters. C_o refers to the equilibrium chloride concentration at the concrete surface, while C_{cr} indicates the threshold chloride concentration that initiates corrosion. Both C_o and C_{cr} are expressed as a percentage of the concrete's weight.

Therefore, from this study we can say that equation (14) has four random variables in which corrosion initiation time is dependent.

5.5. Loss of area of steel reinforcement

The time-dependent area of steel reinforcement can be determined using equation (15). This calculation applies to reinforced concrete elements with bars of equal diameter and identical corrosion resistance over time.

$$A(t) = \begin{cases} \frac{n\pi D_i^2}{4} \text{ for } t \leq T_i \\ \frac{n\pi^{D(t)2}}{4} \text{ for } T_i \leq t \leq T_i + \frac{D_i}{r_{corr}} \\ 0 \text{ for } t \geq T_i + \frac{D_i}{r_{corr}} \end{cases} \tag{15}$$

In this context, *n* stands for the number of reinforcing bars, *t* represents the elapsed time, r_{coor} indicates the corrosion rate in mm/year, and D_i is the initial diameter of the reinforcement.

$$D(t) = D_i - r_{corr}(t - T_i) \tag{16}$$

Where, $D(t)$ is the diameter of a bar under corrosion. As described in equation (16) the reduction in diameter of a bar can be calculated as;

$$D_i - D(t) = 0.0232 \int_{T_i}^{T} i_{coor}(t) dt \tag{17}$$

It is important to note that a corrosion current density of $i_{coor} = 1 \frac{\mu\text{A}}{\text{cm}^2}$ corresponds to a typical corrosion penetration rate of 11.6 μm per year when the corrosion rate is evaluated using this current density value $\boldsymbol{i}_{\text{corr}}$[22].

If it is assume a constant annual corrosion rate, equation (17) can be rewritten as follows:

Table 2: Stochastic variable for determining the resistance of concrete bridges [28].

Description	Mean^a [MPa]	Mean^a [mm]	Mean^a [mm]	Standard deviation^b [mm]	Distribution type^c
Steel yield strength (fy)	289	-	-	25	Log-Normal
Concrete cube strength (fcu)	30	-	-	6	Log-Normal
Slab thickness (t)	-	550	-	10	Normal
Concrete cover (c)	-	60	-	8	Normal
Model uncertainty factor	-	-	1	0.05	Normal

[a] The measure for the average behavior of random variable.

[b] Standard deviation is the measure for the variability of the random variable.

[c] Specified types of probability distribution function the random variables are characterized by its moment or by its parameter.

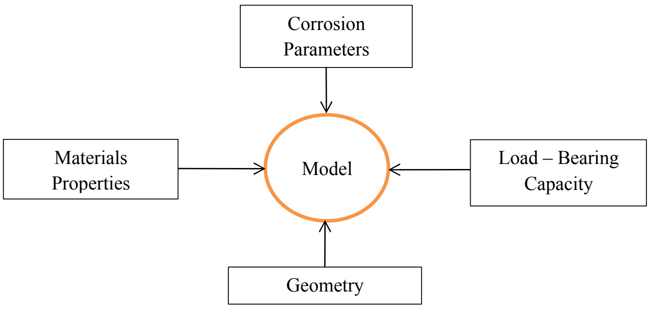

Figure 10: Model output and the input variables uncertainties.

$$D_i - D(t) = 0.0232\, i_{coor}(t - T_i) \tag{18}$$

Next, the corrosion rate can be defined as

$$r_{coor} = 0.0232\, i_{coor} \tag{19}$$

6. Probabilistic modeling

The new structure design, in addition to the existing structural analysis, is fraught with both the applied load and the load and the bearing capacity of the uncertain structure, along with many uncertainties. Instead, the probability of failure should be met; and the probability of failure will never be zero [29,38]. The flow diagram of the probability model is shown in Fig. 10.

