UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION
Progress by innovation

This project was undertaken with the financial support of:
Ce projet a été réalisé avec l'appui financier de :
Environment and Climate Change Canada
Environnement et Changement climatique Canada

LCCA
LOW CARBON CONSTRUCTION ASSOCIATION

LC^3: A Guide to Best Practices for Scalable, Affordable, and Sustainable Low-Carbon Building

Acknowledgements

AUTHORS: Low Carbon Construction Association

PROJECT COORDINATION: Rasha Abdrabu, Industrial Development Officer, UNIDO

FOR CORRESPONDENCE REGARDING THIS REPORT : industrialdecarb@unido.org, contact@lowcarbon.construction

This paper was developed under the Decarbonization of the cement and concrete sector in Thailand project activities.

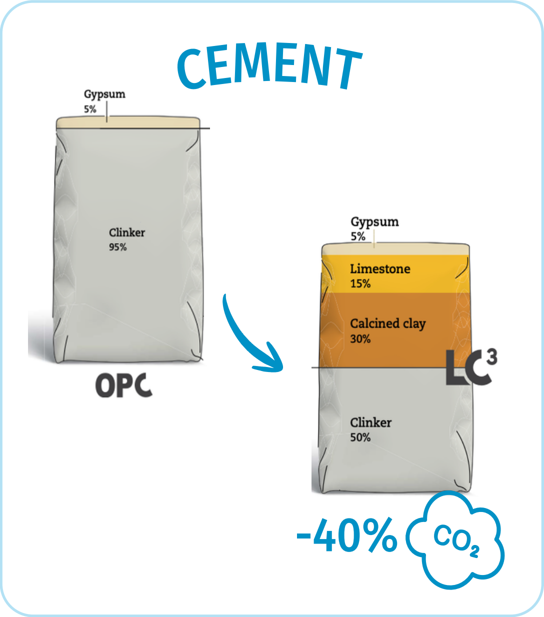
Acronyms

ASR : Alkali-silica reaction
ASTM : American Society for Testing and Materials
CAPEX : Capital expenditure
CCUS : Carbon Capture, Utilization & Storage
DSC : Differential Scanning Calorimetry
EN : European Norm
IEA : International Energy Agency
LC^2 : Limestone Calcined Clay
LC^3 : Limestone Calcined Clay Cement
OPC : Ordinary Portland Cement
OPEX : Operational Expenditure
PCE : Polycarboxylate ether
R^3 : Rapid, Relevant and Reliable
SCC : Self-Compacting Concrete
SCM : Supplementary Cementitious Material
SNF : Sodium Naphthalene Formaldehyde
TG : Thermogravimetry
UHPC : Ultra-High-Performance Concrete
VMA : Viscosity-Modifying Admixture
VRM : Vertical roller mill
XRD : X-ray Diffraction
XRF : X-ray Fluorescence

Table of contents

Companies' examples

What is LC^3?



LC^3 – A breakthrough in blended cement

Limestone Calcined Clay Cement (**LC^3**) is an innovative low-carbon blended cement that can be produced using existing technologies. It **significantly reduces the CO_2 footprint of cement** production while **maintaining** — and in many cases enhancing — the **performance** of concrete and mortar.

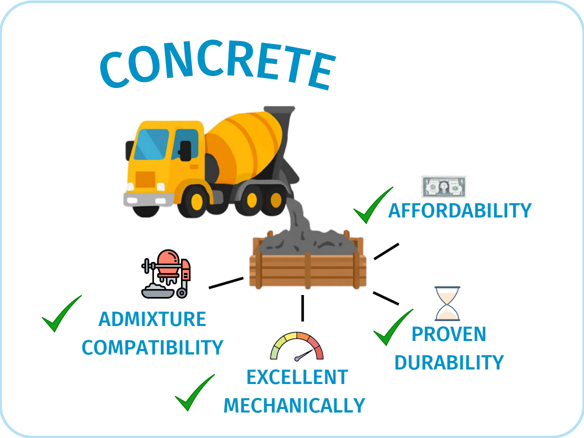
LC^3 is a family of cement where the number denotes the clinker content. For example, **LC^3-50** replaces 50% of clinker — the most carbon-intensive component of cement — with a combination of calcined clay and limestone, resulting in up to **40% lower CO_2 emissions** compared to traditional Ordinary Portland Cement (**OPC**), without compromising mechanical or durability performance.

