Iberoamerican Journal of Industrial Engineering

LC³ Cement: Systematic Literature Review and XRD Characterization of Regional Soils

Cimento LC³: Revisão Sistemática da Literatura e Caracterização por DRX de Solos Regionais

Humberto Vicentino Neto[1*], Alex Morin Carneiro[2], Vitor Hugo Astun Dionísio[3], Berenice Marins Toralles[4], Luana Toralles Carbonari [5]

[1 * 2 3 4 5] Universidade Estadual de Londrina (UEL), Londrina, PR, Brasil.
[1*] humberto.vicentin@uel.br [2] alex.morin.carneiro@uel.br [3] vitor.dionisio@uel.br [4] toralles@uel.br
[5] carbonari@uel.br
***Corresponding Author: Neto, H.V.**

ABSTRACT: The decarbonization of civil construction drives the search for alternative materials. In this context, this study assesses the feasibility of Limestone Calcined Clay Cement (LC³) using tropical soils in their natural condition. The research adopts a mixed methodology: a systematic literature review using the Systematic Search Flow (SSF) method and the mineralogical characterization of soils from Londrina (PR, Brazil). The survey across Compendex, Web of Science, and Scopus databases mapped 68 studies and identified a scientific gap: the predominance of research on beneficiated clays, neglecting the logistic potential of raw soil. In the experimental stage, X-Ray Diffraction (XRD) served as a screening tool. Results indicate that local soils (Latosoil and Nitosoil) possess the essential crystalline phases—kaolinite and gibbsite—for LC³ production. The obtained mineralogical validation supports the progression to calcination and mechanical testing stages, pointing to the use of unbeneficiated regional soils as a viable strategy for developing countries.

KEYWORDS: LC³ cement; Tropical soils; Systematic review; XRD; Sustainability.

RESUMO: A descarbonização da construção civil impulsiona a busca por materiais alternativos, contexto no qual este estudo avalia a viabilidade do cimento Limestone Calcined Clay Cement (LC³) produzido com solos tropicais em condição natural. A pesquisa adota uma metodologia mista: uma revisão sistemática da literatura via método Systematic Search Flow (SSF) e a caracterização mineralógica de solos de Londrina (PR). O levantamento nas bases Compendex, Web of Science e Scopus mapeou 68 estudos e identificou uma lacuna científica: a predominância de pesquisas com argilas beneficiadas, o que negligencia o potencial logístico do solo bruto. Na etapa experimental, a Difração de Raios-X (DRX) atuou como ferramenta de triagem. Os resultados indicam que os solos locais (Latossolo e Nitossolo) apresentam as fases cristalinas essenciais — caulinita e gibbsita — para a produção de LC³. A validação mineralógica obtida fundamenta o avanço para etapas de calcinação e ensaios mecânicos, apontando o uso de solos regionais não beneficiados como estratégia viável para países em desenvolvimento.

PALAVRAS CHAVE: Cimento LC³; Solos tropicais; Revisão sistemática; DRX; Sustentabilidade.

1. INTRODUCTION

The pressure to curtail carbon dioxide emissions in civil construction has positioned Portland cement production at the center of environmental debates, given its significant impact on global emission matrices. In this landscape, LC³ cement (Limestone Calcined Clay Cement) has emerged as a technically consistent alternative for reducing clinker content by combining calcined clay and limestone filler. The synergy between these materials fosters the formation of stable carboaluminates and contributes to the densification of the hydrated matrix, maintaining adequate levels of mechanical performance.

Despite recent strides, a disparity remains between international literature and the actual conditions found in tropical regions. The majority of studies employ beneficiated clays—washed, sieved, or concentrated—which does not always reflect the mineralogical availability of residual soils found in areas such as northern Paraná. These materials, generally composed of kaolinite, quartz, gibbsite, and iron oxides, may exhibit distinct behaviors during the calcination and hydration of the LC³ system, justifying a preliminary analysis of their characteristics.

The economic viability of this technology in Brazil depends, to a large extent, on the utilization of local resources with minimal processing. Therefore, before advancing to calcination stages and mechanical testing, it is essential to verify whether the mineralogy of available soils meets the minimum requirements of the LC³ system, particularly regarding the presence of kaolinite.

