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Factors Influencing the Carbonation Rate of Concrete and Their Implications for Infrastructure Resilience: A Review

Inamullah Inam
Fazli Rabi Khalid
Wafiullah Mamozai

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Article

Factors Influencing the Carbonation Rate of Concrete and Their Implications for Infrastructure Resilience: A Review

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Inamullah Inam
Fazli Rabi Khalid
Wafiullah Mamozai

Abstract

Concrete carbonation significantly challenges the durability of reinforced concrete structures, particularly in climate change. This review examines the primary factors influencing carbonation rates, including the water-cement ratio, concrete composition, relative humidity, temperature, exposure conditions, and the incorporation of supplementary cementitious materials. Higher water-cement ratios lead to greater porosity and deeper carbonation penetration, while an optimal relative humidity of approximately 70% enhances carbonation. A linear correlation exists between temperature and carbonation depth, with elevated temperatures accelerating the carbonation process. Indoor environments generally exhibit higher carbonation rates compared to outdoor environments. Using mineral admixtures, such as fly ash and ground granulated blast furnace slag, enhances the microstructure of the concrete matrix and improves its resistance to carbonation. The complex interactions among these factors underscore the necessity for a comprehensive approach to mitigate carbonation, particularly as atmospheric CO_2 levels are expected to exceed 1000 ppm by 2100. The insights derived from this review are crucial for shaping construction practices to ensure long-term structural durability and resilience to climate change. By addressing these challenges, the construction industry can adapt to evolving climatic conditions and ensure the durability of critical infrastructure.

Keywords: *Carbonation Resistance, Concrete Durability, Climate Change Impact, Environmental Factors*

1. Introduction

Concrete structures are vital for human settlements globally; however, climate change may accelerate their deterioration [1]. This degradation results from physical, mechanical, and chemical factors, with climate significantly affecting the degradation [2]. Corrosion from chlorides and carbonation poses the greatest risk, with chloride-induced corrosion being severe in coastal areas and carbonation-induced corrosion being more common in urban and industrial areas [3].

Concrete carbonation seriously threatens. This can lead to corrosion in steel reinforcement, resulting in cracks and costly repair [3]. As atmospheric CO_2 levels are projected to exceed 1000 ppm by 2100 [4], understanding carbonation is crucial for enhancing the durability of concrete. This study aims to synthesize the existing literature to identify the critical factors affecting carbonation rates. These findings are vital in guiding construction practices and mitigation strategies to maintain long-term structural integrity.

Existing research on concrete carbonation exhibits several limitations; many studies have investigated the controlling factors of the carbonation of concrete, including water-to-cement ratio, relative humidity, temperature, and the use of supplementary cementitious materials. Most of these variables are individually addressed. Little literature discusses their interactions holistically, especially in changing environmental conditions. Measurement inconsistencies across methods (e.g., phenolphthalein, FTIR) further complicate comparisons. The impact of aggregate properties and cracks on carbonation is not well studied, and the long-term effects of climate change, such as rising CO_2 levels and fluctuating temperatures, are also not fully understood. Furthermore, regional differences and the use of innovative materials, including nanomaterials and alternative binders, have not been sufficiently explored. Bridging the gap between individual variable studies and practical, integrative analysis, this review aims to guide the development of more resilient and sustainable concrete infrastructure.

3. Literature Review

Concrete is the most widely used construction material worldwide. Due to its versatility, strength, and cost-effectiveness, it plays a crucial role in infrastructure development, including roads, bridges, dams, and buildings. However, the durability of concrete is increasingly threatened by environmental stressors, particularly climate change and carbonation. Carbonation occurs when atmospheric carbon dioxide (CO_2) reacts with calcium hydroxide to produce calcium carbonate, which poses significant concerns for the integrity of concrete structures. According to the IPCC 4th assessment report, a significant increase in the CO_2 concentration has been reported from 280 ppm in 1750 to 380 ppm in 2005 and by 2100, the IPCC has predicted CO2 concentrations exceeding 1000 ppm [4].

Concrete carbonation is influenced by W/C ratio, CO_2 concentration, porosity, relative humidity, cementitious supplementary materials, exposure conditions, and temperature. The water-cement ratio is crucial in determining the microstructure of concrete and its resistance to carbonation. Generally, higher W/C ratios increase porosity and permeability, leading to deeper carbonation and reduced durability [5], [6], [7]. However, the relationship is not always linear. It was found that a W/C ratio of 0.48-0.50 optimizes both the workability and strength of carbon nanotube-reinforced concrete [5],[6]. Conversely, it is noted that lower water-binder ratios effectively reduce carbonation, especially in cracked concrete [10][6],[8]. Relative humidity (RH) is another critical factor [12]; carbonation accelerates when RH is below 70%, whereas levels above 70% tend to slow down the process. This non-linear relationship between RH and carbonation depth follows a polynomial function, with the maximum carbonation coefficient occurring at approximately 70% RH [7],[8]. However, Chen and Ho found that the specific pore structure and curing practices significantly influence this relationship, indicating that a relative humidity of 70% may not always yield the highest carbonation rates across all types of concrete [11].

Temperature also affects carbonation, as higher temperatures generally accelerate the process, with studies indicating a linear correlation between temperature and carbonation depth. [15] . However, field studies, such as those conducted by Otieno et al., emphasize that the effects of temperature are highly dependent on regional climatic variability and exposure conditions [16].