Although **comparable to traditional blended cements,** such as slag-based systems, **LC^3 offers a decisive advantage in raw material availability and performance.** While **slag** and **fly ash** together could replace only about **15%** of global **cement production**, suitable **clays** and **limestone needed for LC^3** exist in **quantities well exceeding cement demand** — a demand that continues to grow.

LC^3 concrete – Proven suitable and scalable

The combination of calcined clay and limestone can be implemented in two different ways. In **LC^3**: clinker, calcined clay, uncalcined limestone, and gypsum are all blended together at the cement plant. In contrast, **LC^2** consists of calcined clay, uncalcined limestone, and gypsum only, and can be incorporated directly at the concrete production stage.

Cost-effective and easy to implement, LC^3 behaves like traditional OPC in fresh concrete and is compatible with standard admixtures. Once hardened, it delivers **equal** or **superior strength** and **durability**.



Do we really need cement anymore?

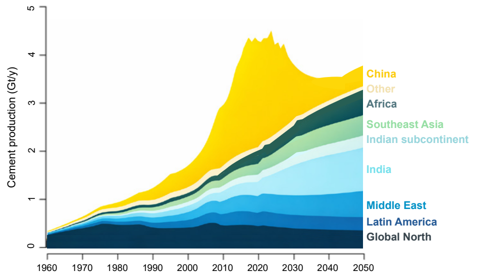
Cement and concrete – The irreplaceable materials

Concrete has a lower embodied carbon footprint than steel, or even brick. Yet its scale of production makes it responsible for nearly **8%** of global CO_2 emissions, mainly from cement manufacturing. Emissions arise not only from **fuel consumption**, but primarily from the **breakdown of limestone** (80% of raw material), which **releases CO_2** above 800°C.

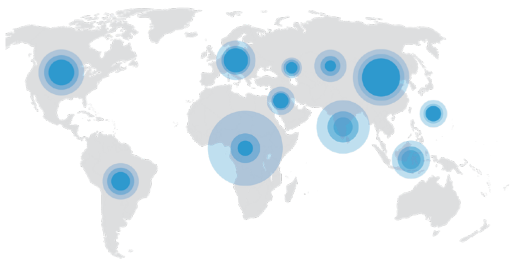
The global **dominance** of **Portland cement** is **no coincidence**: it is rooted in the **chemistry** and **geology** of the Earth. The raw materials required — limestone and clay — are among the most abundant minerals in the Earth's crust. This abundance makes cement a truly universal material: it can be produced and purchased almost anywhere in the world. Moreover, once **incorporated** in **concrete**, no construction material shows such high **versatility**, **durability**, **affordability**, and **mechanical** performance. Importantly, **any concrete** from standard to ultra-high strength can be **made with LC^3**.

With rapid urbanisation and population growth in the Global South, demand for concrete will continue to rise. **The best alternative to concrete is lower carbon concrete.**

Cement production in different regions



Expected growth in global building floor area



© Architecture 2030. All Rights Reserved.
Data Sources: Global ABC, Global Status Report 2017

LC^3 – The leading solution for speed and scale in the Global South

Many levers can reduce CO_2 emissions in cement and construction. The urgent question is: **how do we act now**, **affordably** and **at scale?**

One solution is straightforward: reduce clinker content — the most carbon-intensive component of cement. Every **1% reduction in the global average clinker factor** can **cut** worldwide **CO_2 emissions** by more than **35 million tonnes**. **LC^3** embodies this approach. By significantly lowering clinker content using widely available calcined clay and limestone, it delivers major CO_2 reductions without compromising material properties. Suitable clays — particularly deposits with at least 40% kaolinite — are abundant in the regions where cement demand is set to grow most: **Africa, Latin America, India,** and **Southeast Asia**.