This study aims to evaluate the potential of two residual soils from the Londrina (PR) region as precursors for LC³, correlating their mineralogy with parameters found in the literature. The approach combines two complementary axes: (i) a systematic review based on the Systematic Search Flow (SSF) method, focusing on low-purity clays, and (ii) characterization via X-Ray Diffraction (XRD) of the collected soils. The results intend to offer an initial technical baseline to advance toward subsequent experimental investigations aimed at decarbonizing the regional cement supply chain.

2 METHODOLOGY

The investigation adopted a mixed-method approach comprising two complementary stages: (i) a systematized bibliographic survey to map the state of the art regarding low-purity clays in LC³ ; and (ii) a preliminary mineralogical characterization of residual soils from Londrina (PR) .

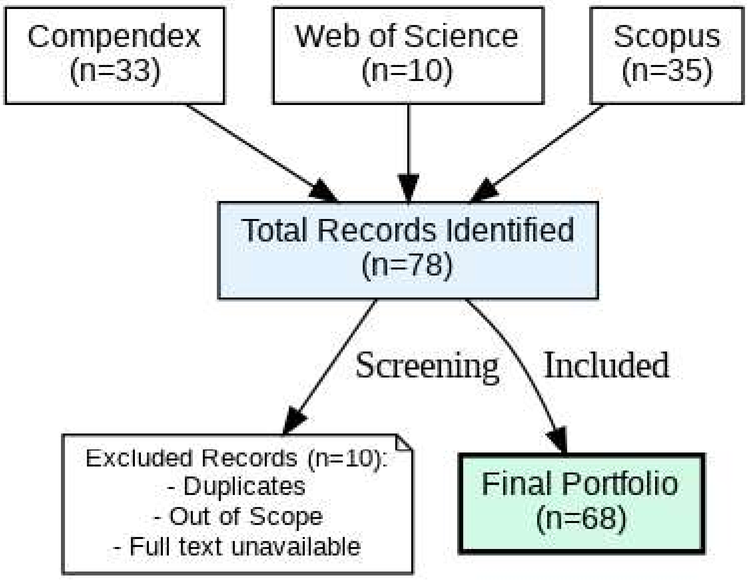
2.1 Systematic Review Protocol (SSF)

The review followed the Systematic Search Flow (SSF) method to ensure the traceability of the search, screening, and eligibility steps. The research was guided by the following question: what evidence exists regarding the technical feasibility of using tropical soils or unbeneficiated clays as precursors in the production of LC³ cement?.

Searches were conducted in the Compendex, Web of Science (WoS), and Scopus databases. The strategy combined the core term ("Limestone Calcined Clay Cement" or "LC3") with descriptors of regional raw materials ("laterite", "tropical soils", "low grade clay", "kaolinitic clay"). Boolean operators and exclusion terms were utilized to remove non-cementitious geotechnical applications.

No temporal limitation was imposed, and the search was restricted to articles and reviews in English. The selection process involved identification, screening, and eligibility. Results were processed using Mendeley software for duplicate removal and the reading of titles and abstracts. The final portfolio consolidated 68 unique articles. The selection flow is detailed in Figure 1

Figura 1. Flowchart of the systematic review process (SSF) .



Source: prepared by the authors

2.2 Mineralogical Characterization of Soils

The experimental stage analyzed two soil profiles collected in the region of Londrina (PR), classified as Red Latosol (*Latossolo Vermelho*) and Red Nitosol (*Nitossolo Vermelho*). The selection of these materials is due to their local geological representativeness and the distinction in their degrees of weathering. The Latosol is characterized by higher degrees of weathering, whereas the Nitosol represents a moderate weathering stage.

Samples were prepared according to ABNT NBR 6457:2016 guidelines, subjected to air drying, clod breaking, and sieving through a 4.8 mm mesh. For mineralogical analysis, a representative aliquot was ground until a fine powder was obtained, totaling a volume of approximately 1 mL per sample.

The identification of crystalline phases was performed at the Multi-User Research Laboratory Center (CMLP) of the State University of Londrina (UEL). The X-Ray Diffraction (XRD) technique was employed using a diffractometer operating with CuKα radiation, a voltage of 40 kV, and a current of 30 mA. Readings were conducted in continuous scan mode ($\theta-2\theta$), covering the angular interval (2θ) from 3º to 80º, with an angular step of 0.05º and an exposure time of 10 seconds per step. Analyses were performed in duplicate to ensure the repeatability of the obtained spectra and reliability in identifying the main peaks of kaolinite, quartz, and iron oxides.