Environmental factors, including wind speed and CO_2 concentration in urban areas, significantly influence the carbonation process. Increased wind speeds and elevated levels of CO_2 have been shown to accelerate carbonation [10],[11]. Additionally, incorporating mineral admixtures, such as fly ash and ground granulated blast furnace slag (GGBS), affects carbonation dynamics, often reducing the alkalinity and resistance of concrete as their proportions increase [19]. These admixtures also modify the microstructure of concrete, which in turn impacts mass transfer and chloride ion diffusion [20]. The interplay between the water-to-binder ratio and the content of admixtures is critical in determining the carbonation coefficient [21]. This underscores the complex relationship among concrete composition, environmental factors, and carbonation resistance.

3.1 Carbonation Mechanism

Concrete is a widely available material used in the construction industry, composed of a mixture of cement, aggregates (such as sand and gravel), and water. Adding water activates the hydration chemical reaction; consequently, it causes the aggregate particles to bond together and enhance the concrete strength. Although the concrete is strong under compression, it is weak under tension. To mitigate this weakness, steel bars are often fixed in concrete; such concrete is known as reinforced concrete (RCC). RCC is extensively employed in civil engineering projects, including buildings, bridges, roads, and pipelines.

Steel corrosion in reinforced concrete is the foremost distress for the resilience of RCC structures, which is often induced by chloride ion penetration or carbonation [18],[24].

Carbonation has attracted increasing attention owing to recent climate changes [25]. Carbonation-induced corrosion is slow; however, it can threaten the durability of the structures. Carbonation can be described by the following chemical reactions [26].

$$Ca(OH)_2 \rightarrow Ca^{2+}(aq) + 2OH^-(aq) \qquad (1)$$

$$Ca^{2+}(aq) + 2OH^-(aq) + CO_2 \rightarrow CaCO_2 + H_2 \qquad (2)$$

$$3CaO \cdot 2SiO_2 \cdot 3H_2O + 3CO_2 \rightarrow 3CaCO_3 \cdot 2SiO_2 + 3H_2O \qquad (3)$$

$$3CaO \cdot 2SiO_2 + \mu H_2O + 3CO_2 \rightarrow 3CaCO_3 \cdot SiO_2 \cdot \mu\, 3H_2O \qquad (4)$$

$$2CaO \cdot 2SiO_2 + \mu H_2O + 3CO_2 \rightarrow 2CaCO_3 + SiO_2 \cdot \mu\, 3H_2O \qquad (5)$$

The porous structure of concrete allows carbon dioxide (CO_2) to diffuse into its pores and react with $Ca(OH)_2$, making ($CaCO_3$) and water (H_2O). Moisture in pores is essential for carbonation [18], [24]. Calcium hydroxide is consumed during hydration, forming calcium silicate hydrate (C-S-H) and CaO, which reacts with CO2 to create carbonates.

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

During cement hydration, (C-S-H) generates calcium oxide (CaO), which reacts with carbon dioxide to make carbonates. The residual CO_2 interacts with C-S-H, producing additional calcium carbonate ($CaCO_3$). Water is crucial for this process, acting as a solvent for CO_2 and facilitating its dissolution into carbonic acid (H_2CO_3) [23]. The pore network in concrete enables water to diffuse from smaller to larger pores, where it reacts with CO_2 to initiate carbonation [15],[19],[20],[21].

$$CO_2 + H_2O \rightarrow H_2CO_3$$

The high alkalinity of concrete, owing to calcium hydroxide ($Ca(OH)_2$), creates a protective film around the embedded steel bars. At a pH of approximately 12.5, this environment fosters a protective layer of iron oxide (Fe_2O_3) on the steel exterior, thereby preventing corrosion. This layer forms when hydroxide ions (OH^-) react with dissolved iron ions (Fe^{2+}) in the concrete pore solution and oxidize with atmospheric oxygen (O_2) [30].

Carbonation reactions deplete ($Ca(OH)_2$), lowering the pH of the concrete matrix. This reduction compromises the protective layer that shields the steel reinforcement from corrosion [31]. The weakened steel-concrete bond leads to corrosion and increases the corrosion product volume [28]. This volumetric expansion induces internal stresses, which further degrade the protective layer.

3.2 Carbonation Measurement Methods

Carbonation measurement is crucial for assessing concrete structures' durability and service life. Various methods have been established and employed to determine the carbonation depth, including destructive and non-destructive techniques. The experimental methods for measuring the degree of carbonation in concrete include qualitative and quantitative approaches, with a choice depending on the specific purpose of the measurement. This review discusses the advantages and limitations of these methods.

Phenolphthalein is a common indicator used to assess carbonation in concrete. This method involves applying a phenolphthalein solution to the newly cut surface of a concrete specimen. The concrete surface remains colourless in the presence of carbonation, whereas the carbonated section becomes pink [27],[28]. This destructive method provides immediate visual results, is widely used in laboratory experiments, and may not accurately represent the semi-carbonated zone because of its limited pH perception range [32].

