# LC³-Based Net-Positive Concrete for Mass Housing: Optimizing Strength, Cost, And Embodied Carbon

Prof. Naga Sheshu Babu T[1], Pawar Kiran Vithoba[2], Ashraf Sahil Rangraiz[3], Sharma Shivani Sanjay[4], Patil Jay Sambhaji[5], Kharjul Akshada Somnath[6]

[1]*Assistant Professor, Department of Civil Engineering, Sandip Institute of Technology and Research Centre, Nashik*

[2,3,4,5,6]*UG Final Students, Department of Civil Engineering, Sandip Institute of Technology and Research Centre, Nashik*

***Abstract*—Limestone Calcined Clay Cement (LC3) is a sustainable alternative to conventional Portland cement that significantly reduces carbon emissions while maintaining comparable mechanical and durability properties. LC3 is produced by partially replacing clinker with calcined clay and limestone, thereby lowering energy consumption and $CO_2$ emissions during manufacturing. This study examines the composition, performance, and environmental benefits of LC3 cement. Experimental findings indicate that LC3 exhibits satisfactory compressive strength, improved resistance to chloride penetration, and enhanced long-term durability. Furthermore, the reduced clinker content contributes to a lower carbon footprint and promotes resource efficiency. The results demonstrate that LC3 cement offers a viable and eco-friendly solution for sustainable construction, supporting global efforts toward reducing greenhouse gas emissions in the cement industry.**

***Index Terms*—Limestone Calcined Clay Cement (LC3), Low-Carbon Cement, Sustainable Construction, Mechanical Properties, Durability, Hydration Mechanism, Carbon Footprint Reduction, Supplementary Cementitious Materials (SCMs), Green Concrete, Environmental Sustainability.**

## I. INTRODUCTION

The construction industry is one of the largest contributors to global carbon dioxide ($CO_2$) emissions, primarily due to the extensive use of Ordinary Portland Cement (OPC) in concrete production. Cement manufacturing accounts for approximately 7–8% of global anthropogenic $CO_2$ emissions, resulting from both the calcination of limestone and the combustion of fossil fuels during clinker production. As concerns regarding climate change and sustainable development continue to grow, the development of environmentally friendly cementitious materials has become a major research focus. Among the various alternatives proposed, Limestone Calcined Clay Cement (LC3) has emerged as a promising low-carbon cement technology capable of significantly reducing greenhouse gas emissions while maintaining satisfactory mechanical and durability properties.

LC3 is a blended cement system composed mainly of clinker, calcined clay, limestone, gypsum, and a small quantity of other additives. Typically, LC3 contains approximately 50% clinker, 30% calcined clay, 15% limestone, and 5% gypsum. The reduction in clinker content is the primary factor contributing to the lower carbon footprint of LC3 compared to conventional Portland cement. Since clinker production is the most energy-intensive and carbon-emitting stage of cement manufacturing, partially replacing clinker with supplementary cementitious materials such as calcined clay and limestone results in substantial environmental benefits.

The performance of LC3 is attributed to the synergistic interaction between calcined clay and limestone. During hydration, calcined clay provides reactive alumina, which reacts with calcium carbonate from limestone to form stable carboalumination phases. These reactions contribute to enhanced microstructural refinement, improved pore structure, and increased durability of the cement matrix. Additionally, the filler effect of finely ground limestone improves particle packing and promotes hydration, resulting in improved early-age strength development. Consequently, LC3 exhibits mechanical properties comparable to or even exceeding those of conventional Portland cement under certain conditions.

One of the major advantages of LC3 is its ability to reduce carbon emissions by up to 40% compared to traditional OPC, depending on the composition and production process. Furthermore, LC3 requires lower calcination temperatures for clay activation, typically around 700–850°C, compared to approximately 1450°C required for clinker production. This reduction in thermal energy demand contributes to lower fuel consumption and reduced environmental impact. The adoption of LC3 technology therefore aligns with global sustainability goals, including carbon neutrality targets and the transition toward greener construction practices.

Despite its considerable potential, challenges remain regarding the widespread implementation of LC3 technology. Variations in clay mineralogy, calcination conditions, and material processing can influence the performance of LC3. Therefore, ongoing research is focused on optimizing mix proportions, understanding hydration mechanisms, evaluating long-term durability, and developing standardized specifications for commercial applications. Continued investigation is essential to ensure consistent quality and facilitate broader adoption in the construction sector.

In conclusion, Limestone Calcined Clay Cement represents a significant advancement in sustainable cement technology. By reducing clinker content and utilizing abundant natural resources, LC3 offers an effective strategy for lowering carbon emissions while maintaining desirable engineering properties. Its environmental, technical, and economic advantages position LC3 as a viable alternative to conventional Portland cement and a key contributor to the future of sustainable construction. As global efforts intensify to mitigate climate change and promote resource-efficient infrastructure development, LC3 is expected to play an increasingly important role in transforming the cement and concrete industry.