3 RESULTS AND DISCUSSION

The results obtained from the Systematic Search Flow (SSF) protocol and the mineralogical characterization of Londrina soils are presented in this section.

3.1 Systematic Review

The systematic review initially enabled a bibliometric overview of scientific production on LC³, followed by a descriptive synthesis of the selected studies and the resulting thematic organization of the portfolio.

The bibliometric survey highlighted a continuous growth in LC³ publications over the last decade, with a sharp expansion starting in 2020. This trend reflects the consolidation of LC³ as a promising alternative for clinker reduction and CO_2 emission mitigation in the cement sector. The annual evolution of publications retrieved from the Engineering Village database is presented in Figure 02, which highlights the consistent advancement of the topic and the broadening of its investigative scope

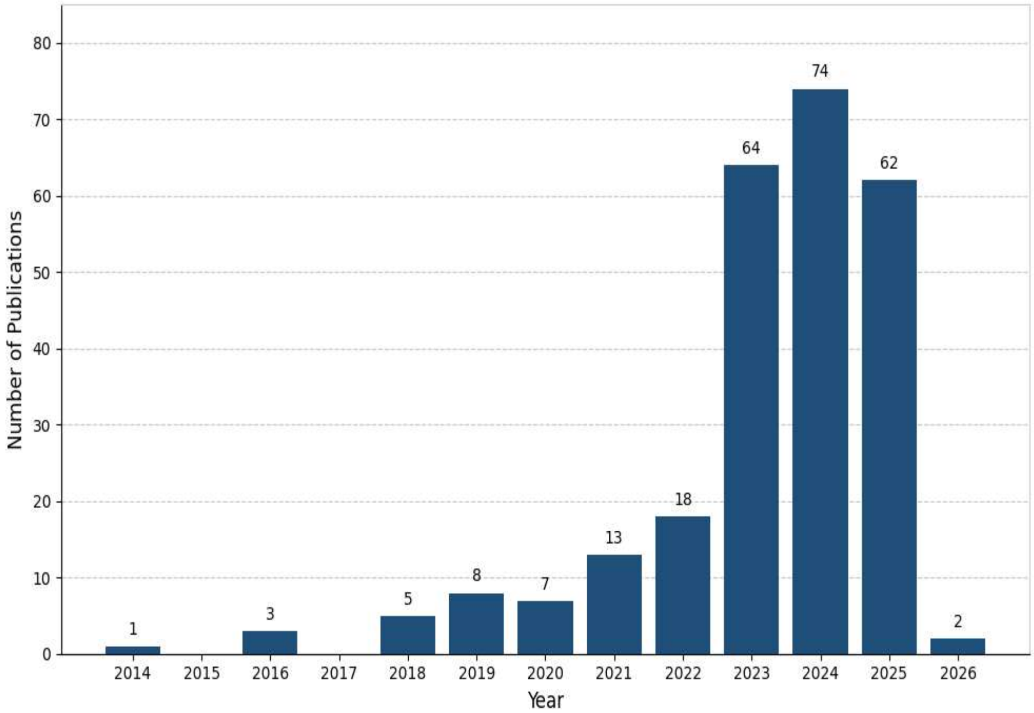
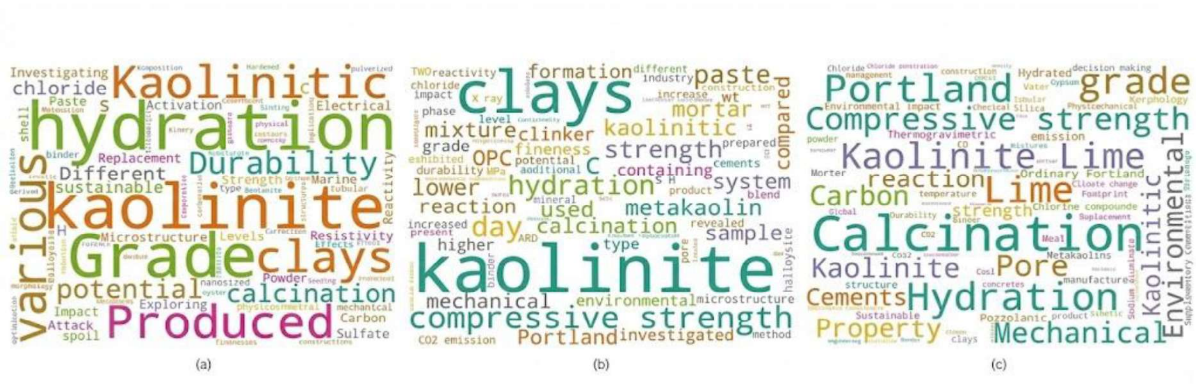


Figura 1: Annual evolution of scientific production on LC³ (Compendex Database)

Source: prepared by the authors

Following the initial mapping, the application of the SSF allowed for the consolidation of a portfolio composed of **68** articles, after excluding duplicates and studies outside the thematic scope. To deepen the interpretive stage, the corpus was subjected to text mining techniques widely used in knowledge organization analyses.

