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Original Research Article

Sustainability and Durability Properties of Limestone Calcined Clay Cement (LC3): Insights from Recent Research

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Abstract

During the production of cement, a significant amount of CO2 emissions is generated. To address this issue, Lime Stone Calcinated Clay (LC^3) was introduced in cement as a sustainable alternative, reducing the use of cement by 40-50% by replacing LC3 in the cement. This study investigates the effectiveness of LC3 in the hydration process, microstructural analysis, and sustainability. At the time of hydration, calcium hydroxide was generated, which, when mixed with metakaolin, produced a significant amount of CSH gel, thereby enhancing the mechanical strength and microstructural properties. Sturdy carboaluminates are created when limestone and aluminates interact, increasing chloride and sulfate resistance. Geometrical stability is ensured by controlled ettringite development and calcium Aluminate Ferrite trisubstituted (Aft)- Alumina-Ferric oxide-mono (AFm) transitions, although reinforcement is sustained by carbonation resistance. LC^3 attains mechanical and durability properties when compared with conventional cement by decreasing emissions by reducing approximately 50% clinker factor and calcination temperatures from 700-900 °C.

Keywords: LC^3, lower clinker, durability, CO_2 emissions, sustainability.

1. INTRODUCTION

In the construction sector, the demand for cement is high, and during its production, significant amounts of carbon dioxide are generated, contributing to environmental issues. According to the investigation by Onsongo *et al.*, (2025) and Rodrigues and Joeskes (2010), the leading cause of climate change is the cement industry, which produces 8% of carbon dioxide emissions worldwide. To mitigate carbon dioxide emissions, alternative materials and sustainable production methods have been developed (Ighalo *et al.*, 2020; Adhikari, 2021). However, some functional drawbacks and economic challenges hinder the extensive use of these approaches (Ighalo & Adenuyi, 2020). Combined with limestone, calcined clay, gypsum, and clinker, it has become a sustainable alternative that can substitute a significant amount of cement. On the other hand, the blend with regular Portland cement can reduce carbon dioxide emissions by 40-50% (Kaptam *et al.*, 2024). As demonstrated by many researchers in their review journals and conferences from 2010 to 2025, LC3 investigations has increase significantly in the past ten years (Fig.1). Beyond these benefits on the environment LC3 leads to superior performance in enhancing mechanical and durability properties, which makes suitable for construction under extreme conditions (Fig.2). Based on the research outcomes, Lime Stone Calcinated Clay can achieve better results over ordinary cement to a limit of 10% in compressive strength at 90days curing period and 45% protect from entry of water (Sirangi & Prasad, 2023). According to Maraghechi *et al.*, (2018) and Ram *et al.*, (2022), the binding of kaolinite with calcinated clay critically affects material behavior. It has also been observed that medium kaolinite levels can reduce unexpected chloride diffusion. Limestone calcined clay can improve its flexibility through carbonation and chloride intrusion by introducing recycled materials, including sand. The changes observed in microstructural analysis, which involve the formation of calcium aluminate silicate hydrate (C-A-S-H) and carboaluminate phases, contribute to these enhancements. These phases strengthen the matrix, reduce voids, and improve resistance to critical agents (Sui *et al.*, 2022).

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Table 1: Key Chemical Reactions in LC³ Hydration

S. No	Mechanism	Chemical reactivity	Hydration	Significance	References
1	Initial hydration of OPC (0–24 h)	$2C_3S + 6H_2O \rightarrow C_3S_2H_3 + 3CH2C_2S + 4H_2O \rightarrow C_3S_2H_3 + CH$	Calcium–silicate–hydrate (C–S–H), Calcium hydroxide (CH)	Provides calcium hydroxide, which reacts with calcined clay and promotes early age strength enhancement	Parashar *et al.*, 2022
2	Metakaolin based pozzolanic reaction (1–7 days)	Metakaolin (Al_2SiO_7) + CH + $H_2O \rightarrow$ C–A–S–H	Calcium–alumino–silicate–hydrate (C–A–S–H)	Decreases the calcium hydroxide content, improves the matrix's microstructure, and enhances its mechanical and durability performance.	
3	Limestone–Carboaluminate development (3–28 days)	Aluminate from calcined clay + $CaCO_3$ + CH + $H_2O \rightarrow$ Monocarboaluminate/ Hemicarbonate	Mono carboaluminate (Mc), Hemicarbonate (Hc)	Stabilizes alumina-based compounds, decreases porosity, and increases resistance to chlorides and sulphate attacks.	Zunino *et al.*, 2023;
4	Ettringite Formation / AFt (Initial stage)	$C_3A + 3CaSO_4 \cdot 2H_2O + 26H_2O \rightarrow C_6AS_3H_{32}$ (Ettringite)	Ettringite (AFt)	Enhances early age volume expansion and maintains long-term stability	Dhandapani *et al.*, 2021
5	AFt–AFm Conversion (Later stage)	$C_6AS_3H_{32}$ + CH $\rightarrow C_4ASH_{12}$ (Monosulfate / AFm)	Monosulfate (AFm)	Decreases long-term expansion by facilitating sulfate to carbonate modification in AFm structures to develop carboaluminates	
6	Carbonation / CO_2 Interaction (Long-term)	C–S–H + $CO_2 \rightarrow CaCO_3$ + silica gel	Calcite, silica gel	Lower pH levels may affect the protective environment around reinforcement under significant reduction.	Shao *et al.*, 2025

The addition of secondary cementitious materials (SCMs) and the formation of carboaluminate lead to a different hydration process of Limestone Calcined Clay Cement compared to that of conventional Portland cement. In this context, aluminates extracted from calcined clay fuse with limestone to produce strong carboaluminates. Ca(OH)2, released by clinker hydration, combines with metakaolin to produce additional C-A-S-H gels. Furthermore, enhancing chloride and carbonation resistance, paired with controlled ettringite formation, and stabilizing Aft-to-AFm transitions, facilitates shape and volume stability (Kanavaris *et al.*, 2023). The mechanical durability performance of Limestone Calcined Clay Cement has been improved through chemical reactions, as illustrated in Table 1 and characterized in Fig. 3.

Focusing on its durability under extreme conditions, this investigation evaluates Limestone Calcined Clay Cement as a sustainable substitute for traditional cement. Structural stability, decrease in carbonation, resistance to chlorides, and moisture permeation are included in the investigation. The significance of raw materials and their aspects, like kaolinite content, calcinated clay reaction, and the use of recycled aggregates. The main aim is to enhance formulation measures that promote the use of Limestone Calcined Clay Cement in building projects. Its validity and environmental performance are high, as it strikes a balance with lower carbon emissions.

