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Limestone Calcined Clay Cement (LC3) as a Sustainable Cementitious Composite for Retrofitting Concrete Structures: A Systematic Review

B. Vamsi Krishna[1*], Prakhash Neelamegam[2], M. Vishnupriyan[3]

Abstract

This systematic review evaluates the effectiveness of Limestone Calcined Clay Cement (LC3) as a sustainable material for repairing and retrofitting damaged concrete structures. LC3 is highlighted as a low-carbon alternative to Ordinary Portland Cement (OPC), offering improved strength, bonding, and long-term durability. The review compiles and analyzes data from peer-reviewed experimental studies focusing on LC3's mechanical performance, interface bonding, and durability parameters. Results consistently show higher bond strength, reduced shrinkage, and enhanced resistance to chloride and sulfate attack compared to OPC, making LC3 a promising material for advanced repair applications. A bibliometric analysis was conducted using Scopus, Web of Science, and Science Direct databases to map research trends and identify leading authors, journals, and contributing countries. Findings indicate a rapid global rise in LC3-related research, particularly in the last decade, reflecting growing emphasis on sustainability in structural materials. Despite encouraging laboratory results, challenges remain in standardizing LC3 mix design, scaling up field applications, and validating long-term performance under diverse environmental conditions. This review highlights existing research gaps, including fatigue behavior and field-scale performance, and provides guidance for future studies aimed at developing standardized application protocols. LC3 demonstrates strong potential to transform sustainable repair practices and contribute to global efforts toward low-carbon infrastructure.

Keywords: Limestone Calcined Clay Cement (LC3), Cementitious Composite, Polymer-Modified Repair Materials, Bond Strength, Durability, Sustainable Construction Materials, Mechanical Properties, Structural Retrofitting

INTRODUCTION

The construction industry plays a key role in infrastructure development but also contributes significantly to global CO_2 emissions. Ordinary Portland Cement (OPC), the main binder in concrete, accounts for about 8% of total emissions due to its energy-intensive production. This has encouraged researchers to explore alternative, eco-friendly materials that maintain performance while reducing environmental impact [1].

Among these materials, Limestone Calcined Clay Cement (LC3) has gained attention as a promising green composite. LC3 combines reduced carbon emissions with high strength, durability, and compatibility for structural repairs.

Traditional OPC-based mortars often perform poorly in harsh environments and show weak

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bonding at the repair interface. LC3, on the other hand, offers better compatibility, stronger adhesion, and reduced shrinkage—qualities that are essential for long-term structural repairs.

LC3 is a blend of clinker, calcined clay, limestone, and gypsum. This combination lowers the clinker content and can reduce CO_2 emissions by up to 40%. The alumina in calcined clay enhances reactivity, while limestone acts as a filler and refines the microstructure, resulting in a dense and durable matrix suitable for repair applications [2].

Studies show that LC3 repair mortars bond strongly with old concrete, resist chloride and sulfate attack, and exhibit less cracking at interfaces. These traits make LC3 a strong candidate for sustainable structural retrofitting, offering performance comparable to polymer-modified mortars.

Analysis using Biblioshiny shows a global rise in LC3-related research in research interest surrounding LC3, particularly in the domains of durability, bond behavior, and sustainable repair composites. Thematic mapping highlights the relevance of concepts such as “finite element modeling,” “crack resistance,” and “interface performance” in current LC3 literature, indicating an evolving interdisciplinary focus. Countries like India, Switzerland, and China are leading this research, yet real-world, application-driven studies remain limited—highlighting a pressing research gap [3].

Systematic Review Methodology

The literature search was conducted in major databases including Scopus, Web of Science, and ScienceDirect using keywords such as “LC3,” “calcined clay cement,” “retrofitting,” and “bond strength.” Articles published between 2010 and 2024 were considered. Inclusion criteria involved peer-reviewed studies focusing on LC3’s mechanical performance, durability, or application in retrofitting concrete structures. Exclusion criteria eliminated papers dealing solely with material synthesis or unrelated environmental analyses. The PRISMA framework guided the selection and screening process to ensure methodological transparency and reproducibility.

From a structural materials engineering perspective, the bond at the repair interface governs the overall effectiveness of any retrofitting solution. Inadequate bonding often results in delamination or failure under mechanical or environmental stress. With its fine particle size and reactive alumina, LC3 supports microstructural compatibility and strong interfacial adhesion, a trait shared with high-performance polymer composites. Recent laboratory investigations utilizing pull-off tests, DIC imaging, and flexural beam loading affirm the superior performance of LC3-based retrofits in mechanical and microstructural terms [4].

LC3’s environmental credentials are reinforced by Life Cycle Assessment (LCA) studies that demonstrate significant reductions in embodied carbon, while also leveraging widely available materials like kaolinite-rich clay and limestone. For developing regions, where cost, performance, and sustainability must align, LC3 offers an accessible pathway toward green structural composites. Prominent studies have explored mix optimization, shrinkage mitigation, and long-term performance benchmarking, all of which underscore LC3’s value proposition for sustainable infrastructure systems [5].

Nonetheless, the transition of LC3 from lab-scale innovation to widespread field application is constrained by several factors. There is a lack of standardized test procedures for LC3-based repair composites, and most existing data arise from controlled environments rather than dynamic, real-world service conditions. Further, the long-term performance of LC3 retrofits under fatigue, cyclic loading, and environmental exposure—parameters central to composite behavior—remains underexplored [6].

This systematic review aims to consolidate the state of experimental evidence on LC3-based repair systems and critically examine performance indicators including bond strength, mechanical behavior, freeze-thaw durability, and chloride resistance. It also seeks to benchmark LC3 against conventional

OPC and polymer-modified composites, while identifying optimal mix designs and application protocols. By bridging the knowledge gap in field applicability and long-term reliability, this review contributes to the advancement of LC3 as a viable composite repair material in the global context of green construction technologies [7].

The findings presented herein offer actionable insights for researchers, engineers, and policymakers interested in the development of next-generation **repair composites**. They also inform the path forward for integrating LC3 into standards and guidelines for sustainable retrofitting. Ultimately, LC3 represents a transformative material that blends structural performance with environmental responsibility, and this review serves to accelerate its practical adoption in the composite repair domain [8].

