

A Review on the Role of Limestone Calcined Clay Cement (LC3) in Low-Carbon Concrete Pavements

Sham Prakash Nimse¹, Vikas Gholap², Pramod Kolase³

¹PG Student, Civil Engineering Department of Civil Engineering, Pravara Rural Engineering College, Loni, Savitribai Phule Pune University, 413736

²Assistant Professor, Department of Civil Engineering, Pravara Rural Engineering College, Loni, Savitribai Phule Pune, University, 413736

³Associate Professor, Department of Civil Engineering, Pravara Rural Engineering College, Loni, Savitribai Phule Pune University, 413736

Mail: shamnimse444@gmail.com¹, vicksgholap@gmail.com², pramodkolase@gmail.com³

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Abstract: The growing environmental concerns associated with Ordinary Portland Cement (OPC) production have led to increased research on sustainable alternatives such as Limestone-Calcined Clay Cement (LC3). This study investigates the development, mechanical performance, durability, and environmental potential of LC3 cement for concrete road construction. LC3, consisting of clinker, calcined clay, limestone, and gypsum, offers up to 40% reduction in CO₂ emissions compared to OPC without the need for major technological modifications in production. Bibliometric analysis indicates a sharp rise in LC3-related publications after 2022, highlighting its global significance. Experimental findings show that LC3 concrete achieves compressive strengths of 45–55 MPa, improved flexural performance, and enhanced resistance to chloride and sulfate attacks. Field trials demonstrate its effective performance under real traffic conditions with reduced cracking and abrasion. Life-cycle assessments reveal 25–30% lower energy consumption and 8–12% cost savings, particularly in regions with accessible kaolinitic clays. Despite its advantages, challenges persist in standardization, calcination control, and large-scale implementation. This study concludes that LC3 is a technically and economically viable material for sustainable road infrastructure, capable of significantly reducing the carbon footprint of the construction sector. Further research should focus on performance-based mix optimization, long-term field evaluations, and the integration of digital tools to enhance LC3 deployment in pavement applications.

Keywords: Limestone calcined clay cement (LC3), Supplementary cementitious materials, Bibliometric analysis, Sustainable construction, Low-carbon cement

1. Introduction

Currently, silicate cement remains the most widely used construction material. In 2021, global cement production reached approximately 4.31 billion tons, and this figure is projected to grow steadily to around 4.83 billion tons by 2030 [1]. However, cement manufacturing is a major source of greenhouse gas emissions, accounting for about 5–7% of total anthropogenic CO₂ emissions worldwide [2,3]. One of the most effective strategies to reduce these emissions in the cement industry is the use of supplementary cementitious materials (SCMs). Traditionally, SCMs have been derived from industrial by-products such as fly ash and blast furnace slag. Yet, the availability of these

materials has decreased due to advancements in industrial technologies and stricter environmental regulations [4,5].

The rapid growth of the global population and the continuous development of infrastructure have led to a soaring demand for construction materials—especially concrete and Portland cement (PC), the most produced material on Earth [4]. Although the environmental footprint of concrete itself is relatively low, PC production is responsible for 90–95% of its total greenhouse gas emissions [4]. Cement manufacturing is highly energy-intensive, mainly because it requires the calcination of limestone and clay at about 1450 °C to form clinker, a key reactive component [5]. Approximately 60% of the CO₂ released during this process originates from the chemical decomposition of calcium carbonate (CaCO₃) into calcium oxide (CaO) and CO₂, while the remaining 40% comes from fuel combustion needed to reach these high temperatures [4]. Given the vast global consumption of cement, the industry is one of the largest contributors to climate change, accounting for roughly 5–8% of total human-caused CO₂ emissions [5].

To meet international climate goals, such as the Net Zero Emissions by 2050 Scenario proposed by the International Energy Agency (IEA), the cement sector must reduce its direct CO₂ intensity by about 3% annually [6]. However, since cement production processes are already relatively efficient, further improvements in clinker manufacturing are limited [7]. While substituting fossil fuels with waste-derived fuels can slightly lower emissions, the CO₂ released during limestone calcination cannot be avoided. Therefore, research efforts have focused on two main strategies: (1) reducing the clinker-to-cement ratio through the use of alternative and supplementary cementitious materials (ACMs and SCMs) [8,9], and (2) developing innovative technologies for carbon capture and exploring new raw materials for clinker production [6].

