

Concrete Carbonation Mechanisms and Depth Prediction Methods

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Abstract

This literature review explores the crucial topic of carbonation resistance in concrete buildings in the context of sustainable building practices and the need to lower carbon dioxide emissions. Over time, concrete undergoes a natural aging process called carbonation, which reduces the structural integrity of the material. In order to forecast the depth of carbonation in concrete, a variety of analytical techniques have been created and used. This study presents a thorough and current evaluation of the best techniques for assessing carbonation resistance, contributing to the creation of long-lasting and sustainable infrastructure by combining information from a variety of sources. The impact of carbonation on carbon dioxide emissions in the construction industry is a major concern, so this review also looks at how these phenomena are connected and how increasing carbonation resistance can help cut down on greenhouse gas emissions. Researchers, engineers, and politicians may use the knowledge gained from this assessment to help them make educated decisions about the creation and maintenance of concrete, thereby supporting environmentally friendly building practices and furthering the global sustainability agenda.

Key words: Analytical techniques, Carbonation resistance, Greenhouse gas emissions, Concrete

Introduction

Since 1950, the amount of carbon dioxide (CO₂) emitted into the atmosphere has increased significantly, undoubtedly exacerbating the issue of carbonated concrete structures [1]. One of the most typical problems affecting the durability of concrete is carbonation [2]. It is explained as a chemical process in which calcium carbonate is mostly produced and CO₂ penetrates concrete through microdefects. The mechanical qualities of the structures deteriorate as a result, causing reinforcing steel to corrode [3]. Therefore, the carbonation process needs to be defined and forecasted in order to avoid such a serious safety risk.

The moisture diffusion model and the reaction-diffusion theory have both been used to examine the carbonation of cementitious materials, leading to the development of several theoretical models of carbonation [4]. These models were built around the principles of the laws of mass conservation and

diffusion established by Fick. The theoretical model had a wider range of applicability than the empirical or semi-empirical model since it employed parameters with clear physical meaning [5]. In-depth descriptions of the carbonation process, many durability-coupling difficulties, and the composition of the cementitious material service environment have been the focus of the majority of research on carbonation models so far [6]. Even though mechanical stresses are present in the majority of concrete structures, the effects of stress damage on concrete carbonation models have not received adequate attention in the literature. There have been several investigations by researchers who are aware of it. Demonstrated that it is important to take into account how stress and environmental pressures interact.

The study's primary contributions include

Determination of cement substitutes that can be utilized in building

An examination of the merits and downsides of various curing processes used in the construction industry

Examining the impact of water-to-cement ratio on carbonation resistance.

Research into how temperature, pressure, CO₂ concentration, and relative humidity (RH) affect carbonation resistance

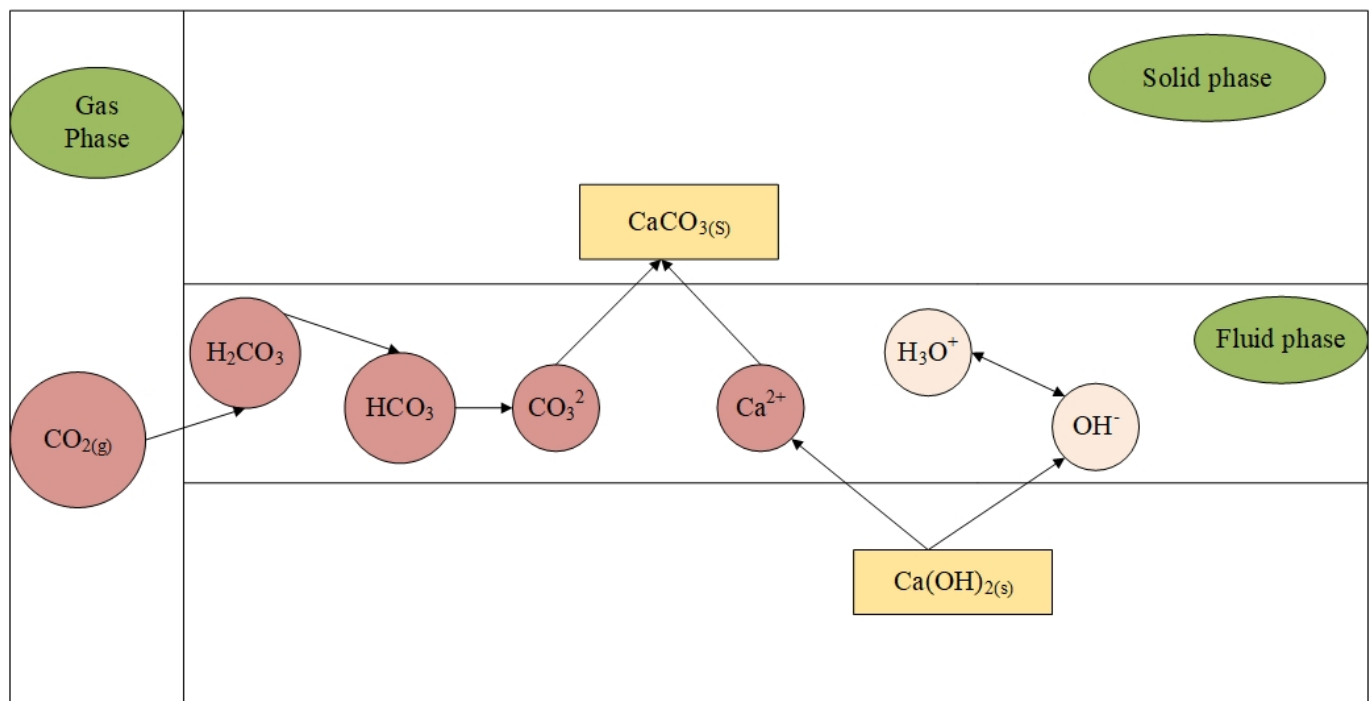
Need for study

Environmentally friendly building techniques are becoming more and more necessary as a result of the construction industry's significant impact on world resource utilization and greenhouse gas emissions. Cement, a crucial component of concrete, has a significant influence on the world as a whole. The depletion of the natural resources required to produce cement is a growing and pressing problem, contributing 7-8% of the CO₂ emissions in the globe.

Investigating several eco-friendly cement replacements and evaluating how well they withstand carbonation are the goals of this review. The focus of the study is focused on the methods employed to evaluate the inclusion of substitute materials in the manufacturing of concrete. In this review, a variety of substitutes for cement are discussed, and their carbonation resistance is assessed under various conditions including "RH, CO₂ conc., temperature, and pressure." The study evaluates how different cement to water ratios and curing methods affect the resistance to carbnn of substitute materials. Important information will be provided by the study's findings about the appropriateness of various sustainable materials as [cement alternatives](#) in the production of concrete.

Carbonation Mechanism

When carbon dioxide (CO_2) penetrates concrete's porous structure, the environment's pH is lowered and the steel reinforcement's passivation layer is compromised, potentially causing corrosion. This is referred to as carbonation. In a 2015 study by Cui *et al.* [7], accelerated carbonation testing on various concrete grades revealed that at low CO_2 concentrations (2-20%), there was a substantial increase in carbonation depth, while at high concentrations (50-100%), the increase was minimal, attributed to microstructure modifications that densify the concrete's top layer, slowing CO_2 diffusion. In 2014, Morandea *et al.* [8] investigated the kinetics, microstructure changes, and water release during carbonation of cement-based materials, using both destructive and non-destructive techniques to evaluate carbonation profiles in cement pastes and mortar specimens exposed to CO_2 over varying periods.



Diffusion of CO_3^{2-} and Ca^{2+} in pores

Figure 1: Carbonation Mechanism Scientific layout

Table 1: Mechanism of Carbonation

Author	Testing method	Analysis simulation	Equation	Result

Cui <i>et al.</i> [7]	Mercury Intrusion Porosimeter	SEM	= Concentration of carbonation (1)	Concrete carbonation depths at levels of 50 and 100 CO ₂ were essentially the same.
Morandea <i>et al.</i> [8]	Gamma-Ray Attenuation Method, Thermogravimetric analysis	-	+H (2)	A microstructure of highly dense networks was evident at high CO ₂ concentrations.
Sheng Ji <i>et al.</i> [9]	pH indicators, Chemical composition	SEM	(3)	An examination of the cross sections of concrete revealed that carbonated concrete is divisible.
Zhu <i>et al.</i> [10]	Reinforcement corrosion	Kolmogorov-Smirnov test	(4)	The probabilistic evaluation of reinforcement corrosion caused by chloride intrusion and carbonation in concrete.
Shui <i>et al.</i> [11]	Fourier Transform Infrared Spectroscopy, Differential Scanning Calorimetry	TEM, XRD, XRF, FTIR and TG/DSC	(5)	Concrete's carbonation resistance can be improved by using C-LDHs and R-LDHs.