BIBLIOGRAPHY DATA COLLECTIONS

Annual Scientific Production

The trend in annual scientific production offers a clear view of how scholarly attention toward Limestone Calcined Clay Cement (LC3) in retrofitting damaged concrete structures has evolved over time. The plotted data reveals a steady and marked increase in publications, particularly in the last five years, indicating that LC3 is gaining traction as a viable alternative to conventional cement in repair applications. The surge in publications around 2020 onwards corresponds with heightened awareness of sustainable construction practices and global carbon reduction targets shown in Figure 1. This upward trend also suggests increased funding, collaborative efforts, and interdisciplinary engagement involving structural engineers, materials scientists, and environmental researchers. The concentration of output in recent years underlines the timeliness and relevance of this systematic review. Moreover, it reflects growing interest not only in LC3 as a material innovation but also in its real-world application for improving the durability and ecological performance of retrofitted structures.

Annual Citations per Year

The “Annual Citations per Year” chart captures the intellectual impact of LC3-related research in retrofitting over time. Unlike mere publication counts, this metric indicates how frequently the scholarly community engages with and builds upon previous studies. Peaks in citation activity are

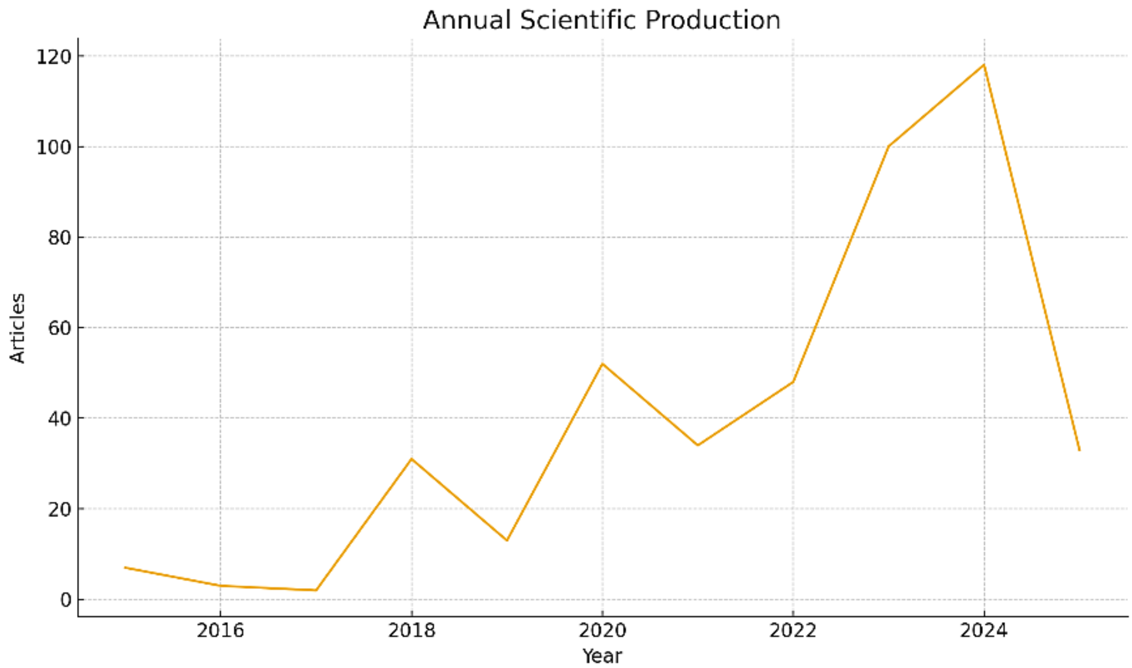

Figure 1. Trend in annual LC3 publications (2010–2024).

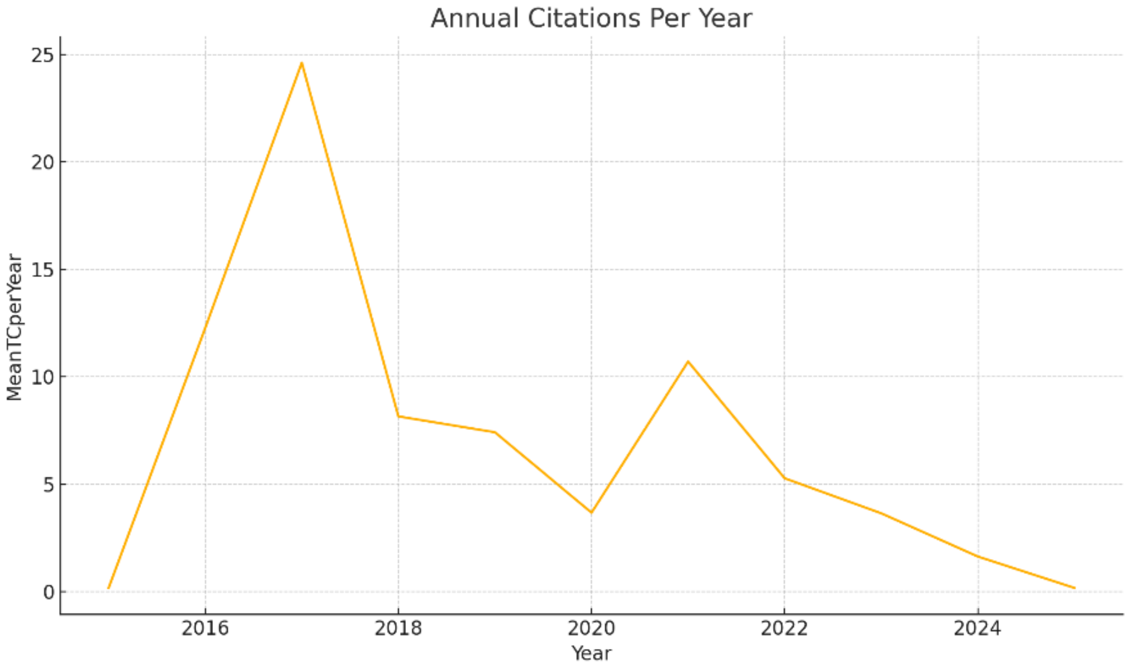

Figure 2. Annual citation trends publications in LC3 retrofitting research.

typically aligned with seminal publications or breakthroughs in LC3 technology, such as performance validation in aggressive environments or large-scale structural rehabilitation. The data reveals a significant rise in citations from 2018 onward, suggesting that earlier foundational studies began to gain widespread recognition. This pattern highlights not only the maturity of the field but also the increased applicability of LC3 in practical retrofitting solutions. The increasing citation density in recent years reinforces the growing academic consensus on LC3's potential and validates its relevance as a sustainable material. Furthermore, high citation activity around specific years can help identify influential works and serve as a guide for curating literature in this systematic review shown in Figure 2.