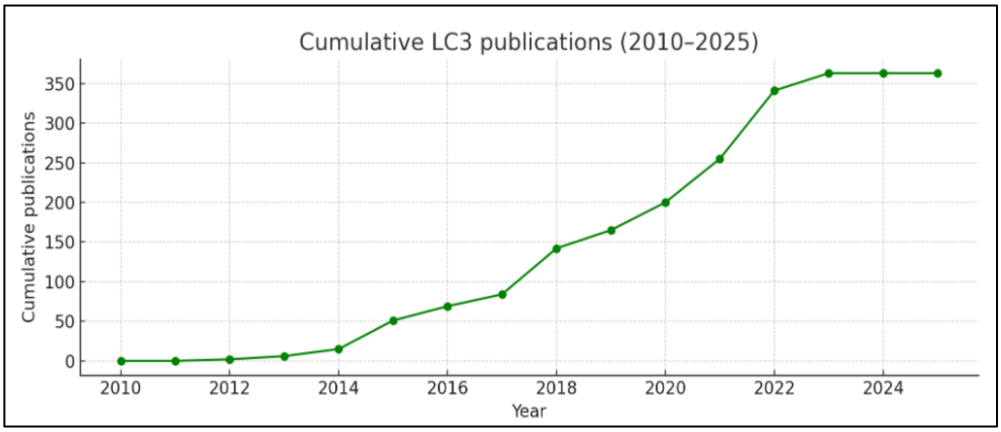

Fig. 1: Publication trends for Limestone Calcined Clay Cement from 2010 to 2025 indicate a gradual increase in annual research findings, with a dramatic rise after 2018 (Scopus database search results for "Limestone Calcined Clay Cement")

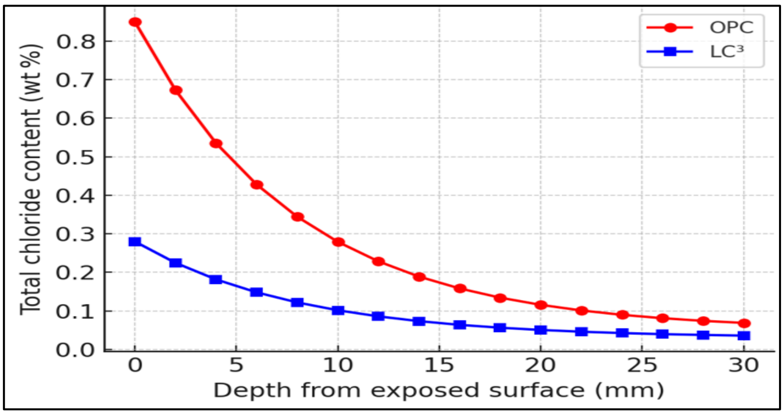

Fig. 2: Based on Nguyen *et al.*, (2020) and Sirangi & Prasad (2023), demonstrating LC³'s significantly developed strength and durability performance compared with normal portland cement

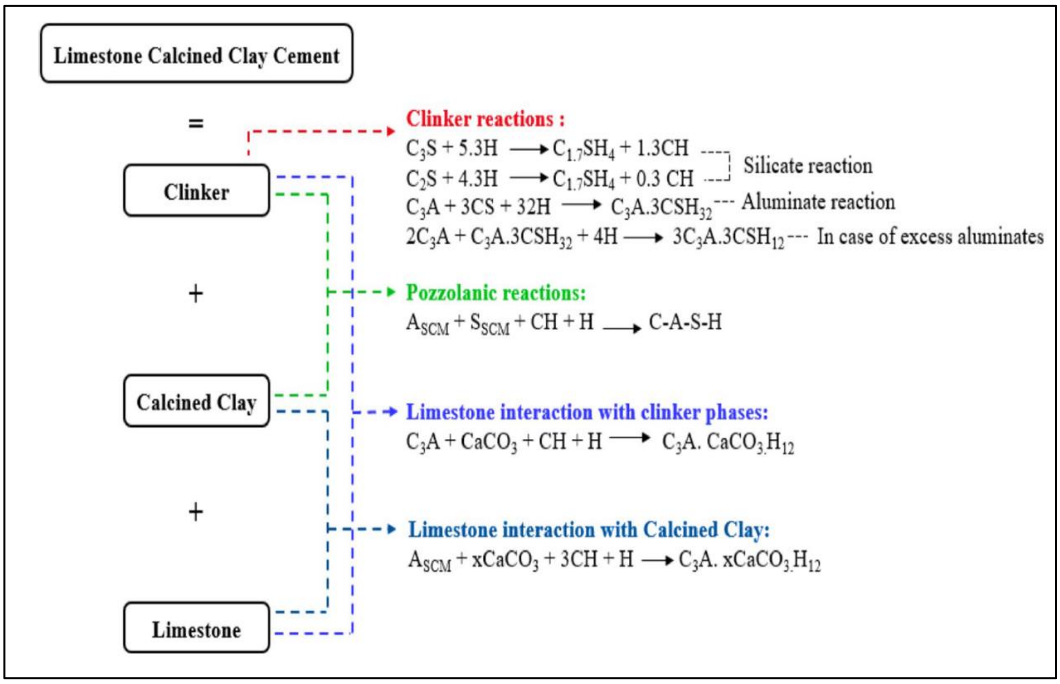

Fig. 3: The diagram represents the principal chemical reaction in the LC³ binder, which involves clinker hydration, pozzolanic reaction of calcined clay (metakaolin) with portlandite, and development of carboaluminate phases via alumina–limestone interaction (Renuka *et al.*, 2025)

2. Durability properties

In contrast to conventional cements, LC^3 is highly recognized for its capability to reduce carbon emissions while developing significant durability. Various tests have validated its suitability for challenging work conditions by testing its hardened properties, chloride resistance, and microstructural analysis. As per Sirangi (2023), Limestone Calcined Clay Cement concrete conquered traditional cement by attaining a 10% rise in 90-day compressive strength and a 45% improvement in moisture resistance. These improvements reduce the eventuality of degradation by moisture-caused expansion, shrinkage, and wetting-drying cycles. The calcinated clay reaction can generate a dense microstructure, which is highly responsible for durability. Despite enough calcinated clay, LC^3 also illustrated an outstanding chloride diffusion resistance, by achieving parallel to traditional cement under similar exposure (Nguyen *et al.*, 2020). It was mentioned that a medium kaolinite content in calcinated clay can resist chloride ingress, by permitting the use of affordable, locally available clays (Marghechi *et al.*, 2018; Sun *et al.*, 2023). Bending strength improves and reduces complete porosity for developing C-A-S-H and carboaluminate phases, reducing micro-pore affinity (Sui etal, 2022). In addition, collate to CEM II binders, LC^3, which integrates recycled materials like sand, providing greater strength, carbonation resistance, and chloride resistance, by decreasing its ecological impact (Jan *et al.*, 2024)

2.1 Moisture ingress resistance

A primary consideration influencing concretes persistence is moisture intrusion resistance, altering permeability and sorptivity. In this connection LC^3 constantly achieved greater than conventional cement by improving 45% resistance to moisture have been recorded (Sirangi and Prasad 2023). This is evidenced by the calcinated clay fineness and how they mix with limestone and clinker to produce a fine pore structure that avoids fluid flow. Calcined clays kaolinite is critical whereas moderate kaolinite content substantially lowers moisture absorption and chloride interruption beyond the requirement of premium clays, decreasing material cost (Maraghechi *et al.*, 2018). The mixture is more developed by supplementary material interactions among metakaolin and CH, which reduces sorptivity and porosity (Shah *et al.*, 2020).

