Conciencia Digital

ISSN: **2600-5859**
Vol. 9 No. 2, pp. 151 – 177, abril - junio 2026
Revista multidisciplinar
Artículo de revisión bibliográfica

www.concienciadigital.org

Investigación sobre la carbonatación del concreto: un campo específico con poca integración de perspectivas urbanas, de salud y sostenibilidad

Concrete carbonation research: a niche field with limited integration of urban, health, and sustainability perspectives

[1] Diego Hernán Hidalgo Robalino https://orcid.org/0000-0003-1341-8206
Escuela Politécnica Nacional (EPN), Quito, Ecuador.
Magister en Ingeniería Estructural
dihidalgoro@uide.edu.ec

Artículo de Investigación Científica y Tecnológica
Enviado: 22/01/2026
Revisado: 11/02/2026
Aceptado: 20/03/2026
Publicado: 05/05/2026
DOI: **https://doi.org/10.33262/concienciadigital.v9i2.3679**

Cítese: Hidalgo Robalino, D. H. (2026). Investigación sobre la carbonatación del concreto: un campo específico con poca integración de perspectivas urbanas, de salud y sostenibilidad. *ConcienciaDigital*, *9*(2), 151 - 177. https://doi.org/10.33262/concienciadigital.v9i2.3679

CONCIENCIA DIGITAL, *e*s una revista multidisciplinar, **trimestral,** que se publicará en soporte electrónico tiene como **misión** contribuir a la formación de profesionales competentes con visión humanística y crítica que sean capaces de exponer sus resultados investigativos y científicos en la misma medida que se promueva mediante su intervención cambios positivos en la sociedad. https://concienciadigital.org
La revista es editada por la Editorial Ciencia Digital (Editorial de prestigio registrada en la Cámara Ecuatoriana de Libro con No de Afiliación 663) www.celibro.org.ec

Esta revista está protegida bajo una licencia Creative Commons en la 4.0 International. Copia de la licencia: http://creativecommons.org/licenses/by-nc-sa/4.0/

Conciencia Digital

ISSN: 2600-5859
Vol. 9 No. 2, pp. 151 – 177, abril - junio 2026
Revista multidisciplinar
Artículo de revisión bibliográfica

www.concienciadigital.org

Palabras claves: Carbonatación del concreto, corrosión de armaduras, revisión bibliográfica, bibliometría, infraestructura urbana.

Resumen

Introducción: la carbonatación del concreto es uno de los principales mecanismos de deterioro en estructuras de hormigón armado, especialmente en contextos urbanos. Este fenómeno ha sido abordado en múltiples investigaciones, aunque persisten vacíos en su análisis integral desde perspectivas interdisciplinarias que incluyan salud, sostenibilidad y entorno urbano. **Objetivo**: analizar el estado del arte sobre la carbonatación del concreto, sus mecanismos, efectos estructurales, variables ambientales asociadas y vacíos de investigación, mediante un estudio bibliométrico y revisión sistemática de literatura científica indexada. **Metodología**: revisión bibliográfica con enfoque cuantitativo-bibliométrico. Se utilizó el software R con el paquete *Bibliometrix* para analizar tendencias, autores, países, palabras clave y vacíos temáticos en artículos científicos relacionados con la carbonatación del concreto. **Resultados**: la mayoría de investigaciones se concentran en aspectos fisicoquímicos del fenómeno, con escasa vinculación a variables urbanas, normativas locales, salud pública y sostenibilidad. Se identifican oportunidades de investigación multidisciplinaria. **Conclusión**: la carbonatación del concreto continúa siendo un fenómeno activo en estudio. Sin embargo, su abordaje en contextos reales urbanos y su vínculo con políticas públicas, diseño estructural y planificación urbana aún es limitado, lo que abre un nicho relevante para futuras investigaciones. **Área de estudio general**: Ingeniería. **Área de estudio específica**: Materiales de construcción / Patología estructural. **Tipo de estudio**: Revisión Bibliográfica.

Keywords: Concrete carbonation, reinforcement corrosion, literature review, bibliometrics, urban infrastructure.

Abstract

Introduction: concrete carbonation is one of the main degradation mechanisms in reinforced concrete structures, especially in urban environments. Although extensively studied, this phenomenon still lacks integrative approaches that consider health, sustainability, and urban planning perspectives. **Objective**: to analyze the state of the art on concrete carbonation, including its mechanisms, structural effects, associated environmental variables, and research gaps, through a bibliometric and systematic review of indexed scientific literature. **Methodology**: bibliographic review with a quantitative-bibliometric approach. The R software and *Bibliometrix* package were used to identify trends, leading authors, countries, keywords,

Concienca Digital
ISSN: 2600-5859
Vol. 9 No. 2, pp. 151 – 177, abril - junio 2026
Revista multidisciplinar
Artículo de revisión bibliográfica
www.concienciadigital.org

and thematic gaps in scientific publications related to concrete carbonation. **Results**: most research focuses on the physicochemical aspects of the phenomenon, with limited integration of urban variables, local regulations, public health concerns, and sustainability. Opportunities for interdisciplinary research were identified. **Conclusion**: concrete carbonation remains an active research topic. However, its study in real urban contexts and its connection with public policies, structural design, and urban resilience remains insufficient, revealing a relevant niche for future studies. **General Area of Study**: Engineering. **Specific area of study**: Construction materials / Structural pathology. **Type of study**: Review article.

1. Introduction

Concrete carbonation is a chemical process in which Carbon Dioxide (CO_2) from the environment penetrates the pore structure of concrete and reacts with calcium hydroxide to form calcium carbonate. This process reduces the alkalinity of concrete and, in doing so, compromises the passive layer that protects embedded steel reinforcement, leading to corrosion and potential structural degradation (Papadakis et al., 1991a; Chang & Chen, 2006). As a result, carbonation has become one of the most significant durability concerns in reinforced concrete structures worldwide (Cui et al., 2015).

The mechanisms of carbonation have been widely studied, both experimentally and through mathematical modeling (Papadakis et al., 1989; Ichikawa et al., 2024). Numerous studies have focused on how variables such as CO_2 concentration, humidity, temperature, and material composition influence carbonation rates (Rostami et al., 2012; Huet et al., 2005). In particular, the incorporation of supplementary cementing materials such as fly ash or slag has been shown to alter the carbonation resistance of concrete (Papadakis, 2000).

Despite these advances, most research has focused on controlled environments, with limited attention given to how carbonation develops in urban settings. Urban concrete structures, especially in polluted or poorly maintained environments, may be more susceptible to carbonation due to higher CO_2 levels and aggressive atmospheric conditions (Lau et al., 2024; Apostolopoulos & Papadakis, 2008).

Furthermore, concrete has been identified as a potential carbon sink over long service periods, with implications for sustainability and environmental accounting (Pade &

ISSN: 2600-5859
Vol. 9 No. 2, pp. 151 – 177, abril - junio 2026
Revista multidisciplinar
Artículo de revisión bibliográfica

www.concienciadigital.org

Guimaraes, 2007). However, the dual role of concrete as both a vulnerable material and a potential mitigation medium raises complex questions about its long-term performance in urban infrastructure.

The intersection of carbonation, sustainability, and public health in the built environment is still poorly understood. In Latin America, where rapid urbanization, aging infrastructure, and environmental stressors often coincide, the effects of carbonation may be especially severe, yet underrepresented in global literature.

To address these gaps, this study presents a Scopus-based bibliometric analysis of scientific publications on concrete carbonation. Emphasis is placed on urban contexts, sustainability concerns, health-related implications, and Latin American contributions. Using bibliometric techniques and thematic coding, this work aims to identify research trends, intellectual structures, and regional disparities, establishing a foundation for future interdisciplinary investigations.