By the mean values and the standard deviations, the uncertain parameters are modeled, as are the correlation coefficients between stochastic variables. The stochastic variables are assumed to be normally distributed. Model uncertainty, physical uncertainty, and statistical uncertainty are some examples of uncertainty. In model uncertainty the model is itself a defective representation of reality. Model uncertainty, physical uncertainty, and statistical uncertainty are some examples of uncertainty. Monte Carlo simulations are used to establish the distribution function of the load-bearing capacity, and for service life predictions, a probabilistic model is additionally used. At the structural level, the capacity to load-bearing decreases for moments and shear force, which affect the stiffness of the member [24,29].

7. Discussion

In the realm of modeling and simulation, predictive likelihood and statistical modeling techniques are employed to estimate the effects of loading and failure probabilities over time. Meanwhile, empirical studies and laboratory tests are utilized to investigate carbonation and chloride-induced corrosion, advocating for advancements in concrete mix design and protective measures to enhance structural resilience. In terms of environmental impact, all studies emphasize the significant role of environmental factors such as humidity, temperature, and CO_2 concentration in deterioration processes. Specifically, traffic loading and its statistical distribution are addressed, along with the detrimental effects of carbonation and chloride penetration on concrete durability. In terms of maintenance and durability strategies, proactive maintenance planning using predictive likelihood is proposed, potentially leading to cost savings by efficiently targeting necessary repairs. Understanding material properties and environmental interactions is emphasized to optimize concrete mixes and implement effective protective strategies, thereby enhancing the long-term durability of concrete structures.

When exposed to chlorides and carbonation, steel rebars in mortars made with selected blended cements show numerous critical corrosion features. Blended cements carbonate faster than Portland cement, with free chloride concentrations similar but somewhat different. Carbonated cements have more free chloride than non-carbonated ones. Blended cement mortar mixes had higher overall porosities than OPC mortar, and carbonation reduced pore size distributions depending on amorphous-phase concentration. Due to high water-to-cement ratios, quick carbonation, and varying hydration levels, these results should be interpreted cautiously. Carbonation caused more corrosion damage than other causes, with blended cements displaying more but shallower damage. OPC had lower corrosion rates than blended cements, whereas chloride exposure stabilized or lowered mixed cement corrosion. Both carbonated and non-carbonated mortars showed the same trend. ER probes were more accurate early on, but galvanostatic pulse methods exaggerated rates in carbonated mortars and underestimated them in non-carbonated ones. These anomalies may be due to improper corrosion modeling. Carbonated blended cements may exhibit less severe corrosion propagation than OPC and non-carbonated cements due to shallower damage, but corrosion localization, maximal rate, and long-term evolution are unknown. Faster carbonation may influence natural processes, making generalizations dubious. Therefore, conclusions should be carefully analyzed to prevent large uncertainty when applying them to varied environments [64].

Reinforced concrete (RC) is favored in construction for its high compressive strength and moderate tensile strength, but it faces significant degradation primarily from carbonation and rebar corrosion. The scientific community debates the extent of structural damage caused by carbonation and subsequent rebar corrosion, prompting extensive research and reviews of related studies. This paper synthesizes various findings on carbonation and corrosion processes, identifying contributing factors and discussing strategies for mitigation. Emphasis is placed on material selection and environmental considerations to combat these issues. The study focuses on modeling carbonation in concrete to determine the optimal concrete cover thickness for reinforced elements. Carbonation lowers the pH of concrete, diminishing its protective properties against steel reinforcement corrosion. Statistical curve-fitting is employed to develop universal carbonation models for different concrete types based on empirical data. The inclusion of fly ash in concrete can enhance its protective qualities under certain conditions, but its benefits diminish in environments rich in CO_2 and chlorides. Investigating carbonation's impact on steel corrosion in concrete structures reveals its significant role in pH reduction and subsequent weakening of protective capabilities. The study underscores the importance of understanding concrete material characteristics such as water-cement ratio and binder composition to mitigate corrosion risks effectively. It suggests that judicious use of fly ash can enhance concrete durability, contingent upon specific environmental conditions. Overall, tailored solutions adapted to distinct exposure conditions are crucial for ensuring the long-term integrity of concrete structures. The study highlights the importance of a probabilistic approach in durability design, enabling a more rational selection of durability parameters for RC structures. The presented model provides a practical tool for predicting the service life of new structures and assessing the quality of newly built structures, ensuring they meet the specified durability requirements.