LC^3 mix shows unique performance in chloride penetration and carbonation resistance (Jan etal., 2024), optimizing them for marine and de-icing salt setting. To lower mass loss and sustain compressive strength over a long-term service, innovative alternations like microcapsule insertion have beem recommended to develop resistance to sulphates and self-healing ability (Du etal., 2024). As displayed in Fig 4, LC^3 consistently surpasses OPC in avoiding the entry of moisture for a long period by attaining less sorptivity and water absorption.

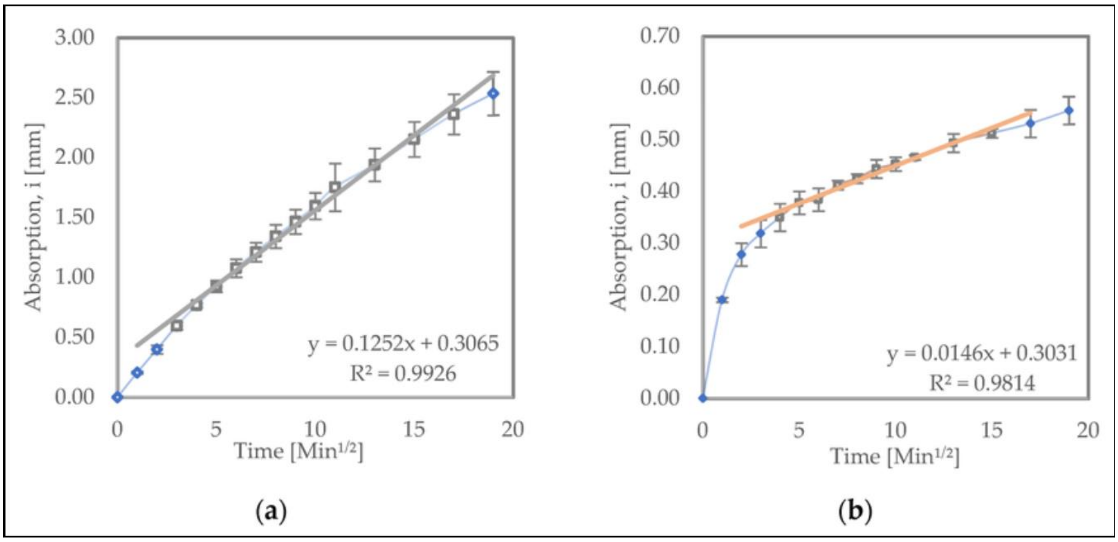

Fig. 4: Sorptivity results for (a) OPC and (b) LC^3 samples exposed to water uptake tests. LC^3 demonstrates reduced water absorption compared with OPC, highlighting improved resistance to capillary suction (Odhiambo *et al.*, 2022)

2.2 Chloride ingress

The durability of limestone calcined clay cement (LC^3) concerning chloride ingress—a critical factor influencing concrete performance in maritime and de-icing environments—has been dramatically improved by a recent study. Long-term penetration investigations and diffusion coefficients are the primary methods for assessing chloride ingress. Research suggests that LC^3's durability is greatly impacted by the amount of kaolinite present in its clay components. As an illustration, medium-kaolinite clay's enhanced pore structure and chlorine-binding ability result in a 50% and 36% decrease in the chloride migration and diffusion coefficients, respectively, when compared to Portland cement (Ram *et al.,* 2022).

Despite a reduction in compressive strength, LC³ samples showed remarkable resistance to chloride penetration, with diffusion coefficients significantly lower than those of Ordinary Portland Cement (OPC), according to a thorough analysis of LC³ compositions containing low-grade marine clay. This resistance demonstrated the resilience of LC³ against chloride infiltration and was constant regardless of the kaolinite concentration or replacement level (Hu *et al.,* 2024).

More investigation indicates that, compared to pure Portland cement, diffusivity is reduced by two orders of magnitude at moderate kaolinite content levels (≈ 50%). Maraghechi *et al.,*(2018) suggest that even clays with a moderate kaolinite content can significantly improve LC³'s resistance to chloride penetration, negating the need for high-grade clays to achieve positive durability outcomes. Environmental factors and microstructural features also affect chloride infiltration and material composition. Natural pozzolans like Trass and Pumice were shown to be effective in reducing both carbonation and chloride attack in combined hostile conditions, as seen by the up to 76% decrease in the chloride diffusion coefficient that was seen in these situations (Kazemian *et al.,* 2021).

In addition, long-term analyses have shown that exposure, weather, and micro environmental factors all have a significant impact on the mechanisms of chloride intrusion. Practical tools for forecasting and evaluating the long-term risk of chloride-induced corrosion in reinforced concrete structures are provided by sophisticated modelling techniques that take into account several variables, including diffusion, convection, chloride binding, and concrete ageing (Nguyen *et al.*, 2017; Zacchei & Bastidas-Arteaga, 2022). In comparison to OPC, LC³ achieves much lower chloride penetration at all measured depths, as illustrated in Fig. 5. Its improved salt-binding capacity and modified pore structure, which combine significantly to increase resistance to chloride intrusion, are responsible for this excellent performance (Marangu, 2020).

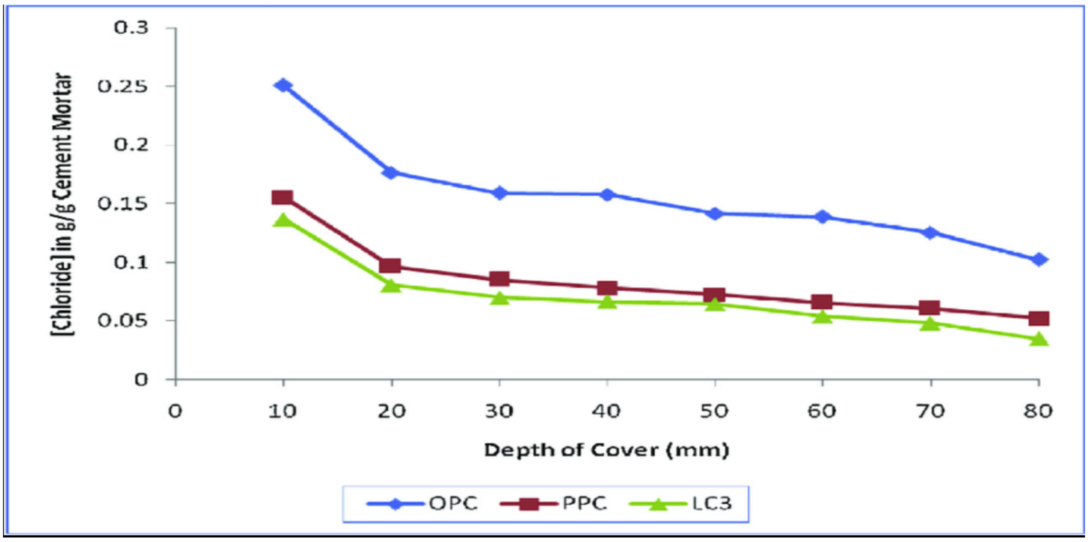

Fig. 5: Chloride concentration at different depths for LC³, PPC, and OPC at a w/c ratio of 0.50. (Marangu 2020)

2.3 Carbonation resistance

A sustainable binder that significantly lowers CO2 emissions while boosting concrete's durability is limestone calcined clay cement (LC³). It is crucial to comprehend LC³'s carbonation resistance, especially in light of the functions of pozzolanic reactions and limestone. Limestone enhances LC³ performance in several ways. It serves as a filler, increasing the cement matrix's packing density, and it offers nucleation sites, which encourage other components to hydrate and increase carbonation resistance. Carboaluminates are created when calcined clay and limestone interact, densifying the pore structure and lowering permeability (Ram *et al.,* 2022; Sirangi & Prasad, 2023). However, a diluting effect that could reduce long-term strength can result from partially substituting limestone for cement. By employing fine limestone particles, which improve early-age strength through filler and nucleation effects without substantially sacrificing later-age durability, this can be lessened (Wang & Luan, 2018).