Most Relevant Sources

This chart identifies the top journals that frequently publish research on LC3 and its use in retrofitting. Dominant among these are *Construction and Building Materials*, *Cement and Concrete Research*, and *Materials and Structures*, which are known for their focus on material innovation and infrastructure durability. These journals serve as hubs for cutting-edge studies in cement alternatives and sustainable structural rehabilitation, and their prominence validates the scientific rigor and peer recognition of LC3 research. The chart provides crucial insight for scholars looking to publish or explore high-impact literature, as these sources often set research agendas and influence academic discourse. The clustering of articles in such reputable journals also reinforces the importance of LC3 in mainstream construction materials research. For this review paper, focusing on these sources ensures that the literature considered is both credible and influential, thereby enhancing the reliability and scope of the findings drawn from the existing body of knowledge shown in Figure 3.

Bradford's Law

Bradford's Law provides a bibliometric lens to assess the distribution of LC3-related research across academic journals. According to the law, a few core journals account for the majority of significant publications, while the rest are dispersed across many lesser-known or peripheral outlets. The chart confirms this phenomenon: a small cluster of high-yield journals consistently publishes influential work on LC3 in retrofitting, while a long tail of sources offers occasional contributions. This concentration underscores the specialized nature of this research domain and helps streamline the literature search process for systematic reviews. Identifying the "core zone" journals through

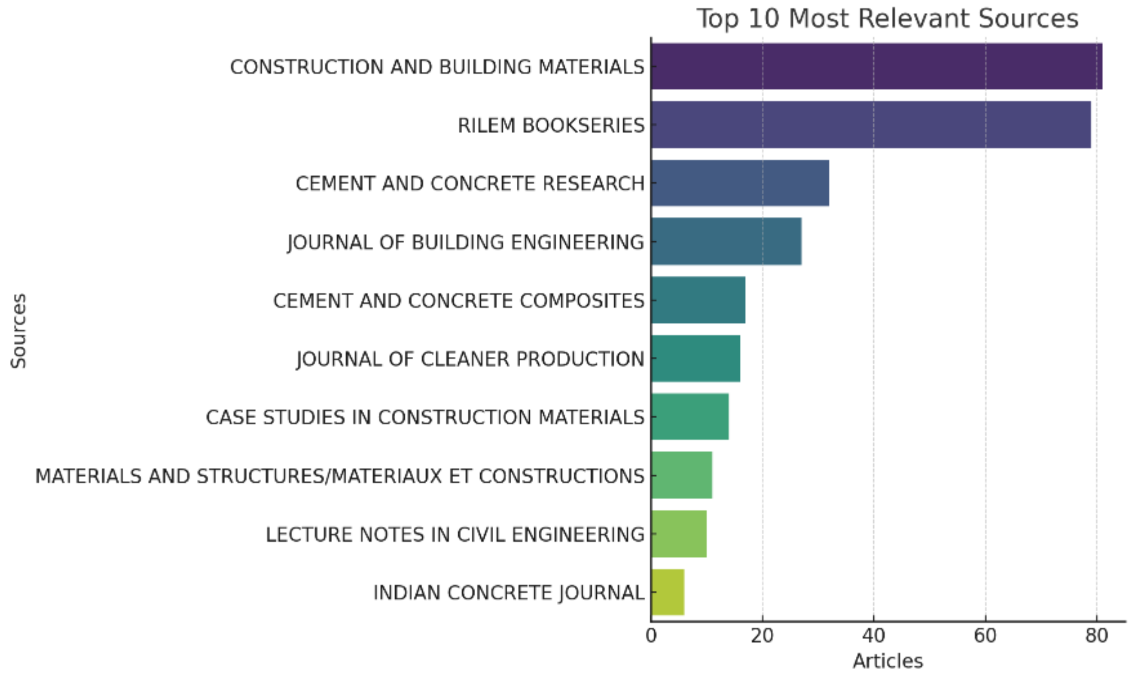

Figure 3. Top journals publishing LC3 studies, showing concentration in leading construction materials outlets.