This represents more than climate action. It is a development opportunity — enabling local production, job creation, infrastructure and economic growth while transitioning to a lower-carbon cement industry.

Lower clinker. Lower carbon. Immediate impact. At scale.

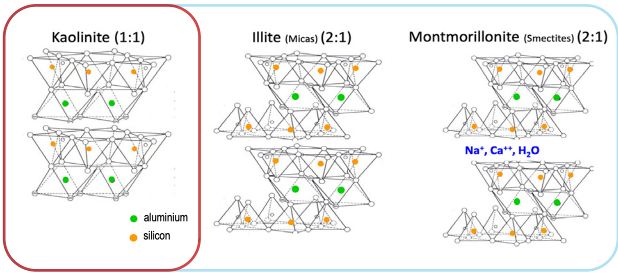
Raw clays: types and suitability

Raw clay types: key impact on future calcined clay reactivity

The **geological assessment** of raw clays is the starting point for calcined clay production. Clays consist of layers of silica tetrahedra and alumina octahedra, arranged in different layer structures, primarily **1:1** and **2:1** type. In 1:1 clays, such as **kaolinite**, a single alumina layer is adjacent to a single silica tetrahedral layer. When heated to around 800° C, kaolinite undergoes dehydroxylation followed by structural rearrangement, transforming into a highly disordered phase known as **metakaolin**. This **structural disorder** significantly **enhances reactivity** through pozzolanic reactions, enabling higher property development when used as a Supplementary Cementitious Material (SCM). By contrast, **other clay types**, including 2:1 clays, are **less reactive** under similar conditions.

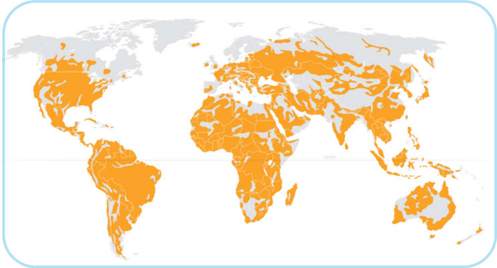
LC³ can be produced from a **wide variety of clay resources**, as even **low purity clays** with **kaolinite** contents as low as about **30–40%** can still be effectively utilized. In many cases, national geological surveys only classify clays with more than 60 % kaolinite, which **underestimates the total pool of clays suitable for LC³ production**. This broader range of usable clays is particularly attractive because such kaolinite-bearing soils are **widely distributed globally**, especially in **regions where cement demand is expected to grow most**, making them a strategic resource for sustainable construction. Due to the natural variability of clays and the presence of impurities such as iron oxides or carbonates, thorough mineralogical and chemical characterisation remains essential to evaluate resources and control the calcination process.

Different clay types



Most desirable

Distribution of kaolinitic clays worldwide



Map produced by Zoï Environment Network, July 2023

Raw clay characterisation and suitability assessment

The suitability of clays as SCMs is most reliably assessed using **thermal analysis**. By measuring the weight loss occurring between **400 and 600 °C**, this method allows the estimation of the amount of dehydroxylating clay minerals. A weight loss above **5%** in this temperature range generally indicates a clay suitable for use as an SCM.

Additional indicators of suitable clays include a **high alumina content** (Al_2O_3 > 18%) and a relatively high **alumina-to-silica ratio** (Al_2O_3/SiO_2 > 0.4).

Complementary and more sophisticated **techniques** such as X-ray fluorescence (**XRF**), X-ray diffraction (**XRD**) and Thermogravimetry (**TG**) can provide **additional characterisation**, with information on the main mineral phases present for instance. Thermal analysis nevertheless provides the most direct and quantitative insight into the transformations occurring during calcination, making it the preferred method for evaluating raw clays for SCM production and assessing their overall potential.

From raw to calcined clays

Clay calcination and quality control

Clay calcination is the **critical step** that imparts **reactivity**. While dehydroxylation — removal of chemically bonded -OH groups — is largely complete at 600°C, further heating to around 800°C increases structural disorder and transforms the raw clay into a highly reactive SCM. The key parameter to control is calcination temperature.