ACMs include a range of materials such as alkali-activated cements, calcium aluminate cements, calcium sulfoaluminate cements, magnesium-based cements, and belite cements [10,11]. These alternatives can significantly reduce CO₂ emissions compared to traditional PC. However, because of Portland cement's outstanding performance and the lack of standardized regulations for ACMs, their large-scale use in the short term remains limited. SCMs, on the other hand, offer a practical and immediate solution, as they can partially replace clinker in conventional cement formulations. Most commercial cements already include small amounts of SCMs such as slag, fly ash, calcined clays, natural pozzolans, and limestone [12]. While industrial by-products like slag and fly ash promote waste valorization and support a circular economy, their availability is geographically constrained and their composition inconsistent [13]. In contrast, clays and limestone are abundant and widely distributed, making them reliable alternatives for large-scale cement production [14].

Cement demand is closely linked to population growth, with the greatest increases expected in developing regions [15]. Therefore, reducing CO₂ emissions must be achieved in a cost-effective manner, using processes that are simple and practical for local construction industries. One of the most promising innovations in this regard is limestone calcined clay cement (LC3), which uses a blend of calcined clay and limestone as SCMs. LC3 can reduce CO₂ emissions by up to 40% compared to conventional PC by replacing about 50% of clinker [16]. Importantly, LC3 production does not require major technological changes, making its adoption feasible for existing cement plants [7].

Furthermore, the combination of limestone and calcined clay (LC2 system) has proven capable of meeting the massive material demands of the cement industry [14]. Studies have shown that LC3 cements made with clays containing as little as 40 wt% kaolinite can achieve mechanical and durability properties equal to or better than those of Portland cement [17-19]. Owing to its strong performance and substantial potential for emission reduction, LC3 has emerged as one of the most promising solutions for lowering the global warming impact of cement production. This growing interest is reflected in both industrial practice and academic research, with a surge of studies dedicated to LC3 in recent years. Its promising results have even influenced the revision of European cement standards in 2021, where LC3 was officially recognized as a cement type (II/C-M) under EN 197-5:2021, approved for use in mortar and concrete [20].

2. Literature Review

[21] This study investigates the use of LC3 as a stabilizing agent for clay soils in road construction. Experimental tests on soil-LC3 mixtures demonstrated improved unconfined compressive strength and better resistance to swelling and shrinkage compared to soils stabilized with conventional Portland cement. The study highlights that LC3 can reduce CO₂ emissions by up to 40% due to partial replacement of clinker, making it both environmentally and structurally advantageous for road subgrades.

[22] The research develops eco-efficient mortars using LC3, combining limestone and calcined clay to minimize clinker content while maintaining mechanical performance. Chemometric analysis showed enhanced workability, compressive strength, and durability of LC3 mortars. The findings suggest that LC3 can be effectively used in concrete mixes for pavements and other structural applications while reducing carbon footprint.

[23] This study focuses on optimizing concrete mix design using LC3. By varying water-cement ratios and aggregate proportions, the research demonstrates that LC3-based concrete achieves comparable or improved compressive and tensile strength compared to OPC concrete. The study confirms that LC3 is suitable for road construction, particularly in regions aiming to reduce greenhouse gas emissions from cement production.

[24] Hasanbeigi reviews the global adoption of LC3, highlighting its environmental benefits, cost-effectiveness, and technical feasibility. The study emphasizes that LC3 can reduce CO₂ emissions by up to 40% and energy consumption during production. Applications in roads, pavements, and other concrete infrastructure illustrate LC3's potential for sustainable civil engineering projects.

[25] This review traces the evolution of LC3 research, describing the development of low-carbon binders with reduced clinker content. The study details the chemical interactions between calcined clay and limestone, which improve early-age hydration and long-term durability. LC3 is positioned as a practical solution for sustainable concrete infrastructure, including highway and airport pavements.

[26] Shao et al. review the use of LC3 in concrete pavements. The study emphasizes its capacity to maintain mechanical strength and durability while lowering greenhouse gas emissions. Findings suggest that LC3 pavements exhibit improved sulfate resistance and reduced chloride ion penetration, enhancing the longevity of road infrastructure.