Non-destructive techniques have also been used to assess the carbonation depth of concrete. Techniques such as Fourier Transform Infrared Spectroscopy (FTIR) and Non-linear Resonant Ultrasound Spectroscopy (NRUS) have been explored for their ability to detect carbonation by observing chemical transformations within the concrete matrix [34].

Gammadensimetry, thermogravimetric analysis, and chemical analysis are effective methods for determining carbonation profiles in concrete, even in the presence of calcareous aggregates [35]. Furthermore, infrared spectroscopy is a more precise technique for assessing carbonation progress in concrete than the phenolphthalein test, offering early warnings of carbonation in structural concrete [36]. The depth of carbonation in concrete can be twice as deep as previously measured using the phenolphthalein indicator, with the TGA, XRDA, and FTIR methods providing more accurate results [37].

Gamma-ray measurement is a non-destructive system for determining carbonation profiles in concrete, whereas thermogravimetric analysis is appropriate for laboratory and core samples [35]. Carbonation assessment in concrete can be effectively conducted using Non-linear Resonant Ultrasound Spectroscopy because the non-linear parameter is knowingly influenced by the occurrence of carbonation [38].

Additionally, methods such as measuring electrical resistivity and concrete air diffusion have been shown to correlate with carbonation depth. Carbonation typically increases resistivity while decreasing air permeability [33].

Each method has its strengths and weaknesses, and the choice of methodology often relies upon the assessment's specific needs, including accuracy, speed, and non-destructiveness. Comparison of different measurement techniques is shown in Table 1.

TABLE I
Comparison of Carbonation Measurement Techniques

Method	Type	Advantages	Limitations	Application
Phenolphthalein Test	Destructive	Quick and easy to use; widely adopted in labs	Limited pH range, does not accurately identify semi-carbonated zones	Suitable for initial laboratory assessments
Fourier Transform Infrared Spectroscopy (FTIR)	Non-destructive	High precision; detects chemical transformations	Requires specialized equipment and expertise	Useful for detailed structural analysis
Thermogravimetric Analysis (TGA)	Semi-destructive	Accurate in distinguishing carbonation depth	Requires concrete samples, not applicable in-field	Effective for lab analysis of cores and samples
Gamma-ray Measurement	Non-destructive	Provides accurate carbonation profiles	Expensive and equipment-intensive	Best for monitoring carbonation in critical structures
Non-linear Resonant Ultrasound Spectroscopy (NRUS)	Non-destructive	Sensitive to carbonation-induced changes in concrete	Advanced method needs skilled operators	Applicable for early detection in critical infrastructure
Electrical Resistivity Measurement	Non-destructive	Correlates resistivity changes with carbonation	Indirect measurement, influenced by environmental factors	Good for on-site, quick assessments
Air Permeability Test	Non-destructive	Indicates permeability changes due to carbonation	Requires calibration for environmental conditions	Useful for long-term performance monitoring

2. Methods

This review employs a descriptive approach to systematically analyze and synthesize the literature on the carbonation of concrete. A comprehensive search was conducted using academic databases, including IEEE Xplore, Scopus, ScienceDirect, ASCE Library, PubMed, ICE Virtual Library, and Google Scholar. The search focused on key terms such as "carbonation of concrete," "measurement methods," and "factors influencing carbonation."

The inclusion criteria focused on research addressing critical aspects of carbonation, such as the effects of water-cement ratios, environmental conditions, and the role of mineral admixtures. Approximately 67 peer-reviewed articles that met these criteria were identified. The reference sections of selected studies were also reviewed to uncover additional relevant sources.

Key findings were analyzed to identify trends, research gaps, and interactions among factors influencing carbonation. The results were synthesized and presented using tables and figures to enhance clarity and support a comprehensive analysis and future research directions.

4. Factors Influencing Carbonation

4.1 Effects of W/C Ratio

W/C ratio is one of the most important parameters affecting the carbonation rate of concrete. Previous studies have indicated that an increase in the water-to-cement ratio substantially affects the porosity of concrete, and concrete becomes more porous. The porous structure of concrete allows carbon dioxide (CO2) to diffuse into concrete and accelerate the carbonation process [34],[35]. In particular, the results of porosity and shrinkage tests, as well as observations from the scanning electron microscope (SEM), have shown that W/C ratios higher than 0.35-0.40 exhibit increased pores and larger calcium hydroxide crystals, which are more susceptible to carbonation [40]. In particular, studies indicate that the amount of un-hydrated cement and capillary pores increases with an increase in the W/C ratio, which tends to enhance the porosity and possibility of carbonation [5],[6]. The W/C ratio influences the microstructure and permeability of the concrete matrix; a lower W/C ratio results in a denser microstructure with reduced permeability [5],[36].

The microstructure of concrete, especially the (C-S-H) gel, significantly affects its carbonation behaviour [42]. A well-developed C-S-H gel enhances concrete's mechanical properties and durability by reducing the permeability and limiting the CO2 diffusion pathways [43]. Mineral admixture materials such as fly ash or limestone fillers can also boost carbonation resistance by refining the pore structure [8].

Moreover, the type of cement used and the existence of specific additives can alter these dynamic behaviours. For example, mineral admixtures or (SCMs), such as ground granulated blast furnace slag and silica fume, can affect the carbonation depth nonetheless of the W/C [44]. Moreover, incorporating waste materials, such as OLED glass powder, has been found to boost the CO2 absorption of concrete, indicating that both material composition and W/C ratio are key factors in the carbonation process [45].