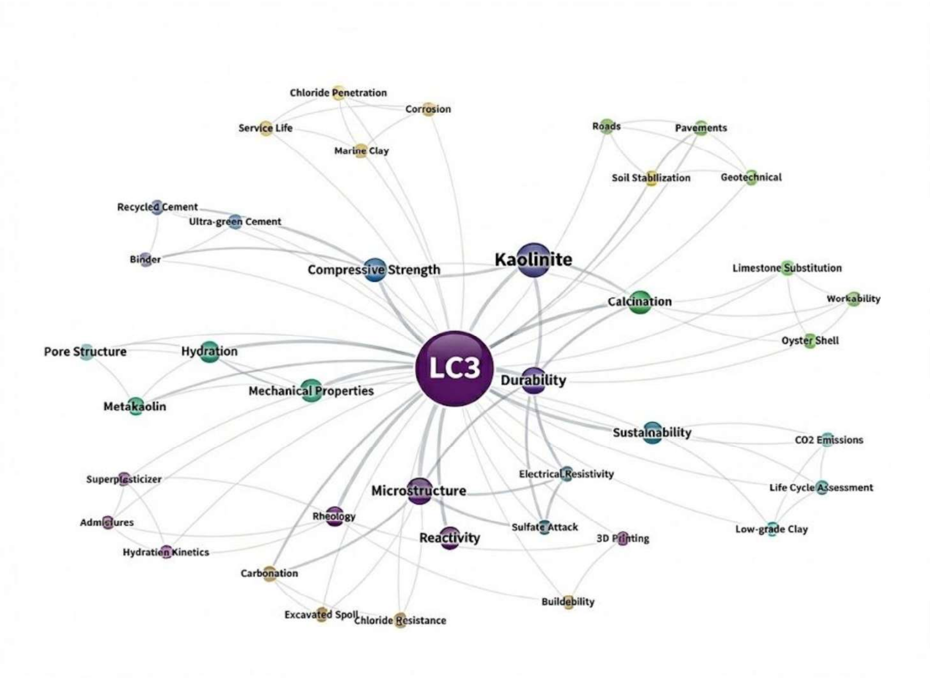
Word clouds were generated from the titles, abstracts, and keywords of the selected studies, allowing for the identification of recurrence patterns and thematic concentration. The three representations reveal a predominance of terms related to clay mineralogy, the calcination process, and the behavior of the hydrated system, with notable prominence of **kaolinite**, **calcination**, **hydration**, **durability**, **compressive strength**, and **clays**. The recurrence of these descriptors confirms that the quality of the clay fraction and the sulfate balance are central axes of discussion within the scientific community dedicated to LC³. Figure 03 presents the generated word clouds.



Source: prepared by the authors

Beyond frequency analysis, the thematic proximity between descriptors was evaluated to identify conceptual clusters. The thematic network represented in Figure 04 evidences the centrality of the term **LC³** as an integrating node for subthemes such as hydration, microstructure, durability (chlorides, carbonation, sulfates), sustainability, and the performance of low-quality clays.

The observed connections reinforce three consolidated axes in the literature: (i) mineralogical suitability of the clay; (ii) influence of calcination conditions on reactivity ; and (iii) mechanical performance and durability of binders formulated with heterogeneous or residual raw materia



Source: prepared by the authors

Figura 3:Thematic network mapping of terms related to the general research field

These behaviors align with literature trends (Table 1), which highlight the potential superior performance of moderately weathered clays. The data suggest a convergence: the mineralogy of Paraná soils, especially the Nitosol, meets international qualitative requirements. It is noted that the presence of crystalline kaolinite phases is a necessary condition, but not sufficient; the confirmation of performance will depend on effective dehydroxylation during calcination, which is the subject of the next stages of this research.