## II. STUDY AREA

This study focuses on the evaluation of Limestone Calcined Clay Cement (LC3) as a sustainable alternative to Ordinary Portland Cement (OPC). LC3 is blended cement consisting of clinker, calcined clay, limestone, and gypsum, designed to reduce carbon emissions and energy consumption in cement production.

The research investigates the physical, mechanical, durability, and environmental properties of LC3 concrete. Fresh concrete properties such as workability and setting time are analysed, while hardened concrete properties including compressive strength, tensile strength, and flexural strength are evaluated at different curing periods.

The study also examines the durability performance of LC3 concrete through tests related to water absorption, permeability, chloride resistance, and sulphate resistance. Microstructural behaviour and hydration mechanisms are assessed to understand the interaction between calcined clay and limestone and their contribution to strength development.

Additionally, the environmental benefits of LC3, particularly the reduction in $CO_2$ emissions and clinker consumption, are analysed. A comparative assessment between LC3 and Ordinary Portland Cement is conducted to determine the feasibility, sustainability, and practical application of LC3 in modern construction.

The overall objective of this study is to assess the potential of LC3 as an eco-friendly, durable, and cost-effective cementitious material for sustainable infrastructure development.

## III. LITERATURE REVIEW

Limestone Calcined Clay Cement (LC3) has emerged as one of the most promising low-carbon alternatives to Ordinary Portland Cement (OPC). The increasing concern over carbon emissions from the cement industry has encouraged researchers to develop sustainable cementitious materials that can reduce environmental impact without compromising performance. Several studies have investigated the properties, durability, environmental benefits, and practical applications of LC3.

According to recent review studies, LC3 is a blended cement system consisting of approximately 50% clinker, 30% calcined clay, 15% limestone, and 5% gypsum. The reduction in clinker content significantly decreases carbon dioxide ($CO_2$) emissions and energy consumption during cement production. Researchers have reported that LC3 can reduce $CO_2$ emissions by approximately 30–40% compared to conventional

OPC while maintainingcomparable mechanical and durability properties.

Research conducted on the hydration mechanism of LC3 has shown that the combination of calcined clay and limestone produces synergistic reactions that enhance cement performance. The reactive alumina present in calcined clay reacts with calcium carbonate from limestone to form carboalumination phases. These hydration products refine the pore structure and improve the microstructural properties of concrete. Studies have confirmed that the formation of additional hydration products contributes to enhanced strength development and durability.

Several researchers have investigated the mechanical properties of LC3 concrete. Experimental results indicate that LC3 exhibits compressive strength comparable to or higher than OPC at later curing ages. The improved particle packing and pozzolanic reactions contribute to strength gain over time. Studies have also reported satisfactory tensile and flexural strength performance, making LC3 suitable for structural applications. Furthermore, the incorporation of calcined clay enhances the overall performance of cementitious composites by improving the bond between cement paste and aggregates.

Durability performance is another important area extensively studied by researchers. Literature indicates that LC3 concrete possesses superior resistance to chloride penetration, sulphate attack, and alkali-silica reaction compared to conventional cement systems. The refined pore structure and reduced permeability minimize the ingress of harmful substances, thereby increasing the service life of concrete structures. Several studies have concluded that LC3 provides excellent durability under aggressive environmental conditions, making it suitable for marine and infrastructure applications.

Environmental sustainability remains the primary advantage of LC3 technology. Numerous researchers have emphasized that the lower clinker content significantly reduces greenhouse gas emissions associated with cement production. Unlike fly ash and ground granulated blast furnace slag, whose availability is declining, calcined clay is abundant and widely available in many regions of the world. This makes LC3 a sustainable and scalable solution for future cement production. Life-cycle assessment studies have demonstrated substantial reductions in carbon footprint, energy consumption, and resource depletion when LC3 is used as a replacement for OPC.

The economic feasibility of LC3 has also been explored by various researchers. Studies suggest that the raw materials required for LC3 production, particularly limestone and low-grade kaolinitic clay, are readily available and relatively inexpensive. Existing cement manufacturing facilities can often produce LC3 with minimal modifications, reducing capital investment requirements. As a result, LC3 offers both environmental and economic benefits, especially in developing countries where sustainable infrastructure development is a priority.

Recent investigations have extended the application of LC3 to advanced construction technologies such as 3D printing, engineered cementitious composites, geotechnical engineering, and marine structures. Researchers have reported that LC3 exhibits promising performance in these applications due to its enhanced durability and sustainable characteristics. Large-scale infrastructure projects have also begun adopting LC3 technology, demonstrating its practical feasibility and growing industrial acceptance.