2. Methodology

a. Research design: this study adopts quantitative, non-experimental, and documentary research design, based on bibliometric analysis. The approach focuses on analyzing scientific production on concrete carbonation through indicators such as publication trends, collaboration networks, and thematic structures, as proposed in previous bibliometric studies.
b. Type of Research: the investigation is descriptive and retrospective, relying on a systematic review of published literature. It does not manipulate variables but rather interprets metadata patterns and thematic content across time (Papadakis et al., 1991b; Cui et al., 2015).
c. Research Level: descriptive level, oriented to classify, summarize, and interpret patterns in global and regional scientific output related to carbonation in concrete structures. The analysis identifies gaps in knowledge, regional disparities, and underexplored connections with sustainability, health, and urban resilience field (Ahmed et al., 2025; Wang et al., 2025; Torres-Acosta et al., 2024; Chen et al., 2025).
d. Research Modality: the modality corresponds to a documentary review, supported by bibliometric and content analysis techniques. It aims to enrich theoretical understanding of carbonation, especially from an interdisciplinary and Latin American perspective.
e. Method: the Scopus database was queried using the keyword "concrete carbonation" on July 25, 2025. A total of 833 documents were retrieved. The dataset included metadata such as authorship, year, keywords, abstracts, and citations. The Bibliometrix R package was used for analysis. Documents were further coded based on thematic keywords (urban, sustainability, health, Latin America). This mixed

Concienca Digital

ISSN: 2600-5859
Vol. 9 No. 2, pp. 151 – 177, abril - junio 2026
Revista multidisciplinar
Artículo de revisión bibliográfica

www.concienciadigital.org

approach allowed both quantitative insight and thematic classification (Papadakis, 2000; Pade & Guimaraes, 2007).

f. Ethics: as the study is based exclusively on published documents and secondary data, no human participants were involved, and ethical committee approval was not required.

3. Results

This section presents the results derived from the bibliometric analysis of research on concrete carbonation. Through quantitative techniques applied to the scientific literature indexed in Scopus, patterns of publication volume, keyword co-occurrence, thematic structure, and collaborative networks were identified and interpreted. The findings provide insight into the evolution of knowledge production, the main conceptual clusters, and the geographical distribution of research efforts. Additionally, a thematic classification was conducted to contextualize the data within urban, sustainability, health, and Latin American frameworks, enabling a multidimensional understanding of how carbonation studies intersect with broader societal challenges. To enrich the bibliometric dataset with a thematic perspective, a classification process was performed based on the presence of four strategic terms: "urban," "sustainability," "health," and "Latin America." These themes were selected due to their relevance to the contextualization of carbonation phenomena in densely populated, environmentally vulnerable, and socioeconomically diverse settings. The classification was conducted using spreadsheet functions applied to the title, abstract, and author keywords of each document. For each term, binary values were assigned: a value of "1" indicated the presence of the term in each textual field, and "0" indicated its absence. The results are summarized in **Table 1**.

Table 1

Frequency of strategic terms by textual field in the bibliometric dataset

Field	Urban	Sustainability	Health	Latin America
Keywords	7	2	13	0
Abstract	38	12	13	0
Title	5	3	3	0
Total	50	17	29	0

3.1. General overview of the dataset

The bibliometric dataset comprises 818 documents on concrete carbonation, retrieved from the Scopus database. As shown in **Figure 1**, the general bibliometric indicators reveal that the publications span a period from 1971 to 2025, with an annual growth rate of 6.75%, indicating a steady and growing interest in the topic over the past five decades.

A total of 1947 authors contributed to the dataset, with an average of 3.69 co-authors per document, and only 63 documents being authored by a single researcher. The elevated level of international collaboration (16.75%) reflects the global relevance of concrete carbonation, particularly in the context of climate resilience, infrastructure durability, and sustainable construction. The documents were published across 380 diverse sources, highlighting the interdisciplinary nature of the field, which includes journals in civil engineering, materials science, environmental studies, and sustainability. On average, each document received 20.7 citations, and the mean document age is 10.5 years, suggesting a balance between foundational literature and emerging research. The dataset also included 1728 distinct author keywords, offering a rich base for analyzing thematic trends and keyword co-occurrence networks in subsequent sections.

Figure 1

General bibliometric indicators of the dataset on concrete carbonation research (Scopus, 1971–2025)

3.2. Scientific production trends

The annual scientific production on concrete carbonation has experienced significant evolution over the past five decades. From 1971 to the early 2000s, the number of publications remained low, with fewer than 10 articles per year. A turning point occurred after 2005, when the publication rate began to rise steadily, reflecting the increasing awareness of carbonation as a critical factor in concrete durability and carbon emissions mitigation. A sharp upward trend is observed from 2010 onward, culminating in the highest output in 2024, with more than 65 articles published. This surge coincides with growing academic and industrial interest in sustainability, decarbonization strategies, and the role of construction materials in climate change adaptation. The apparent decline in 2025 is due to incomplete indexing for the current year. This production curve underscores the progressive consolidation of concrete carbonation as a mature and expanding research field, responding to both scientific inquiry and practical engineering challenges in infrastructure management and environmental performance. As shown in **Figure 2**, the annual scientific production demonstrates a clear upward trend, particularly after 2010, highlighting the growing relevance of carbonation research.

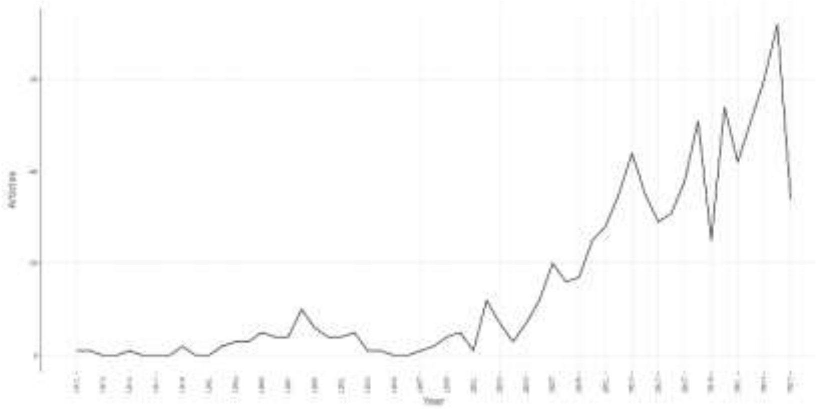
Conciencia Digital

ISSN: 2600-5859
Vol. 9 No. 2, pp. 151 – 177, abril - junio 2026
Revista multidisciplinar
Artículo de revisión bibliográfica

www.concienciadigital.org

Figure 2

Annual scientific production on concrete carbonation from 1971 to 2025.

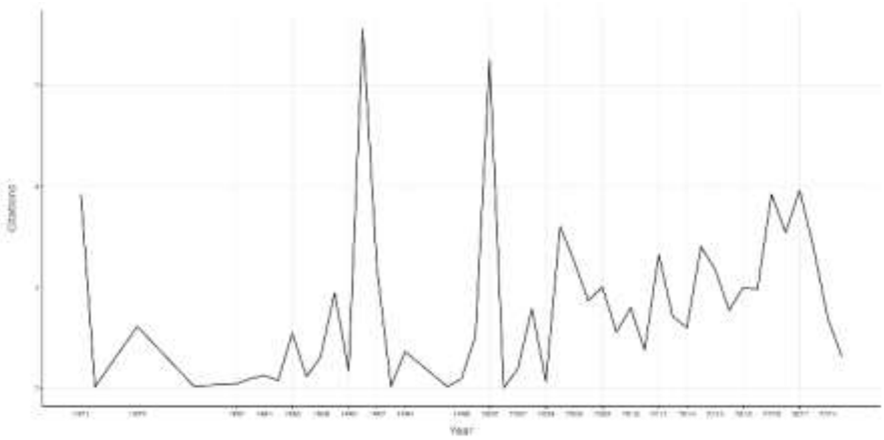


3.3. Numerical modeling outcomes

Figure 3 shows the temporal distribution of average citations per article. Although early publications from the 1970s and 1980s show sporadic citation activity, a marked increase in citation frequency can be observed from the 1990s onward. Notably, peaks in citation averages occur around the years 1991, 2000, and 2022, suggesting the publication of influential articles during those periods. Despite fluctuations, the overall trend reflects a growing academic interest and recognition of key contributions to the field of concrete carbonation. Recent years (post-2020) display a slight decline in citation averages, which may be attributed to the shorter time frame available for citation accumulation.

Figure 3

Temporal evolution of average article citations per year



3.4. Most relevant sources

An analysis of the most prolific sources in the field of concrete carbonation reveals a

Concienca Digital
ISSN: **2600-5859**
Vol. 9 No. 2, pp. 151 – 177, abril - junio 2026
Revista multidisciplinar
Artículo de revisión bibliográfica
www.concienciadigital.org

concentration of publications in key journals. *Construction and Building Materials* leads significantly with 64 documents, followed by *Cement and Concrete Research* (21), *Applied Mechanics and Materials* (18), and *Materials and Structures* (17). Other notable sources include *Materials*, *Advanced Materials Research*, and *Case Studies in Construction Materials*, each with over 12 publications. This distribution reflects the interdisciplinary nature of the field, spanning structural engineering, materials science, and sustainability. The dominance of construction- and materials-oriented journals underscores the applied and practical focus of carbonation research.