Table 1 Main studies on LC³ focusing on kaolinite, tropical clays, and residual materials

Author(s) / Year	**Precursor material type**	**Kaolinite content/quality (description)**	**Relevant comment for this study**
Antoni et al. (2012)	**Synthetic and natural metakaolinitic clays**	**High reactivity**	**Describes the alumina-limestone synergy in the formation of carboaluminates and C-A-S-H.**
Scrivener; Martirena; Avet (2018)	**Good quality calcined clays + limestone filler**	**Moderate to high content, well-characterized clays**	**Consolidates the LC³ concept and the "classic" formulation (~50% clinker, 30% clay, 15% limestone).**
Avet; Scrivener (2018, 2019)	**Different clays in LC³**	**Systematic variation of kaolinite content**	**Shows the existence of an optimum kaolinite window; excess may unbalance sulfates and hydration.**
Maraghechi et al. (2018)	**LC³ exposed to chlorides**	**Good quality calcined clay**	**Relates refined microstructure and higher chloride binding to lower ionic diffusion.**
Hay; Celik (2023)	**Low reactivity kaolinitic clays**	**Low kaolinite content / "low-grade" clay**	**Demonstrates that lower quality clays can be employed with fineness and sulfate adjustments.**
Arruda Jr. et al. (2023)	**Kaolinitic waste from the Amazon region (Brazil)**	**Waste with dominant kaolinitic fraction**	**Explores Brazilian kaolinite sources, combining performance evaluation with CO2 emissions.**
Leo; Alexander; Beushausen (2023)	**African residual clays**	**Low to medium grade lateritic clays**	**Shows the viability of residual clays in LC³, through dosage calibration and calcination.**
Li et al. (2024)	**Locally excavated spoil with washing and sieving**	**Fine fraction enriched in kaolinite after beneficiation**	**Uses excavated soil as a starting point, but always with prior separation of the clay fraction.**
Hu et al. (2024)	**Low-grade marine clay in LC³**	**Low purity clay**	**Addresses durability (chlorides and carbonation) in systems with less pure clays.**

Author(s) / Year	Precursor material type	Kaolinite content/quality (description)	Relevant comment for this study
Koutsouradi et al. (2025)	Low-quality clays and limestone waste	Mixture of clay and waste with different contents	Discusses the impact of granulometry and calcination on LC³ produced with heterogeneous materials.
de Matos et al. (2025)	LC³ with tailings (mining and ceramic waste)	Kaolinitic fractions associated with waste	Explores the combination of LC³ with different residual alumina and calcium sources.
Silva et al. (2024)	LC³ with different clays and sulfate optimization	Clays with varied kaolinite contents	Emphasizes the importance of sulfate balance in systems with clays of non-ideal composition.

Source: prepared by the authors

The general trend observed corresponds directly with conclusions presented in different regions of the world. Clays with high kaolinite content exhibit superior reactivity; however, recent studies demonstrate that residual or lower-purity clays can also yield satisfactory performance, provided that parameters such as calcination temperature, fineness, and sulfate balance are adequately adjusted. Results obtained in African, Asian, and South American contexts reinforce that LC³ admits greater mineralogical heterogeneity when the clay fraction remains the primary contributor of reactive alumina.

3.2 Mineralogical Characterization – XRD of Regional Soil

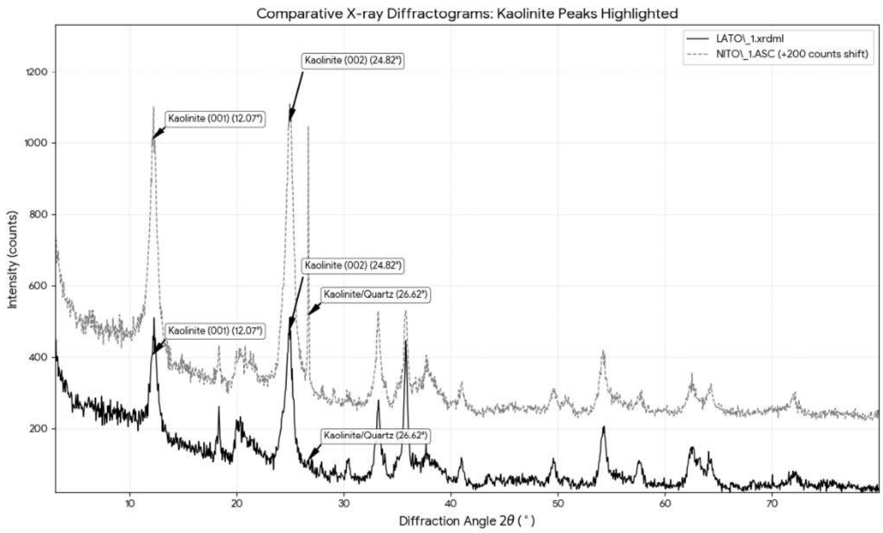
Subsequently, the mineralogical evidence from regional soils is discussed to establish correspondences between international literature and the observed local characteristics. Thus, in parallel with the systematic review, regional soils from Londrina were mineralogically characterized to evaluate their potential as a clay source.