Calcination is typically carried out in **rotary kilns** (either new or retrofitted from clinker production) or **flash calciners**. Both can produce **similar products** at **comparable cost**, though they differ in feedstock handling and in the final product's characteristics, such as particle fineness, tendency to agglomerate, or energy efficiency.

Consistent **quality** of **calcined clays** at the plant is ensured through key control techniques, primarily aimed at assessing their reactivity. Methods such as TG, differential scanning calorimetry (**DSC**), **methylene blue testing**, and **XRD** are commonly used to verify proper calcination and confirm the desired level of reactivity.

Flash calciner

Rotary kiln

Conventional cement (left) and LC³ (right) wall – Swiss example

©Induni-Maulini

Colour challenge – An industrial example

A common **industrial concern** is the colour of calcined clays once incorporated into cement and concrete.

While some markets (e.g., Switzerland) appreciate it, others do not have a positive perception.

This colour comes from **the presence of iron-rich phases in the clay**.

A **simple adjustment** to the cooling process can **modify the colour** without affecting performance, ensuring **both aesthetics, functionality and customer acceptance**.

From raw to calcined clays

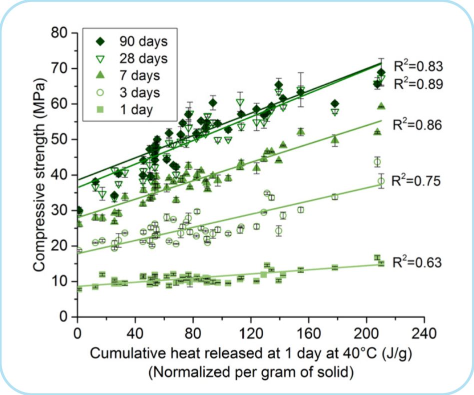
Calcined clay reactivity testing: standardized and aligned with cement testing

In the **cement industry, reactivity** is typically **assessed** using **calorimetry**, as it strongly **correlates with strength development**. For **LC³**, the **reactivity of calcined clay** is **the key parameter** when considering its use as a **SCM.** Several techniques have been demonstrated for this purpose, including calorimetry, strength testing, and chemical methods.

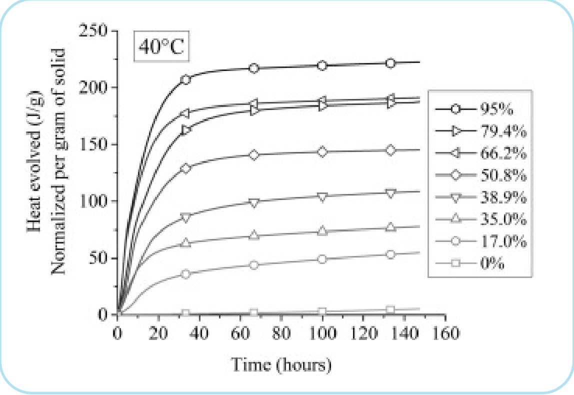
The LC³ team has systematically studied clay reactivity and successfully standardized its most important test: **the R³ test** (Rapid, Relevant, and Reliable), now recognized by ASTM (**ASTM C1897**). This differential scanning calorimetry-based method evaluates calcined clay reactivity in a chemical environment similar to cement paste. It provides high-quality results **using** standard **equipment familiar to the cement industry**, enabling **smooth assessment of quality and reactivity without changing existing practices**.

Importantly, **results from the R³ test have been shown to correlate closely with compressive strength**, the principal property of interest in concrete, which also governs other performance aspects. This ensures that reactivity assessments are not only scientifically robust but also directly relevant to concrete performance, supporting reliable and consistent production of LC³-based cements.

Cumulative heat released after 1 day at 40 °C (R³ conditions) versus compressive strength of LC³-50 mortars in time



Cumulative heat released evolution over time for calcined clays with various kaolinite content



Several **other standardized techniques are also available to assess calcined clay reactivity**, including the **Indian lime reactivity test** for instance.