By combining empirical data with complex algorithms to predict corrosion behavior under varied environmental conditions, advanced modeling techniques and predictive methods significantly improve the understanding and mitigation of corrosion caused by carbonation in reinforced concrete structures. These techniques, which take into account variables like the characteristics of the concrete material, exposure to the environment, and loading circumstances, enable the accurate calculation of carbonation depth and corrosion rates. They include empirical, physical, probabilistic, and deterministic models [11]. In order to provide dependable information for maintenance and durability planning, empirical models such as those developed by Ekolu, Kokubu, and Hakkinen [11], for example, have demonstrated great accuracy in forecasting carbonation depths under various conditions. Furthermore, the use of probabilistic methods, like Monte Carlo simulations, makes it possible to evaluate the chance of structural failures, which helps with preventative maintenance plans. These models also make it easier to optimize concrete mix designs by using supplemental cementitious materials (SCMs) like fly ash, which, in certain situations, increase the durability of concrete. Large datasets can also be processed by artificial intelligence and machine learning to find trends and improve the forecasting power of these models. In general, the incorporation of sophisticated modeling methods contributes to the creation of resilient maintenance plans and better concrete mix compositions that extend the lifespan and dependability of reinforced concrete constructions.

The study introduces an innovative tool for estimating the lifetime distribution of maximum loading effects on bridges, focusing on deterioration primarily caused by chloride ingress. Utilizing statistical modeling of Weigh-In-Motion (WIM) data, it simulates bridge traffic loading patterns to derive a population for comprehensive statistical analysis. The method of predictive likelihood is employed to establish a lifetime distribution of the maximum loading effect, incorporating variability sources more effectively than conventional characteristic values. Laboratory studies underscore the significant impact of environmental factors, particularly relative humidity (RH), on carbonation rates in concrete. Specific RH levels are identified as optimizing or hindering carbonation rates, which vary based on concrete properties such as compressive strength and cement type. The review of test methods for chloride penetration and carbonation emphasizes the necessity for standardized testing to accurately assess concrete durability. Carbonation diminishes concrete pH, weakening its protective capacity against steel corrosion, a process influenced by material characteristics like water-cement ratio, binder composition, and the use of supplementary materials such as fly ash. Environmental conditions, including high CO_2 and chloride concentrations, exacerbate carbonation and corrosion effects, underscoring the importance of accurate predictive models for carbonation depth and corrosion risk in designing resilient concrete structures tailored to specific material properties and environmental exposures.

8. Conclusion

The degradation of reinforced concrete structures from carbonation and rebar corrosion presents significant challenges to their longevity and performance. This review emphasizes the critical importance of understanding the carbonation process and its direct impact on corrosion mechanisms. Effective strategies for mitigating these issues, such as incorporating supplementary materials like fly ash and developing precise predictive models, are essential for designing durable concrete structures. Future research efforts should concentrate on refining these models and exploring innovative materials to further improve the durability of reinforced concrete constructions. These studies collectively underscore the necessity for comprehensive approaches to predict and mitigate the deterioration of concrete structures, integrating predictive modeling, empirical studies, and standardized testing. Such integrated approaches are pivotal in advancing understanding and enhancing the durability and reliability of infrastructure. Future research should continue to integrate these methods to formulate robust maintenance strategies and develop materials capable of withstanding environmental challenges, thereby extending the service life of concrete structures.