Despite its numerous advantages, several challenges remain. Researchers have identified variability in clay mineralogy, calcination conditions, and raw material quality as factors influencing LC3 performance. Additional research is required to optimize mix proportions, improve long-term durability predictions, and establish standardized testing procedures. Carbonation resistance, high-temperature behaviour, and large-scale field performance continue to be important areas for future investigation.

In summary, the literature demonstrates that LC3 is a highly promising sustainable cement technology capable of significantly reducing carbon emissions while maintaining excellent mechanical and durability performance. The availability of raw materials, lower production costs, environmental benefits, and growing industrial adoption make LC3 a viable alternative to Ordinary Portland Cement. Continued research and development are expected to further improve its performance and facilitate widespread implementation in the global construction industry.

## IV. MATERIALS AND METHOD

The materials used in this study include Ordinary Portland Cement (OPC) clinker, calcined clay, limestone powder, gypsum, fine aggregate, coarse aggregate, and water. LC3 cement is prepared by partially replacing clinker with calcined clay and limestone in suitable proportions. Calcined clay is obtained by heating kaolinitic clay at 700–850°C and then grinding it into fine powder.

MIX PROPORTION

The LC3 binder generally consists of approximately 50% clinker, 30% calcined clay, 15% limestone, and 5% gypsum. A control mix using OPC is also prepared for comparison. The water–cement ratio is kept constant for all mixes.

PREPARATION OF MATERIALS

Clay is dried, crushed, and calcined in a furnace, then finely ground. All materials are weighed according to the mix design before mixing.

MIXING AND CASTING

Dry materials are mixed first, followed by gradual addition of water to obtain a uniform concrete mix. Concrete is cast into standard moulds such as cubes (150 mm), cylinders (150 × 300 mm), and prisms (100 × 100 × 500 mm), and compacted properly. Specimens are demoulded after 24 hours and cured in water for 7, 28, and 56 days.

TESTING METHODS

Workability is measured using a slump test. Compressive strength is tested using cube specimens, whilecede split tensile and flexural strength are determined using standard testing procedures. Results of LC3 concrete are compared with OPC concrete to evaluate performance.

## V. RESULTS AND DISCUSSION

1. Workability Results

The workability of LC3 concrete was found to be slightly lower compared to Ordinary Portland Cement (OPC) concrete. This is mainly due to the higher water demand of calcined clay, which increases the surface area and absorption capacity of the mix. However, the use of a superplasticizer improved workability and helped achieve a consistent slump. Overall, LC3 concrete showed satisfactory workability suitable for normal construction practices.

2. Compressive Strength Results

The compressive strength of LC3 concrete showed a gradual increase with curing age. At early ages (7 days), LC3 concrete exhibited slightly lower strength than OPC concrete. However, at 28 and 56 days, LC3 concrete achieved comparable or even higher strength values in some mixes.

This strength gain is attributed to the pozzolanic reaction of calcined clay and the formation of additional hydration products such as carboalumination phases. These products refine the pore structure and improve the density of the concrete matrix. The results indicate that LC3 develops strength more effectively at later ages.

3. Split Tensile Strength

The split tensile strength of LC3 concrete was found to be similar to OPC concrete. A slight improvement was observed in some mixes due to better bonding between cement paste and aggregates. The refined microstructure contributes to improved resistance against tensile cracking.

4. Flexural Strength Results

Flexural strength results showed that LC3 concrete performs comparably to OPC concrete. The presence of calcined clay improves internal bonding and reduces micro-cracks, which enhances resistance to bending stresses. This indicates that LC3 can be effectively used in structural applications where flexural performance is important.

5. Durability Performance

LC3 concrete demonstrated improved durability characteristics compared to OPC concrete. It showed lower water absorption and reduced permeability, indicating a denser microstructure. Resistance to chloride ion penetration and sulphate attack was also improved due to reduced pore connectivity and formation of stable hydration products.

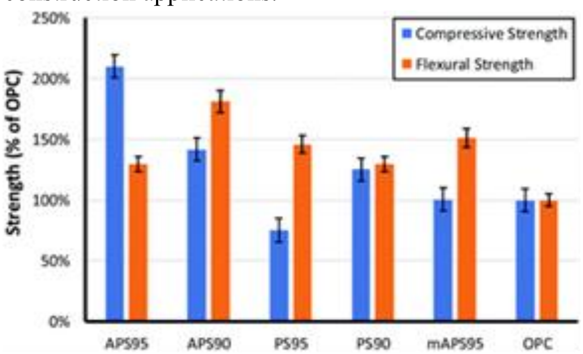
These properties make LC3 suitable for structures exposed to aggressive environmental conditions such as marine and industrial environments.