In 2014, Sheng Ji *et al.* [9] categorized carbonated concrete into four zones, including fully carbonated, partially carbonated with varying pH values, partially carbonated with consistent pH values, and not carbonated at all. They defined the production of partially carbonated and fully carbonated zones while outlining the three stages of concrete carbonization. In 2016, Zhu *et al.* [10]

introduced a probabilistic model that considered the combined effects of chloride intrusion and carbonation in reinforced concrete structures, impacting the corrosion of steel reinforcement. Their model integrated heat, moisture, chloride ions, and carbon dioxide transport, with corrosion initiation criteria based on pH reduction or free chloride ion concentration. Finally, in 2018, Shui *et al.* [11] proposed a concrete with enhanced carbonation resistance by utilizing materials resembling modified Layered Double Hydroxides (LDHs). They evaluated and performed structural analysis on various Mg-Al-LDH compositions, showing that structural changes occur above 252.8°C. This LDHs' effects on concrete were compared and evaluated for carbonation resistance.

Table 2: Analytical approaches in the existing review

Author & Citation	Aim	Methodology	Analytical Approaches	Draw back
Cui <i>et al.</i> [7] 2015	Study the effect of CO ₂ concentration on carbonation in concrete	Carbonation testing at various CO ₂ concentrations	Scanning Electron Microscopy (SEM) to analyse CO ₂ diffusion in concrete	investigating the connection between CO ₂ concentration and carbonation depth
Morandea <i>et al.</i> [8] 2014	Investigate carbonation kinetics, microstructure changes, and water release in cement-based materials	Accelerated carbonation experiments under specific conditions	Phenolphthalein spray testing, thermogravimetric analysis, mercury intrusion porosimetry	Understanding carbonation profiles and effects on cement pastes and mortar specimens
Sheng Ji <i>et al.</i> [9] 2014	Propose a classification of concrete carbonation zones and stages of development	Theoretical framework for dividing carbonated concrete into zones and stages	The development of concrete carbonation in three stages	Classifying concrete into fully carbonated, partially carbonated, and not carbonated zones

Zhu <i>et al.</i> [10] 2016	Develop a probabilistic model for chloride intrusion and carbonation in reinforced concrete	Probabilistic model considering multiple transport processes	Identifying conditions for the onset of corrosion	Studying the combined effects of chloride intrusion and carbonation leading to steel reinforcement corrosion
Shui <i>et al.</i> [11] 2018	Design a concrete with increased carbonation resistance using modified Layered Double Hydroxides (LDHs)	Production and evaluation of various Mg-Al-LDHs with different compositions	Evaluating the structural alteration of LDHs and the impact on carbonation resistance	Enhancing carbonation resistance in concrete by using modified LDHs

Carbonation : A Nonlinear Phenomenon

In 2019, Felipe Felix *et al.* [12] proposed an ANN model to simulate the diffusion of carbon dioxide (CO₂) through concrete, estimating the level of carbonation over time and evaluating the impact of different training techniques and network architectures. A total of 120 networks were trained with various characteristics to assure the model's efficacy, and it was constructed utilizing a reliable experimental test database that included 278 results for non-accelerated tests of concrete carbonation depth. Despite the complex and nonlinear nature of concrete carbonation, the suggested ANN model demonstrated its ability to provide reliable predictions. In a separate study in 2016, Eiras *et al.* [13] investigated the carbonation process in cement-based materials by analyzing linear and nonlinear dynamic vibration responses. They conducted accelerated carbonation tests on mortar samples, monitoring the carbonation development using data from standard resonant frequency tests, providing insights into the material's carbonation progression.

Effect of carbonation depth in relative humidity

Researchers have examined the factors influencing carbonation depth in concrete. Gruyaert *et al.* (2012) conducted experiments on concrete examples with different curing times and slag content, proposing a novel approach considering continuous hydration effects. They found that despite poorer carbonation resistance in blast-furnace slag (BFS) concrete compared to [ordinary Portland cement](#) (OPC) concrete, the carbonation depth at the concrete's 50-year lifespan was generally acceptable.

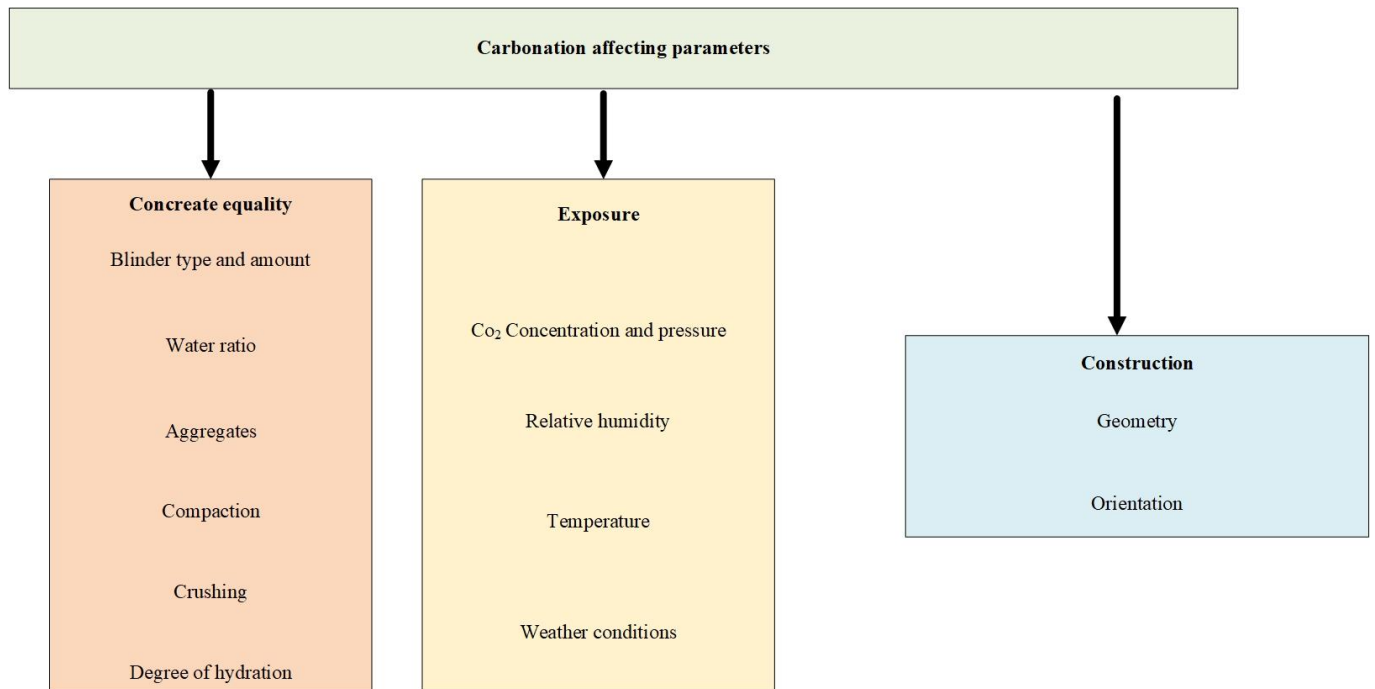


Figure 2: Carbonation depth parameters

Chen *et al.* (2018) investigated the impact of temperature, CO₂ concentration, and relative humidity on carbonation depth and compressive strength of concrete, revealing substantial connections. Liu *et al.* (2020) developed a unique prediction model for carbonation depth, considering material composition and environmental parameters, using dimensionless processing to estimate component contents and pH value.

Table 3: Analysis in relative humidity

Author	Testing method	Relative humidity	Result
Gruyaert <i>et al.</i> [14] 2012	Accelerated carbonation tests	70%	According to vacuum saturation studies, carbonated BFS concrete is more vulnerable to the intrusion of hostile components.
Chen <i>et al.</i> [15] 2018	XRD, ESEM	70%	Concrete's compressive strength and carbonation depth are substantially impacted by relative humidity.
Liu <i>et al.</i> [16] 2020	X-ray diffraction	80%	To evaluate the rate of carbonated acceleration or the degree to which simulated and real surroundings are similar in time

Keun Kim <i>et al.</i> [17] 2009	Method I (ideal case) and Method II (practical case)	60%	The strength reduction coefficient equations employed in the rebound number approach to account for the impact of surface carbonation exhibit significant value variation.
Lu <i>et al.</i> [18] 2018	pH value	90%	Decreased when the microenvironment's relative humidity increased
Hun Han <i>et al.</i> [19] 2013	Schmidt hammer	10%	For port concrete buildings, the carbonation depth's coefficient of variation varied from 0.36 to 0.66.