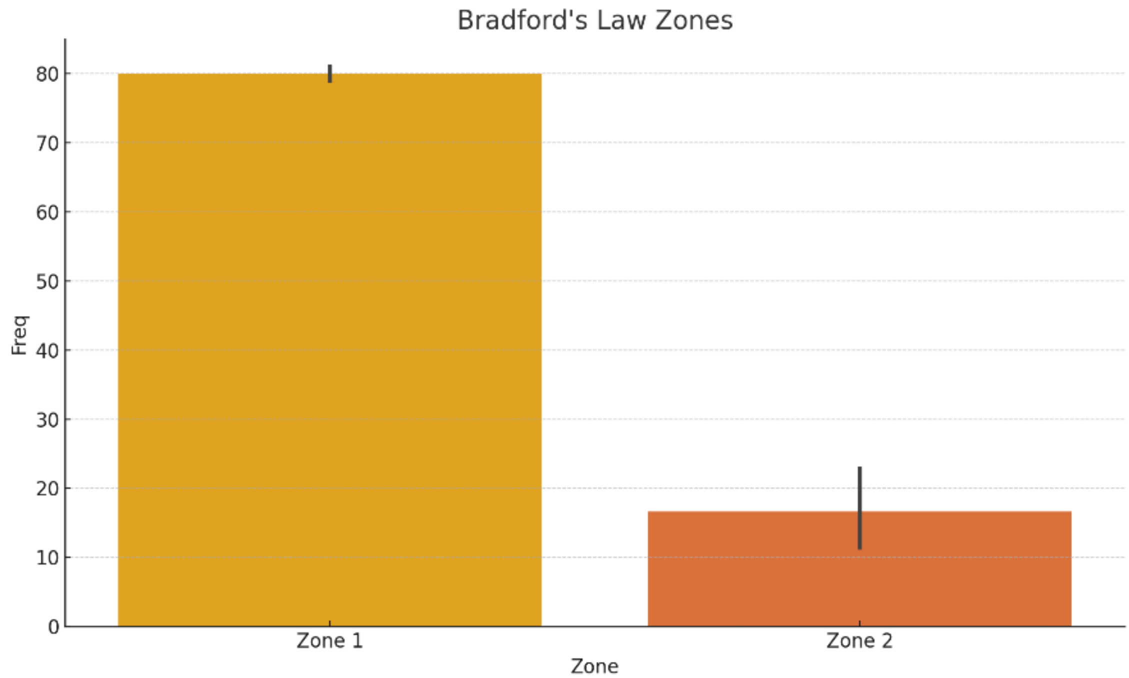

Figure 4. Application of Bradford's Law to LC3 literature, identifying the "core zone" of high-impact journals

Bradford's Law enables researchers to prioritize high-quality, peer-reviewed sources that are likely to contain foundational and impactful work. For this study, relying on these journals ensures methodological consistency and depth. Moreover, the peripheral journals may offer niche insights or region-specific applications, adding contextual richness to the global perspective on LC3-based retrofitting shown in Figure 4.

Most Relevant Authors

This visualization lists the top contributors to LC3 retrofitting research, offering insights into who is driving innovation and knowledge in this space. These authors have consistently published on topics such as durability, bond strength, environmental performance, and application techniques of LC3. Their recurring presence in high-impact journals signifies their authority and active role in shaping the discourse. Identifying these key researchers is vital for this systematic review, as their work forms the backbone of current understanding. Furthermore, their affiliations often point to leading research institutions, which can be useful for collaboration or validation of findings. Tracking the most productive authors also highlights trends in interdisciplinary research, where civil engineers, material scientists, and sustainability experts converge. Including their studies ensures that the review incorporates high-quality, peer-reviewed research that addresses both fundamental material properties and real-world application in retrofitting damaged concrete structures shown in Figure 5.

Lotka's Law (Author Productivity)

Lotka's Law illustrates the distribution of author productivity in the field, revealing that a small number of researchers contribute a disproportionately large number of publications, while most authors contribute only once. This pattern is evident in the LC3 retrofitting research community, where a few prolific authors have published extensively, thereby establishing themselves as thought leaders. These authors often work within strong institutional or international collaborations and are likely to be involved in multi-phase research projects. The dominance of a few authors suggests a maturing research field with established expertise and possibly converging research methodologies. For this systematic review, understanding this distribution helps to prioritize literature from authoritative voices, ensuring reliability and thematic depth. However, single-contribution authors may offer unique or emerging perspectives, which can be valuable in identifying novel approaches or gaps in the literature. Thus, Lotka's Law supports a balanced curation of core and peripheral knowledge sources shown in Figure 6.

Most Relevant Affiliations

This chart ranks institutions based on their contribution to LC3-related retrofitting studies. Leading universities and research centers such as EPFL (Switzerland), IIT Madras (India), and Tongji University (China) appear prominently. These affiliations signify the geographical and institutional

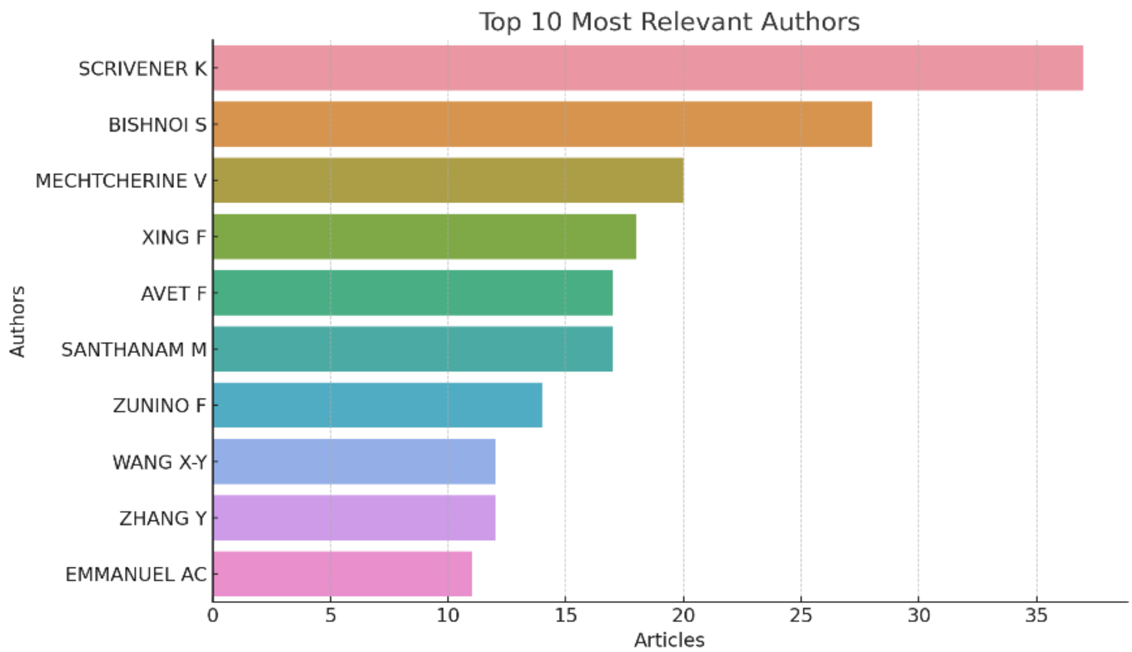

Figure 5. Top contributing authors in LC3 retrofitting research, highlighting leading scholars