4.2 Effect of Cement Content

The cement content significantly affects the carbonation depth of concrete. A higher cement content generally increases the carbonation depth owing to more $Ca(OH)_2$ in the pore solution, which reacts with CO_2 to procedure ($CaCO_3$) [41],[42]. However, although it can enhance the initial strength and reduce porosity, excessive cement can also increase the carbonation risk if not balanced with supplementary materials [38],[43]. Mineral admixtures such as fly ash, silica fume, and ground granulated blast-furnace slag (GGBS) can mitigate carbonation effects by refining the pore structure and improving concrete durability, leading to lower carbonation depths than conventional Portland cement [43],[44].

The type of cement significantly affects the carbonation resistance. Concrete with ground granulated blast-furnace slag shows lower carbonation rates than normal Portland cement (OPC) because of pozzolanic reactions that enhance the microstructure [48], [50]. In contrast, using limestone powder as a partial cement replacement can increase carbonation rates if not managed properly, as it may dilute the alkalinity of the concrete [46],[47]. Balancing the cement content and supplementary materials is essential; higher cement content can improve early strength but may also increase the risk of carbonation-induced corrosion if the concrete is not adequately protected [41],[42].

4.3 Effect of Aggregates

Aggregates act as filler materials in concrete, significantly affecting its strength and durability. The size of the aggregates is critical for carbonation resistance. Larger aggregates create voids and irregularities, increasing CO2 diffusion and carbonation depth [38],[39]. In contrast, finer aggregates produce a denser microstructure and lower permeability, thereby improving carbonation resistance [55].

Research has shown that aggregate quality significantly affects carbonation resistance [56]. Understanding the interaction between the W/C ratio and aggregate size is crucial because optimal ratios enhance the carbonation resistance of concrete [57]. Aggregate distribution is also important; a random distribution can lead to non-uniform carbonation depths, underscoring the influence of aggregate grading [58]. Furthermore, the type and size of aggregates, including recycled aggregates, affect carbonation dynamics [58].

4.4 Effect of Relative Humidity

The relative humidity is a crucial factor in the carbonation process, as it determines the level of capillary saturation in concrete, which influences the availability of pore water required for the carbonation reaction [43], [59]. Studies have shown that increasing the relative humidity from 57% to 70% can substantially boost carbonation rates, but further increasing it to 80% may reduce the carbonation depth owing to excess pore water saturation [28],[30]. This indicates that the optimal RH range for effective carbonation is typically between 50% and 75% [61]. Additionally, the relationship between humidity and CO_2 concentration is complex; although higher CO_2 levels can promote carbonation, their effects vary across different humidity levels [43], [62]. According to Liu et al. (2020), carbonation is rapid at approximately 70% humidity. Additionally, the correlation between the relative humidity and carbonation depth was modelled as a polynomial function [11]. Fig.1 and 2 show the polynomial relation between relative humidity and carbonation front (0% to 20%) and from (40-80%) [14]. Furthermore. Below 70% RH, factors such as fly ash substitution and CO2 concentration have a greater impact, whereas, beyond 70%, carbon dioxide concentration and relative humidity become the dominant factors [63].

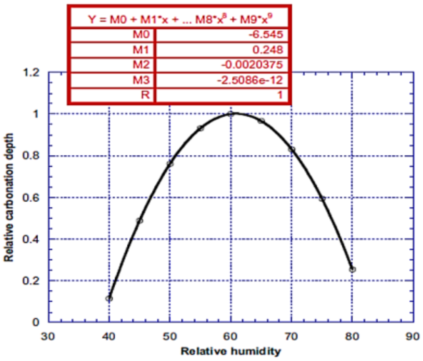

Fig.1: Relation between relative humidity (40–80%) and carbonation depth. [14]

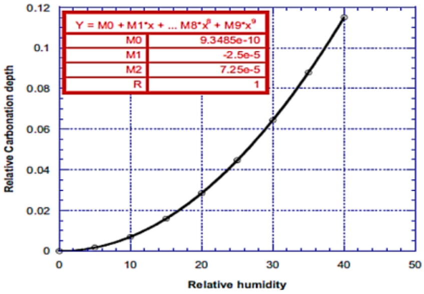

Fig.2: Relation between relative humidity (0–20%) and carbonation depth

The strength of concrete is linked to carbonation and relative humidity. For instance, in Fig.3, the test results denote that the samples exposed to CO_2-rich and humid conditions showed higher compressive strength than those cured in either wet or dry environments, indicating that carbonation may enhance strength under specific humidity levels [64].

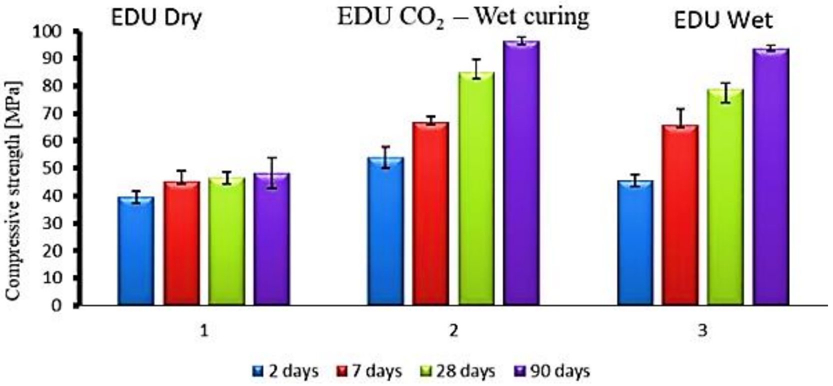

Fig.3. Compressive strength of heavyweight concrete EDU (dried samples) [64].

