

Reducing Clinker-Related Carbon Emissions with Calcite and Calcined Clay: The Chemistry, Performance, and Practical Potential of LC3 Cement

Ali Hasan^{1*}, Wasfi Khiralla Albadry², Wesam Al farsi³

¹ Civil engineering Department, Faculty of engineering and petroleum, University of Benghazi, Libya

² Civil engineering Department, Faculty of engineering, University of Benghazi, Libya

³ College of Science and Technology, Qaminis

*Corresponding author: Ali.hasan@uob.edu.ly

الحد من انبعاثات الكربون المرتبطة بالكلنكر باستخدام الكالسيت والطين المكلس: الكيمياء والأداء
والإمكانات العملية لأسمنت (LC3)

علي حسن^{1*}، وصفي خير الله البدري²، وسام الفارسي³
¹ قسم الهندسة المدنية، كلية الهندسة والبتترول، جامعة بنغازي، ليبيا
² قسم الهندسة المدنية، كلية الهندسة، جامعة بنغازي، ليبيا
³ كلية العلوم والتقنية، قمينس

Received: 19-08-2026; Accepted: 21-09-2026; Published: 30-09-2026

Abstract:

Clinker production is responsible for the majority of greenhouse gas emissions associated with ordinary Portland cement, driven by both high-temperature kiln energy consumption and the chemical decarbonization of limestone. Limestone calcined clay cement (LC3) presents a highly effective and scalable near-term solution to mitigate these environmental impacts by substantially reducing clinker content. This review examines the fundamental thermochemical, hydration, and microstructural mechanisms that govern LC3 systems, emphasizing that their exceptional performance extends far beyond simple physical dilution. The synergistic interaction between reactive silica and alumina from calcined clay, particle packing and nucleation from fine calcite, and sulfate regulation creates a dense, refined binder matrix. These components react to form secondary calcium-silicate-hydrate (C-(A)-S-H) gels, stable carboaluminate phases (hemicarboaluminate and monocarboaluminate), and ettringite, which compensate for the reduced clinker fraction. Furthermore, this paper analyzes key practical considerations, including optimal mixture design, sulfate balance, mechanical strength development, chloride and carbonation durability, and life-cycle carbon emissions. Evidence from recent literature indicates that optimized LC3 formulations can decrease clinker content to approximately 50% and lower cement-related carbon dioxide emissions by 30% to 40%. However, realizing these benefits requires rigorous local characterization of raw materials, precise calcination control, and performance-based standard validation under specific exposure conditions.

Keywords: LC3; limestone calcined clay cement; calcite; calcined clay; clinker reduction; carboaluminate; low-carbon cement; durability; life-cycle assessment.

الملخص

يُعد إنتاج الكلنكر المسؤول الأكبر عن انبعاثات غازات الدفيئة المرتبطة بالأسمنت البورتلاندي العادي، وذلك نتيجة استهلاك الطاقة العالي لأفران التسخين وإزالة الكربون كيميائياً من الحجر الجيري. يُمثل أسمنت الحجر الجيري والطين المكلس ($LC3$) حلاً فعالاً وقابلاً للتطبيق على المدى القريب للتخفيف من هذه الآثار البيئية من خلال خفض نسبة الكلنكر بشكل كبير. تستعرض هذه الدراسة المراجعة الآليات الحرارية الكيميائية وآليات الإماهة والتطور المجهرية الأساسية التي تحكم أنظمة ($LC3$)، مؤكدةً أن أدائها الاستثنائي يتجاوز بكثير مجرد التخفيف الفيزيائي. إن التفاعل التآزري بين السيلكا والألومينا التفاعليتين المستمدتين من الطين المكلس، وتحسين رص الحبيبات والنوى بواسطة الكالسيت الدقيق، وضبط الكبريتات، يخلق مصفوفة رابطة كثيفة ومكررة. تتفاعل هذه المكونات لتكوين مواد هلامية ثانوية من نوع ($C-(A)-S-H$)، ومراحل كربوألومينات مستقرة (هيميكربوألومينات ومونوكربوألومينات)، ومادة الإترينجيت، مما يعوض انخفاض نسبة الكلنكر. علاوة على ذلك، تحلل هذه الورقة الاعتبارات العملية الرئيسية، بما في ذلك التصميم الأمثل للمخاليط، والتوازن الكبريتاتي، وتطور القوة الميكانيكية، ومقاومة الكلوريدات والكربنة، وانبعاثات الكربون خلال دورة الحياة. تشير الأدلة المستمدة من الأدبيات الحديثة إلى أن تركيبات ($LC3$) المحسنة يمكنها خفض محتوى الكلنكر إلى نحو 50% وتقليل انبعاثات ثاني أكسيد الكربون المرتبطة بالأسمنت بنسبة تتراوح بين 30% إلى 40%. ومع ذلك، فإن تحقيق هذه الفوائد يتطلب توصيفاً محلياً دقيقاً للمواد الخام، وتحكماً دقيقاً في عملية التكليس، والتحقق من المعايير القائمة على الأداء في ظل ظروف التعرض ذات الصلة.