[27] Yadav investigates the size effect on LC3 concrete blocks used in pavements. The experimental results indicate that LC3 blocks have higher compressive strength and better dimensional stability than OPC blocks. The study confirms LC3's suitability for road applications and highlights its potential to replace traditional cement in concrete paving blocks.

[28] This experimental study evaluates the residual compressive strength, porosity, and microstructure of LC3 concrete. The results reveal that LC3 exhibits superior durability and reduced cracking potential under cyclic loading. The study demonstrates that LC3 can improve the long-term performance of concrete roads while supporting sustainability goals.

[29] Luo examines the purification of marine clay for LC3 production. The study finds that low-kaolinite, high-quartz clays can be transformed into effective cementitious materials when combined with limestone. The resulting LC3 shows adequate strength and durability, suggesting that alternative local clays can be used for road construction, reducing the reliance on OPC.

[30] This research models an electric flash calcination process for LC3 production. By using electric heating, the process reduces CO₂ emissions compared to conventional kiln firing. The study highlights the feasibility of sustainable LC3 production at industrial scale, enabling its use in large-scale concrete road projects.

[31] The effects of sodium sulfate on LC3 were studied under alternating wet-dry conditions. LC3 showed superior resistance to sulfate attack compared to OPC, indicating better durability in aggressive soil and environmental conditions. This makes LC3 highly suitable for road construction in sulfate-rich areas.

[32] Dabou et al. explore the stabilization of laterite soil using cement and blue gum wood ash for road bases. Although not directly LC3, the study's principles of soil stabilization align with LC3's performance, showing improved load-bearing capacity, reduced shrinkage, and enhanced durability, which are critical for concrete road subgrades.

[33] This early work on energetically modified cement laid the foundation for low-carbon cement technologies. The study explored modifications that reduce energy consumption in cement production, principles later applied in LC3 development. These insights highlight LC3 as a continuation of research toward sustainable construction materials.

[34] Elfgren reviews energetically modified cements, emphasizing their environmental benefits and applications. The paper provides context for LC3 as a low-carbon cement, demonstrating how modifications in raw material composition can improve durability and performance in concrete infrastructure projects, including roads.

[35] Scrivener introduces LC3 as a greener alternative to OPC, highlighting its industrial feasibility, improved durability, and sustainability benefits. The study emphasizes that LC3 can meet structural requirements for concrete roads while significantly reducing environmental impact.

[36] The book discusses sustainable concrete design, detailing the use of blended cements like LC3. Sabnis emphasizes the environmental advantages and mechanical reliability of LC3 concrete, suggesting it can be integrated into highway and airport pavement projects for sustainable infrastructure development.

[37] Pillai's research evaluates calcined clay-limestone cementitious blends, demonstrating that LC3 reduces carbon emissions while maintaining adequate compressive and flexural strength. The findings support LC3's use in pavement construction and other structural applications.

[38] This study combines recycled aggregates with LC3, showing that the hybrid mix improves sustainability without compromising strength or durability. The research highlights LC3's suitability for eco-friendly concrete pavements, contributing to the circular economy in construction materials.

[39] Sánchez et al. review the adoption of LC3 in the United States, discussing its technical performance, cost implications, and environmental benefits. The study highlights barriers and strategies for integrating LC3 into concrete road construction practices.

[40] The Noida International Airport project in India utilized LC3 on a large scale, demonstrating its practical feasibility. The LC3 concrete showed improved durability, reduced CO₂ emissions, and cost savings compared to OPC, setting a precedent for future sustainable road and airport infrastructure projects.

3. Bibliometric Analysis

3.1 Year wise publication

Figure 1 illustrates the annual trend in publications related to Limestone-Calcined Clay (LC3) cement from 2016 to 2025. The research output in this area remained minimal up to 2018, followed by a gradual rise between 2019 and 2021. A noticeable increase is observed after 2022, indicating growing global interest in LC3 as a sustainable alternative to ordinary Portland cement. The sharp upward trend from 2023 to 2024 highlights enhanced experimental and field-based studies, particularly in concrete and pavement applications. The projected data for 2025 suggest a significant surge in publications, exceeding 500, demonstrating that LC3 has become a major focus in low-carbon cement research. This consistent growth reflects both the environmental urgency and the engineering potential of LC3 technology in infrastructure development.