In the field of concrete carbonation, various studies have explored factors affecting carbonation depth and concrete durability. Gruyaert *et al.* (2012) investigated the impact of blast-furnace slag content on carbonation resistance over time, finding that despite poorer resistance compared to OPC concrete, After 50 years, BFS concrete's level of carbonation is typically satisfactory under most circumstances. Temperature and carbonation depth have a linear connection, according to research by Chen *et al.* (2018) investigated the impact of temperature on compressive strength and carbonation depth, as well as the impact of CO₂ concentration and relative humidity. Furthermore, Liu *et al.* (2020) developed a unique prediction model for carbonation depth, incorporating material and environmental parameters, and introduced a method for comparing the carbonation acceleration rate in simulated and natural environments, providing valuable insights for concrete design and maintenance to ensure long-term durability.

Table 4: Analytical approaches in the existing review

Author & Citation	Aim	Methodology	Analytical Approaches	Drawbacks
Gruyaert <i>et al.</i> [14] 2012	Assess carbonation depth in BFS concrete	Accelerated carbonation tests on concrete	Novel approach considering continuous hydration impact	Comparison of carbonation in BFS and OPC concrete

Chen <i>et al.</i> [15] 2018	Study effects of temperature and CO ₂ on concrete properties	Experimentation and analysis of temperature, CO ₂ concentration, and humidity	Linear link between temperature and carbonation depth	Examined the impact of temperature on carbonation depth and compressive strength as well as the impact of CO ₂ concentration and relative humidity
Liu <i>et al.</i> [16] 2020	Develop a prediction model for carbonation depth	Data analysis and simulation of carbonation depth	Dimensionless processing, component materials, and environmental parameters	Concrete's depth at which carbonation will occur predicted
Keun Kim <i>et al.</i> [17] 2009	Investigate strength-level-dependent carbonation influence	Field tests and data analysis on concrete strength levels	For the strength reduction coefficient, a new equation	Impact of carbonation on concrete strength
Lu <i>et al.</i> [18] 2018	Assess carbonation effects on fly ash concrete	Controlled tests and analysis of fly ash concentration	Depth of carbonated and partially carbonated zones	Impact of fly ash and environmental conditions on carbonation
Hun Han <i>et al.</i> [19] 2013	Examine carbonation in harbor concrete structures	In-situ data measurements and reliability analysis	Connections between carbonation depth, concrete strength, and cover depth	Impact of carbonation on harbor structures

Carbonation Depth in Thermal Conductivity

The critical factors influencing carbonation in concrete and its impact on thermal performance and structural properties. Al-Ameeri *et al.* (2021) developed a comprehensive carbonation degradation model, considering internal parameters and external factors, and validated it through accelerated carbonation tests. Lu *et al.* (2022) the impacts of temperature were examined for CO₂-cured cement paste, it was discovered that temperature has a major impact on the carbonation process and the material's characteristics, compressive strength, and microstructure. Mi *et al.* (2019) proposed a CO₂ diffusion model based on Fick's second law, considering the effects of aggregates and ITZ, and validated it through concentration distribution analysis. Kwon *et al.* (2021) presented models for CO₂ uptake in plain and limestone-blended concrete during service and recycling phases. Steiner *et al.* (2022) highlighted the stressing the importance of water-to-cement ratios and limestone content in affecting diffusion coefficients and compressive strength, the study also examined the impact of moisture content and CO₂ diffusivity on carbonation and presented a test protocol to identify the effective CO₂ diffusion coefficient. The building and civil engineering industries stand to benefit from a better knowledge of carbonation in concrete as a result of the combined efforts of these research.

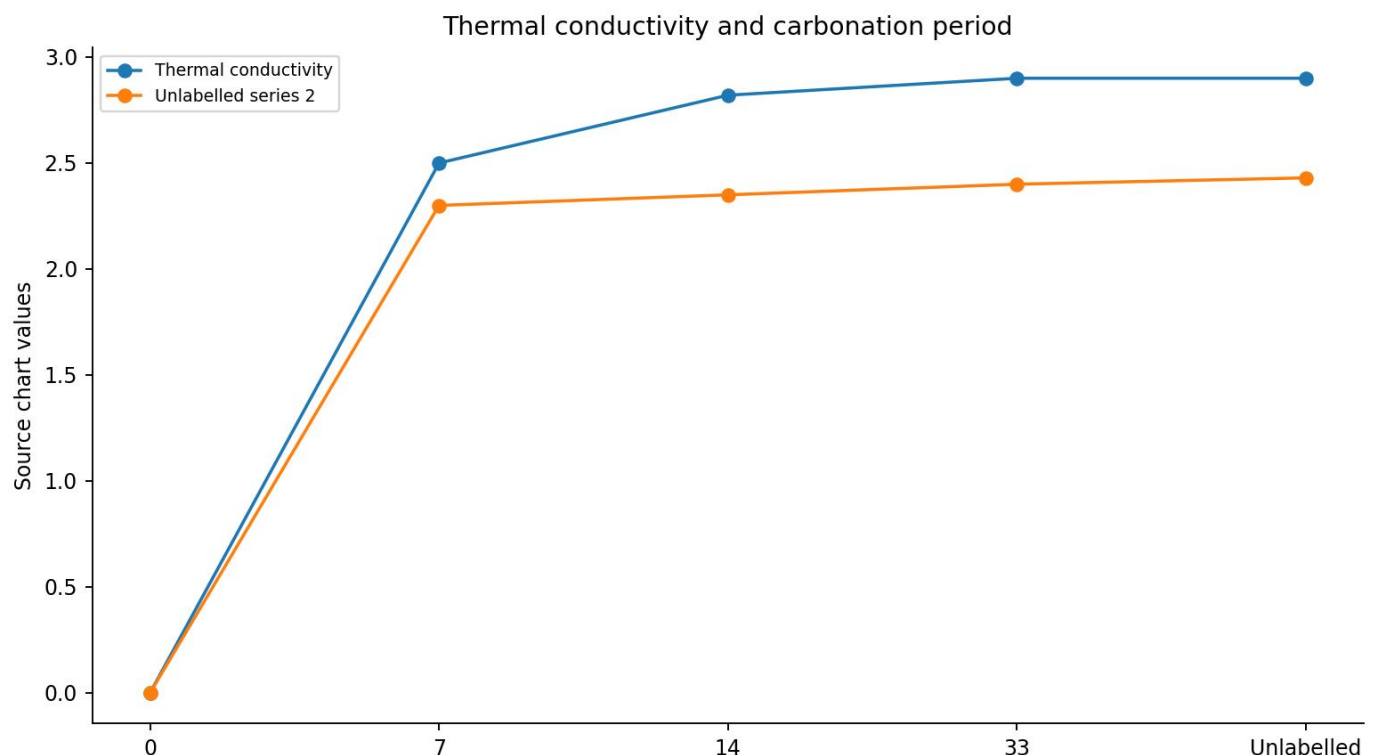


Figure 3: Overall average in the existing works

Table 5: Analytical approach in existing work

Author & Citation	Aim	Methodology	Analytical Approaches	Drawbacks
AL-Ameeri <i>et al.</i> [20] 2021	Develop a carbonation degradation model	Experimental tests, modeling	Simultaneous solution of diffusivity and reaction activities of $\text{Ca(OH)}_2(\text{aq})$ and $\text{CO}_2(\text{aq})$	Effects of carbonation on concrete with various parameters
Lu <i>et al.</i> [21] 2022	Investigate temperature effects on carbonation, compressive strength, and microstructure	Experimental tests, analysis	Kinetic regulation of carbonation, analysis of structural and morphological changes	Influence of temperature on carbonation and material properties
Mi <i>et al.</i> [22] 2019	Develop a CO_2 diffusion model for concrete	Theoretical modeling, experimental data comparison	Fick's second law-based diffusion model, mass conservation, comparison with experimental data	Effects of CO_2 diffusion in concrete under different loads
Kwon <i>et al.</i> [23] 2021	Present a model for measuring CO_2 uptake rate in plain and blended concrete	Modeling, experimental assessment	Cement hydration model, carbonation depth model, CO_2 uptake model	Measurement of CO_2 uptake in service and recycling phases
Steiner <i>et al.</i> [24] 2022	Study the impact of moisture content and CO_2 diffusivity in concrete	Test procedure, analysis	Determination of effective CO_2 diffusion coefficient and water diffusion coefficient	Effects of moisture and CO_2 diffusion on carbonation

Carbonation of Concrete Blended

In 2019, Teixeira *et al.* [25] conducted a study on accelerated carbonation testing, X-ray diffraction analysis, and thermogravimetric analysis, researchers examined cementitious pastes containing coal fly ash (CFA) and biomass fly ash (BFA). They found that CFA and BFA exhibited distinct chemical and mineral compositions, but both materials displayed similar behavior in terms of carbonation. Notably, BFA appeared to enhance the alkalinity of the mixtures, which could have beneficial implications for ash management and the development of building materials. In 2020, Chiranjikumari Devi *et al.* [26] investigated the effects of sulfate exposure and the addition of graphene oxide on the carbonation and compressive strength of concrete mixes with recycled concrete aggregates (RCA). Their findings indicated that as the proportion of graphene oxide increased, the carbonation depth decreased in 100% RCA mixes, although carbonation depth increased with higher CO₂ exposure. Additionally, they confirmed the formation of ettringites and anhydrites using X-ray diffraction analysis in samples subjected to sulfate exposure for 90 days. These studies provide valuable insights into the behavior of alternative ash materials and the impact of graphene oxide on carbonation in concrete mixes.