الكلمات المفتاحية: أسمنت ($LC3$)؛ أسمنت الحجر الجيري والطين المكلس؛ الكالسيت؛ الطين المكلس؛ خفض الكلنكر؛ الكربوألومينات؛ الأسمنت منخفض الكربون؛ المتانة؛ تقييم دورة الحياة.

1. Introduction

Cement remains essential to modern construction, but its environmental cost is difficult to ignore. Most emissions associated with Portland cement come from clinker production. Manufacturing clinker requires raw materials to be heated to around 1450 °C, which consumes large amounts of energy. At the same time, limestone breaks down chemically and releases carbon dioxide. This means that switching to cleaner kiln fuels, although important, cannot fully decarbonize cement production. Reducing the amount of clinker in cement is also necessary (Habert et al., 2020; International Energy Agency [IEA], 2024). Limestone calcined clay cement, widely known as $LC3$, is attracting attention because it offers a realistic route to lower clinker content using materials that are widely available in many regions. $LC3$ typically combines clinker, calcined clay, limestone, gypsum, and minor constituents. Its value lies in the interaction between calcined clay and limestone. These materials do more than replace clinker by mass: they affect hydration, phase development, pore structure, and ultimately the strength and durability of the binder (Antoni et al., 2012; Scrivener et al., 2018).

This review discusses the mechanisms through which calcite and calcined clay lower clinker-related emissions. It focuses on the thermochemical basis of the system, hydration chemistry, microstructural development, practical mixture design, durability, and life-cycle implications. It also highlights issues that require careful control, particularly clay quality, gypsum dosage, carbonation resistance, and the need for local material testing.

2. Why Clinker Reduction Matters

The environmental impact of cement is closely linked to the amount of clinker it contains. Clinker production releases carbon dioxide from two main sources. The first is fuel combustion in the kiln. The second is calcination, the decomposition of calcium carbonate into calcium oxide and carbon dioxide: $CaCO_3 \rightarrow CaO + CO_2$. Because calcination emissions are built into Portland clinker chemistry, they cannot be eliminated simply by replacing fossil fuels with renewable energy.

Reducing clinker content therefore addresses both major emission sources at the same time. When clinker is replaced with materials that require less processing energy and do not undergo kiln decarbonation, the carbon intensity of the final cement decreases. This is why the use of supplementary cementitious materials has long been recognized as one of the most effective strategies for reducing cement-sector emissions (IEA, 2024; Scrivener et al., 2018).

3. How LC3 Reduces Emissions

3.1 Direct clinker substitution

The simplest mechanism is direct substitution. LC3 replaces a portion of clinker with calcined clay and limestone. Every tonne of clinker avoided prevents part of the fuel use, process emissions, grinding demand, and raw-material handling associated with clinker manufacture. In optimized LC3 systems, clinker content can approach 50%, compared with substantially higher clinker contents in conventional Portland cement (Scrivener et al., 2018).

3.2 Lower-temperature clay activation

Suitable kaolinitic clays are activated at much lower temperature than clinker. Calcined clay is commonly produced at approximately 700–850 °C, whereas Portland clinker requires temperatures close to 1450 °C. During calcination, kaolinite loses structurally bound water and becomes a more reactive, disordered aluminosilicate. This process creates a material capable of reacting during cement hydration while requiring less thermal energy than clinker production (Rashad, 2013; Avet et al., 2016).