Two samples were collected according to ABNT NBR 6457:2024, representing different pedogenetic stages: a **Latosol**, highly weathered, and a **Nitosol**, of moderate weathering. Only the clay fraction was analyzed, consistent with international literature, as this fraction determines the supply of reactive alumina after calcination.

The obtained diffractograms disclose significant differences, particularly regarding the intensity of kaolinite peaks (001) and (002), which are more pronounced in the Nitosol. Figure 04 presents the comparative diffractograms. The greater sharpness and intensity of the peaks in the Nitosol sample suggest a higher kaolinite content or better crystallinity of the clay fraction. Conversely, the Latosol shows smoother peaks and an elevated background, consistent with the presence of iron oxides typical of highly weathered soils.

These behaviors are compatible with trends observed in the studies synthesized in Table 01, which highlight the better performance of moderately weathered clays compared to materials excessively enriched in oxides.

***Figure 04**:* Comparative diffractograms of the clay fractions of Londrina soils.



Source: prepared by the authors.

The joint analysis of the data suggests an important convergence: the mineralogy detected in the evaluated soils, particularly the Nitosol, is compatible with what the literature identifies as suitable for the LC³ route. Nevertheless, it is crucial to highlight that the presence of kaolinite does not, in itself, guarantee expected performance. The subsequent stage—calcination—will be decisive in confirming the reactivity of these phases and their effective contribution to the system.

4 FINAL CONSIDERATIONS

The systematic review structured by the SSF method consolidated 68 studies that reinforce the decisive influence of the clay fraction on the performance of LC³ cements. However, the portfolio analysis showed that the majority of research utilizes previously beneficiated materials, which contrasts with the reality of developing regions where the use of raw natural resources tends to be more economically viable.

In the experimental realm, the results obtained for Londrina (PR) soils demonstrated that the region's typical weathering did not compromise their potential as precursors. The diffractograms revealed the consistent presence of kaolinite, especially in the Nitosol, indicating that these materials meet the preliminary mineralogical parameters associated with the LC³ route.

Based on this evidence, it is concluded that the evaluated soils possess characteristics compatible with the initial requirements of the technology. The mineralogical characterization stage thus fulfills its screening role, providing technical support to advance to controlled calcination and mechanical evaluation phases. The results reinforce that utilizing unbeneficiated residual soils represents a promising alternative for expanding the adoption of lower environmental impact cements within the Brazilian context.

REFERENCES

Antoni, M.; Rossen, J.; Martirena, F.; Scrivener, K. (2012). Cement substitution by a combination of metakaolin and limestone. *Cement and Concrete Research*, 42(12), 1579–1589.

Arruda Jr., E.S.; de Sales Braga, N.T.; Barata, M.S. (2023). Life cycle assessment to produce LC³ cements with kaolinitic waste from the Amazon region, Brazil. *Case Studies in Construction Materials*, 18, e01729.

Avet, F.; Scrivener, K. (2018). Investigation of C–A–S–H composition, morphology and density in Limestone Calcined Clay Cement (LC³). *Cement and Concrete Research*, 115, 70–79.

Avet, F.; Martirena, F.; Scrivener, K. (2019). Evaluation of the hydration of LC³ blends. *Cement and Concrete Research*, 107, 124–135.

Bahman-Zadeh, F.; Ramezanianpour, A.A.; Zolfagharnasab, A. (2022). Effect of carbonation on chloride binding capacity of LC³ and binary pastes. *Journal of Building Engineering*, 52, 104447.

Bernal, I.M.R.; Shirani, S.; Cuesta, A.; Santacruz, I.; Aranda, M.A.G. (2021). Phase and microstructure evolutions in LC³ binders by multi-technique approach including synchrotron microtomography. *Construction and Building Materials*, 300, 124054.