3.5.Core journals and Bradford's law analysis

Applying Bradford's Law enabled the identification of core journals contributing the most to the field of concrete carbonation. The core zone, shaded in grey, includes a small subset of journals that collectively account for a considerable proportion of the published articles. Notably, *Construction and Building Materials* and *Cement and Concrete Research* dominate this core, consistent with their leading roles observed in previous analyses. This concentration pattern aligns with Bradford's principle, which posits that scientific productivity is often distributed unevenly across sources. Beyond the core, a long tail of journals contributes sporadically, illustrating the broader interdisciplinary reach of carbonation-related studies across materials science, civil engineering, and sustainability domains.

3.6. Journal impact based on H-Index

The impact of the journals contributing to the field of concrete carbonation was assessed using the H-index metric. Construction and Building Materials stands out with the highest H-index of 31, indicating both a high volume of publications and consistent citations over time. It is followed by Cement and Concrete Research (H = 18) and Cement and Concrete Composites (H = 9), both recognized for their influence in cementitious material science.

Other prominent sources include Journal of Building Engineering, Journal of Materials in Civil Engineering, and Materials and Structures, each with an H-index of 8, reflecting their importance in disseminating research on durability and structural performance. The presence of multidisciplinary journals such as Journal of Cleaner Production and Applied Sciences indicates an intersection between materials engineering and environmental sustainability within the topic. This ranking highlights the significant role of specialized journals in advancing knowledge on concrete carbonation, while also emphasizing the growing contribution of broader scientific platforms.

3.7. Thematic evolution trends

The cumulative evolution of the most frequent keywords provides insights into the thematic development of concrete carbonation research over time. The keyword

Conciencia Digital
ISSN: 2600-5859
Vol. 9 No. 2, pp. 151 – 177, abril - junio 2026
Revista multidisciplinar
Artículo de revisión bibliográfica
www.concienciadigital.org

"carbonation" shows a consistent upward trajectory since 2010, positioning it as the core term within the literature. In contrast, keywords such as *"corrosion," "durability,"* and *"CO2"* have gained prominence since around 2012, reflecting increasing concern with environmental impact and material longevity. More recent entries like *"sustainability"* indicate an emerging focus on eco-conscious approaches within the field. This temporal keyword analysis highlights both consolidated research areas and emerging thematic priorities in the domain. The cumulative evolution of keywords reveals a clear growth trend, particularly for core terms such as "carbonation," "durability," and "CO_2," reflecting the increasing relevance of these topics over time.

3.8. Most relevant authors in the field

The analysis of author productivity revealed a highly concentrated group of contributors within the field of concrete carbonation. The most prolific author is Wang et al. (2025) with 17 publications, followed by Moreno (2010) with 15 documents. Muntean (2023) and Wang et al. (2013) also demonstrated significant productivity, each contributing 14 publications to the dataset. A cluster of authors including Aiki & Kumazaki (2020), Andrade et al. (1986), Chen et al. (2022), Chen (2016), Liu et al. (2012) each published 12 documents, reflecting a substantial involvement in the topic. This distribution suggests the presence of a core group of researchers consistently contributing to the advancement of the field, driving key innovations, and shaping thematic trends in carbonation studies. The results illustrate the main patterns and trends identified in the analysis, providing a visual representation of the data discussed.

3.9. Temporal distribution of publications by leading authors

The temporal evolution of publications by the most prolific authors reveals distinct patterns of research activity within the field of concrete carbonation. Andrade et al. (1986) stands out as the earliest contributor, with publications spanning from 1979 to 2020, indicating long-term engagement in the topic. In contrast, authors such as Wang et al. (2025) have shown a marked increase in output in recent years, particularly after 2018, suggesting a surge of interest and contributions from emerging researchers. Notably, Moreno (2010), Muntean & Böhm (2007), Moreno et al. (2004), and Chen et al. (2022) demonstrate consistent productivity over a sustained period, reflecting their ongoing involvement in carbonation-related investigations. The varying onset and intensity of publication trajectories highlight the interplay between foundational and contemporary contributors to the field.

3.10. Author productivity analysis based on Lotka's law

The distribution of author productivity within the dataset was analyzed in accordance with Lotka's Law. Most authors (over 75%) contributed to only one publication,

Concienca Digital
ISSN: 2600-5859
Vol. 9 No. 2, pp. 151 – 177, abril - junio 2026
Revista multidisciplinar
Artículo de revisión bibliográfica
www.concienciadigital.org

indicating a highly skewed authorship pattern. The frequency of authors decreases exponentially with the number of documents written, as expected in bibliometric distributions. The observed data (solid line) closely aligns with the theoretical curve predicted by Lotka's Law (dashed line), confirming the prevalence of occasional contributors in the field of concrete carbonation. This pattern underscores the interdisciplinary and widespread interest in the topic, where many researchers contribute sporadically while a small core group maintains continuous scholarly output.

3.11. Author's local impact based on h-Index

The h-index was used to identify the most influential authors in the field of concrete carbonation. Liu et al. (2012) & Papadakis (2000) both achieved the highest h-index score of 9, followed closely by Wang et al. (2013), Silva et al. (2014), Muntean (2023), Neves et al. (2013), and Wang et al. (2025) each with an h-index of 8. These values indicate consistent citation impact across multiple publications. Notably, Andrade et al. (1986), reached an h-index of 7, while Aiki & Timoshin (2017), Muntean & Böhm (2009), and, Chen et al. (2022) registered scores of 6. The h-index, as an integrated measure of productivity and citation impact, highlights the sustained academic relevance of these researchers in the topic area. This metric provides a more nuanced view than publication count alone, emphasizing authors whose works have consistently influenced the scientific discourse on carbonation processes in concrete.

3.12. Leading institutions in concrete carbonation research

The analysis of institutional contributions reveals that Tongji University is the most prolific institution in the field of concrete carbonation, with a total of 54 published articles. This is followed by Central South University (22 articles), China University of Mining and Technology (21), and Southeast University (19). Several other institutions, including Shenzhen University and Xi'an University of Architecture and Technology, each contributed 16 publications. Notably, Kangwon National University and the Universidad Autónoma de Yucatán also appear among the top contributors, highlighting the involvement of both Asian and Latin American institutions in this area of study. These findings emphasize the significant role of Chinese universities in advancing research on carbonation mechanisms, durability assessments, and sustainability in cement-based materials.

3.13. Publication trends of leading institutions over time

The temporal evolution of publications from the top five contributing institutions in the field of concrete carbonation reveals distinct growth patterns. Tongji University demonstrates a consistent and steep upward trend since 2006, clearly positioning itself as the dominant contributor. In contrast, institutions such as Central South University, China

Conciencia Digital
ISSN: 2600-5859
Vol. 9 No. 2, pp. 151 – 177, abril - junio 2026
Revista multidisciplinar
Artículo de revisión bibliográfica
www.concienciadigital.org

University of Mining and Technology, and Southeast University exhibit more moderate but steady increases in output, with most of their publication activity concentrated after 2010. This pattern suggests a growing institutional engagement with carbonation-related research in recent decades, particularly among Chinese universities.

3.14. Scientific output and collaboration by country

The analysis of scientific production by country reveals that China is by far the leading contributor to concrete carbonation research, with over 180 documents, the majority of which are the result of Single-Country Publications (SCP). This highlights China's strong internal research capacity. Korea, France, Italy, and Japan follow, each with moderate levels of production and a notable share of multiple-country publications (MCP), indicating international collaboration. Countries like Portugal, Spain, and Poland show a balanced contribution, while the USA, Brazil, and Germany demonstrate lower overall output. The prevalence of SCPs over MCPs across most countries suggests a tendency toward domestic research initiatives, although several European and Asian countries maintain a healthy level of international cooperation.

3.15. Geographic distribution of scientific production

The global distribution of publications related to concrete carbonation research, illustrated in the world map, shows significant international participation. Countries highlighted in blue represent those contributing to the scientific literature, with China (in dark blue) emerging as the dominant contributor. This widespread involvement demonstrates the global relevance of the topic, with notable activity across Asia, Europe, North America, and parts of Latin America, Africa, and Oceania. However, disparities persist, as some regions particularly in Central Africa and parts of the Middle East remain underrepresented, suggesting potential gaps in research capacity or focus. As presented in **Figure 4**, the analysis highlights the main trends observed in the data.