The primary source of the pozzolanic activity in LC³ is calcined clay. The production of more calcium silicate hydrates (C–S–H) by the reaction between the clay and calcium hydroxide upon thermal activation is crucial for enhancing the binder's mechanical and microstructural characteristics. Additionally, resistance to carbonation and other aggressive agents is increased by this mechanism (Jan *et al.,* 2024; Krishnan *et al.,* 2019). Research using different pozzolans, like fly ash and metakaolin, demonstrates their function as additional cementitious elements that improve durability by decreasing permeability and fine-tuning the pore structure (Giménez-García *et al.*, 2016; Shi, 2001).

As illustrated in Fig. 6, two representative natural-exposure carbonation scenarios are presented. In the first case (orange line), LC³ shows higher carbonation depths—reported in several accelerated and some field studies—where calcium hydroxide availability is low. In the second case (green line), optimized LC³ mixes with higher kaolinite content, improved curing, and tailored mix designs produce carbonation depths comparable to or slightly lower than OPC. These results emphasise that carbonation resistance in LC³ is highly dependent on mix composition and exposure conditions.

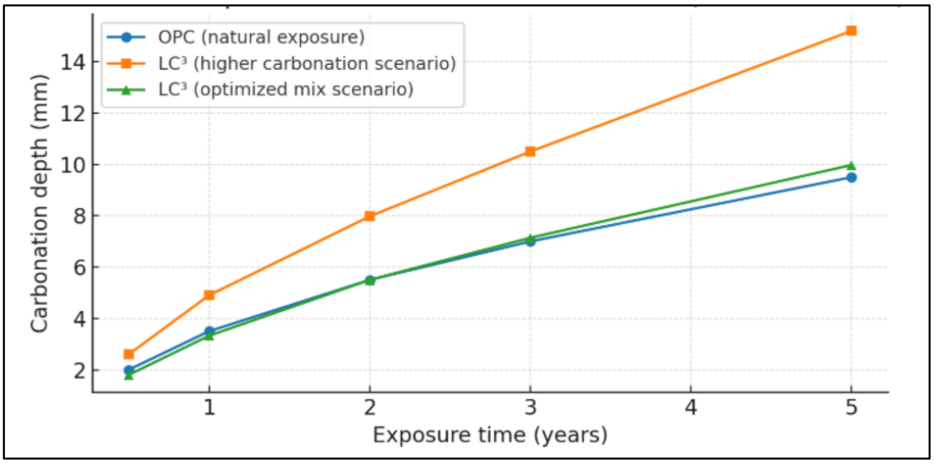

Fig. 6: Natural exposure scenarios for carbonation resistance of LC³ compared with OPC: (1) higher carbonation for LC³ (orange line) in cases of low calcium hydroxide availability; (2) optimized LC³ mixes (green line) with high kaolinite content, adequate curing, and tailored mix design showing carbonation depths comparable to or lower than OPC (Zunino & Scrivener, 2022; Avet & Scrivener, 2018; Shao *et al.*, 2025)

2.4 Sulfate attack

Because of its resilience in sulfate-rich conditions, limestone calcined clay cement (LC³) has become a viable substitute for ordinary Portland cement (OPC). Its performance against sulphate assault has been assessed in recent investigations, which have shown both important benefits and areas for additional research. Decreased sulphate penetration and expansion: LC³ shows less sulphate penetration and expansion when exposed to sodium sulfate solutions than OPC. The development of stable calcium carboaluminate phases, which are less susceptible to sulfate-induced expansion, is principally responsible for this improvement. Further enhancing resistance is the improved pore shape in LC³, which restricts sulphate ion entry (Suma & Santhanam, 2018).

Impact of calcined clay and limestone content:

As calcined clay and limestone replace clinker, sulphate resistance rises. Compared to mixes with 15% replacement, mortars with 30% and 45% replacement levels showed lower sulphate penetration depths and lesser sulfate-bearing phases. This emphasises how crucial it is to maximise the amounts of limestone and calcined clay in LC³ formulations.

Long-term performance and microstructural stability:

LC³ withstands sulphate exposure without losing its mechanical strength or microstructural integrity. This is accomplished by creating a thick microstructure and stable hydration products (Arbab *et al.*, 2025). LC³ mortars exhibit noticeably less sulfate-induced expansion throughout the test than OPC, as indicated in Table 2.

The stabilisation of AFm phases as hemicarbonate/monocarboaluminate and the decrease in permeability brought about by pozzolanic refining are responsible for this improvement. The information is taken from Avet *et al.*, (2018), Zunino & Scrivener (2021), and Dhandapani *et al.*, (2021).

Table 2: Comparison of sulfate-induced expansion between OPC and LC³ mortars, showing reduced expansion in LC³ throughout the test period due to AFm phase stabilization and lower permeability

S. No	Age (days)	OPC Expansion (%)	LC³ Expansion (%)	Source
1	28	0.035	0.015	Dhandapani *et al.*, 2021
2	56	0.072	0.030	Dhandapani *et al.*, 2021
3	90	0.115	0.048	Zunino & Scrivener, 2021
4	180	0.165	0.070	Zunino & Scrivener, 2021
5	365	0.240	0.095	Avet *et al.*, 2018

2.5 Alkali–silica reaction

Because of its promising durability properties, especially its resistance to the alkali-silica reaction (ASR), limestone calcined clay cement (LC^3) has garnered much attention. Because of the chemical interaction between reactive aggregates and alkali hydroxide ions in the pore solution, ASR is a significant durability concern in cementitious systems. An expanding gel created by this reaction may break and cause long-term structural deterioration. According to empirical research, LC^3 has a significantly higher resistance to ASR than regular Portland cement (OPC). When optimizing kaolinite concentration, calcination conditions, and mix design, LC^3 blends can successfully limit expansion and related damage from ASR (Scrivener *et al.*, 2018).

SCMs, or supplemental cementitious materials, such as Pozzolans, fly ash, and silica fume, are other mitigating techniques that can chemically change the pore solution to lower reactivity and physically limit the expansion of ASR gel. Pozzolanic additions decrease the concentration of alkali hydroxide in the pore solution, refine the microstructure, and decrease the reactive silica content (Menéndez *et al.*, 2020; Ramjan *et al.*, 2021). Products of industry when calcined and utilised as SCMs, some industrial by-products, such as drinking water treatment sludge, have shown promise. These materials can increase ASR resistance by decreasing expansion and improving mechanical qualities (Duan *et al.*, 2020).