Blasi, E.; Di Bella, C.; Choorackal, E.; Garufi, D.; Schmidt, T. (2025). Use of low-grade kaolinite clays in the production of limestone calcined clay cement. *Journal of Sustainable Cement-Based Materials*, 14(1), 209–221.

de Matos, P.R.; Doerner, G.; Nazário, S.D.S.; Folgueras, M.; Rodríguez, E.D. (2025). Limestone calcined clay cements (LC³) produced with iron ore tailings and ceramic waste: Hydration, mechanical performance and rheology. *Construction and Building Materials*, 458, 139604.

Hay, R.; Celik, K. (2023). Performance enhancement and characterization of LC³ produced with low-reactivity kaolinitic clay. *Construction and Building Materials*, 392, 131831.

Her, S.; Im, S.; Liu, J.; Park, D.; Bae, S. (2024). Exploring the potential of pulverized oyster shell as a limestone substitute in LC³ and its implications for performance. *Construction and Building Materials*, 425, 135918.

Hu, Y.; Xiong, L.; Yan, Y.; Geng, G. (2024). Performance of LC³ incorporating low-grade marine clay. *Case Studies in Construction Materials*, 20, e03283.

Hussain, S.M.F.; Sheikh, M.D.; Jamil, T.; Ayub, T.; Hu, C. (2023). Initial search for low-grade clay in Pakistan for producing LC³ ecofriendly cement. *Low Carbon Materials and Green Construction*, 1(1), 15.

Koutsouradi, A.; Muzenda, T.R.; Jensen, P.A.; Georget, F.; Matschei, T. (2025). Impact of clay calcination method on the physicochemical properties of LC³. *Construction and Building Materials*, 473, 140939.

Leo, E.S.; Alexander, M.G.; Beushausen, H. (2023). Optimization of LC³ binders with African clays based on compressive strength and hydration. *Cement and Concrete Research*, 173,

107255.
Li, Y.; Yi, P.; Du, H.; Sun, X.; Xing, F. (2024). Activation of locally excavated spoil for utilization in LC³. *Construction and Building Materials*, 420, 135518.
Maraghechi, H.; Avet, F.; Wong, H.; Kamyab, H.; Scrivener, K. (2018). Performance of LC³ with various kaolinite contents with respect to chloride transport. *Materials and Structures*, 51, 125.
Py, L.G.; Neto, J.S.A.; Longhi, M.A.; Kirchheim, A.P. (2024). Evaluation of ultrafine calcined clays for LC³ regarding sulfate requirement, water demand and strength. *Materials and Structures*, 57(1), 13.
Rehman, M.U.; MacLeod, A.J.N.; Aldridge, L.; Tang, Z.Q.; Gates, W.P. (2025). Differences in hydration kinetics and phase development of Australian bentonite and kaolinite-based LC³. *Materials and Structures*, 58(6), 226.
Ribeiro, F.R.C.; Silvestro, L.; Py, L.G.; de Matos, P.R.; Kirchheim, A.P. (2024). Hydration kinetics and rheology of LC³ incorporating superplasticizer and clay-mitigating admixtures. *Case Studies in Construction Materials*, 20, e03364.
Scrivener, K.; Martirena, F.; Avet, F.; Maraghechi, H.; Hanpongpun, W.; Favier, A. (2018). Impacting factors and properties of LC³. *Green Materials*, 7(1), 3–14.
Silva, M.R.C.; Andrade Neto, J.D.S.; Walkley, B.; Kirchheim, A.P. (2024). Exploring sulfate optimization in LC³: limitations and insights. *Cement and Concrete Research*, 175, 107375.
Yu, T.; Zhang, B.; Yuan, P.; Liu, H.; Setti Belaroui, L. (2023). Effects of calcination temperature of halloysite on LC³: mechanical performance and hydration evolution. *Construction and Building Materials*, 389, 131709.
Zhang, Z.; Shao, H.; Yu, Q.; Yin, S. (2025). Hydration performance and carbon reduction potential of LC³ derived from shield spoil tailings. *Construction and Building Materials*, 485, 141854.
Zolfagharnasab, A.; Ramezanianpour, A.A.; Bahman-Zadeh, F. (2021). Investigating the potential of low-grade calcined clays to produce durable LC³ against chloride attack. *Construction and Building Materials*, 303, 124541.

ARTICLE HISTORY

RECEIVED : 23/11/2025
ACCEPTED: 02/11/2025