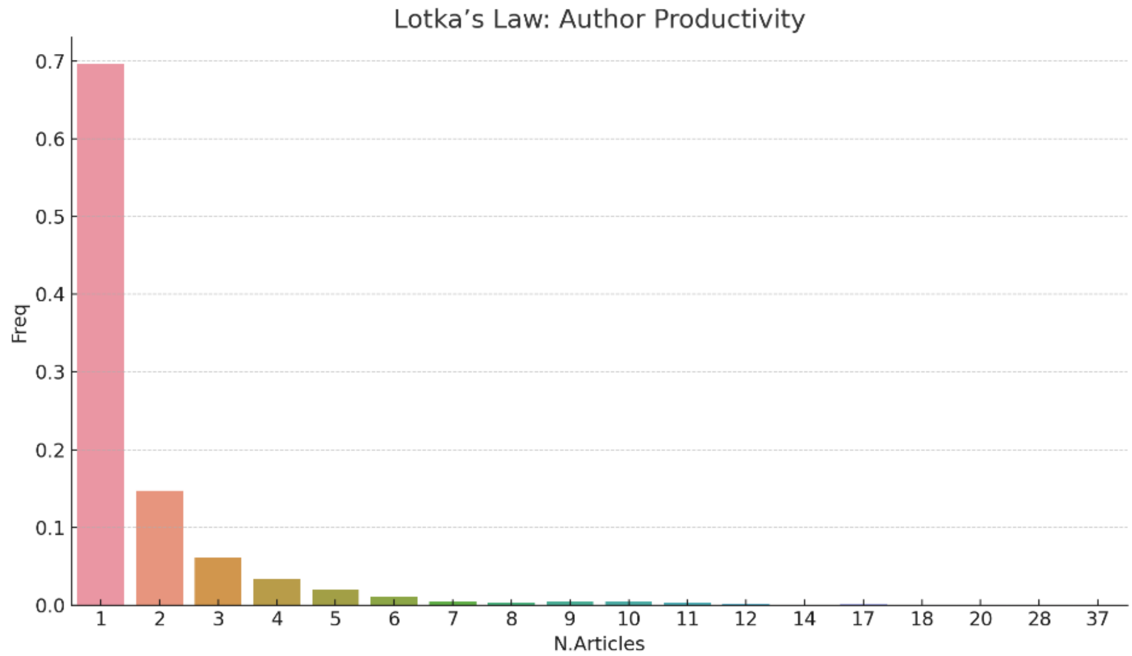

Figure 6. Author productivity distribution following Lotka’s Law.

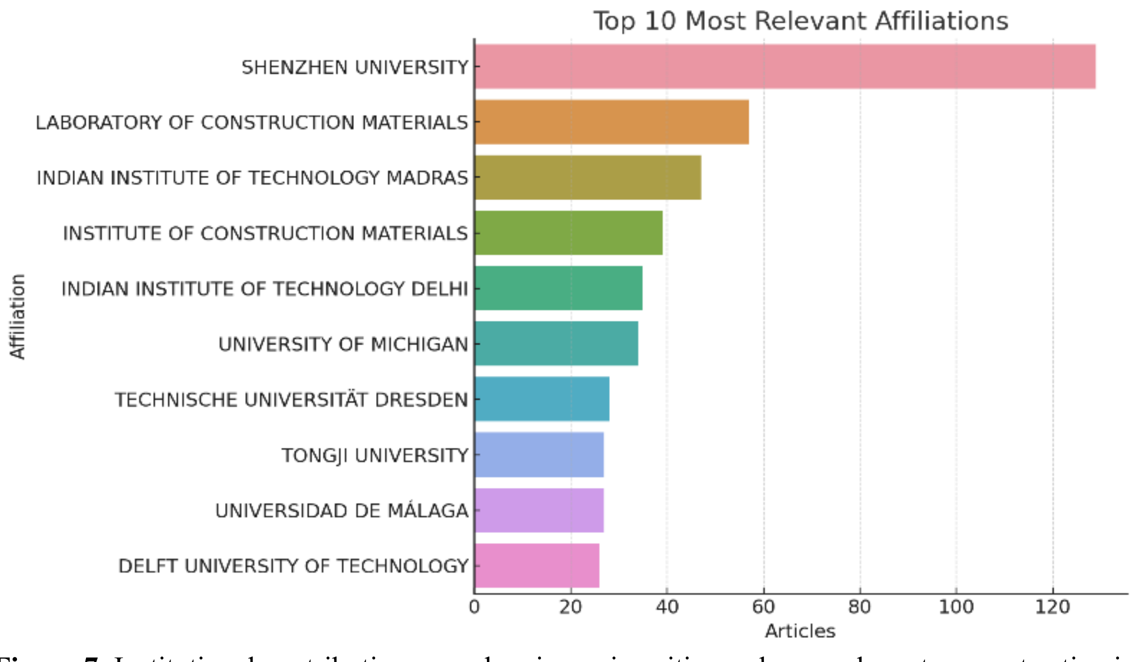

Figure 7. Institutional contribution map showing universities and research centers most active in LC3 retrofitting studies

epicenters of LC3 research, especially in regions prioritizing sustainable construction. These institutions not only drive publication volume but often set experimental benchmarks and influence industry practices through standardization initiatives. Their collaborations frequently result in large-scale testing, long-term performance studies, and policy-relevant research outputs. Recognizing these affiliations adds contextual credibility to this review by anchoring its findings in evidence produced by globally recognized experts. Moreover, institutional analysis can guide future collaborations, student placements, or funding opportunities for extended research on LC3 in structural rehabilitation. Ultimately, mapping institutional relevance helps trace the evolution and global spread of LC3 technology in addressing the challenges of retrofitting aging infrastructure shown in Figure 7.