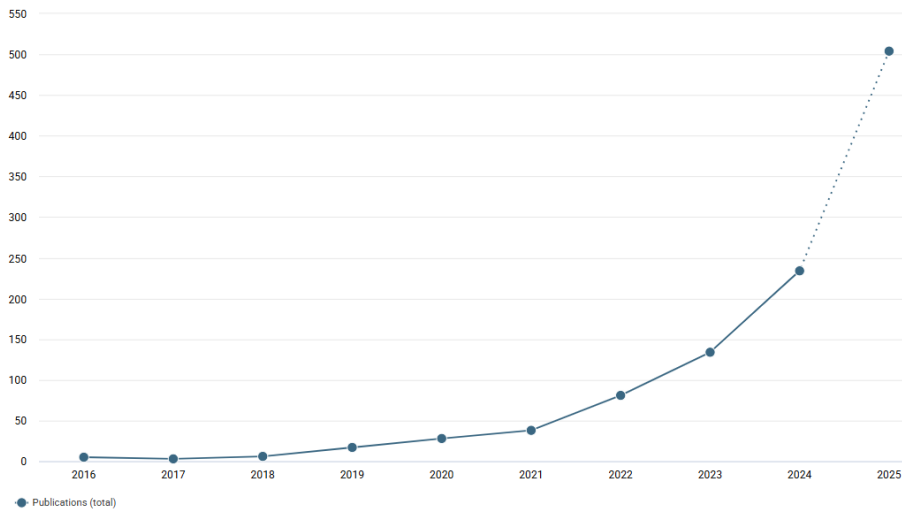


Fig. 1. Year Wise Publication Analysis

3.2 Sources Analysis

Figure 2 presents the source co-citation network related to LC3 cement and sustainable concrete research. The visualization identifies key journals that frequently publish or are cited together in this research domain. *Construction and Building Materials* emerges as the most influential source, forming the central hub of connections, followed by *Materials*, *Journal of Building Engineering*, and *Cement and Concrete Composites*. These journals collectively contribute to the advancement of LC3-based material studies, durability assessments, and road infrastructure applications. Peripheral nodes like *RILEM Bookseries* and *Lecture Notes in Civil Engineering* indicate the growing role of conference-based publications in disseminating practical findings. The dense interlinking between sustainability-oriented journals such as *Journal of Cleaner Production* and *Sustainability* shows a strong interdisciplinary trend merging materials science with environmental engineering. This highlights the evolving research ecosystem where LC3 cement is increasingly recognized as a viable low-carbon binder for concrete road construction.