Sheltered concrete carbonation resistance in metropolitan tropical climates is 10-20% lower than open exposure. SCM concretes exhibit equivalent or greater long-term carbonation resistance to OPC concretes, as evidenced by the increase in carbonation depth (Δxd) at ages >5 years. Improved pore refinement and moisture conditions may give SCM-based concretes equivalent long-term carbonation depth to OPC concretes. The linear relationship between accelerated and natural carbonation coefficients is strongly affected by SCM use and material composition. This study also includes how to use the former calculations, the existing drawing and the analysis of inspection data used for the reliability analysis. The same assessment method can be applied to the service life assessment of reinforced concrete bridges.

Machine learning and AI could improve carbonation-induced corrosion forecasting models. These tools can analyze large, complicated datasets to find patterns and correlations that older methods miss. More accurate and adaptive models can be created by training machine learning algorithms on past data to predict corrosion behavior under different environmental circumstances. AI approaches can also optimize these models in real time, improving predictions as fresh data becomes available. This is useful for accounting for corrosion processes' complex nature, which are affected by temperature, humidity, and material qualities. Researchers and engineers can improve reinforced concrete structure durability and safety by using machine learning and AI to create more dependable and robust models.

References

[1] Koch G H, Brongers M P H, Thompson N G, Virmani Y P & Payer J H. *Corrosion Costs and Preventive Strategies in the United States.* NACE International (2002).

[2] Nace I. *International Measures of Prevention, Application, and Economics of Corrosion Technology (IMPACT).* NACE International (2016).

[3] Stewart M G & Rosowsky D V, Time-dependent reliability of deteriorating reinforced concrete bridge decks, *Structural safety*, 20(1) (1998) 91–109. doi:10.1016/s0167-4730(97)00021-0.

[4] Rozière E, Loukili A, El Hachem R & Grondin F, Durability of concrete exposed to leaching and external sulphate attacks, *Cement and Concrete Research*, 39(12) (2009) 1188–1198. doi:10.1016/j.cemconres.2009.07.021.

[5] Fotso Lele H, Beushausen H & Alexander M, A practical carbonation model for service life design of reinforced concrete structures, *Scientific African*, 20 (2023) e01677. ISSN 2468-2276. doi:10.1016/j.sciaf.2023.e01677.

[6] Malami S I, Val D V, Suryanto B, Salman H A & Wang X H, Probabilistic approach to the sustainability assessment of reinforced concrete structures in conditions of climate change, *Structural Safety*, 107 (2024) 102428. ISSN 0167-4730. doi:10.1016/j.strusafe.2023.102428.

[7] Papadakis V G, Vayenas C G & Fardis M N, A reaction engineering approach to the problem of concrete carbonation, *AIChE Journal*, 35(10) (1989) 1639–1650. doi:10.1002/aic.690351008.

[8] Li K. *Durability design of concrete structures: Phenomena, modeling, and practice.* John Wiley & Sons (2017).

[9] Flint M M & Billington S L, A probabilistic framework for performance-based durability engineering: Application to corrosion in reinforced concrete, *Structures Congress*, 2011 ( ) (2011) 1949–1960. doi:10.1061/41171(401)170.

[10] Bertolini L, Elsener B, Pedeferri P & Polder R. *Corrosion of Steel in Concrete: Prevention, Diagnosis, Repair.* Wiley-VCH (2013). doi:10.1002/9783527651696.

[11] Zhou Y, Gencturk B, Willam K & Attar A, Carbonation-induced and chloride-induced corrosion in reinforced concrete structures, *Journal of Materials in Civil Engineering*, 27(9) (2015) 04014245. doi:10.1061/(asce)mt.1943-5533.0001209.

[12] Val D V, Chernin L & Stewart M G, Experimental and numerical investigation of corrosion-induced cover cracking in reinforced concrete structures, *Journal of structural engineering*, 135(4) (2009) 376–385. doi:10.1061/(asce)0733-9445(2009)135:4(376).