The availability of **multiple methods** allows users to **select the approach that best suits their needs**. The R³ test remains the primary method due to its strong correlation with compressive strength — the key property for evaluating SCM performance in concrete.

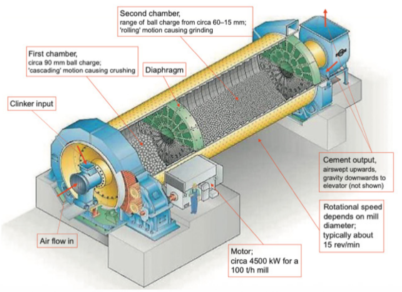
From calcined clay to blended cement

Milling and blending of LC^3

The final stage of cement manufacturing consists of **milling and blending** the main components. In LC^3 production, manufacturers can follow different approaches without changing equipment, as the **typical machinery used for conventional cement production is fully suitable**, requiring **no additional investment**. One option is to produce LC^3 directly at the cement plant by **co-grinding all components together** — clinker, calcined clay, limestone, and gypsum — into a single blended cement. Co-grinding requires a proper understanding of the constituent material properties to optimize the outcome.

Alternatively, materials can be **ground separately**. Calcined clay and limestone may be milled together (producing **LC^2**), while clinker and gypsum are milled independently. The streams are then **blended** to obtain **LC^3**. In some cases, **LC^2** itself may be the **final product**, with blending completed later during concrete production.

Industrial ball mill diagram



Adapted from Lea's Chemistry of Cement and Concrete, based on ThyssenKrupp AG

Clay milling without (left) and with (right) grinding aids

Industrial expertise and grinding optimization – Enabling reliable LC^3 production

During cement milling, fine particles tend to agglomerate, which can reduce grinding efficiency and result in an uneven particle size distribution. **Traditional grinding aids** can help mitigate this by acting at the particle surface to reduce inter-particle attraction. In the context of LC^3, where clinker, calcined clay, and limestone have different hardness, grindability, and surface properties, grinding aids improve dispersion and facilitate more stable and efficient co-grinding. While their primary role is in milling, certain formulations can also contribute to enhanced early-age strength development of the cement.

Beyond the use of **additives**, the choice of proper grinding equipment and optimized milling processes is critical to achieving consistent particle size and high-quality cement. **Industrial-scale LC^3** production relies on well-controlled milling parameters, including grinding media and mill speed, to ensure efficient particle size reduction and uniform blending of components. Combined with process control strategies and industrial know-how, these measures enable the large-scale production of LC^3 with reliable quality, supporting its performance across a wide range of concrete applications. **As industrial deployment expands**, there remains significant **room for further improvement, and continued optimization** of grinding and blending practices is expected to **enhance** even more the **robustness**, efficiency, and **overall performance** of LC^3 systems.

Fresh concrete properties

Fresh LC^3 concrete

Fresh properties are critical for concrete, as they determine ease of placement, versatility, and influence later hardened performance. Incorporating calcined clays and limestone affects concrete rheology, but **practical experience from construction projects worldwide** shows that **LC^3 requires only a minimal increase in admixture demand**, such as superplasticizers. Importantly, the same admixtures used for OPC are fully compatible with LC^3, allowing for straightforward adaptation without major changes in mix design.

The setting time of LC^3 may be shorter than OPC but can be **easily controlled** by **simple retarders** such as phosphoric acid.

Beyond fluidity and setting time, **cohesiveness is essential**: it prevents segregation, ensures uniform aggregate distribution, and promote consistent mechanical properties in the hardened state. Extensive studies and real-life applications show that LC^3 concrete exhibits **excellent cohesiveness**, even exceeding that of OPC concrete, resulting in reliable, high-quality hardened performance in the finished structure.

Fresh LC^3 concrete applied on-site – Courtesy of Pr. Fernando Martirena

From fresh properties to field performance — LC^3 in Self-Compacting Concrete (SCC)

A clear illustration of LC^3's fresh-state performance is its behaviour in **SCC**. Unlike conventional concrete, which requires mechanical vibration for proper consolidation, SCC flows and compacts under its own weight. Reducing or eliminating vibration can save time and labour, while facilitating placement in complex or densely reinforced structures.