Figure 4

Geographic distribution of publications on concrete carbonation research

ISSN: **2600-5859**
Vol. 9 No. 2, pp. 151 – 177, abril - junio 2026
Revista multidisciplinar
Artículo de revisión bibliográfica

3.16. *Countries' production overtime*

The temporal evolution of scientific production in the field of concrete carbonation reveals a marked increase in research activity over the past two decades. While publication levels remained minimal until the early 2000s, a significant upward trend is observed from 2010 onward. China shows a sharp and sustained growth, particularly after 2015, becoming the clear leader in cumulative publication output. In contrast, other countries display moderate but steady increases. This trend highlights the growing scientific interest in carbonation phenomena, driven by its implications for the durability and sustainability of concrete structures under environmental exposure.

3.17. *2026 Citation impact by country*

China leads the total number of citations received with a considerable margin, accumulating 3,836 citations, which reflects both high publication output and significant academic influence. France and Portugal follow, with 957 and 954 citations respectively, indicating strong European contributions to the field. Canada, Korea, and Italy also show notable impact with over 450 citations each. The distribution underscores China's dominant position not only in terms of volume but also in research visibility and influence, followed by several key players in Europe and North America.

3.18. *Most cited articles in carbonation research*

The top 10 most globally cited articles in the field of concrete carbonation. The most influential publication is by Papadakis et al. (1991a, 1991b) in *ACI Materials Journal* with 696 citations, followed by another of his works Papadakis (2000), in *Cement and Concrete Research* with 591 citations. Other highly cited articles include studies by Rostami et al. (2012), Chang & Chen (2006) and Pade & Guimaraes (2007) each exceeding 390 citations. These documents primarily appear in top-tier journals such as *Cement and Concrete Research*, *Construction and Building Materials*, and *Electrochimica Acta*. The concentration of citations reflects both the foundational nature of these works and their continued relevance in carbonation and durability research.

3.19. *Most frequent keywords in carbonation-related research*

The most frequently occurring keywords in publications related to concrete carbonation, the term *carbonation* leads with 496 occurrences, followed closely by *concrete carbonation* (463), highlighting the thematic focus of the literature. Other prominent terms include *concretes*, *concrete*, *reinforced concrete*, and *durability*, indicating strong interest in material properties and long-term performance. Technical terms like *carbonation depth*, *carbon dioxide*, and *corrosion* further underscore the emphasis on degradation mechanisms and environmental interactions. These keywords reflect the multidisciplinary nature of carbonation research, spanning materials science, structural

Concienca Digital
ISSN: 2600-5859
Vol. 9 No. 2, pp. 151 – 177, abril - junio 2026
Revista multidisciplinar
Artículo de revisión bibliográfica
www.concienciadigital.org

durability, and environmental engineering.

3.20. Keyword cloud of carbonation-related research

The most prominent keywords are *carbonation*, *concrete carbonation*, and *concrete*, indicating their significant role in the field. Other relevant terms include *reinforced concrete*, *carbonation depth*, *durability*, and *carbon dioxide*, which emphasize the material degradation mechanisms and durability concerns under carbonation processes. Additionally, the presence of terms such as *chlorine compounds*, *accelerated carbonation*, and *fly ash* suggests ongoing research into environmental interactions and mitigation strategies. The size of each word corresponds to its relative frequency, providing a visual summary of the dominant themes in the literature.

3.21. Keyword frequency tree map in carbonation research

Based on their frequency of occurrence in indexed literature. The largest blocks correspond to the term *carbonation* (496 occurrences) and *concrete carbonation* (463 occurrences), highlighting the central focus of current research. Other significant terms include *concrete*, *concrete*, *reinforced concrete*, *durability*, and *carbonation depth*, each reflecting critical aspects such as material types, performance evaluation, and structural vulnerability. Secondary topics such as *corrosion*, *carbon dioxide*, *fly ash*, *chlorine compounds*, and *compressive strength* also appear with notable frequency, suggesting attention to environmental interactions and mechanical properties. The percentage associated with each term indicates its proportional representation in the dataset, allowing for an intuitive understanding of the thematic priorities in the scientific community.

3.22. Keyword frequency tree map in carbonation research overtime

The cumulative occurrences of the most frequent keywords in scientific publications related to concrete carbonation from 1971 to 2025, a significant increase in research output starting in the early 2000s, with a steeper rise observed after 2010. Keywords such as *carbonation*, *concrete carbonation*, *concretes*, and *concrete* show the highest growth rates, indicating their centrality in the literature. Terms like *durability*, *reinforced concrete*, and *carbonation depth* have also shown a consistent upward trend, reflecting sustained interest in performance-related aspects of concrete structures. The acceleration in cumulative frequency suggests an expanding academic focus on the environmental and mechanical implications of carbonation in reinforced concrete, particularly in the context of durability and service life prediction.

3.23. Trends in scientific keywords over time

The temporal emergence and evolution of key terms associated with concrete carbonation research from 1984 to 2025, not only the first appearance of each term but also their

Conciencia Digital
ISSN: 2600-5859
Vol. 9 No. 2, pp. 151 – 177, abril - junio 2026
Revista multidisciplinar
Artículo de revisión bibliográfica
www.concienciadigital.org

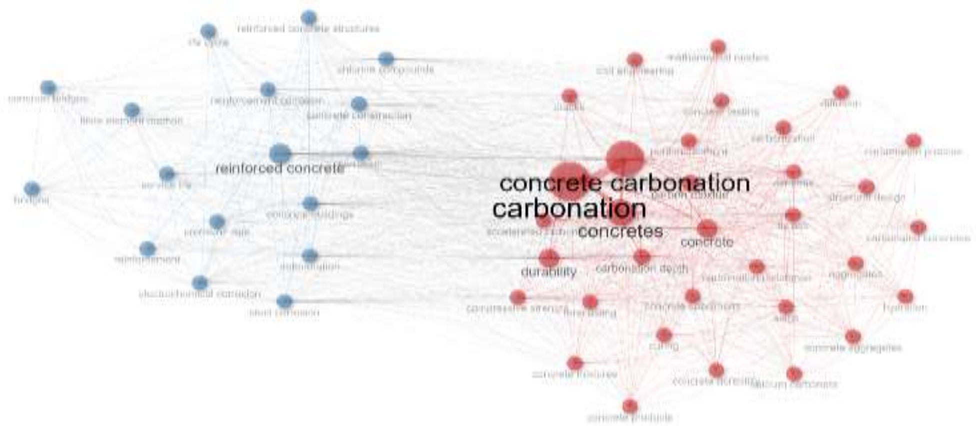
persistence across subsequent years, indicating continued scholarly relevance. Larger circles represent a higher frequency of term usage each year. Foundational terms such as *carbonation*, *concrete carbonation*, *durability*, and *reinforced concrete* have maintained long-term visibility, reflecting their significant role in the discourse. More recent entries such as *machine learning*, *carbon capture and utilization*, and *prediction modelling* suggest a progressive integration of computational methods and sustainability-oriented approaches. This temporal mapping underscores the field's evolution from traditional material characterization toward interdisciplinary solutions addressing environmental challenges and predictive durability assessments.

3.24. Keyword co-occurrence Network

Figure 5 illustrates the co-occurrence network of keywords related to concrete carbonation research. The network is composed of two principal clusters: one centered around "carbonation," "concrete carbonation," and "concretes" (red nodes), and another around "reinforced concrete" (blue nodes). Node size reflects term frequency, while edge thickness indicates the strength of co-occurrence between terms. The red cluster reveals a high degree of interconnectivity among durability-oriented and material science terms such as *carbon dioxide*, *carbonation depth*, *concrete mixtures*, *compressive strength*, and *fly ash*, highlighting a focus on material performance and degradation mechanisms. The blue cluster, on the other hand, is associated with structural and service-life-related terms such as *reinforcement corrosion*, *concrete bridges*, *service life*, and *corrosion rate*, indicating a complementary focus on structural integrity and lifespan. This bifurcation demonstrates a thematic dichotomy in the literature between material behavior under carbonation exposure and its implications for structural performance. The bridging terms (*corrosion*, *concrete construction*, *deterioration*) suggest interdisciplinary crossover between materials engineering and structural durability research.