(6)

Hydration reactions

Carbonation reactions

Table 6: Blending components with results

Author	Blending components	Blending (%) Ratio	Result
Teixeira <i>et al.</i> [25] 2019	Biomass fly ash, Coal fly ash	10%, 90%	When coal and biomass fly ash, or solely biomass ash, are used in concrete, European standards and research have demonstrated good performance.

Chiranjikumari Devi <i>et al.</i> [26] 2020	Ordinary Portland Cement and fly ash	70%,30%	The mix with 100% recycled concrete aggregate (RCA) and no graphene oxide (GO) showed a comparatively high mass gain.
Lippiatt <i>et al.</i> [27]	Fly ash , Mineral carbonation	-	Carbon-neutral construction materials can result in a 20% reduction in CO2 emissions
Anwar <i>et al.</i> [28]	Fly ash, Silica Fume With Ordinary Portland Cement	0.4%	When compared to the control mix made up of solely OPC, the ternary cementitious blends significantly demonstrated resistance to the entry of chloride ions.
Justnes <i>et al.</i> [29] 2020	Cement limestone, silicious fly limestone	30%, 4%	The increased porosity caused by blending materials, a lower water-to-cement ratio (wc) can be used for blended cements compared to pure Portland cement.
Li <i>et al.</i> [30] 2021	Nano-silica (NS) and Micro-silica (MS)	5%, 15%	When combined with MS, the cementing efficiency factors (CEFs) of NS were shown to be at least 48% greater than those of MS.

Lippiatt *et al.* (2019) highlighted that concrete and cement emissions contribute significantly to global CO2 emissions and proposed a method for carbonating concrete debris and blocks, which not only improves product performance but also sequesters CO2. Anwar *et al.* (2020) the impacts of various environmental factors on cured concrete were evaluated, it was discovered that the total and dissolved contents had changed. Justnes *et al.* (2020) explained that fly ash-containing mortars carbonate faster due to their unique hydrate assemblage with less calcium-containing species susceptible to carbonation. Li *et al.* (2021) investigated the impact of nano-silica (NS) and micro-silica (MS) on concrete carbonation and water absorption, revealing that a combination of NS and MS resulted in significantly higher cementing efficiency, offering potential benefits for concrete production with reduced environmental impact.

Table 7: Analytical models in existing work

Author & Citation & Year	Aim	Methodology	Drawbacks
Teixeira <i>et al.</i> [25] 2019	Study the behavior of fly ashes in cementitious pastes	Thermogravimetric analysis, X-ray diffraction analysis, accelerated carbonation testing	Comparison of chemical and mineral makeup of coal fly ash (CFA) and biomass fly ash (BFA), examining carbonation behavior, and assessing potential benefits for ash management and building materials.
Chiranjikumari Devi <i>et al.</i> [26] 2020	Investigate the effects of graphene oxide on RCA mixes	Sulfate solution testing, carbonation depth assessment, X-ray diffraction analysis	Analyzing the impact of graphene oxide on recycled concrete aggregates (RCA) mixes, especially concerning carbonation depth and sulfate resistance.
Lippiatt <i>et al.</i> [27]	Explore the potential of carbonating concrete debris and blocks	Utilizing innovative technologies, conversion of calcium- or magnesium-rich minerals into carbonates	Addressing the need to reduce global CO ₂ emissions by mass-producing concrete and sequestering CO ₂ through carbonation while creating marketable products.
Anwar <i>et al.</i> [28] 2020	Assess concrete behavior under different exposure conditions	Immersion in artificial seawater, exposure to temperature, relative humidity, and CO ₂ variations, titration analysis	Evaluating the effects of exposure conditions on concrete properties, including total and soluble content, to understand concrete durability.
Justnes <i>et al.</i> [29] 2020	Investigate the carbonation behavior of fly ash-containing mortars	Analyzing hydrate assemblage, calcium content, and phases	Exploring the accelerated carbonation rate in fly ash-containing mortars and attributing it to factors like calcium hydroxide content and hydrate phases.

Li <i>et al.</i> [30] 2021	Study the effects of NS and MS on concrete carbonation and sorptivity	Carbonation and water absorption tests, SEM imaging, cementing efficiency evaluation	Assessing the impact of nano-silica (NS) and micro-silica (MS) on concrete properties, with a focus on carbonation and water sorptivity, and evaluating cementing efficiencies.
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Cement with fly ash added carbonates

The research mentioned look into many facets of fly ash and how it affects concrete and other materials. According to Bier's research, concrete carbonation may be sped up by using less Ca(OH)_2 in the cement paste, which is made possible by the presence of fly ash. Abdalqader *et al.* (2019) explore the strength and durability of concrete, while Kavyateja *et al.* (2020) introduce alccofine as a partial replacement for fly ash, improving self-compacting concrete's analytical techniques. Chen *et al.* (2021) discuss the effects of carbonation on cement mortar incorporating fly ash, highlighting its impact on strength and resistance to chloride ion penetration. AL-Maqate *et al.* (2022) experiment with heavy oil fly ash for optoelectronic applications, and Wang *et al.* (2022) examine the use of fly ash in place of coal gangue fines for alkali-activated slag materials. These studies contribute valuable insights into the utilization of fly ash in construction and other innovative applications.

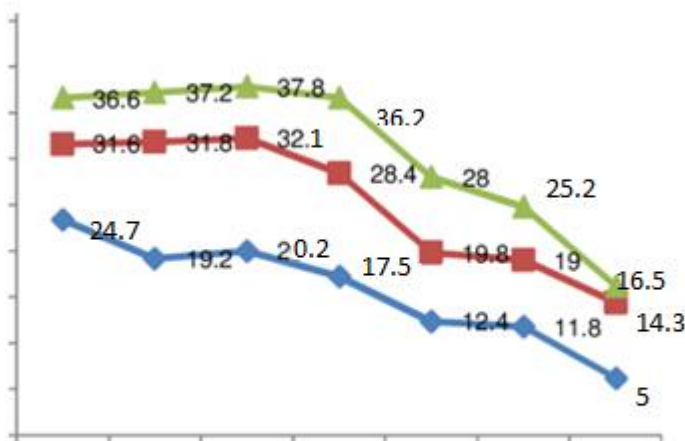


Figure 4: Overall average in the existing works

Table 8: Analytical Approaches in existing work

Author & Year	Aim	Methodology	Analytical Approaches	Drawbacks
Abdalqader et al. [31] (2019)	To comprehend the durability and strength development of NC-SF concrete and NC-SF concrete treated with MgO.	Concrete testing (compressive strength, split tensile strength, water absorption, etc.) and microstructure analysis (TGA, ATR-FTIR, PXRD).	Concrete testing, microstructure analysis using TGA, ATR-FTIR, and PXRD.	Assessing the performance and long-term behavior of concrete mixes containing NC-SF and NC-SF treated with MgO.
Kavyateja et al. [32] (2020)	To investigate the impact of adding alccofine as a partial replacement and fly ash on self-compacting concrete.	Analyzing concrete using thermogravimetric analysis, X-ray diffraction analysis, Fourier transform infrared spectroscopy, and scanning electronic microscopy.	Thermogravimetric analysis, X-ray diffraction analysis, FTIR, and SEM analysis.	Alccofine and fly ash addition enhances the analytical methods of self-compacting concrete.
Chen et al. [33] (2021)	To study the effects of carbonation treatment and curing on cement mortar incorporating FA and its resistance to chloride ion penetration.	Examining the behavior of cement mortar with carbonation treatment, carbonation curing, and FA incorporation.	Carbonation treatment, carbonation curing, pore structure analysis, and assessment of FA surface changes.	investigating the effects of carbonation on hydration heat, free CaO concentration, the development of strength, and resistance to chloride ion penetration.