SCC achieves its **high flowability** through increased **paste content** and the **use of admixtures** such as superplasticizers and viscosity-modifying agents (VMAs). However, this elevated fluidity can increase the risk of segregation and bleeding. Here, LC^3 offers a clear advantage: its higher intrinsic viscosity improves stability, helping maintain a uniform distribution of aggregates and ensuring a more consistent and cohesive concrete mix.

Mechanical properties of LC³ concrete

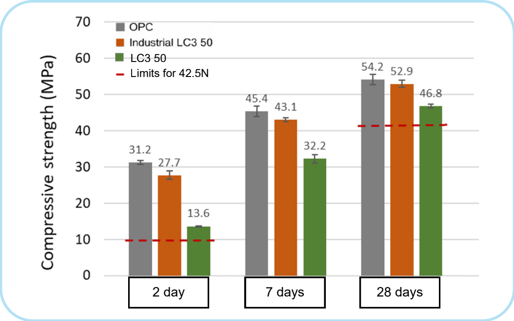
Compressive strength of LC³ concrete: the influence of industrial scale production

Compressive strength is the **most critical mechanical property of concrete**, as it governs the material's ability to withstand structural forces. In practice, **concrete** is typically **designed** to meet a target **compressive strength class** (e.g., C20, C25, C30 … C55), ensuring consistency and reliability for structural applications. LC³ can be formulated to meet **all these strength classes**, making it **suitable across the full spectrum of concrete applications**.

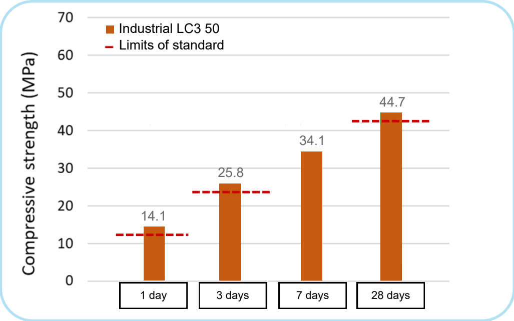
Comparative laboratory studies of OPC and LC³ with 50% replacement (LC³-50) have shown that **LC³-50** can **achieve compressive strengths comparable to OPC**. However, comparing laboratory-prepared LC³-50 with industrially produced OPC does not provide a realistic assessment of performance particularly at early ages.

While **early-age strength** of **lab-prepared** LC³-50 may appear lower, industrial-scale production, with optimized grinding and blending, allows for a more balanced and accurate comparison. Under controlled, large-scale conditions, LC³-50 concrete can develop strength rapidly, even with low-grade clays. This is largely due to industrial production techniques, such as optimized clinker grinding, the use of grinding aids, and other process adjustments that enhance early-age hydration, enabling LC³-50 to achieve compressive strength levels comparable to those of OPC.

Compressive strength comparison: OPC, lab-prepared LC³-50 and industrial LC³-50 – Swiss example



Compressive strength of industrial LC³-50 – Colombian example



Suitable for standard-grade and high-strength concrete?

LC³ has demonstrated its **suitability across the full spectrum of structural concrete applications**. It can be tailored to meet the requirements of **standard-grade concretes** used in foundations, slabs, and walls, as well as **high-strength mixes** for demanding structural elements such as high-rise buildings, long-span bridges, and other critical infrastructure. With appropriate mix design and optimization, LC³ can even be integrated into advanced systems such as ultra-high-performance concrete (**UHPC**) for exposure to harsh environments, or extremely slender designs for instance.

This versatility highlights that LC³ can match OPC in terms of structural capability — while simultaneously supporting sustainability objectives and maintaining cost efficiency.