[13] Chandler K A. Marine environments. In: Netherlands T, ed., *Marine and Offshore Corrosion; Butterworth-Heinemann: Amsterdam.* Butterworth-Heinemann (1985), pp. 38–50. doi:10.1016/b978-0-408-01175-4.50008-8.

[14] Shreir L L, Jarman R A & Burstein G T. *Corrosion: Metal/Environment Reactions.* Butterworth-Heinemann (2013).

[15] Zhang X G, Yu Q & Zhang L J. Temperature effect on corrosion behavior of carbon steel in 3.5 (2011).

[16] Fuhaid A F A & Niaz A, Carbonation and corrosion problems in reinforced concrete structures, *Buildings*, 12(5) (2022) 586. ISSN 2075-5309. doi:10.3390/buildings12050586.

[17] Fontana M G. *Corrosion Engineering.* McGraw-Hill (1986).

[18] Visalakshi T & Bhalla S. Carbonation corrosion assesment in reinforcement of normal and flyash concrete using piezo sensors. In: *International Conference on Corrosion.* CONCOR, New Delhi (2013).

[19] Roberge P R. *Corrosion Engineering: Principles and Practice.* McGraw-Hill (2008).

[20] Revie R W & Uhlig H H. *Corrosion and Corrosion Control: An Introduction to Corrosion Science and Engineering.* John Wiley & Sons (2008). doi:10.1002/9780470277270.

[21] Schweitzer P A. *Corrosion and Corrosion Protection Handbook.* CRC Press (2010). doi:10.1201/9781315140384.

[22] Alonso C, Andrade C, Castellote P et al., Chloride threshold values to depassivate reinforcing bars mbedded in a standardized opc mortar, *Cement and Concrete Research*, 30 (2000) 1047–1055. doi:10.1016/s0008-8846(00)00265-9.

[23] Kashani M M, Maddocks J & Dizaj E A, Residual capacity of corroded reinforced concrete bridge components: State-of-the-art review, *Journal of Bridge Engineering*, 24(7) (2019) 03119001.

[24] Cairns J, Du Y & Law D, Structural performance of corrosion-damaged concrete beams, *Magazine of Concrete Research*, 60(5) (2008) 359–370. doi:10.1680/macr.2007.00102.

[25] Enright M P & Frangopol D M, Probabilistic analysis of resistance degradation of reinforced concrete beams under corrosion, *Engineering Structures*, 20(11) (1998) 960–971.

[26] Hong H P, Assessment of aging reinforced concrete structures, *Journal of Structural Engineering*, 126(12) (2000) 1458–1465.

[27] Lounis Z. Probabilistic modeling of chloride contamination and corrosion of concrete bridge structures. In: *Proceedings of the Fourth International Symposium on Uncertainty Modeling and Analysis (ISUMA '03), Canadian Crown, 2003* (2003).

[28] Middleton C R & Thoft-Christensen P, Industrial application of structural reliability theory, *Paris, France* (1997) 21–33.

[29] Nowak A S & Collins K R. *Reliability of structures.* McGraw-Hill, Boston (2000). doi:10.1201/b12913.

[30] Schiessl P. *Corrosion of steel in concrete.* Rep. RILEM No TC60-CSC RILEM, Chapman and Halll, London (1988).

[31] Stewart M G, Reliability-based assessment of ageing bridges using risk ranking and life cycle cost decision analysis, *Reliability Engineering and System Safety*, 74 (2001) 263–273. doi:10.1016/s0951-8320(01)00079-5.

[32] Bhatta N, Adhikari A, Ghimire A, Bhandari N, Subedi A & Sahani K, Comparing crushed brick as coarse aggregate substitute in concrete: Experimental vs. numerical study, *Iranian Journal of Science and Technology, Transactions of Civil Engineering* (2024) 1–20. ISSN 2364-1843. doi:10.1007/s40996-024-01407-8.

[33] Stewart M G, Wang X & Nguyen M N, Climate change impact and risks of concrete infrastructure deterioration, *Eng. Struct*, 33 (2011) 1326–37. doi:10.1016/j.engstruct.2011.01.010.