Physical and chemical improvements to LC^3 and other composite cements improve durability by reducing water sorptivity, which limits water ingress, a crucial factor in the progression of ASR, and increasing compressive and flexural strengths (Aslani *et al.*, 2023; Fernandez-Jimenez *et al.*, 2006). Figure 7 illustrates how LC^3 with a 30-weight percent clinker substitution considerably decreased expansion in accelerated ASR testing (ASTM C1260), keeping values within the ~0.20% Australian standard limit. The establishment of stiff C–S–H and C–A–S–H phases, which limit expansion cracking, and delayed ASR gel formation are associated with this improvement.

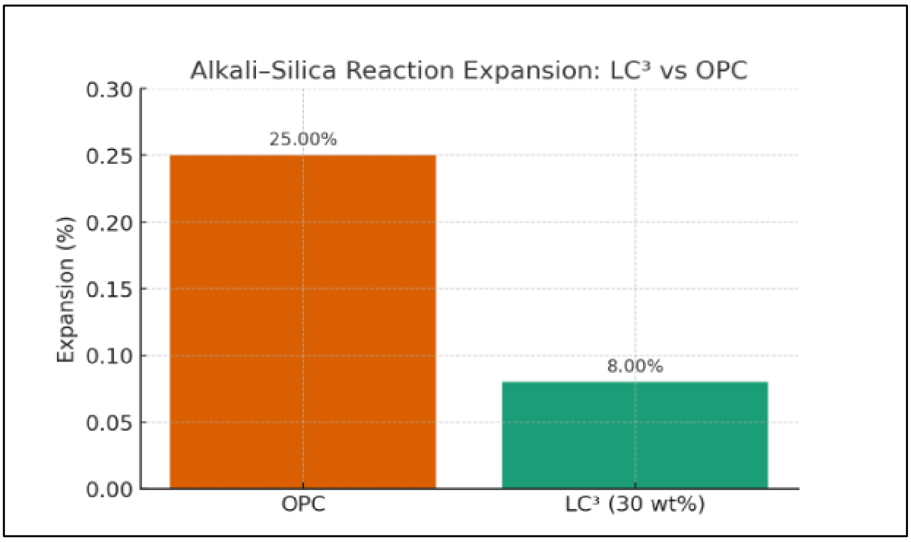

Fig. 7: Expansion of mortar bars under accelerated ASR conditions (ASTM C1260) for LC^3 and OPC mixes, showing substantially lower expansion for LC^3. Data adapted from Nguyen *et al.*, (2020)

3. MICROSTRUCTURAL STUDIES

Compared to traditional Portland cement, Limestone Calcined Clay Cement (LC^3) is a sustainable binder that minimises CO_2 emissions by making the most of plentiful raw materials like limestone and calcined clay. The performance and durability of LC^3 are determined mainly by the carboaluminate and calcium aluminate silicate hydrate (C–A–S–H) phases, according to microstructural studies.

Hydration product formation:

According to metal intrusion-enhanced imaging, LC^3 initially produces an inhomogeneous microstructure, while carboaluminates and C-A-S-H gradually contribute to mechanical strength and microstructural homogenization at later ages (Sui *et al.*, 2022). Even when clinker hydration is decreased, the phases of hemicarboaluminate and monocarboaluminate are especially advantageous, enhancing mechanical performance (Parashar & Bishnoi, 2021).

Effect of curing temperature:

Higher curing temperatures increase the amount of aluminium incorporated into the C–A–S–H gel while decreasing the amounts of ettringite and carboaluminates. This demonstrates how sensitive LC^3 hydration is to temperature (Mishra *et al.*, 2019).

Effect of kaolinite content:

Hydration kinetics are greatly impacted by variations in the calcined kaolinite content. While higher kaolinite levels inhibit the formation of carboaluminate hydrate, they increase metakaolin reactivity and C-A-S-H formation (Avet & Scrivener, 2017).

The function of portlandite. Increased portlandite concentration in low-clinker systems encourages the development of carboaluminate and the metakaolin reaction, which are associated with increased compressive strength (Sun *et al.*, 2023).

Utilising coal gangue waste in LC^3 for ultra-high-performance concrete applications can lower costs and embodied carbon. However, it may also leave a lot of unreacted particles that compromise long-term strength. This is one example of alternative raw materials and SCMs (Luo *et al.*, 2023). It has been demonstrated that adding recycled sand increases resistance to carbonation and chloride infiltration (Jan *et al.*, 2024). Although it delays hydration and marginally decreases strength, adding biochar as an additional cementitious material can increase environmental benefits (Wang & Wang, 2023).

Mechanical performance:

LC^3 is excellent for structural applications since it usually achieves lower early-age strength than OPC but matches or surpasses OPC's late-age strength while offering better flexural strength (Huang *et al.*, 2020). Figure 8: Microstructure of LC^3 paste displaying the distribution and morphology of the carboaluminate (CO_3-AFm) and C–A–S–H gel phases. In LC^3 systems enriched with aluminium from calcined clay, the grey-toned matrix represents C–A–S–H, the primary binding phase, creating an amorphous, interconnecting structure. Alumina from calcined clay and carbonate from limestone react to generate carboaluminate phases (monocarboaluminate or hemicarboaluminate), which are indicated by cyan-colored regions. The pore structure is refined, porosity is decreased, and mechanical performance is enhanced when C-A-S-H and carboaluminates are present together (modified from Sun, Zunino & Scrivener, 2024).