Moreover, Fig.4 shows the capillary pore volume of mortar before and after carbonation in the two research papers, which affects the micro-structure and porosity of concrete, resulting in decreased total pore volume and increased density of the concrete [16],[60]. This aligns with the findings that compressive strength is inversely related to porosity and that smaller pore sizes contribute to improved concrete strength [66].

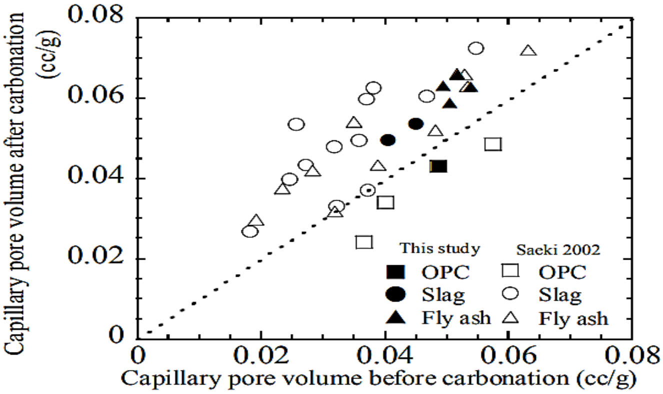

Fig.4. Capillary pore volume of mortar before and after carbonation [13], [36]

4.5 Exposure Environmental Conditions

Exposure conditions, specifically indoor versus outdoor environments, significantly impact concrete carbonation. Two researchers highlighted that indoor-exposed concrete specimens tend to exhibit higher carbonation rates than those exposed outdoors [67] [16]. Moreover, [67] reported a steeper carbonation front for indoor exposure, with a fully carbonated cement gel to a depth of 45mm. In contrast, outdoor exposure showed a more gradual gradient over only 10mm. [16] corroborated this by showing that indoor-exposed specimens had higher carbonation rates than their outdoor-exposed counterparts, regardless of concrete quality or curing duration.

From Fig. 5, the results can be obtained that the indoor and outdoor sheltered and unsheltered environments have significant effects on the carbonation rates of concrete. Indoor conditions show a higher carbonation depth because of the higher concentration of CO2 compared with outdoor conditions. In the case of outdoor exposure, the sheltered environment exhibited higher carbonation than outdoor unsheltered exposure. Meanwhile, conflicting perspectives exist regarding carbonation measurement methods; phenolphthalein tests often indicate higher carbonation depths outdoors, and thermogravimetric analysis and advanced methods suggest the opposite. Variations in experimental setups, environmental conditions, and assessment methods contribute to these inconsistencies, highlighting the need for standardized approaches to understand these dynamics better. A study conducted by Parrott and Killoh confirms these inconsistencies [68]. This contradiction may be due to the different methodologies used to assess carbonation depth. Zhao et al. also contributed to this discussion by demonstrating that concrete exposed to natural carbonation (indoors) attained lower carbonation rates than those kept in accelerated carbonation chambers, which could be considered a proxy for harsher outdoor conditions [69]. In summary, the reviewed literature indicates that indoor exposure conditions tend to accelerate the carbonation process in concrete compared with outdoor exposure. This is attributed to the steeper carbonation front and higher carbonation rates observed in indoor environments [16], [67].

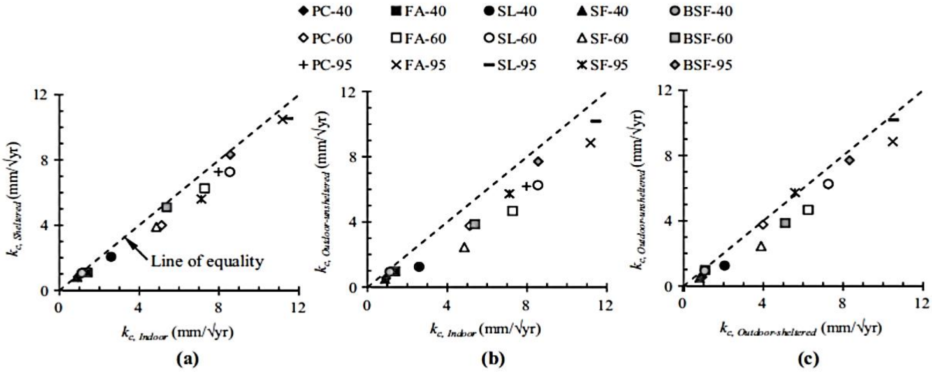

Fig.5. Effect of exposure environment on carbonation of concrete under exposure conditions indoor, outdoor sheltered, and outdoor unsheltered of 28-days-cured concretes [67].