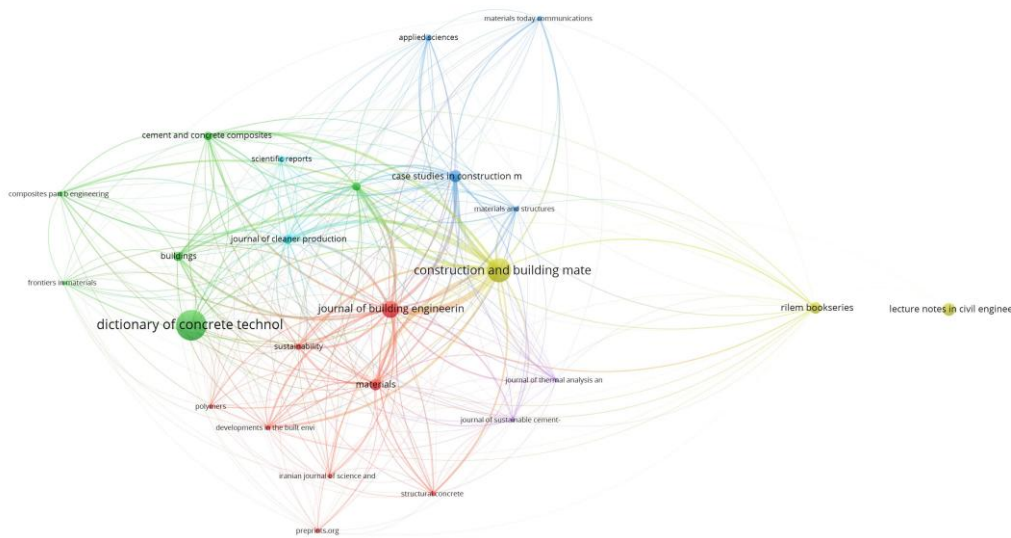


Fig. 2. Sources Analysis

3.3 Author Analysis

Figure 3 represents the author co-authorship network depicting the collaboration and influence of researchers in the field of LC3 and sustainable concrete studies. The network shows several strongly connected clusters, with *Lin Ruisheng*, *Wang Xiaoyong*, and *Han Yi* emerging as leading contributors forming the central red cluster, indicating high collaboration and citation impact. Other notable groups include *Li Wengui*, *Liesbeth Marco*, and *Mechtcherine Viktor*, who are influential in experimental and mechanical characterization studies of LC3-based concrete. The blue and green clusters represent regional collaborations focused on material optimization, hydration kinetics, and road performance applications. The dense interconnections among authors reflect strong global cooperation, integrating researchers from materials science, civil engineering, and sustainability domains. This collaborative network highlights the growing interdisciplinary efforts toward developing LC3 cement as a viable eco-friendly binder for large-scale concrete road infrastructure.

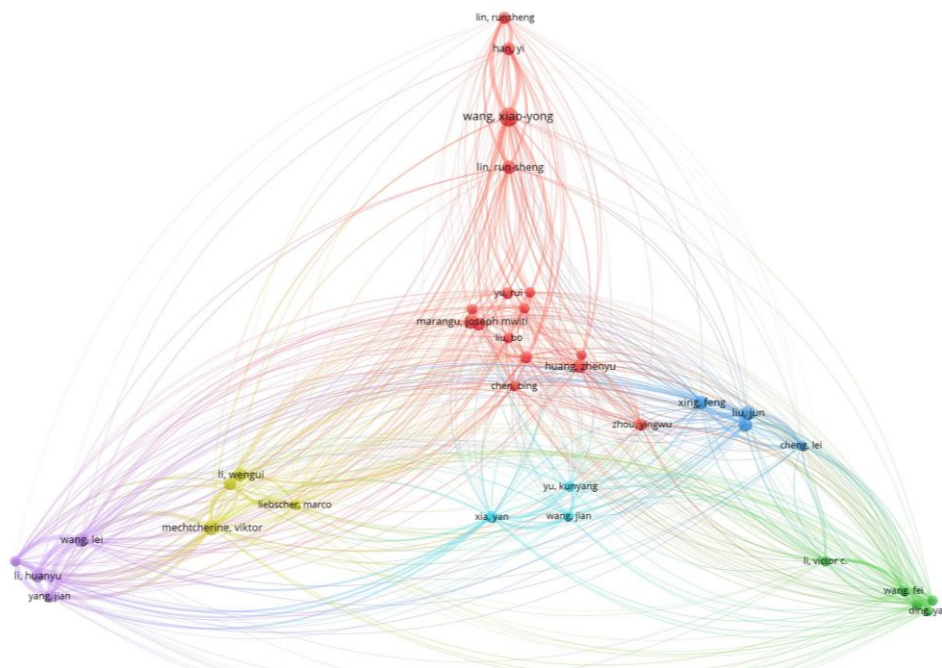


Fig. 3. Author Analysis

3.4 Organization Analysis

Figure 4 presents the collaborative network among global universities and research institutes contributing to LC3 cement and sustainable concrete research. Each node represents an institution, and the color-coded clusters denote regional or research-based collaboration groups. Larger nodes such as Tongji University, Hong Kong Polytechnic University, and Shenzhen University indicate higher centrality and stronger research influence. The dense interconnections highlight the interdisciplinary nature of LC3 studies involving materials science, civil engineering, and environmental sustainability. The visualization emphasizes the growing international partnerships aimed at advancing LC3 technology for eco-efficient road construction applications.