Figure 5

Keyword co-occurrence network



Concienca Digital
ISSN: **2600-5859**
Vol. 9 No. 2, pp. 151 – 177, abril - junio 2026
Revista multidisciplinar
Artículo de revisión bibliográfica
www.concienciadigital.org

3.25. Thematic structure of the scientific discourse

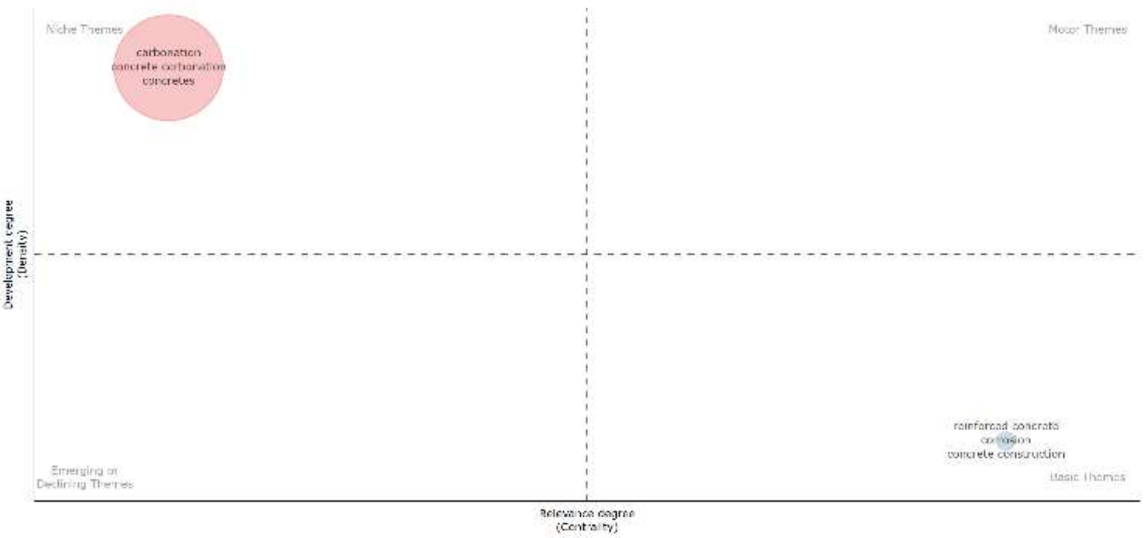
Figure 6 presents the thematic map of keyword clusters in concrete carbonation literature based on centrality (relevance) and density (development). The map reveals two distinct quadrants occupied by the main clusters:

- The upper-left quadrant (Niche Themes) is dominated by the cluster containing "carbonation," "concrete carbonation," and "concretes." This indicates a well-developed but internally specialized body of knowledge that, despite its richness, is weakly connected to other themes. These topics represent focused, mature areas of study driven by domain-specific expertise in material science and deterioration mechanisms.
- The lower-right quadrant (Basic Themes) includes "reinforced concrete," "corrosion," and "concrete construction." These are foundational concepts that are broadly connected across the research field but show lower internal development. Their position suggests that they serve as structural pillars for multiple research directions but may require further depth in specialized exploration.

Notably, the absence of themes in the Motor Themes (upper-right) and Emerging/Declining Themes (lower-left) quadrants suggest that while the field is methodologically solid and well-established, it may lack rapidly developing or interdisciplinary frontiers. This opens an opportunity for innovation by bridging niche and basic themes through interdisciplinary integration or emerging techniques such as AI-based deterioration modeling or environmental sustainability assessment.

Figure 6

Thematic map based on centrality and density of co-occurring keywords



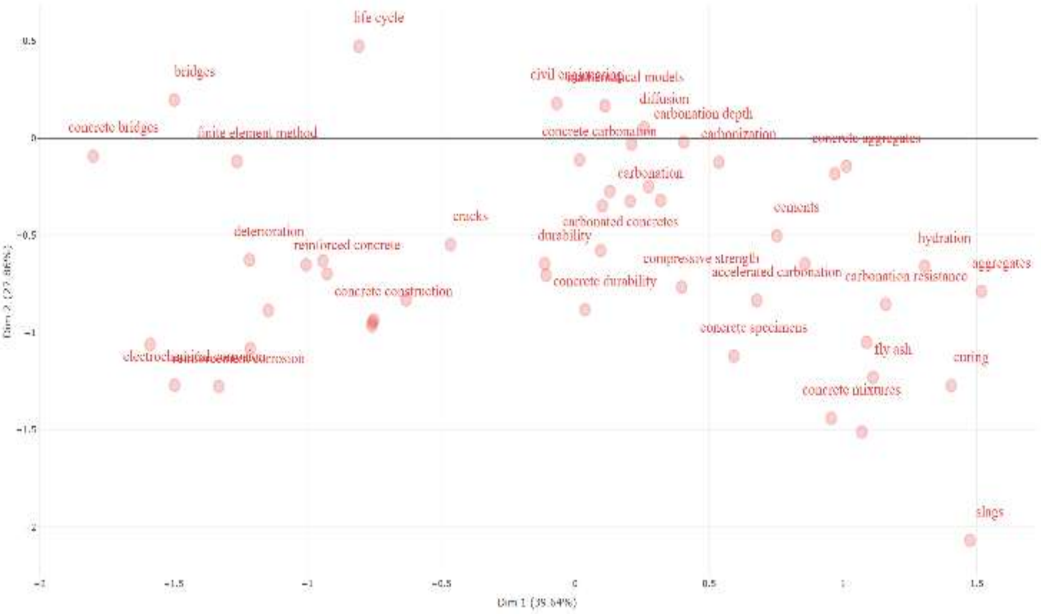
ISSN: **2600-5859**
Vol. 9 No. 2, pp. 151 – 177, abril - junio 2026
Revista multidisciplinar
Artículo de revisión bibliográfica

3.26. Factorial analysis

Figure 7 displays the correspondence analysis plot, revealing the conceptual structure of research topics in the field of concrete carbonation. The analysis was performed using dimensionality reduction, where Dimension 1 (39.64%) and Dimension 2 (27.86%) account for a cumulative 67.5% of the total variance. The right quadrants concentrate terms like "carbonation," "carbonation depth," "accelerated carbonation," and "carbonated concretes," which are tightly grouped, confirming the strong interrelationship of carbonation-specific terminology. This cluster reflects a highly cohesive line of research centered on the carbonation mechanism, its measurement, and its impact on concrete durability. The left quadrants reveal a secondary cluster encompassing "reinforced concrete," "corrosion," "concrete bridges," and "electrochemical corrosion." These terms are positioned farther from the carbonation core but remain conceptually linked, indicating a parallel focus on durability in reinforced structures exposed to carbonation-induced degradation. Terms such as "life cycle," "mathematical models," "fly ash," and "slag" appear more isolated, suggesting emerging or peripheral areas with potential for integration into the central research themes. This spatial distribution highlights the dual structure of the literature: one domain rooted in carbonation kinetics and materials, and another in structural degradation and performance, offering opportunities for interdisciplinary linkage.

Figure 7

Correspondence analysis of keywords related to concrete carbonation

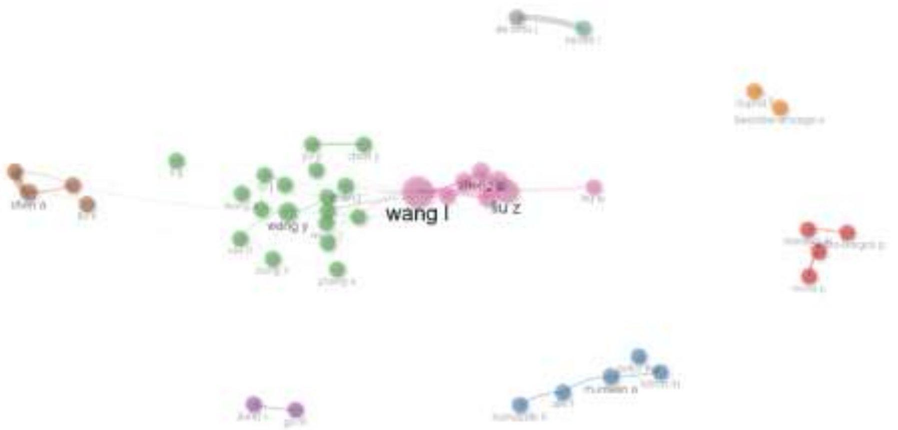


3.27. Collaboration network

Figure 8 illustrates the co-authorship network among the most prolific researchers in concrete carbonation studies. Nodes represent individual authors, while edges denote co-authored publications. The node size reflects the author's publication volume, and color clusters represent distinct collaboration groups based on network modularity. The central node, Wang et al. (2025) emerges as the most influential contributor, indicated by its larger size and multiple connecting edges, particularly within the pink cluster, which includes Zhang et al. (2024) and Liu et al. (2012). This cluster denotes a tightly knit group with high intra-collaboration frequency and strong output. The green cluster, led by Wang et al. (2025) forms another significant community, reflecting collaborative efforts based in China. Notably, Chen et al. (2022) and Liu et al. (2012) appear in a brown cluster, indicating a more isolated but cohesive subgroup. Peripheral authors such as Peter (2007) and Muntean & Böhm (2009) in the blue cluster, and Neves et al. (2013) in the gray cluster, demonstrate limited but distinct collaborative patterns, indicating emerging or geographically distinct research teams. This network topology highlights key opinion leaders and core scientific alliances in the field, offering insights into potential collaboration strategies and trend identification.