[34] Sahani K, Joshi B R, Khatri K, Magar A T, Chapagain S & Karmacharya N, Mechanical properties of plastic sand brick containing plastic waste, *Advances in Civil Engineering*, 2022(1) (2022) 8305670. doi:10.1155/2022/8305670.

[35] Thoft-Christen C R, Assessment of the reliability of concrete slab bridges, *Dept. of Building Technology and Structural Engineering*.

[36] Government of Nepal, Ministry of Physical Infrastructure and Transport, Department of Roads, Bridge Branch. *Guideline for quality management for concrete bridges* (2018).

[37] Ivanov O L, Honfi D & Stripple H, Uncertainty and variation in lca - implementation of probabilistic methods to assess environmental impacts of infrastructures, *Lund University, TVBK: No.*, 3070.

[38] Joint Committee on Structural Safety. JCSS probabilistic model code. techreport (2001). URL `https://www.jcss-lc.org/jcss-probabilistic-model-code/`, ISBN 978-3-909386-79-6.

[39] Regmi K R, Sahani K & Sahani S K, Mineral additives in concrete durability: A comprehensive review, *Asian Journal of Science, Technology, Engineering, and Art*, 1(2) (2023) 377–393. ISSN 3025-5287. doi:10.58578/ajstea.v1i2.2112.

[40] Commission, for the investigation of abuse of authority (ciaa), "the collapsed jabdighat bridge over babai river in bardiya, *Bardiya district* (2018) 5.

[41] Zhang X G, Yu Q & Zhang L J. Temperature effect on corrosion behavior of carbon steel in 3.5 (2011).

[42] Kavi J. *Nondestructive evaluation of corrosion in reinforced concrete structures with or without FRP wraps*. West Virginia University (2015).

[43] Finšgar M & Jackson J, Application of corrosion inhibitors for steels in acidic media for the oil and gas industry: A review, *Corros Sci*, 86 (2014) 17–41. doi:10.1016/j.corsci.2014.04.044.

[44] Ghanooni-Bagha M, Shayanfar M A & Smh F, Cracking effects on chloride diffusion and corrosion initiation in rc structures via finite element simulation, *Scientia Iranica*, 21(3). doi:10.24200/.

[45] Ghanooni-Bagha M, Shayanfar M A, Shirzadi-Javid A A & Ziaadiny H, Corrosion-induced reduction in compressive strength of selfcompacting concretes containing mineral admixtures, *Construction and Building Materials*, 113(1) (2016) 221–228. doi:10.1016/j.conbuildmat.

[46] Rathnarajan S, Dhanya B, Pillai R G, Gettu R & Santhanam M, Carbonation model for concretes with fly ash, slag, and limestone calcined clay - using accelerated and five - year natural exposure data, *Cement and Concrete Composites*, 126 (2022) 104329. ISSN 0958-9465. doi:10.1016/j.cemconcomp.2021.104329.

[47] Ghanooni-Bagha M, Zarei S, Savoj H R & Shayanfar M A, Timedependent seismic performance assessment of corroded reinforced concrete frames, *Periodica Polytechnica Civil Engineering*, 63(2) (2019) 631–640. doi:10.3311/PPci.12653.

[48] Gjørv O E & Vennesland E B A H S. Electrical resistivity of concrete in the oceans. In: *Offshore Technology Conference, Houston, TX, USA* (1977). doi:10.4043/2803-MS.

[49] IPCC, Climate change 2007: The physical science basis, *Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, New York, NY, USA*. doi:10.1017/9781009157896.

[50] Kaveh A, Massoudi M S & Ghanooni-Bagha M, Structural reliability analysis using charged system search algorithm, *Iranian Journal of Science and Technology*, 38(2) (2014) 439–448. doi:10.22099/IJSTC.