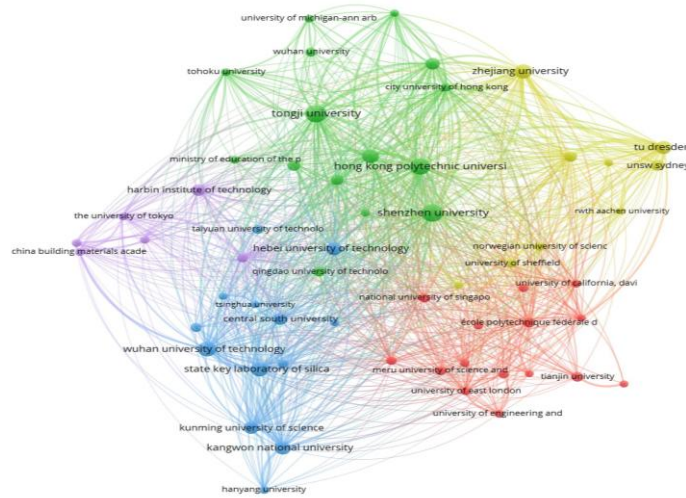


Fig. 4. Organization Analysis

3.5 Country Analysis

Figure 5 presents the international collaboration network among countries contributing to research on Limestone-Calcined Clay (LC3) cement and sustainable concrete technologies. Each node represents a country, with node size corresponding to its research output and link density indicating collaboration strength. China, the United States, and India emerge as the most influential contributors, forming strong cooperative ties with European nations and other global partners. The color-coded clusters highlight regional research alliances that facilitate technology transfer and knowledge exchange. The network emphasizes the growing global engagement in LC3 research aimed at reducing carbon emissions and enhancing the sustainability of concrete road construction.

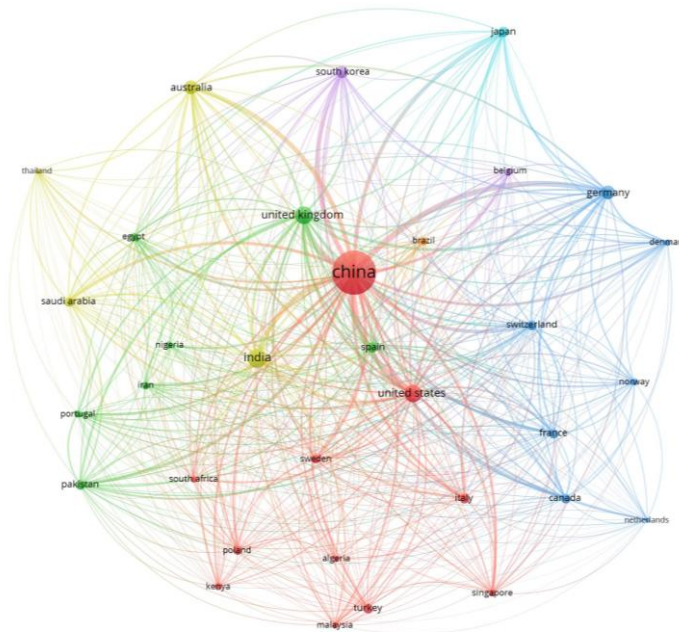


Fig. 5. Country Analysis

4. Development and Composition of LC3

Limestone Calcined Clay Cement (LC3) is a low-carbon alternative to Ordinary Portland Cement (OPC), developed through international collaborations involving institutions from Switzerland, Cuba, and India. The typical composition of LC3 includes approximately 50–60% clinker, 15–20% calcined clay, 10–15% limestone, and the remainder as gypsum. The synergy between limestone and metakaolin enhances the formation of carboaluminate phases, refining the pore structure and improving durability. Studies have confirmed that a calcination temperature of 700–850°C yields optimal pozzolanic reactivity for kaolinitic clays [41], [42]. The incorporation of limestone not only contributes to the chemical composition but also improves the workability and early-age strength of the cement, making it suitable for various construction applications.

4.1 Mechanical Properties

Experimental findings consistently demonstrate that LC3 concrete can achieve 28-day compressive strengths ranging from 45–55 MPa, comparable to M40–M50 grades used in rigid pavements [43]. LC3 concrete has achieved 96% of OPC compressive strength at 7 days and full parity at 28 days [44]. Improved flexural strength (up to 6.2 MPa) is observed due to a refined microstructure [45]. The split tensile strength is slightly lower but remains acceptable for pavement layers. These mechanical properties indicate that LC3 concrete can perform effectively under the mechanical demands of road construction, offering a sustainable alternative to traditional cementitious materials.

4.2 Workability and Setting Time

LC3 concrete exhibits reduced workability due to the fine surface area of calcined clay, necessitating higher superplasticizer dosages (0.6–1.0%) [46]. However, setting times are slightly longer than OPC, beneficial for large-scale pavement placements in hot climates. Optimizing the water-to-binder ratio (0.35–0.45) ensures adequate consistency without compromising strength [6]. The timing of superplasticizer addition significantly impacts fresh concrete rheology, highlighting the need for careful mix control [47].