3.3 Limestone is used without kiln decarbonation

In LC3, limestone or calcite is ground and blended with the cement. It is not heated in the clinker kiln to produce calcium oxide. As a result, the limestone fraction used in the blended cement does not generate the same process emissions that would occur if it were converted to clinker. Limestone also contributes to performance through packing, nucleation, and chemical interaction with clay-derived alumina, so its role is not limited to replacing clinker volume (Zunino & Scrivener, 2021).

4. The Role of Calcined Clay

Calcined clay is the reactive part of the LC3 system. When kaolinitic clay is heated, it loses hydroxyl groups and its crystal structure becomes less ordered. This makes silica and alumina more available for reaction. During hydration, these species react with calcium hydroxide released by clinker hydration and contribute to the formation of additional binding phases.

A simplified form of the pozzolanic reaction is: $\text{SiO}_2 + \text{Ca(OH)}_2 + \text{H}_2\text{O} \rightarrow \text{C-S-H}$. When reactive alumina is present, calcium aluminosilicate hydrate, often written as C-(A)-S-H, can also form. These products help strengthen the matrix and reduce the connectivity of pores. The quality of the calcined clay is crucial. Kaolinite content, impurity minerals, calcination temperature, residence time, and fineness all influence its reactivity and water demand (Avet et al., 2016; Rashad, 2013).

5. The Role of Calcite

5.1 Packing and nucleation

Fine calcite particles can improve how solid particles pack together in the fresh paste. They also provide surfaces on which hydration products can form. This nucleation effect can speed up early hydration of alite, the main early-strength phase in Portland cement. The result is that some of the strength loss expected from clinker dilution can be recovered at early ages (Zunino & Scrivener, 2021).

5.2 Carboaluminate formation

Calcite also has an important chemical role. Carbonate ions from limestone can react with reactive alumina supplied by calcined clay. This reaction forms carboaluminate phases,

especially hemicarboaluminate and monocarboaluminate. These phases help stabilize the hydration system and can improve the volume of solid hydration products. Antoni et al. (2012) showed that combining metakaolin with limestone can support better mechanical performance than Portland cement alone at a high replacement level because of these coupled hydration reactions.

The exact phase assemblage depends on gypsum content, sulfate availability, temperature, and the reactivity of the clay. For this reason, limestone should not be considered an inert filler in LC3. Its contribution is closely linked to the alumina released from the calcined clay and to the overall sulfate balance of the system (Zunino, 2024).

6. The Synergy Between Clay and Calcite

The performance of LC3 comes from a coordinated set of reactions. Clinker provides early hydration products and calcium hydroxide. Calcined clay supplies reactive silica and alumina. Calcite improves particle packing, provides nucleation sites, and supplies carbonate ions. Gypsum regulates the reaction of aluminates and supports ettringite formation. Together, these processes create a denser and more efficient binder structure than would be expected from simple clinker dilution.

Table 1: Main hydration products and phase contributions in LC3 systems

Component	Main contribution	Effect on the hydrated binder
Clinker	Initial hydraulic reaction and calcium source	Forms early C-S-H and releases Ca(OH) ₂
Calcined clay	Reactive silica and alumina	Forms additional C-(A)-S-H and supplies alumina for carboaluminates
Calcite/limestone	Filler, nucleation surface, and carbonate source	Improves packing, accelerates hydration, and forms carboaluminates
Gypsum	Sulfate regulator	Controls aluminate reaction and supports ettringite formation

The main hydration products in LC3 include C-(A)-S-H-type gel, ettringite, hemicarboaluminate, and monocarboaluminate. These products can fill pore space and reduce pore connectivity. This explains why LC3 can retain competitive strength even though it contains less clinker. Recent reviews describe the LC3 mechanism as a combination of physical packing, accelerated hydration, phase stabilization, and chemical synergy between clay-derived alumina and limestone carbonate (Zunino, 2024; Qadr et al., 2026).