AL-Maqate et al. [34] (2022)	To explore the use of heavy oil fly ash (HOFA) doped calcium carbonate (CaCO ₃) for optoelectronic applications.	Creating nano and thin-film samples with HOFA and CaCO ₃ using the spin coating approach on glass substrates.	Spin coating technique for sample creation and control.	Repurposing HOFA from power plants for optoelectronic applications and reducing its negative environmental impact.
Wang et al. [35] (2022)	To investigate the use of thermally activated coal gangue fines (CGF) in alkali-activated slag materials (AASM) without grinding.	Experimenting with CGF at different calcination temperatures and studying its impact on AASM properties.	Analysis of AASM properties with varying CGF calcination temperatures.	Analyzing the microstructure, flow, heat of hydration, compressive strength, and reactivity of AASM with thermally activated CGF.

Carbonation blends in variation materials

In recent years, several studies have explored innovative approaches to improve concrete construction's resilience and sustainability. Luo *et al.* (2022) investigated the carbonation resistance of PVA fiber concrete, finding that the addition of PVA fibers can significantly increase resistance, with the optimal fiber length and content balance. Wu *et al.* (2022) introduced a smart anode concept using Mg to monitor carbonation levels in concrete and protect steel structures within it. Ekolu *et al.* (2021) examined natural carbonation in concrete with supplemental cementitious materials, addressing the complexities of carbonation modeling in modern concrete mixes. Gu and Li (2020) proposed a methodology to update carbonation-induced deterioration models with inspection data for existing reinforced concrete structures. Qin *et al.* (2021) explored urea's efficiency in carbonate conversion, microbial growth, and urease activity.

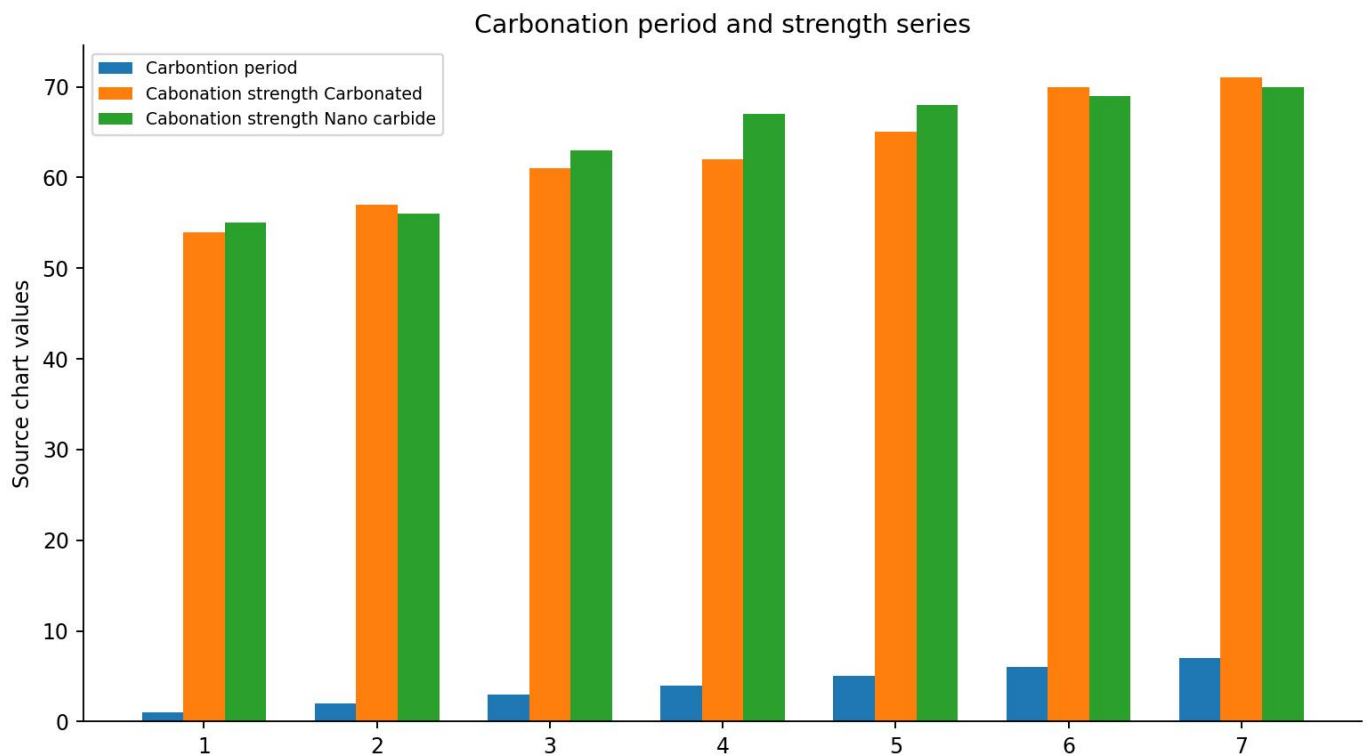


Figure 5: Overall average in the existing works

Mallek *et al.* (2021) investigated carbonation and chloride penetration resistance of self-compacting rubberized concrete. Sangoju *et al.* (2019) emphasized performance-based durability requirements for concrete in real-world construction conditions. Dias Andrade *et al.* (2021) improved the mechanical performance of eco-friendly structural concretes with steel slag aggregates, while Kwon *et al.* (2021) presented models for measuring CO₂ uptake in plain and blended concrete. Pu *et al.* (2021) investigated the properties and environmental impact of carbonated recycled concrete aggregates.

Table 9: Problem Identification in existing work

Author & Year	Aim	Methodology	Analytical Approaches	Draw back
Luo <i>et al.</i> 2022 [36]	Test carbonation model of PVA fiber concrete	Accelerated carbonation experiments	Examination of carbonation resistance with varying parameters	Influence of PVA fiber length and volume content

Wu <i>et al.</i> 2022 [37]	Develop a smart Mg anode for concrete	Testing Mg anode in simulated concrete pore solutions	Assessment of Mg anode sensitivity and current efficiency	Detection of carbonation in concrete and steel protection
Ekolu <i>et al.</i> 2021 [38]	Predict natural carbonation in concrete	Analysis of data with different SCMs in concrete	Development of a natural carbonation prediction model	Complexity of carbonation modeling with SCMs
Gu & Li 2020 [39]	Update carbonation-induced deterioration models	Use inspection data to update models	Examination of updating impact with different data	Assess durability of existing RC structures
Qin <i>et al.</i> 2021 [40]	Measure urea to carbonate conversion efficiency	Test urea concentration's effect on conversion	Application of the $0.51 + 0.08^{(e^{0.5x})}$ rule	Efficiency of urea to carbonate conversion
Mallek <i>et al.</i> 2021 [41]	Study resistance to carbonation and chloride penetration	Measurements of concrete properties	Assessment of durability with varying rubber content	Impact of rubber concentration on concrete strength
Sangoju <i>et al.</i> 2019 [42]	Analyze concrete durability with performance-based requirements	Assessment of concreting procedures	Development of performance-based requirements	Variability in concrete used in actual construction
Dias Andrade <i>et al.</i> 2021 [43]	Evaluate mechanical performance of eco-friendly structural concretes	Testing concretes with steel slag aggregates	Assessment of concrete properties with different aggregates	Durability of cement-based composites with steel slag

Kwon <i>et al.</i> 2021 [44]	Measure CO ₂ uptake rate in concrete	Use cement hydration model and carbonation model	-	Carbonation depth and CO ₂ uptake in concrete
Pu <i>et al.</i> 2021 [45]	Investigate carbonated recycled concrete aggregates	Study properties and environmental effects	-	Effects of carbonation on RCAs and concrete

Carbonation based on minerals

Zhang *et al.* (2022) investigated the mineral carbonation process with zeolite and its pozzolanic activity. Dhandapani *et al.* (2022) explored calcined clays' effect on cementitious systems' porosity and durability, as well as. Robati and Oldfield (2022) conducted a comprehensive embodied carbon assessment for different building structures, highlighting the potential of mass timber in reducing carbon emissions. Abdelshafy and Walther (2022) proposed a strategy for carbon capture and utilization (CCU) in the construction sector. Ngo *et al.* (2021) developed a numerical model for simulating various aspects of concrete behavior. Lastly, Xiao *et al.* (2020) demonstrated the carbon absorption capacity of recycled concrete, showing significant emissions reductions as recycled components replace virgin materials in concrete production. These studies collectively contribute to the ongoing efforts to make construction more sustainable and environmentally friendly.

Table 10: Problem Identification in existing work

Author & Year	Aim	Methodology	Analytical Approaches	Draw back
Zhang <i>et al.</i> [46] 2022	Explore zeolite's pozzolanic reaction mechanism	XRD and MAS NMR studies, hydration experiments	Identification of pozzolanic products	Mineral composition, pozzolanic activity of CH/zeolite specimens
Dhandapani <i>et al.</i> [47] 2022	Study the effects of calcined clays on concrete	Porosity, pore structure, durability testing	Microstructural changes, CO ₃ -AFm in concretes	Moisture infiltration, chloride intrusion, carbonation, etc.