4.6 Effects of Mineral Admixtures

Mineral admixtures, including fly ash, silica fume, metakaolin, and granulated blast furnace slag, significantly influence concrete carbonation and chloride ions diffusion, thereby affecting the durability of reinforced concrete structures [20], [70]. They alter the microstructure of concrete, which is essential for mass transfer processes such as carbonation [20].

Some studies have shown that mineral admixtures decrease the ability of concrete to withstand against carbonation by reducing the calcium hydroxide content. In contrast, others suggest that finely ground admixtures, combined with proper curing, can enhance carbonation resistance [42-43]. Carbonation curing also enhances the microstructure, improves the compressive strength, and decreases the chloride ion permeability [73].

Mineral admixtures are commonly used in concrete for economic and environmental benefits; however, their carbonation resistance remains a concern. Research indicates that SCMs such as slag, fly ash, and metakaolin improve the durability by modifying the C-A-S-H (Calcium-Alumino-Silicate-Hydrate) phase and integrating it with hydrated aluminate phases during carbonation, resulting in an aluminosilicate with less water than the original hydrates [74]. Another study suggested that SCMs as aggregate replacements offer better carbonation resistance than as cement replacements, although both methods reduce the total chloride content upon exposure to chlorides [75]. Studies have also assessed the efficiency factor (k-value) of SCMs in resisting carbonation and chloride penetration. While k-values evaluate the impact of SCMs on strength and carbonation resistance, they do not reliably indicate chloride penetration resistance. Research has found k-values below 1 for all tested SCMs relevant to both compressive strength and carbonation resistance [76].

Research has revealed that adding metakaolin as a partial replacement for cement boosts the durability properties of concrete, including its resistance to carbonation [77]. Increasing the metakaolin content enhances the transport properties of concrete, thereby reducing its permeability and increasing its carbonation resistance [77]. Similarly, coal fly ash has been recognized for its ability to enhance the carbonation process because it allows for a faster carbonation rate than conventional cement [78]. The incorporation of these materials not only reduces the clinker content in cement, which is responsible for the high CO2 emissions during manufacture but also promotes long-term carbon uptake through carbonation [78].

Figures 6 and 7 show blended cement mixtures, such as PC/FA and PC/BS, have higher carbonation rates than PC concrete under various exposure conditions. However, the PC/BS/SF blends exhibited greater carbonation resistance compared with the PC/FA and PC/BS blends. These findings are supported by previous research [47-51].

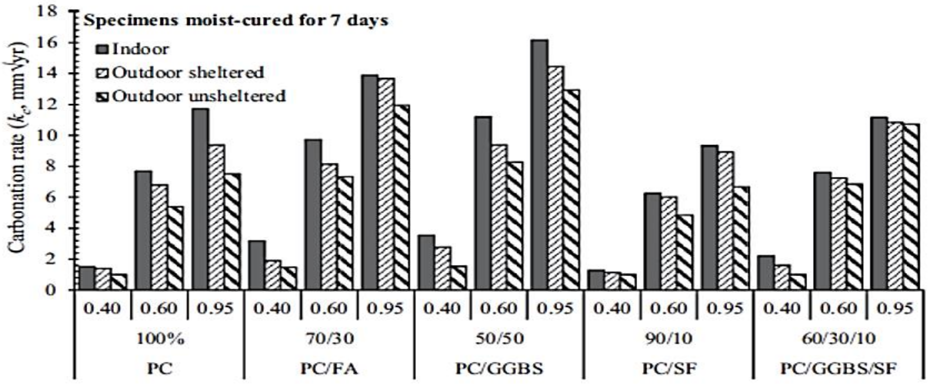

Fig.6. Carbonation rate of concretes kept in a moist room for 7 days [16]

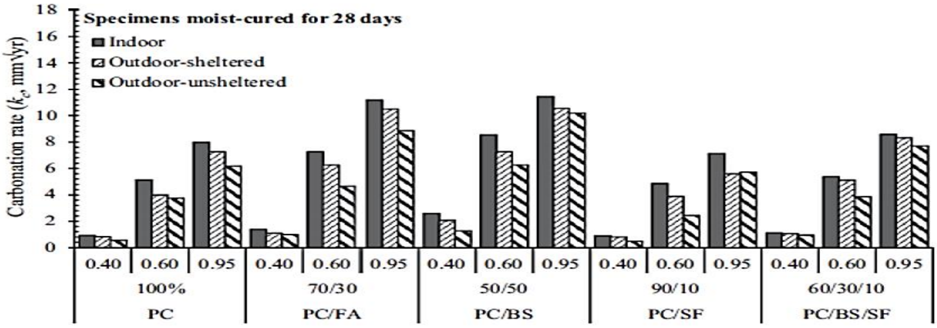

Fig.7: Carbonation rate of concretes kept in a moist room for 28 days [16]

4.7 Effects of Temperature

The temperature significantly affects the carbonation process. Increased temperatures enhance CO_2 diffusion owing to the enhanced molecular activity, leading to faster carbonation rates [84], [85], [86]. Studies indicate that higher temperatures result in greater carbonation depths, particularly in high CO_2 environments [60], [87].

Higher temperatures accelerate carbonation and enhance compressive strength, showing a linear relationship between temperature and carbonation depth [86] supported this finding through laboratory experiments. Tables 2 and 3 show the concrete mixtures and testing conditions with a relative humidity of 70% during testing. Table 3 presents the controlled conditions used in carbonation testing, including temperature, relative humidity, and CO2 concentration.