7. Strength Development and Pore Refinement

Lowering clinker content would normally reduce the amount of hydraulic material available to form strength. LC3 compensates for this in several ways. Calcite promotes early hydration and improves packing. Calcined clay reacts later with calcium hydroxide to form additional binding gel. Carboaluminate phases add solid volume and help stabilize the hydration products. Together, these effects can produce a dense microstructure with lower connected porosity. This does not mean that every LC3 mixture will automatically match Portland cement. Performance depends on the quality of the clay, the clay-to-limestone ratio, fineness, gypsum content, water-to-binder ratio, curing, and chemical-admixture compatibility. The commonly cited clinker level of around 50% is a useful target for research and development, not a universal mixture recipe (Scrivener et al., 2018; Zunino & Scrivener, 2021).

8. Sulfate Balance and Mixture Design

Sulfate balance is one of the most important practical issues in LC3. Calcined clay introduces reactive alumina, while limestone changes the stability of aluminate-containing phases. As a result, the gypsum requirement of LC3 may differ from that of ordinary Portland cement. Too little sulfate can lead to rapid aluminate reactions and poor fresh or early-age behavior. Too much sulfate can also disturb phase development and affect setting and dimensional stability. Mixture optimization should therefore include systematic testing of gypsum content, setting time, heat release, strength development, shrinkage, and phase assemblage. The appropriate dosage depends on the mineralogy and fineness of the clay, limestone characteristics, clinker composition, alkali content, and admixture compatibility. Antoni et al. (2012) emphasized that gypsum should be carefully balanced in limestone–calcined-clay systems because it strongly influences early-age performance.

Table 2: Indicative binder composition ranges for conventional and alternative cements

Indicative binder system	Clinker	Calcined clay	Calcite/limestone	Gypsum
OPC reference	90–95%	0%	0–5%	About 5%
Binary calcined-clay cement	65–70%	25–30%	0–5%	Adjusted to sulfate balance
Typical LC3	45–55%	25–35%	10–20%	Adjusted to sulfate balance
Low-clinker LC3 research blend	40–50%	30–40%	10–20%	Requires detailed optimization

These values should be treated as starting ranges rather than production specifications. The final binder composition must be based on local raw-material characterization and performance testing.

9. Durability Considerations

The refined pore structure of LC3 can reduce water transport and improve resistance to chloride ingress. The aluminate-rich hydration products can also increase chloride-binding capacity. These features make LC3 attractive for reinforced concrete exposed to marine or saline conditions. However, durability is not governed by one property alone, and compressive strength should not be used as the only indicator of long-term performance.

Carbonation is an important issue that requires careful interpretation. LC3 may contain less portlandite than OPC, which can reduce its buffering capacity. Accelerated carbonation tests may therefore suggest greater carbonation susceptibility. Yet recent reviews caution that accelerated test conditions can overestimate carbonation depth because they use high carbon-dioxide concentrations and preconditioning procedures that do not reflect the gradual densification of LC3 under natural exposure (Qadr et al., 2026). For reinforced concrete, carbonation performance should be evaluated using realistic curing, exposure conditions, cover depth, and crack control.

A complete durability programme should include water absorption, sorptivity, electrical resistivity, chloride migration or diffusion, carbonation, sulfate resistance, shrinkage, cracking risk, and post-exposure microstructural analysis. The required tests depend on the intended exposure environment.

10. Life-Cycle Implications

LC3 is frequently reported to reduce cement-related carbon dioxide emissions by around 30–40% compared with conventional Portland cement when clinker replacement approaches 50%. This range is plausible, but it should not be treated as a fixed value. Actual savings depend on the energy used to dry, grind, and calcine the clay; the carbon intensity of electricity and fuel; transport distance; limestone processing; and the functional unit used in LCA (Akinpelu et al., 2026; Gettu & Basavaraj, 2020).

Life-cycle assessment should compare materials that deliver the same function. The functional unit should therefore include strength, durability class, and expected service life rather than simply one tonne of cement. A low-carbon binder that requires more material, intensive curing, or early repair may not deliver the lowest whole-life impact. The strongest environmental case for LC3 occurs when locally available clay and limestone are used efficiently and the resulting concrete provides durable service.