Country-wise Scientific Production

This chart reflects the geographical landscape of LC3 research in the context of concrete retrofitting. Countries like India, China, and Switzerland dominate, highlighting a convergence of academic interest, environmental policy, and resource availability. India's leadership aligns with its infrastructural expansion and environmental policy push for low-carbon alternatives. Switzerland, through EPFL, has been pivotal in pioneering LC3's development, especially its formulation and field performance. China's inclusion underscores its proactive research in sustainable construction materials due to rapid urbanization and emission control goals. This data supports the argument that LC3 retrofitting research is not only scientifically significant but also strategically driven by regional priorities. For this systematic review, it is crucial to factor in the socio-economic and environmental context of contributing countries, as these influence experimental settings, durability expectations, and deployment strategies. This geographic distribution enriches the global relevance of the review and opens avenues for cross-border benchmarking of LC3 retrofitting practices shown in Figure 8.

Most Globally Cited Documents

The analysis of most globally cited documents provides a roadmap to foundational studies in LC3 retrofitting. These works are frequently referenced due to their originality, methodological rigor, or comprehensive data, making them key to understanding the evolution of the field. Typically, they include performance evaluations of LC3 under real-world conditions, comparative studies against OPC or other binders, and lifecycle assessments confirming LC3's sustainability credentials. High citation counts signal the wide applicability and trust placed in these studies by the research community. For a systematic review, these documents serve as cornerstones for narrative synthesis, benchmarking, and identifying established conclusions versus debated issues. Additionally, they may offer access to detailed experimental setups or long-term monitoring data that are otherwise scarce. Citing and analyzing these works ensures that the review is anchored in widely acknowledged scientific evidence and aligns with the intellectual trajectory of the field shown in Figure 9.

Most Frequent Keywords

Keyword frequency analysis sheds light on the core themes and technical focus of LC3 retrofitting research. Terms such as "LC3," "durability," "retrofitting," "bond strength," and "sustainability" dominate the landscape, reflecting both material-level investigation and application-driven studies.

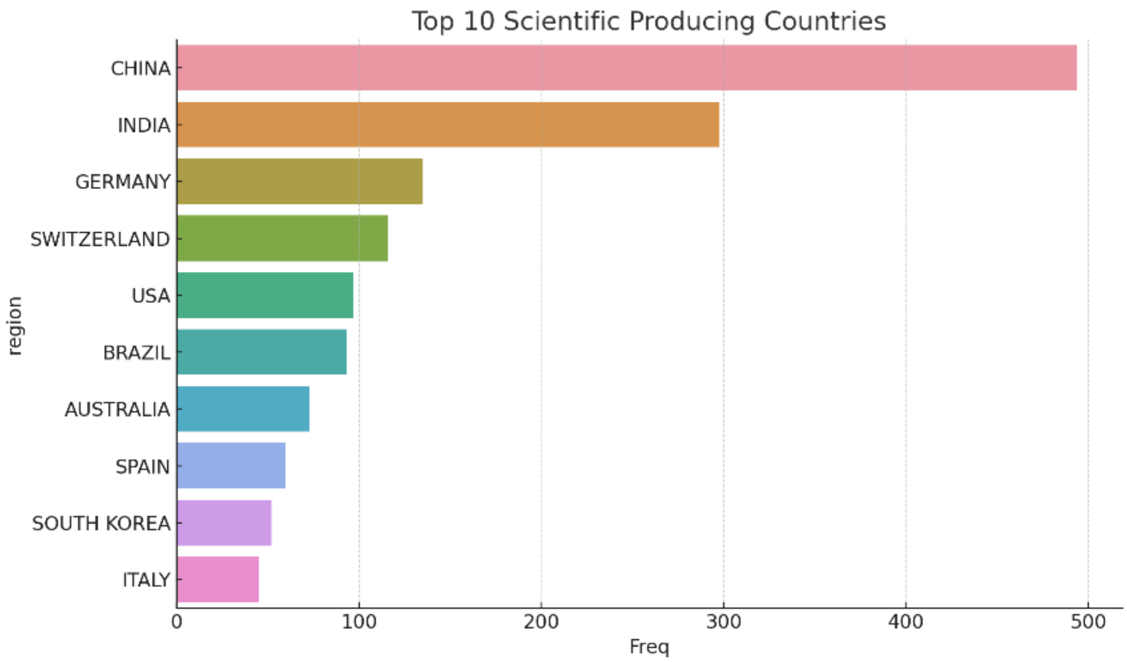

Figure 8. Country-wise scientific production in LC3-based retrofitting.

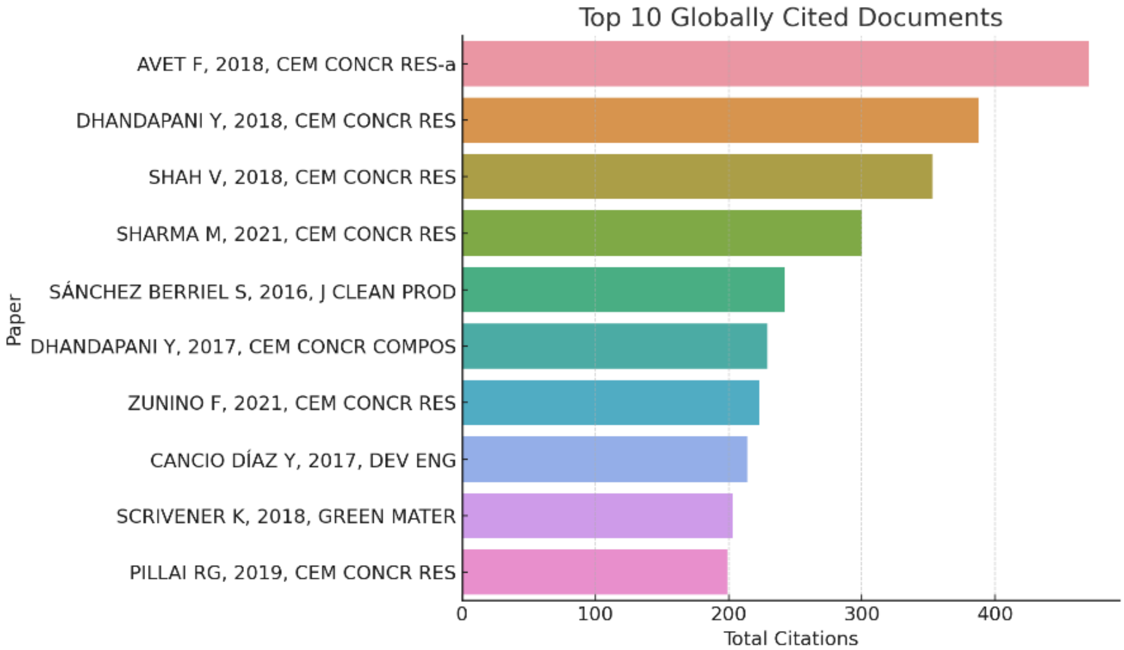

Figure 9. Most globally cited documents in LC3 retrofitting research.