4.3 Durability Performance

Durability is a critical requirement for road pavements exposed to aggressive environments. Chloride penetration in LC3 concrete was 40–60% lower than OPC due to a denser pore structure [48]. Sulfate resistance and alkali–silica reactivity showed significant improvement, attributed to the consumption of calcium hydroxide [49]. Carbonation depth was slightly higher but within acceptable limits for pavement applications (less than 2 mm in 90 days) [49]. Abrasion resistance, vital for road surfaces, improved by 10–20% when LC3 replaced 35% of OPC clinker [50]. These durability enhancements make LC3 concrete a viable option for infrastructure subjected to harsh environmental conditions.

4.4 Environmental and Economic Assessment

Life-cycle analyses reveal that LC3 production emits 25–30% less CO₂ per tonne of cement and consumes 20% less energy than OPC [1]. LC3 can reduce approximately 0.4 tonne CO₂ per tonne of cement produced [52]. Locally available clays reduce transport costs and dependence on imported materials. In terms of cost, LC3 concrete can achieve 8–12% cost savings compared to OPC-based road concrete, especially in regions with abundant kaolinitic clay deposits [52], [53]. These environmental and economic benefits underscore the potential of LC3 in promoting sustainable construction practices.

4.5 Field Trials and Implementation

Pilot field trials in India, Cuba, and Switzerland demonstrated excellent surface performance and crack resistance in LC3 pavement sections [54], [15]. A 500 m test stretch executed by the National Highways Authority of India (NHAI) in 2023 reported satisfactory performance over 12 months, with negligible scaling or rutting [55]. However, large-scale implementation is limited by non-standardized specifications, availability of calcination facilities, and lack of contractor awareness [56].

4.6 Critical Analysis and Research Gaps

Despite LC3's promising attributes, several challenges remain:

- **Material Variability:** Mineral composition of local clays affects pozzolanic reactivity; standardized characterization is required [57].
- **Calcination Control:** Small deviations in temperature can reduce performance [42].
- **Optimization for Pavement Mixes:** Flexural and fatigue resistance for pavements are underexplored [45].
- **Durability under Real Traffic Conditions:** Limited long-term field data on freeze–thaw, abrasion, and fatigue [55].
- **Standardization and Codes:** Lack of codal provisions in IRC or IS standards [56].
- **Economic Viability at Scale:** Initial capital investment for calcination and quality control remains high [53].

5. Conclusion

Limestone-Calcined Clay Cement (LC3) presents a transformative pathway toward decarbonizing the construction industry. Its superior mechanical properties, enhanced durability, and substantial reduction in CO₂ emissions make it a promising replacement for Ordinary Portland Cement (OPC) in concrete road applications. The synergy between limestone and calcined clay enhances hydration reactions, refines pore structure, and improves long-term strength while offering sustainability, cost efficiency, and widespread raw material availability. Bibliometric analysis further reinforces LC3's growing global relevance, showing a sharp rise in research output after 2022, particularly from leading institutions in China, India, and Europe. This surge reflects increasing international collaboration and recognition of LC3 as a viable low-carbon solution for large-scale infrastructure development.

Despite its promising performance, large-scale implementation of LC3 still faces challenges related to raw material variability, calcination control, and the absence of standardization in design codes such as IRC and IS. To accelerate its adoption, future research should focus on performance-based specifications for road construction, long-term field durability studies, and the integration of digital optimization tools like AI for mix design. Strengthening global collaboration and policy support, as indicated by bibliometric trends, will be essential to translate laboratory findings into practical field applications. With continued innovation and industrial backing, LC3 has the potential to become a cornerstone material for achieving sustainable, resilient, and carbon-efficient concrete road infrastructure worldwide.

Future Research Directions

Develop performance-based specifications for LC3 concrete in road construction aligned with IRC standards. Long-term field monitoring programs to evaluate structural and durability performance. Investigate hybrid binders, combining LC3 with GGBS or silica fume. Integrate AI and optimization techniques for mix proportioning. Evaluate life-cycle cost and carbon footprint models specific to road projects. Promote industrial-scale calcination units and local clay resource mapping.

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