Table 2 outlines the mix design of the concrete used for laboratory experiments. Specimens in the form of 100x100x300 mm prisms were cast to measure the carbonation of the concrete. After casting, the specimens were demolded after 24 hours. They were then cured for 28 days in a controlled temperature and relative humidity room, where the temperature was maintained at (20 ± 1) °C and the relative humidity (RH) at (95 ± 4)

%. Subsequently, the concrete prisms were moved to a carbonation chamber for an additional 28 days. According to Tables 2 and 3, three strength grades (C20, C30, and C40) were utilized to evaluate the effects of strength grades on carbonation and compressive strength of concrete, considering varying temperatures and a constant RH level of 70% and CO2 concentration of 20% [86].

Fig. 8 shows the carbonation depth of concrete mixtures in various temperatures, indicating a strong correlation; carbonation increases with temperature. The reaction kinetics depend on the dissolution of hydrates and CO2 availability, both of which are influenced by temperature [15], [88]. In addition, the carbonation depth peaks at approximately 70% relative humidity [8],[85].

TABLE II

Mix Design of Concrete (kg.m-3) [86]

Composition materials		Cement	Fly Ash	Fine Aggregate	Coarse Aggregate	Water	Water Reducer
Concrete strength grad	C20	195	128	785	1045	178	1.8
	C30	270	125	780	1050	172	1.9
	C40	350	122	710	1052	162	2.25

Table III

Testing Condition. [86]

Items	Temperature (^{0}C)	Relative humidity (%)	CO_2 concentration (%)
1	10	70	20
2	20	70	20
3	30	70	20

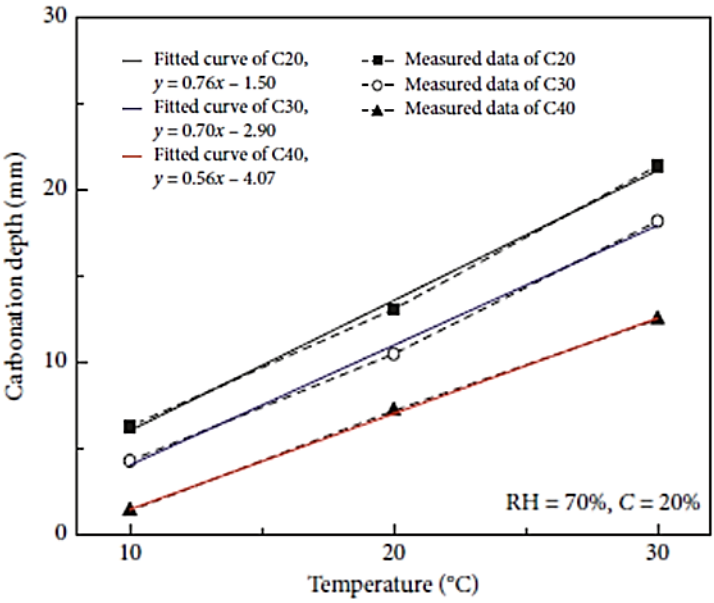

Fig. 8. Carbonation depth profiles of concrete with temperature [86].

5. Discussion

From the detailed literature review, the interactions of the different factors affecting carbonation can be summarized as follows: RH strongly interacts with supplementary materials and W/C ratio; at low RH levels below 70%, materials such as fly ash and slag reduce carbonation due to the limitation in the diffusion of CO_2, while at an optimum RH, about 70%, these materials improve the resistance to carbonation by making the pore structure finer. Higher W/C ratios, combined with optimum RH, increase carbonation due to higher porosity, while lower W/C ratios show better resistance to carbonation under the same conditions. Temperature also plays an important role in accelerating carbonation in materials containing slag or fly ash due to faster CO_2 diffusion and reaction kinetics, especially at RH values of about 70%, where moisture availability supports optimal carbonation. Too many supplementary materials, on the other hand, can decrease carbonation resistance due to insufficient cement content for sustaining alkalinity. Furthermore, indoor exposure conditions, which have higher CO_2 concentrations, tend to increase the rate of carbonation compared to outdoor environments where fluctuating RH can slow the process. Also, larger aggregates with high W/C ratios lead to more porosity and, in turn, diffusion paths that increase carbonation. Table 4 presents the summary table that integrates key interactions between different factors affecting carbonation and provides insights into their combined effects.

TABLE IV

Summary of Factor Interactions Affecting Carbonation

Factor 1	Factor 2	Interaction	Practical Implications
Relative Humidity (RH)	Supplementary Materials	At low RH (<70%), supplementary materials like fly ash and slag slow carbonation due to reduced CO_2 diffusion. At optimal RH (~70%), these materials enhance carbonation resistance by refining the pore structure.	Use proper curing and humidity control for structures with supplementary materials to mitigate carbonation risks.
Relative Humidity (RH)	W/C Ratio	Higher W/C ratios combined with optimal RH (70%) increase carbonation due to higher porosity, while lower W/C ratios resist carbonation better in the same RH range.	Choose lower W/C ratios for structures in humid environments to reduce carbonation risks.
Supplementary Materials	Temperature	Higher temperatures accelerate carbonation in materials with slag or fly ash due to faster CO_2 diffusion and reaction kinetics.	Adjust material compositions (e.g., using silica fume) in tropical regions to enhance carbonation resistance.