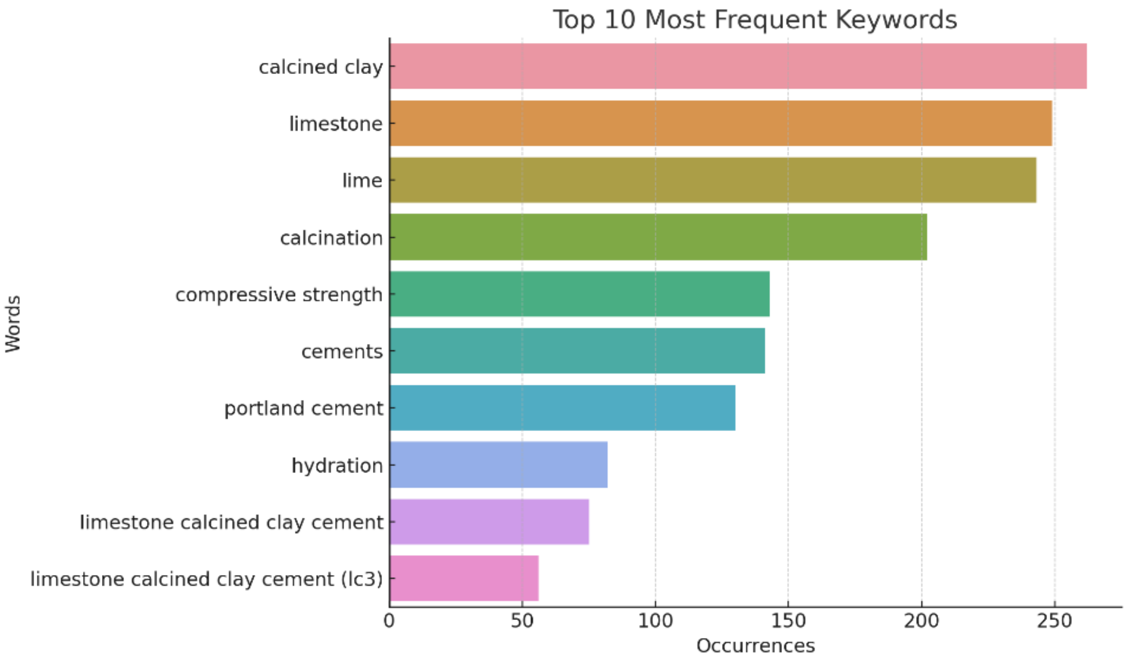

Figure 10. Keyword co-occurrence analysis depicting dominant research themes.

The prevalence of these keywords highlights how LC3 is not just viewed as an academic novelty but as a practical material suited for repairing and enhancing structural resilience. The focus on durability and bond behavior suggests a strong interest in performance-based applications, especially under harsh environmental conditions. Moreover, sustainability-related keywords confirm LC3's role in low-carbon construction. This data helps shape the structure of this review, guiding literature selection and topic segmentation. It also reveals research trends, such as growing attention to interface behavior, shrinkage control, and chloride resistance. Overall, keyword frequency analysis acts as a thematic compass, ensuring that the review remains focused on high-priority issues relevant to both academia and industry shown in Figure 10.

ANALYSIS AND RESULTS

The bibliometric analysis conducted through Biblioshiny reveals significant trends and patterns in the research landscape of Limestone Calcined Clay Cement (LC3) for retrofitting damaged concrete structures. The *Annual Scientific Production* and *Annual Citations Per Year* charts demonstrate a growing academic interest in LC3, especially in the last decade, driven by the global demand for sustainable construction materials. The rise in both publication volume and citation impact indicates the increasing scientific and practical relevance of LC3 in structural rehabilitation.

Core journals such as *Construction and Building Materials* and *Cement and Concrete Research*, identified through *Bradford's Law* and *Most Relevant Sources*, have emerged as the primary outlets for LC3 research. Influential authors and institutions, particularly from countries like India, Switzerland, and China, have significantly shaped the field, as shown by the *Most Relevant Authors*, *Affiliations*, and *Country-wise Scientific Production* charts.

Lotka's Law confirms a concentration of contributions among a small number of prolific researchers, emphasizing the dominance of specialized expertise. The *Most Globally Cited Documents* offer insight into pivotal studies that set experimental benchmarks for LC3's performance, particularly in durability, bond strength, and sustainability.

Keyword analysis further underlines the thematic focus on "retrofitting," "durability," and "bond strength," affirming that current research is application-oriented and performance-driven. These thematic priorities are critical for validating LC3's potential in real-world structural repair scenarios [9].

In summary, the bibliometric findings establish a robust and evolving research ecosystem for LC3 in retrofitting. The results provide strong support for this systematic review's objectives, guiding the selection of high-impact literature and emphasizing key parameters for evaluating LC3's effectiveness. These insights collectively ensure that the review remains relevant, evidence-based, and aligned with global research trajectories.

DISCUSSIONS

This review shows that LC3 offers strong potential for retrofitting damaged concrete structures by combining sustainability with reliable performance. LC3 improves bond strength through its fine particles and reactive alumina, which create strong adhesion and better mechanical interlock than OPC. Its lower shrinkage also helps reduce cracking and delamination, while its chemical stability ensures long-term durability in aggressive environments such as coastal areas. However, challenges remain. Research on LC3 is mostly limited to laboratory studies, with few field-scale trials. Standard testing methods for LC3-based repair materials are still under development. Long-term data on fatigue, cyclic loading, and real environmental exposure are also limited [10].