Robati & Oldfield [48] 2022	Assess embodied carbon of different building types	Monte Carlo analysis, inventory databases	Comparison of embodied carbon for different types	Variability in carbon emissions, building materials, scenarios
Abdelshafy & Walther [49] 2022	Integrate CCU with construction supply chains	Data analysis, location-allocation models	Integration of carbon sources and sinks	Identify carbon sequestration capacity, transportation cost
Ngo <i>et al.</i> [50] 2021	Simulate carbon dioxide and moisture penetration	COMSOL Multiphysics, mass conservation equations	Solve mass conservation equations	Carbon dioxide and moisture penetration in concrete
Xiao <i>et al.</i> [51] 2020	Examine carbon absorption in recycled concrete	Carbonization tests, carbon absorption model	Compare recycled concrete to regular concrete	Carbon emissions reduction with recycled components

Optimization technique in carbonate depth

Optimization techniques to enhance the efficiency and accuracy of measurements and calculations related to carbonate rock depth in geological applications. Notably, Qiao *et al.* (2021) investigated the use of nano- CaCO_3 modified concrete to increase a structure's resistance to sulfate damage in a sulfate-rich environment, demonstrating that 1% nano- CaCO_3 significantly extends the service life by enhancing resistance to sulfate corrosion. In 2022, Biswas *et al.* proposed the formation of powdered CaCO_3 's negative impact on concrete microstructure and introduced machine learning techniques to predict carbonation more effectively. Olatunbsoun Sojobi *et al.* (2021) optimized pretreatment and carbonation conditions, reducing the carbonation time significantly while ensuring environmentally friendly processes. Furthermore, Londhe *et al.* (2021) utilized artificial neural networks and genetic programming to model concrete carbonation based on conditioning parameters, and Nunez *et al.* (2021) introduced using a gradient boosting regression tree model, which shows its superiority over other mathematical formulations, to calculate the carbonation depth in recycled aggregate concrete including different mineral additions.

Table 11: Analytical Approaches in existing work

Author & Year	Aim	Methodology	Analytical Approaches	Analytical Approaches
Qiao <i>et al.</i> [52] 2021	Assess the durability of nano-CaCO ₃	Investigation of concrete in sulfate	Detailed damage evaluation parameters, relative dynamic elastic modulus, and quality evaluation parameters	Relative quality evaluation, relative dynamic elastic modulus, comprehensive damage evaluation parameters
Biswas <i>et al.</i> [53] 2022	Study the impact of powdered CaCO ₃	Machine learning for carbonation prediction	Support Vector Regression (SVR) combined with metaheuristic algorithms	Support Vector Regression (SVR) combined with metaheuristic algorithms
Sojobi <i>et al.</i> [54] 2021	Optimize pretreatment and carbonation	Linear weighted sum approach	Spraying wastewater, air drying, and carbonation conditions	Spraying wastewater, air drying, and carbonation conditions
Londhe <i>et al.</i> [55] 2021	Develop statistical models for	Data-driven approaches (ANNs and GP)	Artificial Neural Networks (ANNs) and Genetic Programming (GP)	Artificial Neural Networks (ANNs) and Genetic Programming (GP)
Nunez <i>et al.</i> [56] 2021	Estimate carbonation depth in recycled	Data analysis and GBRT model	Gradient Boosting Regression Tree (GBRT) model	Gradient Boosting Regression Tree (GBRT) model

Considerations for Load Effects on Carbonated Concrete (Stress and Durability)

Several studies conducted in 2022 addressed various aspects of concrete performance and durability. Shi investigated the impact of persistent stresses on carbonated concrete, noting changes in diffusivity with multi-axial load levels. Ibernón developed voltammetric stainless steel sensors to

detect elements involved in corrosion processes, while Wang proposed a concrete mix design considering stress, carbonation, and environmental goals, using a genetic algorithm. Waseem examined the characteristics of natural aggregate concrete, carbonated recycled aggregate concrete, and aggregate concrete. Ding found a correlation between blast furnace slag replacement ratios and concrete's frost resistance and carbonation rate. Oikonomopoulou *et al.* focused on the impact of mechanical treatment on concretes with recycled aggregates. In 2021, Umbach *et al.* studied structural lightweight concrete with an ultra-high-performance matrix, and Li *et al.* enhanced the performance of recycled aggregate concrete with various treatment techniques.

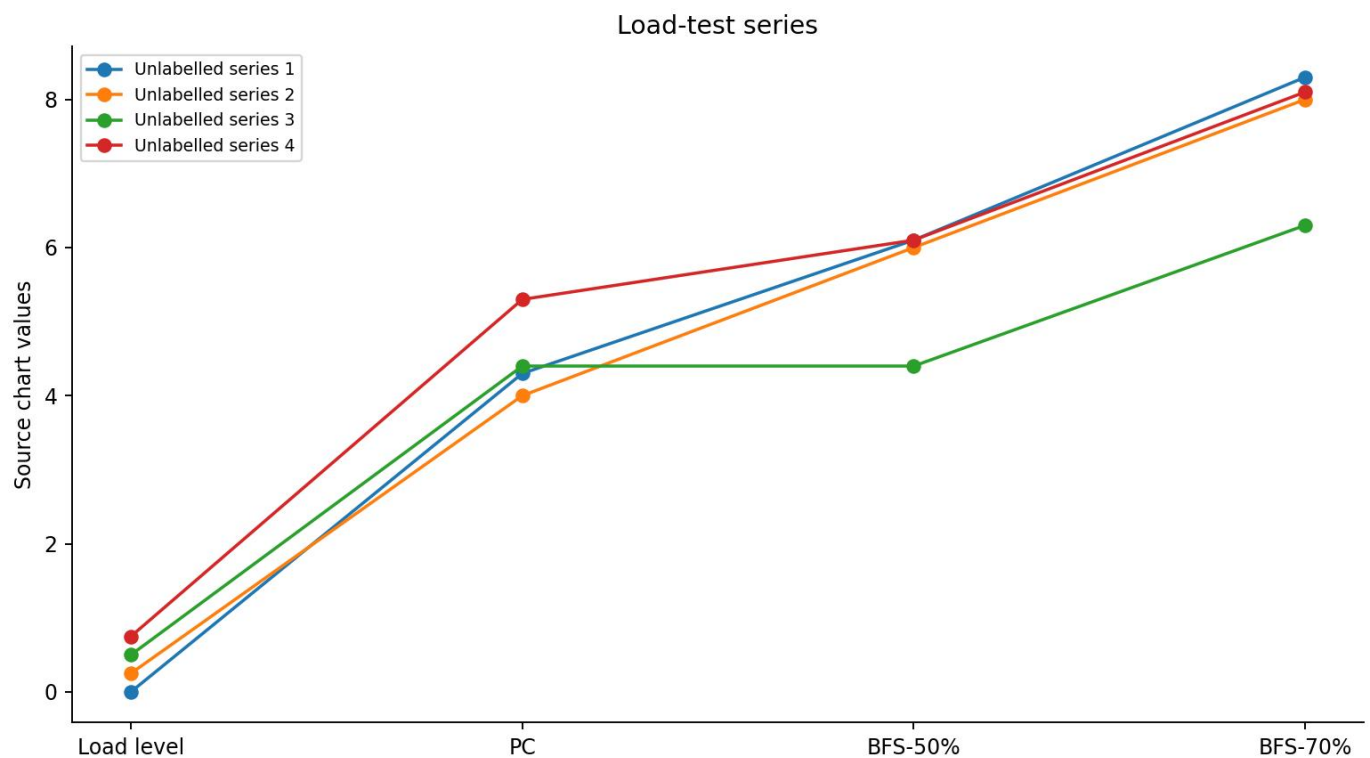


Figure 6: Overall average in the existing works

Table 12: Analytical Approaches in existing work

Author & Year	Aim	Methodology	Analytical Approaches	Drawbacks
Ibernón [58] 2022	Detect corrosion elements in concrete	Voltammetric SS sensors with PCA	Electrochemical methods	Identify corrosion in concrete caused by carbonation or chlorides