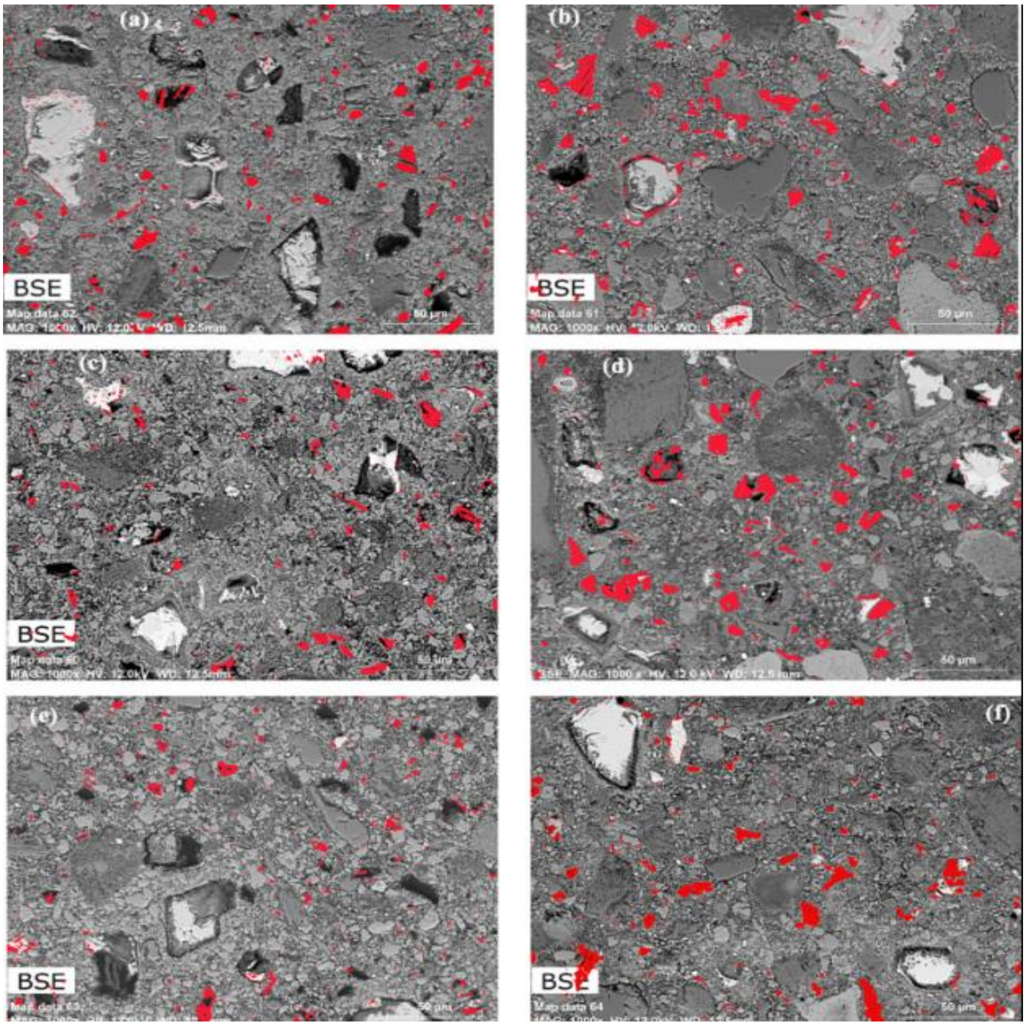

Fig. 8: Backscattered-electron (BSE) images with colour overlays highlighting the distribution of C–A–S–H (gel phase) and CO_3-AFm (carboaluminate) in LC^3 paste. (Sun, Zunino & Scrivener 2024)

4. Mechanical properties

With an emphasis on compressive, tensile, and flexural strengths, recent studies on limestone calcined clay cement (LC³) have investigated its mechanical performance and underlying microstructural variables. The suitability of LC³ for structural and long-lasting concrete applications is determined by evaluating these properties throughout a range of curing ages.

Compressive strength:

Through hydration and pozzolanic processes, LC³'s compressive strength increases over time (Fig. 9). Research indicates that adding fibers increases compressive strength by improving toughness and ductility; the effect varies according to the length and content of the fibers (Maher & Ho, 1994; Wang *et al.*, 2022).

Tensile strength:

Because LC³ is brittle, its tensile strength is lower than its compressive strength, just like other cementitious materials (Li *et al.*, 2009). It has been demonstrated that tensile strength results from modified test procedures are more comparable to those from direct tensile measurements (Liao *et al.*, 2020). Fiber reinforcement can further increase tensile strength by bridging cracks and regulating the spread of microcracks (Maalej & Li, 1994).

Flexural strength:

Usually greater than tensile strength, flexural strength represents the material's behavior under bending. Fiber-containing LC³ composites exhibit better crack management and tension-softening behaviour, increasing early-age flexural strength that gets better with hydration and pozzolanic activity (Maalej & Li, 1994; Li *et al.*, 2009).

Relationship between microstructure and strength:

Adding calcined clay increases packing density and fine-tunes pore structure, directly boosting compressive and flexural strengths. Thus, variations in the composition of LC³ can affect mechanical performance, porosity, and hydration kinetics. Across various mix designs and curing regimes, LC³ concretes from recent investigations have mechanical qualities that are on par with or better than OPC, as summarised in Table 3. These findings demonstrate the potential of LC³ as a high-performing, environmentally friendly cementitious binder.

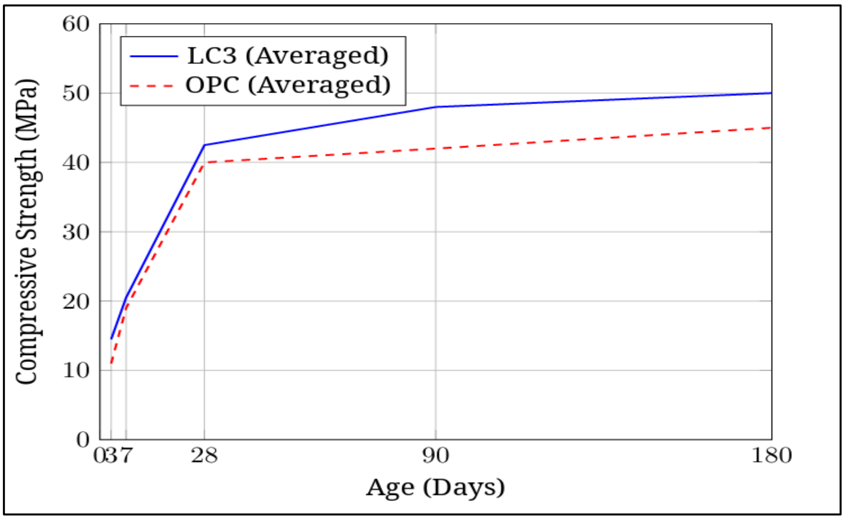

Figure 9: Average compressive strength development of LC³ and OPC concretes from several studies demonstrates that LC³ uses a combination of hydration and pozzolanic activity to achieve similar or greater strength at equivalent curing ages (Dhandapani *et al.*, 2018; Reddy *et al.*, 2020; Yu *et al.*, 2021; Rengaraju & Pillai, 2023; Rath *et al.*, 2025; Wang *et al.*, 2025; Renuka *et al.*, 2025)

Table 3: Mechanical properties of Limestone Calcined Clay Cement (LC³) concretes from recent studies, compared with OPC across various mix designs and curing ages

S No	Source (Year)	Mix Details	Compressive Strength (MPa)	Flexural Strength (MPa)	Tensile/Splitting Tensile Strength (MPa)
1	Rath *et al.*, (2025)	LC3 with 30% surkhi, 4% nano-silica, 100% M-sand replacement, M30 grade	28 days: Enhanced by up to 1.48 times vs. traditional; 90 days: Enhanced by up to 1.36 times	28 days: Enhanced by up to 1.46 times vs. traditional; 90 days: Enhanced by up to 1.37 times	28 days: Enhanced by up to 1.43 times vs. traditional; 90 days: Enhanced by up to 1.26 times
2	Renuka *et al.*, (2025)	LC3-50 (50% clinker replacement	28 days: Comparable to OPC (~40-50)	Not specified	Not specified