Figure 8

Co-authorship network in the field of concrete carbonation research



3.28. Global scientific collaboration network

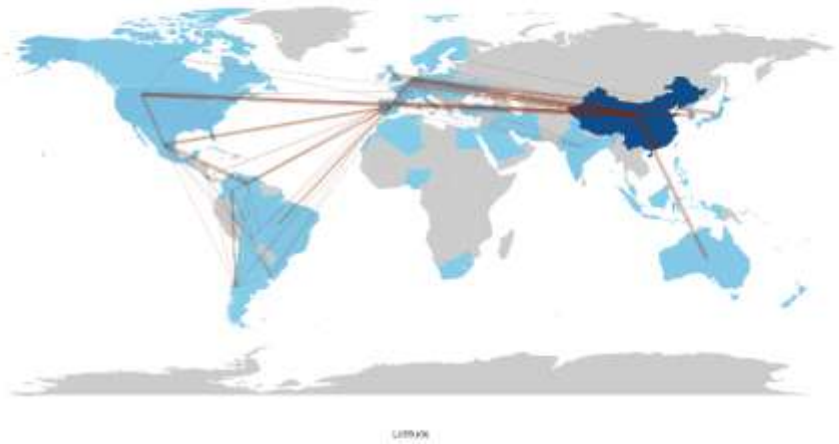
Figure 9 presents a world map highlighting the international collaboration network in the field of concrete carbonation. Each line represents a co-authorship link between countries, while country shading intensity reflects the volume of publications: darker shades indicate higher output. China emerges as the leading contributor, as denoted by the deepest blue, with robust collaborative ties to countries in Europe, North and South America, and Oceania. Notably, strong links are observed with Spain, the United States, Brazil, Australia, and the United Kingdom, indicating a widespread global interest and

ISSN: **2600-5859**
Vol. 9 No. 2, pp. 151 – 177, abril - junio 2026
Revista multidisciplinar
Artículo de revisión bibliográfica

joint efforts in this research area. **Figure 9** demonstrates a pronounced North-South and East-West connectivity pattern, suggesting that while research on carbonation is global, hubs in Asia and Europe dominate scholarly output and partnerships. This distribution may reflect differences in research funding, infrastructure, or vulnerability of infrastructure to carbonation-related deterioration. These findings underscore the importance of international collaboration in advancing knowledge on concrete durability, particularly in addressing climate-related impacts on reinforced concrete structures.

Figure 9

Global scientific collaboration



4. Discussion

The bibliometric and scient metric analysis of the literature on concrete carbonation reveals significant insights into the evolution, structure, and global dynamics of this research field.

4.1. Temporal evolution and emerging trends

As illustrated in the bubble timeline, the interest in carbonation-related terms has increased steadily, particularly after 2005, with a notable acceleration post-2015. The peak frequency observed in terms such as concrete carbonation, carbonation depth, durability, and reinforced concrete corresponds to a growing awareness of the impact of environmental conditions on infrastructure service life (Ekolu, 2020; Zhao et al., 2024). Recent terms such as machine learning, carbon footprint, and CO2 capture suggest a multidisciplinary expansion toward sustainability and climate mitigation (Ji et al., 2010; Castro et al., 2000; Kaewunruen et al., 2018; Al-Khayat et al., 2002; Li et al., 2011; Murali & Sudalaimani, 2020; Peng & Stewart, 2013; Peng et al., 2023; Chen et al., 2021; Ekolu, 2023; Ghanooni-Bagha et al., 2020; Pacheco-Torgal et al., 2013).

Concienca Digital
ISSN: 2600-5859
Vol. 9 No. 2, pp. 151 – 177, abril - junio 2026
Revista multidisciplinar
Artículo de revisión bibliográfica
www.concienciadigital.org

4.2. Co-occurrence and conceptual structure

The co-word network reveals two dominant research clusters: one centered on reinforced concrete and corrosion, and another on concrete carbonation and durability. The size of the nodes and density of links indicate that carbonation, concretes, and durability are highly interconnected with a broad range of terms including compressive strength, carbonation depth, pH, and accelerated tests, aligning with studies focused on material degradation mechanisms and performance prediction (Redaelli & Bertolini, 2011).

4.3. Thematic map and strategic positioning

In the strategic diagram, the cluster formed by carbonation, concrete carbonation, and concrete appears as a well-developed (dense) research niche with moderate centrality. In contrast, reinforced concrete, corrosion, and concrete construction appear as basic and transversal themes with high centrality but lower development. This suggests that carbonation research is technically specialized and methodologically mature but still under-integrated into broader construction and materials science frameworks (Moir & Kelham, 1997; Ke et al., 2020).

4.4. Factorial analysis: cognitive structure

The correspondence analysis confirms the separation between structural-mechanical topics (e.g., reinforced concrete, deterioration, corrosion rate) and physico-chemical or durability-oriented terms (e.g., carbonation, hydration, fly ash, cement). This duality reflects the coexistence of macrostructural and microstructural approaches in carbonation research, as previously discussed (Xue et al., 2022; Chen & Gao, 2020; Vořechovská et al., 2017; Parrot, 1987; Kashef-Haghighi & Ghoshal, 2009).

4.5.Scientific collaboration: author and country networks

The author collaboration network shows that the most prolific and central authors (e.g., Wang et al., 2025) form dense clusters located in China. This correlates with the international collaboration map, which shows that China leads global research in this field, with strong bilateral links to Europe, North and South America, and Oceania. This distribution reflects the combination of environmental exposure concerns, construction volumes, and research investment (Li & Su, 2021) .

4.6.Research gaps and future directions

Despite the extensive studies on carbonation depth prediction and accelerated testing, there is limited integration of in situ monitoring, NDT, and AI-based models. The interaction between carbonation and other degradation mechanisms remains underexplored (Sagoe-Crentsil & Glasser, 1989; Peter, 2007; Brueckner et al., 2014). Emerging research avenues include carbonation as a CO_2 sink, the role of SCMs, and service life modeling in BIM systems (Lin & Han, 2021). Strengthening contributions from Latin America and Africa could enhance the global understanding of carbonation under diverse climatic and construction contexts.

5. Conclusions

- The bibliometric analysis has enabled the identification of the main research themes, leading authors, and collaboration networks within the field of concrete carbonation, with a particular focus on its interaction with reinforced concrete structures. The results indicate that the term "concrete carbonation" represents a high-density but low-centrality topic, classifying it as a niche theme, whereas terms such as "reinforced concrete" and "corrosion" are basic themes, characterized by high centrality but lower development.
- The temporal evolution reveals a steady increase in research interest in this area, especially from 2005 onwards, with a peak in 2016. This trend reflects growing attention to the durability of structures and the sustainability of construction materials. Additionally, co-occurrence and collaboration network analyses confirm that China leads scientific output in this domain, both in terms of volume and author network centrality.
- This landscape provides insight into the current research trends, highlighting the need for further exploration of predictive models, accelerated testing methods, and the influence of variables such as pH, calcium compounds, and environmental conditions. Future research should aim to strengthen the connection between high-density and high-centrality topics, promoting interdisciplinary studies that integrate civil engineering, materials science, and computational modeling.

6. Conflict of interest

The authors declare that there is no conflict of interest in relation to the article presented.

7. Authors' Contribution Statement

All authors contributed significantly to the elaboration of the article.

8. Financing costs

This research was funded entirely with the authors' own funds.