Wang [59] 2022	Optimize concrete mix for cost and CO2 emissions	Genetic Algorithm	Genetic Algorithm	Design concrete mix considering strength, slump, and carbonation durability under stress
Waseem [60] 2022	Study carbonation effects on RAC	Mechanical and nondestructive testing	Mechanical and nondestructive testing	Compare characteristics of NAC, RAC, and CRAC concrete
Ding [61] 2022	Investigate blast furnace slag in concrete	Compressive strength and carbonation rate	Compressive strength and carbonation rate	Examine frost resistance and pore structure with slag replacements
Oikonomopoulou et al. [62] 2022	Improve durability of concrete with recycled aggregates	Mechanical treatment procedure	Compressive strength and mass loss	Assess mechanical qualities of concretes with treated RCA
Umbach et al. [63] 2021	Study structural lightweight concrete	Capillary porosity, chemical attack, freeze-thaw	Corrosion resistance, carbonation, and chloride penetration	Evaluate concrete corrosion, carbonation, and chloride penetration resistance
Li et al. [64] 2021	Enhance RAC performance through treatment	Stress-strain analysis, carbonation resistance	Stress-strain analysis and carbonation resistance	Improve properties and carbonation resistance of RAC

Thermal analysis in carbonation depth

Vogler et al. [65] utilized thermogravimetric analysis to quantify calcium carbonates and portlandite in mortar samples, emphasizing the carbonated zones represented by the differential curves from

DTG. Sohail et al. [66] investigated active and passive steel corrosion in carbonated and noncarbonated concrete, utilizing potentiodynamic polarization curves and Comsol multiphysics software for corrosion parameter analysis. Kellouche et al. [67] suggested a model for a neural network made up of computers to predict the amounts of carbonation in slag concrete, achieving a high correlation of 0.98 with nine input parameters. Tiefenthaler et al. [68] presented an industrial-scale mineralization technique for biogenic CO₂ in concrete aggregate, with an accompanying Life Cycle Assessment demonstrating its efficacy. Al-Fasih et al. [69] assessed the viability of incorporating waste rubber tire crumbs into alkali-activated rubberized concrete using neural network calculations. Ribeiro et al. [70] investigated how dosing recommendations affected the diffusion of chloride in concrete and discovered that the ratio of water to cement was not the main determining factor. Cantero et al. [71] analyzed transport mechanisms of ions reclaimed aggregate combined with crushed recycled concrete in concrete, noting the impact of porosity on ingress resistance. Guo et al. [72] estimated that cements produced since 1930 have absorbed a significant amount of CO₂, with China playing a dominant role in cement production and consumption. These studies collectively contributed to advancing knowledge in concrete science and carbonation assessment.

Rate of cumulative CO₂ in mass

The equilibrium in thermal analysis

Table 13: Problem Identification in existing work

Author & Year	Aim	Methodology	Analytical Approaches	Draw back
Vogler et al. [65] 2021	Assess carbonation in concrete samples	DTG, differential curves, phenolphthalein	Differential curves, chemical analysis	Carbonation depth determination
Sohail et al. [66] 2021	Characterize steel corrosion in concrete	Potentiodynamic polarization curves, modeling	Electrochemical analysis, modeling	Active and passive steel corrosion
Kellouche et al. [67] 2021	Develop an AI model for carbonation level	Artificial neural network, input parameters	Machine learning, correlation analysis	Carbonation level estimation

Tiefenthaler et al. [68] 2021	Demonstrate large-scale carbonation process	Mineralization technique, Life Cycle Assessment	Environmental impact assessment	Carbon dioxide storage in concrete
Al-Fasih et al. [69] 2021	Replace natural aggregates with rubber tires	Numerical model calculations, neural network	Neural network, performance analysis	Concrete performance assessment
Ribeiro et al. [70]	Analyze dosing guidelines and chloride diffusion	Variation in concrete dosing, chloride test	Experimental testing, analysis	Chloride diffusion in concrete
Cantero et al. [71] 2021	Study transport mechanisms in recycled concrete	Ingress resistance assessment, porosity	Experimental testing, analysis	Transport mechanisms in concrete
Guo et al. [72] 2021	Estimate CO ₂ emissions from cement production	Data analysis and estimation	Data analysis, estimation	Cement production emissions

Data analysis in carbonation

In 2022, Duan and Cao employed data analysis, statistical methods, and machine learning techniques to identify influential factors related to carbonation reactions. They examined three areas: (1) the relationship between variables and concrete carbonation; (2) the effects of factors on the uncertainty of carbonation depth; and (3) the relationship between factors, providing quantitative evaluations of both individual parameters and parameter groups. In a similar vein, Londhe [74] explored the prediction of concrete's carbonation coefficient utilizing Model Tree (MT), Random Forest (RF), and Multi-Gene Genetic Programming (MGGP) methodologies, and contrasting them with well-known techniques like Multiple Linear Regression (MLR), Artificial Neural Networks (ANNs), and Genetic Programming. Furthermore, Liu et al. [75] developed a statistical model considering various variables in carbonation, such as ambient temperature, carbon dioxide concentration, relative humidity, and more, utilizing multiple nonlinear regression for different environmental exposures. Their approach yielded promising results in terms of carbonation prediction. In 2021, Azarijafari et al. [76] focused on estimating carbon absorption by US pavements and associated costs, using data

science techniques and pavement management models. This work aimed to enhance our understanding of carbon absorption by pavements and their performance characteristics.

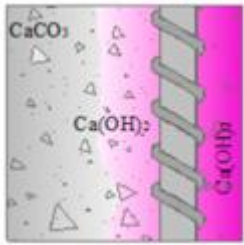


Figure 7: Analysis in carbonation

Table 14: Problem Identification in existing work

Author & Year	Aim	Methodology	Analytical Approaches	Drawbacks
Duan & Cao [73] 2022	Identify influence factors on concrete carbonation.	Statistical methods and machine learning techniques.	Quantitative evaluation of parameters.	1. The relationship between variables and the carbonation of concrete. 2. The effect on carbonation depth uncertainty. 3. Relationships among the variables.
Londhe [74] 2022	Predict carbonation coefficient of concrete.	Model Tree (MT), Random Forest (RF), Multi-Gene Genetic Programming (MGGP).	Comparisons with MLR, ANNs, GP.	Statistically relevant conditioning elements for carbonation mechanism.
Liu et al. [75] 2022	Develop a carbonation coefficient model for concrete.	Multiple nonlinear regression approach.	Model fitted for different exposures.	Variables include ambient temperature, CO2 concentration, relative humidity, etc.

Azarijafari [76] 2021	Estimate carbon absorption by US pavements and its cost.	Data science techniques and regional maintenance procedures.	High-resolution approach for estimation.	Estimate carbon uptake by the national pavement network.
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Carbonate resistance in concrete

In 2021, Sun et al. [77] developed a theoretical calculation model for Microbially Induced Calcium Carbonate Precipitation (MICP) by taking into account ureolysis, geochemistry, solute transport, suspended biomass movement, biofilm formation, and calcium carbonate (CaCO_3) precipitation. Their experiments on fracture healing supported the model's viability, revealing a steady decrease in predicted suspended biomass concentrations in fractures during the experiments, with higher concentrations in larger fissures. In the same year, Mi et al. [78] investigated the carbonation behavior of Recycled Aggregate Concrete (RAC) through accelerated carbonation and bending effects, highlighting significant differences in carbonation depths compared to natural aggregate concrete. Zheng et al. [79] implemented a probabilistic method to evaluate the time-dependent annual damage probability of a 42-story steel frame-RC core tube skyscraper while taking seismic risks and corrosion caused by carbonation into consideration. Additionally, Shah & Bishnoi [80] examined the impact of physical, chemical, and environmental factors on concrete carbonation, highlighting the influence of factors such as relative humidity, porosity, and pore saturation on the rate of carbonation.

Table 15: Analytical Approaches in existing work

Author & Year	Aim	Methodology	Analytical Approaches	Drawbacks
Sun <i>et al.</i> [77] 2021	To develop a theoretical model for fracture healing using Microbially Induced Calcium Carbonate Precipitation (MICP).	Considered solute transport, suspended biomass movement, biofilm development, geochemistry, ureolysis, and CaCO_3 precipitation.	Compared calculated suspended biomass concentrations with experimental outcomes.	Investigated the behavior of suspended biomass in fractures during experiments and its relationship with fissure size.

Mi <i>et al.</i> [78] 2021	To study the carbonation of Recycled Aggregate Concrete (RAC) in different zones and determine steel corrosion zone widths.	Subjected RAC samples to accelerated carbonation and four-point bending. Compared carbonation depths in various zones.	Demonstrated significant differences in carbonation depths between RAC and natural aggregate concrete.	Compared microstructures of mortars in different zones and suggested a technique to determine steel corrosion zone widths.
Zheng <i>et al.</i> [79] 2021	To probabilistically evaluate the yearly damage probability of a 42-story steel frame-RC core tube skyscraper considering carbonation-induced corrosion and seismic uncertainties.	Considered carbonation-induced corrosion and seismic excitations. Accounted for reduction in cross-sectional area and reinforcement strength.	Combined seismic hazard model and conditional fragility.	Evaluated the overall yearly damage likelihood under various aging scenarios.
Shah & Bishnoi <i>et al.</i> [80] 2021	To examine the factors influencing the carbonation process in concrete.	Investigated the effects of physical, chemical, and environmental factors, such as internal relative humidity, porosity, and pore saturation.	Found negligible short-term effects between the quantity of carbonation and water produced during carbonation.	Explored the control mechanisms of carbonation in concrete.