6. Discussion

The improved performance of LC3 concrete can be explained by the synergistic reaction between calcined clay and limestone. Calcined clay provides reactive alumina, which reacts with calcium carbonate from limestone to form stable carboalumination compounds. These reactions contribute to pore refinement and long-term strength development.

Although LC3 shows slightly lower early-age strength, its long-term performance is superior or comparable to OPC. The reduced clinker content significantly lowers $CO_2$ emissions, making LC3 a more sustainable alternative.

Overall, LC3 concrete offers a balance between mechanical performance, durability, and environmental sustainability. The results confirm that LC3 is a viable replacement for OPC in many construction applications.




## VI. CONCLUSION

This study on Limestone Calcined Clay Cement (LC3) concludes that LC3 is one of the most effective and practical alternatives to Ordinary Portland Cement (OPC) for achieving sustainable and low-carbon construction. The experimental and analytical observations clearly indicate that LC3 has the potential to significantly reduce the environmental impact of cement production while maintaining acceptable structural performance.

One of the most important findings of this research is the reduction in clinker content, which directly contributes to lowering carbon dioxide ($CO_2$) emissions. Since clinker production is the most energy-intensive and environmentally harmful stage in cement manufacturing, replacing a portion of clinker with calcined clay and limestone results in a substantial decrease in energy consumption and greenhouse gas emissions. The study confirms that LC3 can reduce $CO_2$ emissions by approximately 30–40% compared to OPC, making it highly relevant in the context of global climate change mitigation efforts.

The workability behaviour of LC3 concrete shows that it requires slightly higher water demand due to the fine particle size and high surface area of calcined clay. This may lead to reduced slump values compared to OPC mixes. However, this limitation is not critical, as it can be effectively managed by optimizing mix proportions and using chemical admixtures such as superplasticizers. Therefore, LC3 remains practical for field applications with proper mix design control.

Regarding mechanical performance, LC3 exhibits a distinct strength development pattern. The early-age strength (7 days) is generally lower than OPC due to slower hydration reactions and higher water demand. However, with continued curing, LC3 demonstrates significant strength gain at 28 and 56 days, often reaching values comparable to or even exceeding OPC. This improved long-term strength is attributed to the pozzolanic reaction of calcined clay, which consumes calcium hydroxide and forms additional calcium silicate hydrate (C–S–H), as well as the formation of carboalumination phases resulting from the interaction between calcined clay and limestone. These hydration products refine the pore structure and increase the density of the cement matrix.

The durability performance of LC3 concrete is another major advantage observed in this study. LC3 exhibits reduced permeability, lower water absorption, and improved resistance to chloride ion penetration and sulphate attack. The refined pore structure and reduced connectivity of capillary pores significantly enhance resistance to aggressive environmental conditions. This makes LC3 particularly suitable for structures exposed to marine environments, chemical exposure, and long-term durability requirements such as bridges, coastal structures, and industrial facilities.

Microstructural considerations further support the improved performance of LC3. The synergy between calcined clay and limestone leads to the formation of stable hydration products, especially carbolines, which contribute to a denser and more stable microstructure. This refinement of internal pore structure not only enhances strength but also improves durability and reduces long-term degradation of concrete.

From an environmental perspective, LC3 offers a highly sustainable solution. The use of low-grade kaolinitic clay and limestone, which are widely available in many regions, reduces dependency on scarce supplementary cementitious materials such as fly ash and slag. Additionally, the lower calcination temperature required for clay activation (approximately 700–850°C compared to 1450°C for clinker production) results in significant energy savings. These factors together make LC3 a scalable and globally applicable technology for sustainable cement production.

Economically, LC3 is also advantageous because it can be produced using existing cement manufacturing infrastructure with minimal modifications. The availability of raw materials and reduced production costs further support its commercial feasibility, especially in developing countries where infrastructure development is rapidly increasing and cost-effective materials are essential.

Despite these advantages, certain limitations are noted. The variability in clay composition, the need for proper calcination control, and slightly reduced early-age strength require careful quality control and mix optimization. Further research is also needed to standardize LC3 production methods, improve early-age performance, and evaluate long-term field behaviour under different environmental conditions.

In conclusion, LC3 cement represents a significant advancement in sustainable construction materials. It successfully balances environmental benefits, mechanical performance, durability, and economic feasibility. While some challenges remain in optimization and standardization, the overall findings strongly support LC3 as a viable and future-ready alternative to Ordinary Portland Cement. Its adoption can play a crucial role in reducing the carbon footprint of the construction industry and supporting global efforts toward sustainable development and climate change mitigation.

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