S No	Source (Year)	Mix Details	Compressive Strength (MPa)	Flexural Strength (MPa)	Tensile/Splitting Tensile Strength (MPa)
		with calcined clay and limestone)			
3	Dhandapani *et al.*, (2018)	LC3 (50:31:15:4 clinker: calcined clay: limestone: gypsum)	28 days: 45-60	28 days: 5-7	Not specified
4	Yu *et al.*, (2021)	LC3-based ECC with ultrahigh-volume limestone-calcined clay, 45% clinker replacement	28 days: 45	28 days: Increased by 2-10% vs. OPC (~10-12)	28 days: ~5
5	Ruan *et al.*, (2022)	LC3 with ultra-high substitution (50% clinker replacement)	28 days: 50	Not specified	Not specified
6	Qinfei Li *et al.*, (2019)	LC3 with limestone, calcined clay, clinker	28 days: 45.6	Not specified	Not specified
7	de Oliveira *et al.*, (2020)	LC3 pastes	28 days: Comparable to OPC (~35-45)	Not specified	28 days: 3.5
8	Yu *et al.*, (2020)	High-tensile SHCC with LC3	28 days: Slightly reduced vs. OPC (~40-50)	28 days: 8	Not specified
9	Wang *et al.*, (2025)	LC3 with 50% metakaolin-limestone, 0% RA (Mix M2)	3 days: 13.6; 7 days: 21.4; 28 days: 37.6; 90 days: 51.6	Not specified	Not specified
10	Wang *et al.*, (2025)	LC3 with 50% metakaolin-limestone, 30% coarse RA (Mix M7)	3 days: 15.1; 7 days: 22.1; 28 days: 35.7; 90 days: 44.1	Not specified	28 days: 2.98
11	Purushotham Reddy *et al.*, (2020)	LC3-based concrete vs. OPC & PPC	28 days: Comparable to OPC (~30-50 for M30/M50)	Not specified	Comparable to OPC (~3-5)
12	Rathnarajan *et al.*, (2022)	LC3 with fly ash, slag	28 days: ~97% of OPC (~35-45); 180 days: Slightly exceeds OPC (~45-50)	180 days: >20% higher than OPC (~7-9)	Inferred higher at later ages (~4-5)
13	Rengaraju & Pillai (2023)	LC3 reinforced concrete	28 days: ~50-60	28 days: Enhanced (~8-10)	Not specified
14	Afroz *et al.*, (2023)	LC3 with 10% waste glass powder	28 days: Higher than OPC (~45-50); 12 months: Max with 10% GP (~55)	28 days: Higher than OPC (~6-7)	28 days: Higher than OPC (~4-5)
15	Hay & Celik (2023)	LC3 vs. OPC, M25 grade	3 days: ~15; 7 days: ~20; 28 days: ~30	28 days: ~5.5	28 days: ~3.5
16	Shoukry *et al.*, (2022)	LC3 with varying kaolinite content	28 days: Comparable to OPC (~30-50)	Not specified	Not specified
17	Sui *et al.*, (2023)	LC3-50 with 41.9-95% kaolinite	28 days: 9-34% higher than OPC (~40-55)	28 days: 17% higher than OPC (~6-8)	28 days: Slightly higher than OPC (~3-4)
18	Ez-zaki *et al.*, (2021)	High-strength strain-hardening	28 days: Improved (~50-60)	28 days: 10-12	Not specified

S No	Source (Year)	Mix Details	Compressive Strength (MPa)	Flexural Strength (MPa)	Tensile/Splitting Tensile Strength (MPa)
		composites with LC3			
19	Sharma *et al.*, (2021)	LC3 with w/b similar to OPC	28 days: Similar to OPC (~35-45)	Not specified	Not specified
20	Avet & Scrivener (2020)	LC3 mortar with waste glass powder	28 days: ~35-45	28 days: ~5-6	Not specified

5. Sustainability aspects

Compared to Ordinary Portland Cement (OPC), Limestone Calcined Clay Cement (LC³) can significantly lower CO_2 emissions and save energy. This is its main environmental advantage. According to several studies, LC³ can reduce CO_2 emissions by 40–50% compared to conventional cement. The primary cause of this decrease is the partial replacement of clinker—the primary source of CO_2 emissions in cement manufacturing—with calcined clay and limestone. About 5% of the world's anthropogenic CO_2 emissions come from the cement sector, so low-carbon and energy-efficient solutions are being developed to increase sustainability. According to research, energy consumption and emissions can be significantly decreased by incorporating cutting-edge energy efficiency methods and encouraging low-carbon inventions (Hasanbeigi *et al.*, 2012).

The use of renewable energy, technical advancements, and higher agricultural and forestry productivity are some of the factors that have been connected to emission reductions in many industries and nations (Li *et al.*, 2022; Raihan *et al.*, 2022; Raihan & Tuspekova, 2022). Site-specific tactics, including industrial energy recovery, have also demonstrated quantifiable advantages in energy conservation and emission reduction. Digitalisation is one example of an innovative approach that has shown synergy between environmental and technological advancements, assisting in the reduction of CO_2 emissions (Wang *et al.*, 2024). LC³ produces an average of about 540 kg of CO_2 per tonne of cement, which is significantly less than the 900 kg produced by OPC and the 810 kg produced by Portland Limestone Cement (PLC), as shown in Fig. 10. The reduced clinker concentration (~50% against 95–100% in OPC) and the use of calcined clay, which necessitates a lower calcination temperature (700–900 °C) than clinker manufacture (1400–1500 °C), are responsible for this 40–50% reduction. The comparison information supports LC³'s contribution to meeting international decarbonisation goals.

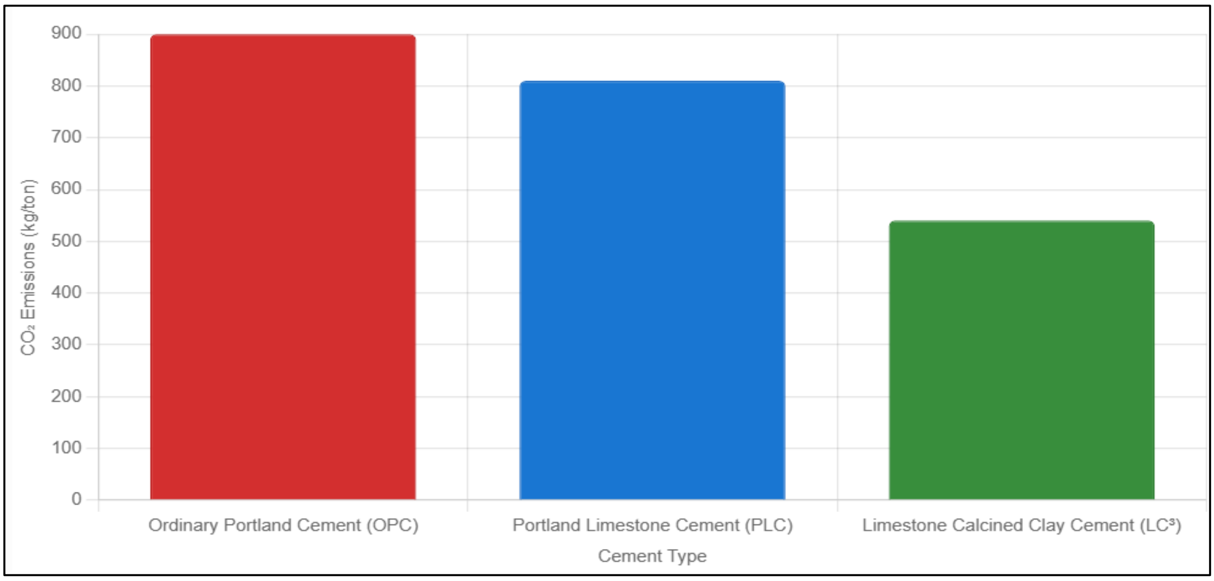

Fig. 10: Comparative CO_2 emissions for OPC, PLC, and LC³, showing LC³'s 40–50 % reduction in carbon footprint due to lower clinker content and reduced calcination temperatures (Scrivener *et al.*,2018, IEA & CSI 2018, and Bishnoi *et al.*, 2014)