[51] Gopal R & Sangoju B, Carbonation-induced corrosion: a brief review on prediction models, *Journal of The Institution of Engineers (India): Series A*, 101 (2020) 247–257. doi:10.1007/s40030-020-00434-8.

[52] Wu L, Li W & Yu X, Time-dependent chloride penetration in concrete in marine environments, *Construction and Building Materials*, 152 (2017) 406–413. doi:10.1016/j.conbuildmat.2017.07.016.

[53] Papadakis V G, Vayenas C G & Fardis M N, Fundamental modeling and experimental investigation of concrete carbonation, *Materials Journal*, 88(4) (1991) 363–373.

[54] Parrott L J, Carbonation, moisture and empty pores, *Advances in Cement Research*, 4(15) (1992) 111–118. doi:10.1680/adcr.1992.4.15.111.

[55] Thiery M, Villain G, Dangla P & Platret G, Investigation of the carbonation front shape on cementitious materials: Effects of the chemical kinetics, *Cement and concrete research*, 37(7) (2007) 1047–1058. doi:10.1016/j.cemconres.2007.04.002.

[56] Ekolu S O, Model for practical prediction of natural carbonation in reinforced concrete: Part 1-formulation, *Cement and Concrete Composites*, 86 (2018) 40–56.

[57] Gettu R, Pillai R G, Santhanam M, Rathnarajan S, Basavaraj A, Raju S & Dhandapani Y. Service life and life-cycle assessment of reinforced concrete with fly ash and limestone calcined clay cement (2019).

[58] Czarnecki L & Woyciechowski P. Evaluation of concrete structures durability under risk of carbonation and chloride corrosion. In: Repair C, ed., *Rehabilitation and Retrofitting IV*. CRC Press (2015), pp. 205–205. doi:10.1201/b18972-130.

[59] Revert A B, De Weerdt K, Hornbostel K & Geiker M R, Carbonation-induced corrosion: Investigation of the corrosion onset, *Construction and Building Materials*, 162 (2018) 847–856. doi:10.1016/j.conbuildmat.2017.12.066.

[60] Harold R F L. A practical carbonation model for service life design of reinforced concrete structures (2021). doi:10.1016/j.sciaf.2023.e01677.

[61] Lee H S, Kim H G, Ryou J S, Kim Y & Woo B H, Corrosion state assessment of the rebar: Experimental investigation by ambient temperature and relative humidity, *Construction and Building Materials*, 408 (2023) 133598. ISSN 0950-0618. doi:10.1016/j.conbuildmat.2023.133598.

[62] Tuutti K. *Corrosion of steel in concrete, Swedish Cement and Concrete Research Institute*. Stockholm (1982).

[63] Rodrigues R, Gaboreau S, Gance J, Ignatiadis I & Betelu S, Reinforced concrete structures: A review of corrosion mechanisms and advances in electrical methods for corrosion monitoring, *Construction and Building Materials*, 269 (2021) 121240. doi:10.1016/j.conbuildmat.2020.121240.

[64] Hren M, Bosiljkov V B & Legat A, Effects of blended cements and carbonation on chloride-induced corrosion propagation, *Cement and Concrete Research*, 145 (2021) 106458. doi:10.1016/j.cemconres.2021.106458.

[65] CPC-18 measurement of hardened concrete carbonation depth, *Materials and Structures*, 21(6) (1988) 453–455. ISSN 1871-6873. doi:10.1007/bf02472327.

[66] Syll A S & Kanakubo T, Impact of corrosion on the bond strength between concrete and rebar: A systematic review, *Materials*, 15(19) (2022) 7016. doi:10.3390/ma15197016.

[67] *DuraCrete - Final Technical Report, The European Union - Brite EuRam III Research Project:"Probabilistic performance based durability design of concrete structures", Document BE95-1347/R17.* CUR, Gouda (2000).

[68] Building Research Establishment and Construction Research Communications Ltd. *Carbonation of Concrete and Its Effects on Durability*. BRE digest. Building Research Establishment (1995). ISBN 9781860810152.