11. Practical Challenges and Research Needs

- Map local clay resources and identify kaolinite content, impurities, and suitable activation conditions.
- Optimize calcination temperature and duration to achieve adequate reactivity with minimum energy use.
- Determine gypsum demand and admixture compatibility for each clay–limestone–clinker combination.
- Develop reliable guidance for workability, setting time, shrinkage, and curing of LC3 concrete.
- Validate long-term chloride, carbonation, sulfate, and cracking performance under field exposure.
- Use region-specific LCA data for energy, transport, raw materials, and service-life scenarios.
- Adopt performance-based standards that permit high clinker substitution while protecting structural safety and durability.

12. Conclusions

1. LC3 reduces clinker-related emissions primarily by replacing clinker with calcined clay and calcite, thereby avoiding a portion of kiln fuel use and limestone-calcination emissions.
 2. Calcined clay is activated at substantially lower temperature than clinker and provides reactive silica and alumina for secondary hydration.
 3. Calcite is not merely a filler: it improves particle packing, provides nucleation sites, and reacts with clay-derived alumina to form carboaluminate phases.
 4. The combined action of clinker hydration, pozzolanic reaction, and carboaluminate formation can refine the pore structure and compensate for lower clinker content.
 5. Well-designed LC3 systems can approach 50% clinker content and may reduce cement-related CO₂ emissions by roughly 30–40%, subject to local processing and LCA conditions.
 6. Reliable implementation requires local material characterization, sulfate optimization, durability testing, and whole-life environmental assessment.
-

References

- [1] Akinpelu, M. A., Lawal, F. O., & Adisa, M. A. (2026). Review of material properties, performance and sustainability of LC3 concrete. *Discover Sustainability*. <https://doi.org/10.1007/s43621-026-04036-5>
- [2] 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. <https://doi.org/10.1016/j.cemconres.2012.09.006>
- [3] Avet, F., Snellings, R., Alujas Diaz, A., Ben Haha, M., & Scrivener, K. L. (2016). Development of a new rapid, relevant and reliable R3 test method to evaluate the pozzolanic reactivity of calcined kaolinitic clays. *Cement and Concrete Research*, 85, 1–11. <https://doi.org/10.1016/j.cemconres.2016.02.015>
- [4] Gettu, R., & Basavaraj, A. S. (2020). Life cycle assessment of LC3: Parameters and prognoses. In *Limestone calcined clay cements* (pp. 485–501). Springer. https://doi.org/10.1007/978-981-15-2806-4_32
- [5] Habert, G., Miller, S. A., John, V. M., Provis, J. L., Favier, A., Horvath, A., & Scrivener, K. L. (2020). Environmental impacts and decarbonization strategies in the cement and concrete industries. *Nature Reviews Earth & Environment*, 1, 559–573. <https://doi.org/10.1038/s43017-020-0093-3>
- [6] International Energy Agency. (2024). *Cement: Breakthrough Agenda Report 2024*. IEA.
- [7] Qadr, B., Aouad, G., Briffaut, M., et al. (2026). A review on the influence of carbonation and chloride ingress on the durability of limestone calcined clay cement. *Discover Applied Sciences*, 8, 995. <https://doi.org/10.1007/s42452-026-08918-1>
- [8] Rashad, A. M. (2013). Metakaolin as cementitious material: History, scours, production and composition—A comprehensive overview. *Construction and Building Materials*, 41, 303–318. <https://doi.org/10.1016/j.conbuildmat.2012.12.001>
- [9] Scrivener, K. L., Martirena, F., Bishnoi, S., & Maity, S. (2018). Calcined clay limestone cements (LC3). *Cement and Concrete Research*, 114, 49–56. <https://doi.org/10.1016/j.cemconres.2017.08.017>
- [10] Zunino, F. (2024). Recent advances in understanding the hydration of limestone calcined clay cements (LC3). *Cement and Concrete Research*, 176, 107430. <https://doi.org/10.1016/j.cemconres.2023.107430>
- [11] Zunino, F., & Scrivener, K. (2021). A fresh view on limestone calcined clay cement (LC3) pastes. *Materials*, 14(11), 3037. <https://doi.org/10.3390/ma14113037>

Disclaimer/Publisher's Note: The statements, opinions, and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of **AJHAS** and/or the editor(s). **AJHAS** and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content.