Carbonation depth prediction by using Machine learning

Growing interest in developing predictive models for concrete carbonation depth using machine learning techniques. Researchers such as Nunez & Nehdi (2021), Hyvert et al. (2010), Chandra Paul et al. (2018), Taffese et al. (2015), Lee et al. (2022), Felix et al. (2021), Kellouche et al. (2017), Liu et al. (2023), Liu et al. (2021), and Duan et al. (2022) have explored various aspects of this problem. They have employed methods such as gradient boosting regression trees, deep learning, artificial neural networks (ANN), and hybrid models like PCA-ANFIS determine the concrete's carbonation depth. These studies have taken into account elements including the cement's composition, the atmosphere,

the CO₂ content, and the characteristics of the concrete mix.

Table 16: Analytical Approaches in existing work

Author & Year	Aim	Methodology	Analytical Approaches	Draw back
Nunez & Nehdi [81]	Develop a model for carbonation in concrete and compare it to other mathematical models	Construction of a database with experimental data. Compare GBRT model to other formulations	Database, GBRT model, Mathematical models	Find a model for estimating carbonation depth.
Hyvert et al. [82]	Analyze the impact of CO ₂ pressure on carbonation. Create an analytical model based on experimental studies	Experimental studies, consideration of cement chemistry, pressure effects	Experimental studies, Analytical modeling	Understand the influence of CO ₂ pressure on carbonation kinetics.
Chandra Paul et al. [83]	Investigate the impact of concrete mix compositions, weathering, and exposure on carbonation. Create an empirical model	Automated neural network search, empirical model, experimental validation	Automated neural network search, Empirical model	Determine the effect of concrete mix on carbonation depth.
Taffese et al. [84]	Propose a machine learning-based carbonation prediction model. Evaluate for accuracy and methodology.	Machine learning model with four learning techniques, factor consideration	Machine learning, Model evaluation	Develop a machine learning model for predicting carbonation depth.

Lee et al. [85]	Use deep learning to forecast carbonation behavior. Compare AIJ model and FEM analysis.	Deep learning model with hierarchical artificial neural networks	Deep learning, Comparison with AIJ model and FEM analysis	Determine if deep learning can predict carbonation behavior.
Felix et al. [86]	Predict carbonation depth in concrete with fly ash addition using ANN. Optimize the model.	Artificial neural network with backpropagation, multiple topologies	Artificial neural network, Model optimization	Optimize the model to predict the depth of carbonation in concrete using fly ash.
Kellouche et al. [87]	Use an ANN to forecast carbonation of fly-ash concrete considering various parameters.	Artificial neural network with inputs (mixture proportions and exposure conditions)	Artificial neural network, Input parameters	Develop a model for predicting carbonation depth in fly-ash concrete.
Liu et al. [88]	Introduce a PCA-ANFIS model for forecasting reinforced concrete carbonation.	PCA combined with ANFIS for dimensionality reduction and modeling	PCA, ANFIS modeling	Create a model for predicting reinforced concrete carbonation.
Liu et al. [89]	Predict carbonation depth in recycled aggregate concrete using machine learning algorithms.	Machine learning models with input variables. Compare different models.	Machine learning models, Model comparison	Forecast carbonation depth in recycled aggregate concrete.
Duan et al. [90]	Select the best influence factors for concrete carbonation using statistical and machine learning techniques.	Statistical and machine learning methods for parameter selection.	Statistical and machine learning techniques	Identify key factors influencing concrete carbonation.

Composition of carbonation depth

Researchers explored various aspects of concrete and construction materials. Zhang et al. (2022) investigated the pozzolanic reaction mechanism of zeolite using X-ray diffraction and MAS NMR, while Dhandapani et al. (2022) examined metakaolin and calcined clays' effects on cementitious systems' durability and performance. Robati & Oldfield (2022) analyzed embodied carbon in different construction structures, highlighting the potential environmental benefits of mass timber construction. Abdelshafy & Walther (2022) explored the connections between carbon capture and utilization (CCU) and construction supply chains. Ngo et al. (2021) developed a numerical model for simulating carbon dioxide penetration, moisture transport, and other factors in concrete. Xiao et al. (2019) demonstrated the reduced carbon emissions associated with recycled concrete. Roziere et al. (2009) investigated the effects of aggregate type, binder composition, and curing conditions on concrete performance, emphasizing the need for accelerated carbonation testing. Yongsheng et al. (2010) examined carbonation in concrete under different environmental conditions. Vogler et al. (2021) studied carbonation in concrete samples under accelerated conditions. Finally, Ameer et al. (2021) investigated the effects of concrete carbonation on corrosion and chloride penetration in reinforced concrete structures.

Table 17: Analytical Approaches in existing literatures

Author & Citation	Aim	Methodology	Analytical Approaches	Drawback
Zhang <i>et al.</i> [91] 2022	Explore mineral composition and pozzolanic reaction of zeolite	XRD, MAS NMR, Pozzolanic activity testing	X-ray diffraction, NMR spectroscopy, Pozzolanic activity assessment	Investigate mineral compositions and pozzolanic reactions of zeolite-based materials
Dhandapani <i>et al.</i> [92] 2022	Study impact of calcined clays on cementitious systems	Porosity, transport qualities, durability performance	Laboratory testing, analysis of durability performance	Examine effects of calcined clays on porosity, moisture infiltration, chloride intrusion, etc.

Robati & Oldfield <i>et al.</i> [93] 2022	Analyze embodied carbon in building materials	Monte Carlo analysis	Monte Carlo analysis of carbon emissions	Investigate carbon emissions and variations in building materials
Abdelshafy & Walther <i>et al.</i> [94] 2022	Assess connections between CCU and construction supply chains	Carbon sequestration, location-based allocation	Mathematical modeling and allocation methods	Estimate CO2 sequestration capacity in concrete facilities and supply chains
Ngo <i>et al.</i> [95] 2021	Develop a numerical model for concrete behavior	COMSOL Multiphysics modeling	Numerical modeling using COMSOL Multiphysics	Simulate CO2 penetration, moisture, heat transfer, and porosity alteration in concrete
Xiao <i>et al.</i> [96] 2019	Investigate carbon emissions in recycled concrete	Carbon absorption model, rapid carbonization tests	Testing and development of a carbon absorption model	Study the potential of recycled concrete to absorb carbon and reduce emissions
Roziere <i>et al.</i> [97] 2009	Examine concrete performance under various conditions	Impact of aggregate, binder, curing on performance	Laboratory testing and assessment of concrete properties	Investigate effects of factors like aggregate type, curing, and binder composition
Yongsheng <i>et al.</i> [98] 2010	Study carbonation of concrete in natural and accelerated environments	pH measurement, phase component analysis	Experimental analysis of concrete properties	Investigate changes in pH values and concrete's carbonation under different conditions

Vogler <i>et al.</i> [99] 2021	Analyze carbonation in concrete under varying conditions	Differential curves from DTG, concrete sample analysis	Sample analysis and differential curves	Evaluate the effects of carbonation in concrete under different conditions
Ameeri <i>et al.</i> [100] 2021	Examine corrosion in RC structures with service-related fractures	Casting concrete prisms, exposure to CO ₂ and chloride	Experimental testing and analysis of concrete properties	Investigate corrosion, chloride penetration, and carbonation effects in concrete

Conclusion

In conclusion, this thorough assessment of the literature digs into the urgent problem of carbonation resistance in concrete buildings, against the background of the crucial change to sustainable construction methods and the important requirement to reduce carbon dioxide emissions. Concrete's structural integrity is seriously threatened by its natural aging process, which is characterized by carbonation. This work builds an up-to-date, comprehensive toolset by carefully analyzing the range of analytical methods used for predicting carbonation depth, greatly advancing the development of resilient and sustainable infrastructure. Additionally, it is stressed how very important the interaction between carbonation and carbon emissions is to the building sector. This analysis emphasizes the complex relationship between these processes and highlights the possibility of increased carbonation resistance in concrete as a tool for reducing greenhouse gas emissions. Researchers, engineers, and politicians may use the knowledge gained from this evaluation to make well-informed decisions that will encourage the use of environmentally friendly building techniques and forward the goals of global sustainability.

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