6. Research Gaps and Future Directions

By replacing clinker with calcined clay and limestone, Limestone Calcined Clay Cement (LC³) offers a 30–40% reduction in CO_2 emissions, making it a promising low-carbon substitute for traditional Portland cement. Despite significant advancements in our understanding of its performance, its widespread implementation is limited by a number of research gaps.

Table 4: Summarises research gaps, suggested study methodologies, and anticipated effects

S. No	Research Gap	Potential Research Approach	Expected Impact
1	Lack of long-term field studies to assess real-world durability and performance under varied environmental conditions.	Conduct multi-year field trials in diverse climates and applications (e.g., bridges, buildings), monitoring parameters like compressive strength, corrosion resistance, and carbonation over 5-10 years using embedded sensors and non-destructive testing.	Provide robust data on long-term reliability, boosting confidence among engineers and regulators, and accelerating market adoption in sustainable construction projects.
2	Limited understanding of the effects of low- or high-kaolinite clays on LC_3 properties, restricting raw material flexibility.	Perform systematic laboratory experiments varying kaolinite content (e.g., 20-95%) in clays, combined with advanced characterization techniques like X-ray diffraction and thermogravimetric analysis, to evaluate hydration kinetics, mechanical strength, and sulfate resistance.	Enable utilization of abundant low-grade clays globally, reducing production costs by 10-20% and expanding LC_3 feasibility in regions with non-ideal clay resources.
3	Insufficient exploration of diverse recycled materials integration in LC_3 formulations, limiting circular economy potential.	Incorporate varied recycled aggregates (e.g., construction demolition waste, industrial byproducts) into LC3 mixes, testing fresh-state properties, mechanical performance, and environmental leaching through standardized ASTM/EN protocols.	Enhance waste valorization, further lowering CO_2 footprints by 15-25% and promoting sustainable practices in urban construction.
4	Need for more comprehensive full life-cycle assessment (LCA) studies, including regional variations and end-of-life scenarios.	Develop cradle-to-grave LCAs using tools like SimaPro or GaBi, incorporating site-specific data on raw material sourcing, transportation, and recycling, across different geographies (e.g., India vs. Europe).	Quantify holistic environmental benefits (e.g., 36-46% GWP reduction), informing policy decisions and supporting green certifications like LEED.
5	Absence of universal standardization for mix design and performance benchmarks, complicating consistent application.	Collaborate with standards bodies (e.g., ASTM, EN) to propose LC3-specific guidelines, based on multi-objective optimization models for mix proportions (e.g., 50% clinker, 30% clay, 15% limestone) and benchmark testing for strength classes.	Streamline design processes, ensure quality control, and facilitate global scalability in building codes.
6	Gaps in evaluating economic feasibility and scalability, particularly for large-scale production and market integration.	Undertake cost-benefit analyses and pilot-scale demonstrations, assessing supply chain logistics, capital investment for calcination facilities, and regional pricing models through economic modelling software.	Demonstrate cost savings (e.g., 20-30% lower than OPC in some contexts), attract investments, and enable widespread commercialization for decarbonizing the cement industry.

7. CONCLUSIONS

This review demonstrates that Limestone Calcined Clay Cement (LC^3) is a feasible binder for contemporary, low-carbon infrastructure because it provides greater durability, competitive mechanical performance, and significant sustainability benefits compared to Ordinary Portland Cement (OPC).

Durability performance:

Because of a refined pore structure resulting from the pozzolanic reaction of calcined clay and the filler effect of limestone, LC^3 shows up to 45% greater resistance to moisture intrusion than OPC. Because of improved chloride binding and a denser microstructure, migration and diffusion coefficients can be lowered by up to two orders of magnitude in chloride-laden environments. Mix design, kaolinite concentration, curing regime, and limestone fineness significantly impact carbonation resistance; optimised mixes perform on par with or better than OPC. Due to AFm phase stabilisation and permeability reduction, LC^3 mortars exhibit decreased sulphate intrusion and expansion, particularly at higher clinker replacement levels. Through chemical reduction of pore alkalinity and physical constraint of gel expansion, LC^3 prevents alkali-silica reaction (ASR) and keeps expansions far below standard limits under accelerated testing.

Mechanical performance:

LC^3 often beats OPC by 10% in 90-day compressive strengths, with gradual increases in tensile and flexural strength. The driving force behind these advancements is a refined microstructure rich in C–A–S–H gels and carboaluminate phases, which lowers porosity and enhances fracture management. Toughness, ductility, and flexural performance are further improved by fibre reinforcement. High performance can be achieved without only using premium clays by making the best use of clays with a reasonable kaolinite percentage.

Microstructural basis:

A thick C-A-S-H gel network and pore-filling carboaluminates are formed when calcined clay's alumina and limestone's carbonate work together. Together, these stages increase packing density, prevent harmful substances from entering, and support the mechanical and durability benefits of LC^3. The amount of kaolinite, the availability of portlandite, the curing temperature, and the addition of additional or recycled components all affect the hydration kinetics and phase assemblages.

Sustainability potential:

By using less clinker (~50%) and lower calcination temperatures (700–900 °C vs. 1400–1500 °C), LC^3 lowers CO_2 emissions by about 40–50% compared to OPC. Additionally, it can use recycled materials without sacrificing functionality. LC^3 is compatible with global decarbonisation goals with digitalisation, industrial energy recovery, and renewable energy.

Priorities for the future:

Standardised durability testing procedures, integrated life-cycle service models, and long-term field studies under various exposure situations should be the main areas of future research to facilitate widespread implementation. The role of LC^3 in providing long-lasting, sustainable, and economical infrastructure will accelerate due to these advancements, which will boost confidence among engineers, legislators, and industry stakeholders.

Highlights

- By reducing the calcination temperature and clinker content, LC^3 decreases CO_2 emissions by 40-50%.
- Hydration produces carboaluminate and pozzolanic reaction to improve durability.
- The metakaolin–CH interaction refines the pore structure and increases strength by forming more C–A–S–H bonds.
- Stable carboaluminates produced by the limestone–aluminate reaction improve resistance to sulphates and chlorides.
- In harsh conditions, LC^3 has a lower permeability and equals or surpasses OPC strength.
- Significant energy savings in cement manufacturing are made possible by calcined clay at 700–900 °C. It also supports worldwide decarbonisation and sustainable building goals.

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