9. References

Ahmed, O., Al-Fakih, A., Adekunle, S. K., & Ahmad, S. (2025). Scopus-based bibliometric analysis of carbon capture in concrete: research components and intellectual connections. *Next Research*, *2*(3), 100426. https://doi.org/10.1016/J.NEXRES.2025.100426

Aiki, T., & Kumazaki, K. (2020). Differentiability of a solution of a free boundary problem describing water adsorption. *Advances in Mathematical Sciences and Applications*, *29*(1), 247–282. https://gakuto.co.jp/docs/download/pdf/amsa_vol29_247-282.pdf

Aiki, T., & Timoshin, S. A. (2017). Existence and uniqueness for a concrete carbonation process with hysteresis. *Journal of Mathematical Analysis and Applications, 449(2), 1502–1519. https://doi.org/10.1016/j.jmaa.2016.12.086*

Al-Khayat, H., Haque, M. N., & Fattuhi, N. I. (2002). Concrete carbonation in arid climate. *Materials and Structures Materiaux Et Constructions*, *35*(251), 421–426. https://doi.org/10.1617/13672

Andrade, C., Alonso, C., & Gonzalez, J. A. (1986). Some laboratory experiments on the inhibitor effect of sodium nitrite on reinforcement corrosion. *Cement Concrete and Aggregates*, *8*(2), 110–116. https://doi.org/10.1520/cca10064j

Apostolopoulos, C. A., & Papadakis, V. G. (2008). Consequences of steel corrosion on the ductility properties of reinforcement bar. *Construction and Building Materials*, *22*(12), 2316–2324. https://doi.org/10.1016/j.conbuildmat.2007.10.006

Brueckner, R., Wright, D., Atkins, C., & Lambert, P. (2014). Risk mitigation of transport structures susceptible to premature degradation in aggressive environments. *In Bridge Maintenance Safety Management and Life Extension Proceedings of the 7th International Conference of Bridge Maintenance Safety and Management Iabmas 2014*, 2670–2676. https://api.pageplace.de/preview/DT0400.9781315760698_A23888595/preview-9781315760698_A23888595.pdf

Castro, P., Moreno, E. I., & Genescá, J. (2000). Influence of marine micro-climates on carbonation of reinforced concrete buildings. *Cement and Concrete Research*, *30*(10), 1565–1571. https://doi.org/10.1016/S0008-8846(00)00344-6

Chang, C.-F., & Chen, J.-W. (2006). The experimental investigation of concrete carbonation depth. *Cement and Concrete Research*, *36*(9), 1760–1767. https://doi.org/10.1016/j.cemconres.2004.07.025

Chen, A., Fang, X., Pan, Z., Wang, D., Pan, Y., & Peng, B. (2022). Engineering practices on surface damage inspection and performance evaluation of concrete bridges in China. *Structural Concrete*, *23*(1), 16–31. https://doi.org/10.1002/suco.202100158

Chen, G., Lv, Y., Zhang, Y., & Yang, M. (2021). Carbonation depth predictions in concrete structures under changing climate condition in China. *Engineering Failure Analysis, 119(104990), 104990. https://doi.org/10.1016/j.engfailanal.2020.104990*

Chen, J. (2016). A study on the properties of high performance concrete with compound mineral admixtures. *International Journal of Simulation Systems Science and Technology*, *17*(36), 48.1-48.9. https://www.researchgate.net/publication/316278450_A_Study_on_the_Properties_of_High_Performance_Concrete_with_Compound_Mineral_Admixtures

Chen, T., & Gao, X. (2020). Use of carbonation curing to improve mechanical strength and durability of pervious concrete. *ACS Sustainable Chemistry and Engineering*, *8*(9), 3872–3884. https://doi.org/10.1021/acssuschemeng.9b07348

Chen, X., Liu, X., Cheng, S., Bian, X., Bai, X., Zheng, X., Xu, X., & Xu, Z. (2025). Machine learning-based modelling and analysis of carbonation depth of recycled aggregate concrete. *Case Studies in Construction Materials, 22(e04162), e04162. https://doi.org/10.1016/j.cscm.2024.e04162*

Cui, H., Tang, W., Liu, W., Dong, Z., & Xing, F. (2015). Experimental study on effects of CO2 concentrations on concrete carbonation and diffusion mechanisms. *Construction and Building Materials*, *93*, 522–527. https://doi.org/10.1016/j.conbuildmat.2015.06.007

Ekolu, S. O. (2020). Implications of global CO2 emissions on natural carbonation and service lifespan of concrete infrastructures – Reliability analysis. *Cement and Concrete Composites*, *114(103744), 103744. https://doi.org/10.1016/j.cemconcomp.2020.103744*

Ekolu, S. O. (2023). Temperature-induced effect of climate change on natural carbonation of concrete structures. *ACI Material Journal*, *120*(1), 101–116. https://doi.org/10.14359/51737335

Ghanooni-Bagha, M., YekeFallah, M. R., & Shayanfar, M. A. (2020). Durability of RC structures against carbonation-induced corrosion under the impact of climate change. *Ksce Journal of Civil Engineering*, *24*(1), 131–142. https://doi.org/10.1007/s12205-020-0793-8

Parrot, L. J. (1987). A review of carbonation in reinforced concrete. *Building research establishment – Department of the environment*. https://es.scribd.com/document/376573980/A-Review-of-Corbonation-in-Concrete

Huet, B., L'Hostis, V., Miserque, F., & Idrissi, H. (2005). Electrochemical behavior of mild steel in concrete: Influence of pH and carbonate content of concrete pore solution. *Electrochimica Acta*, *51*(1), 172–180. https://doi.org/10.1016/j.electacta.2005.04.014

Ichikawa, T., Haga, K., & Yamada, K. (2024). Extraction of carbonation rate from depth profile of concrete carbonation by using pseudo-analytical solution of two-component reaction-diffusion equation. *Journal of Advanced Concrete Technology*, *22*(3), 139–148. https://doi.org/10.3151/jact.22.139

Ji, Y., Yuan, Y., Shen, J., Ma, Y., & Lai, S. (2010). Comparison of concrete carbonation process under natural condition and high CO2 concentration environments. *Journal Wuhan University of Technology Materials Science Edition*, *25*(3), 515–522. https://doi.org/10.1007/s11595-030-0034-y

Kaewunruen, S., Wu, L., Goto, K., & Najih, Y. M. (2018). Vulnerability of structural concrete to extreme climate variances. *Climate*, *6*(2), 40. https://doi.org/10.3390/cli6020040

Kashef-Haghighi, S., & Ghoshal, S. (2009). CO2Sequestration in concrete through accelerated carbonation curing in a flow-through reactor. *Industrial & Engineering Chemistry Research*, *49*(3), 1143–1149. https://doi.org/10.1021/ie900703d

Ke, Y., Fang, Y., Guo, Y., Zhu, S., Zhang, S., & Zhang, X. (2020). Development of novel polycarboxylate superplasticizer and its influence on carbonation performance of concrete. *2020 International Conference on Artificial Intelligence and Electromechanical Automation (AIEA).* https://doi.org/10.1109/AIEA51086.2020.00156

Lau, K., Permeh, S., Faridmarandi, S., Ghahfarokhi, M. S., & Azizinamini, A. (2024). Carbonation-induced corrosion assessment for reinforced concrete structures. *Ampp Annual Conference and Expo 2024*. https://www.semanticscholar.org/paper/Carbonation-Induced-Corrosion-Assessment-for-Lau-Permeh/b113a7f2f95ab8b1414b1a1ee8492e09f21f0614

Li, G., Yuan, Y. S., Liu, X., Du, J. M., & Li, F. M. (2011). Influences of environment climate conditions on concrete carbonation rate. *Advanced Materials Research,* 194–196. https://doi.org/10.4028/www.scientific.net/amr.194-196.904

Li, Y., & Su, Y.-Q. (2021). Gas permeability and meso-structure of fiber reinforced concrete under carbonation based on different pore sizes. *Journal of Jilin University Engineering and Technology Edition*, *51*(4), 1287–1295. https://oversea.cnki.net/kcms2/article/abstract?v=lj-1FT9NYjBiy57aL_MOh0gzNYe9xLhhKEftmZg6e6sfZ3krYHOtgHNMdZpk6wtolZpMcTvsmMgYEsV9sADTDvICa8KtS8sYrALTIEFulFPvFqkLA28ZLyAZSJzKdcwpf-nongomEuImOQ1x-KBC7Xq3488vn7VC8A1TnVz8ElKyNRnO0aApk2tKfyWze0nv&uniplatform=OVERSEA&language=en

Lin, P., & Han, W. (2021). Durability software development of concrete bridge based on BIM Technology. *Journal of Railway Engineering Society*, *38*(3), 80–85. https://www.researchgate.net/publication/355383155_Durability_Software_Development_of_Concrete_Bridge_Based_on_BIM_Technology