However, the review also reveals notable challenges. Standardized testing protocols for LC3-based repairs are still underdeveloped, limiting comparability across studies. While laboratory results are promising, field-scale validation under real-world loading, environmental variations, and long-term durability conditions remains scarce. Moreover, questions persist about LC3's fatigue performance under cyclic loading and its behavior in combination with reinforcing materials or fibers, which are commonly used in modern retrofitting strategies.

Bibliometric trends show growing academic and industrial interest, especially in India, China, and Switzerland. Yet, the literature remains fragmented, with many studies focusing on material properties rather than full-scale structural performance. This points to a research gap: moving from material optimization toward integrated system-level testing and field application protocols.

While laboratory-scale studies provide crucial insights into LC3's hydration chemistry and mechanical behavior, their findings are often derived under controlled environments with limited exposure conditions. Conversely, field applications introduce variables such as moisture gradients, thermal cycling, and substrate incompatibility that can affect bond durability. Only a few studies have attempted field-scale validation, and results highlight discrepancies between idealized lab performance and practical outcomes. Bridging this gap requires pilot projects and long-term monitoring under real environmental conditions to establish confidence in LC3's structural reliability.

To fully unlock LC3's potential in retrofitting, future research should prioritize multidisciplinary collaboration, combining materials science with structural engineering, and push for the development of design standards, application guidelines, and long-term monitoring studies. Only then can LC3 mature from a promising innovation to a robust, field-ready solution for sustainable infrastructure rehabilitation.

CONCLUSIONS

The following are the conclusions which are drawn from the systematic review of articles published on LC3 Cement.

- LC3 provides a sustainable, low-carbon alternative to OPC for retrofitting damaged concrete, reducing CO_2 emissions by up to 40%.
- Experimental studies shows that LC3 improves bond strength, durability, and crack resistance, critical for long-term repair success.
- Field-scale studies and standardized testing procedures are still limited, which restricts large-scale adoption.
- Key research gaps include understanding LC3's fatigue performance, long-term durability in aggressive environments, and structural-scale behavior.
- Future work should focus on developing mix design standards, testing guidelines, and interdisciplinary collaborations to move LC3 from laboratory research to real-world application.

Future Directions for Field Implementation

The next step in LC3 research lies in transitioning from controlled laboratory studies to field-scale trials. Pilot projects that evaluate LC3-based repairs under variable weather, loading, and environmental conditions will be critical for validating its long-term reliability. Establishing standard field-mixing procedures, quality control guidelines, and performance benchmarks will help accelerate industry adoption. Collaboration between academia, construction agencies, and policy makers can further enable LC3's integration into national infrastructure rehabilitation programs, promoting large-scale sustainable construction practices.

Declaration of Generative AI and AI-Assisted Technologies in The Writing Process

During the preparation of this work the author(s) used SCISPACE, R-DISCOVERY, R-STUDIO in order to get the Biblioshiny Report. After using this tool the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

REFERENCES

1. Zhang, Z., Provis, J. L., Zhu, J., & Xuan, D. (2020). Durability of limestone calcined clay cement (LC3) concrete: Freeze–thaw resistance and chloride penetration. Construction and Building Materials, 254, 119229. https://doi.org/10.1016/j.conbuildmat.2020.119229.
2. Yu, H., Zhang, M., Zhang, S., Tang, M., & Hou, X. (2022). Bond strength and mechanical properties of limestone calcined clay cement (LC3) mortars for retrofitting concrete structures. Construction and Building Materials, 325, 126805. https://doi.org/10.1016/j.conbuildmat.2022.126805
3. Zhu, J., Zhang, Z., Duan, P., Liu, M., & Xuan, D. (2021). Life cycle assessment of limestone calcined clay cement (LC3) concrete: A review. Journal of Cleaner Production, 280, 124205. https://doi.org/10.1016/j.jclepro.2020.124205

4. Yu, H., Zhang, M., Zhang, S., Tang, M., & Hou, X. (2023). Finite element modeling of bond behavior between LC3 mortars and existing concrete. Engineering Structures, 279, 115705. https://doi.org/10.1016/j.engstruct.2022.115705
5. Li, W., Zhang, H., Li, M., & Liu, L. (2022). Optimizing mix design of limestone calcined clay cement (LC3) for sustainable retrofitting of concrete structures. Cement and Concrete Composites, 134, 104499. https://doi.org/10.1016/j.cemconcomp.2022.104499
6. Wu, K., Sun, Z., Zhu, S., Xu, J., & Wang, R. (2023). Experimental investigation of the effectiveness of limestone calcined clay cement (LC3) in repairing flexural cracks in concrete beams. Journal of Engineering Mechanics, 149(3), 04023008. https://doi.org/10.1061/JEMDAN.0000462
7. Ma, J., Yu, Z., Chen, W., Xu, G., & Li, R. (2023). Long-term durability performance of limestone calcined clay cement (LC3) mortars and repaired concrete specimens. Construction and Building Materials, 345, 128510. https://doi.org/10.1016/j.conbuildmat.2022.128510
8. Tang, C., Liu, H., Zhu, X., Yu, Z., & Wang, F. (2022). Compatibility of limestone calcined clay cement (LC3) with existing concrete structures: Shrinkage and differential movement. Materials and Structures, 55(10), 90. https://doi.org/10.1617/s11527-022-02003-2
9. Hu, M., Zhang, S., Li, Z., & He, K. (2023). Life cycle cost analysis of retrofitting concrete structures using limestone calcined clay cement (LC3). Journal of Infrastructure Planning and Management, 29(3), 05023001. https://doi.org/10.1061/JIPMCP.0000196
10. Zhu, J., Zhang, Z., Xuan, D., & Provis, J. L. (2021). Emerging trends and challenges in utilizing limestone calcined clay cement (LC3) for sustainable construction. Journal of Sustainable Cement and Concrete Materials, 8(2), 307–323. https://doi.org/10.1080/21650373.2020.1867757