Temperature	Relative Humidity (RH)	At high temperatures, carbonation increases significantly at RH ~70% due to optimal moisture and CO_2 diffusion.	Incorporate surface treatments or coatings to reduce carbonation susceptibility in hot and humid climates.
Supplementary Materials	Cement Content	Excessive supplementary materials can reduce carbonation resistance despite reduced porosity, especially if cement content is insufficient to maintain alkalinity.	Balance supplementary material proportions with cement content to optimize durability.
Exposure Conditions	Relative Humidity (RH)	Indoor exposure accelerates carbonation due to higher CO_2 concentrations, while RH fluctuations in outdoor conditions can slow it.	Provide adequate ventilation in indoor environments to reduce CO_2 buildup and carbonation risks.
Aggregate Size/Grading	W/C Ratio	Larger aggregates combined with high W/C ratios increase porosity and CO_2 diffusion pathways, accelerating carbonation.	Optimize aggregate grading and lower W/C ratios to improve carbonation resistance.

Carbonation Prevention Strategies and Mitigation Methods

Practical prevention strategies include using reduced W/C ratios, where possible, optimizing aggregate grading, and adjusting proportions of supplementary materials with cement content. Appropriate curing, surface treatments, and ventilation shall be carried out in compliance with environmental conditions and material factors.

The best way to mitigate the impacts of high CO_2 exposure is by using high-performance concrete, commonly abbreviated as HPC. It has been observed that carbonation rates are relatively low due to the dense microstructure of HPC [90], [91]. This is achieved by optimizing the water-to-cement ratio and including supplementary cementitious materials, such as silica fume or fly ash. These materials not only enhance the mechanical properties of concrete but also improve its resistance to carbonation. For instance, incorporating SCMs can significantly reduce the carbonation rate of concrete [92][93]. A study performed in Singapore showed that partial replacement of cement with GGBFS in precast concrete effectively reduces carbonation rates [94]. Improvement of carbonation resistance also largely depends on advanced curing techniques. Proper curing methods, such as water curing or membrane-forming compounds, help develop a dense matrix that limits CO_2 ingress [95], [96].

Material innovations offer a second very promising avenue: carbonation-resistant cement blended with higher proportions of pozzolanic materials, such as ground granulated blast furnace slag (GGBS) or calcined clay, reduce the availability of calcium hydroxide and thus improve resistance [92]. For example, bridges in the USA, such as Lake Ray Hubbard Bridge in Texas and Creve Coeure Bridge (St. Louis County, Missouri.), were built with GGBS-blended cement and demonstrated an increased service life due to improved strength and reduced carbonation rates in the coastal environment [97][98].

Moreover, further protection measures, such as applying surface treatments and coatings, enhance the carbonation resistance of concrete [99][100]. CO_2-resistant coatings based on epoxy or silane treatments create a physical barrier to CO_2 ingress, thereby reducing the rate of carbonation and prolonging the service life of concrete structures [101].

Further protection measures, such as applying surface coatings, enhance carbonation resistance [99][100]. CO_2-resistant coatings based on epoxy or silane treatments create a physical barrier to CO_2 ingress [102]. For example, In Japan, surface coating has been carried out on Soda Ash Silo, Kawasaki City, Japan, one of Japan's most prominent logistics companies, which was built 40 years ago. A high-performance, waterborne, elastomeric coating was applied to effectively protect against carbonation [103]. Similarly, in India, anti-carbonation protective coatings are used to protect bridges from the ingress of carbon dioxide, water, and chloride ions [104].

Conclusion

Based on the comprehensive review, the following conclusion can be derived:

- The W/C ratio plays a significant role in the carbonation resistance of concrete; a lower W/C ratio indicates a lower carbonation rate, and vice versa.
- The size, grading, and quality of the aggregates play a leading role in carbonation resistance. Understanding the interaction between W/C ratio, aggregate size, and grading is crucial.
- Environmental factors, such as relative humidity and temperature, also play a vital role in the carbonation of concrete; relative humidity with an optimal range of 50–70% enhances the progress of carbonation. Moreover, elevated temperatures accelerate the CO_2 diffusion into the concrete.
- Supplementary materials, such as fly ash, GGBFS, and metakaolin, improve the microstructure of concrete, resulting in enhanced resistance to carbonation.
- Supplementary materials for aggregate replacement can enhance the carbonation resistance of the concrete. The carbonation resistance increases with the increased content of supplementary materials used as aggregate replacement.
- Understanding the complex interplay between these factors is essential for developing concrete structures that can withstand the projected increases in atmospheric CO_2 and other environmental stresses.
- The findings provide recommendations for designing durable concrete under various environmental conditions.

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About the Authors

Mr. Inamullah Inam, *Senior Teaching Assistant & HOD, Engineering Faculty, Laghman University, Afghanistan.* <*inam.azizi@gmail.com*>

Mr. Fazli Rabi Khalid, *Teaching Assistant, Engineering Faculty, Laghman University, Afghanistan.* <*fazlirabi0650@gmail.com*>

Mr. Wafiullah Mamozai, *Lecturer, Department of Chemistry, Education Faculty, Laghman University, Afghanistan.*