Liu, Z., Deng, D., de Schutter, G., & Yu, Z. (2012). "Salt weathering" distress on concrete by sulfates? In book: Advances in Crystallization Processes, 432-464. https://www.researchgate.net/publication/300816475_Salt_Weathering_Distress_on_Concrete_by_Sulfates

Moir, G. K., & Kelham, S. (1997). Developments in the manufacture and use of Portland limestone cement. *American Concrete Institute ACI Special Publication*, *SP-172*, 797–819. https://trid.trb.org/View/476574

Moreno, E. I. (2010). Discussion of "sources of variations when comparing concrete carbonation results" by F. G. da Silva, P. Helene, P. Castro-Borges, and J. B. L. Liborio. *Journal of Materials in Civil Engineering*, *22*(7), 758. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000075

Moreno, E., Castro-Borges, P., & Cob-Sarabia, E. (2004). Corrosion rates from carbonated concrete specimens. *In the Corrosion 2004*, *New Orleans, Louisiana, March 2004.* https://onepetro.org/NACECORR/proceedings-abstract/CORR04/CORR04/NACE-04439/115777

Muntean, A. (2023). Multiscale carbonation reactions: Status of things and two modeling exercises related to cultural heritage. In *Mathematical Modeling in Cultural Heritage* (pp. 175–185). Springer Nature Singapore. https://doi.org/10.1007/978-981-99-3679-3_11

Muntean, A., & Böhm, M. (2007). Dynamics of a moving reaction interface in a concrete wall. In *International Series of Numerical Mathematics* (Vol. 154). https://doi.org/10.1007/978-3-7643-7719-9_31

Muntean, A., & Böhm, M. (2009). A moving-boundary problem for concrete carbonation: Global existence and uniqueness of weak solutions. *Journal of Mathematical Analysis and Applications*, *350*(1), 234–251. https://doi.org/10.1016/j.jmaa.2008.09.044

Murali Kannan, S. P., & Sudalaimani, K. (2020). Spatial time dependent reliability analysis of carbonation with climate change. *Polish Journal of Environmental Studies*, *29*(6), 4123–4129. https://doi.org/10.15244/pjoes/119100

Neves, R., Branco, F., & De Brito, J. (2013). Field assessment of the relationship between natural and accelerated concrete carbonation resistance. *Cement and Concrete Composites*, *41*, 9–15. https://doi.org/10.1016/j.cemconcomp.2013.04.006

Pacheco-Torgal, F., Miraldo, S., Labrincha, J. A., & De Brito, J. (2013). An eco-efficient approach to concrete carbonation. In *Eco Efficient Concret*, *368-385*. https://doi.org/10.1533/9780857098993.3.368

Pade, C., & Guimaraes, M. (2007). The CO2 uptake of concrete in a 100-year perspective. *Cement and Concrete Research*, *37*(9), 1348–1356. https://doi.org/10.1016/j.cemconres.2007.06.009

Papadakis, V. G. (2000). Effect of supplementary cementing materials on concrete resistance against carbonation and chloride ingress. *Cement and Concrete Research*, *30*(2), 291–299. https://doi.org/10.1016/S0008-8846(99)00249-5

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

Papadakis, V. G., Vayenas, C. G., & Fardis, M. N. (1991a). Experimental investigation and mathematical modeling of the concrete carbonation problem. *Chemical Engineering Science*, *46*(5–6), 1333–1338. https://doi.org/10.1016/0009-2509(91)85060-B

Papadakis, V. G., Vayenas, C. G., & Fardis, M. N. (1991b). Fundamental modeling and experimental investigation of concrete carbonation. *ACI Materials Journal*, *88*(4), 363–373. https://www.concrete.org/publications/internationalconcreteabstractsportal.aspx?m=details&ID=1863

Peng, J., Liao, P., Wang, B., & Tu, R. (2023). Uncertainty analysis of RC carbonation-induced damage affected by climate change. *Journal of Railway Science and Engineering*, *20*(8), 3181–3191. https://oversea.cnki.net/kcms2/article/abstract?v=lj-1FT9NYjCwy43XZqdgJ5k_3ZmlZHvkw75f-hwU13BlnvRH-OM2437wxyMU9UW19JDANVXUQFLs_x9-VUswnfHxgt8qomEBt-oner_WnjICfnST4DzRLrzM3Poxvuo_N_eAMDzghtApW4_JFBWvU0qQ0Sge1QNIXTo2OlvOwFyGShMB76aqRECBxMfDmHye&uniplatform=OVERSEA&language=en

Peng, L., & Stewart, M. G. (2013). Deterioration of concrete structures in Australia under a changing climate. *From Materials to Structures Advancement Through Innovation Proceedings of the 22nd Australasian Conference on the Mechanics of Structures and Materials Acmsm 2012*, 1015–1020. https://www.researchgate.net/publication/300377116_Deterioration_of_concrete_structures_in_Australia_under_a_changing_climate

Peter, M. A. (2007). Homogenisation of a chemical degradation mechanism inducing an evolving microstructure. *Comptes Rendus Mecanique*, *335*(11), 679–684. https://doi.org/10.1016/j.crme.2007.09.003

Redaelli, E., & Bertolini, L. (2011). Electrochemical repair techniques in carbonated concrete. Part I: Electrochemical realkalisation. *Journal of Applied Electrochemistry*, *41*(7), 817–827. https://doi.org/10.1007/s10800-011-0301-4

Rostami, V., Shao, Y., Boyd, A. J., & He, Z. (2012). Microstructure of cement paste subject to early carbonation curing. *Cement and Concrete Research*, *42*(1), 186–193. https://doi.org/10.1016/j.cemconres.2011.09.010

Sagoe-Crentsil, K. K., & Glasser, F. P. (1989). Steel in concrete: Part I - A review of the electrochemical and thermodynamic aspects. *Magazine of Concrete Research, 41*(149), 205–212. https://doi.org/10.1680/macr.1989.41.149.205

Silva, A., Neves, R., & De Brito, J. (2014). Statistical modelling of carbonation in reinforced concrete. *Cement & Concrete Composites, 50, 73–81.* https://doi.org/10.1016/j.cemconcomp.2013.12.001

Torres-Acosta, A. A., Castro-Borges, P., Troconis de Rincón, O., Martín-Pérez, B., Martínez-Molina, W., Alonso-Guzmán, E., Bernabé-Reyes, C., Pérez-López, T., Arista-Perrusquía, C., Crespo-Sánchez, S. E., Pérez-Quiroz, J. T., López-Miguel, A., López-Vazquez, E., Juárez-Cruz, C. E., Rodríguez, J. A., Rodríguez-Gómez, F. J., Baltazar-Zamora, M. A., Landa-Ruiz, L., Maldonado-Bandala, E., … Moreno-Herrera, J. A. (2024). Concrete carbonation in tropical urban and urban/marine environments after 20 years of natural exposure. *Construction and Building Materials*, *450*(138511), 138511. https://doi.org/10.1016/j.conbuildmat.2024.1

Vořechovská, D., Šomodíková, M., Podroužek, J., Lehký, D., & Teplý, B. (2017). Concrete structures under combined mechanical and environmental actions: Modelling of durability and reliability. *Computers and Concrete*, *20*(1), 99–110. https://doi.org/10.12989/cac.2017.20.1.99

Wang, B., Wang, S. Y., Wu, S., Wang, X., & He, X. (2013). Research on carbonation life prediction model of recycled concrete structures. *Applied Mechanics and Materials*, *351–352*. https://doi.org/10.4028/www.scientific.net/amm.351-352.1620

Wang, L., Ma, C., Li, Y., Zhang, M., & Liu, J. (2025). The microstructure evolution of cement pastes and steel corrosion behavior under natural and accelerated carbonation: CO2 concentration, temperature and humidity. *Construction and Building Materials*, 490(142433), 142433. https://doi.org/10.1016/j.conbuildmat.2025.142433

Xue, Q., Zhang, L., Mei, K., Wang, L., Wang, Y., Li, X., Cheng, X., & Liu, H. (2022). Evolution of structural and mechanical properties of concrete exposed to high concentration CO2. *Construction and Building Materials*, 343(128077), 128077. https://doi.org/10.1016/j.conbuildmat.2022.128077

Zhao, Q., Iwama, K., Dai, J. G., Liu, J., Zhang, D., Maekawa, K., & Zhao, X. L. (2024). Deterioration modelling of GFRP-reinforced cement-based concrete infrastructure in service under the natural inland atmospheric environment. *Construction and Building Materials*, 447(138005), 138005. https://doi.org/10.1016/j.conbuildmat.2024.138005