Structural performance of LC³ concrete

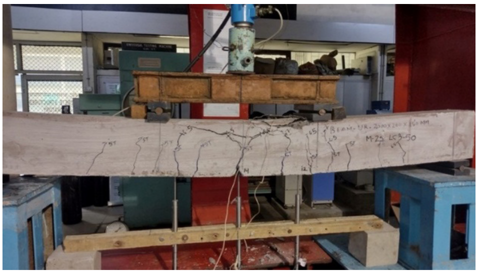
LC³ for structural applications

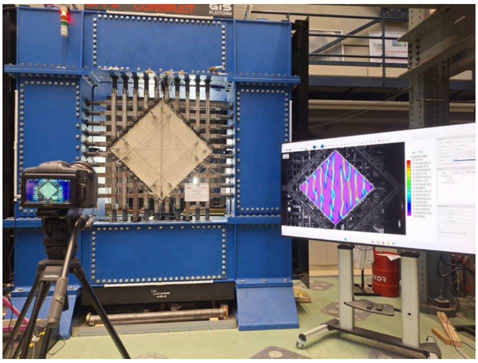
In traditional concrete, structural design is largely based on well-established **relationships** between **compressive strength and other key mechanical properties**. Parameters such as elastic modulus, creep (long-term deformation), shrinkage, and bond with steel reinforcement are not considered in isolation; rather, they are known to correlate reliably with compressive strength.

Extensive research has shown that **LC³ concrete follows the same relationships between compressive strength and these fundamental mechanical properties**. For a given compressive strength level, LC³ exhibits comparable stiffness, shrinkage, and bond performance with reinforcement as OPC concrete. The only exception is **creep** which is **significantly lower** in LC³ system.

Therefore, LC³ concrete can be assessed and **designed** using the **same strength-based mechanical relationships as OPC**, ensuring equivalent structural reliability while offering a more sustainable alternative for construction applications.

Reinforced LC³ concrete beam being tested in flexion – IIT Dehli





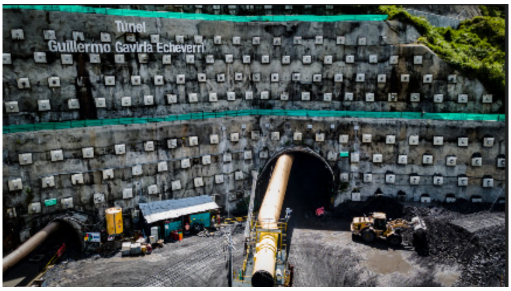
Reinforced LC³ panel being tested – Pr. Ruggiero EPFL

Demonstrated applications in practice

These benefits are demonstrated by **real projects**. The ***Tilia Tower*** in **Switzerland** demonstrates LC³'s suitability for high-rise construction, ***Tunnel Echeverri*** and ***viaduct over the Cauca River*** in Colombia highlight its versatility in underground works, load-bearing and long spanning structural elements. In all cases, LC³ has delivered reliable performance, with contractors noting consistent workability and ease of use, underscoring its practicality as a sustainable alternative to OPC.

Visualisation of Tilia Tower (Switzerland), Tunnel Echeverri, and viaduct over the Cauca River (Colombia)

© 3XN & Itten + Brechbühl



© Cementos Argos

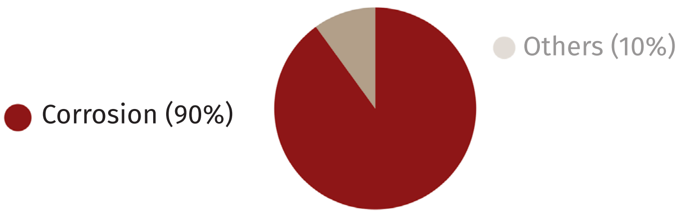
Durability of LC^3 concrete

What does durability mean for concrete?

Durability is the ability of a **structure** to maintain its **intended performance** throughout its **service life** under expected **environmental** and exposure **conditions**.

Durability is **not** an **intrinsic material property**; it is a system-level characteristic. In **concrete**, it is fundamentally governed by the **porous system**, which is determined by the **cement paste** rather than the aggregates. The **quality of the concrete** itself is the **primary factor** controlling **durability**, with key parameters—such as the water-to-binder ratio—playing a central role in defining the porous network. In reinforced concrete structures, durability issues are most often (in around 90% of the cases) associated with **reinforcement corrosion**, but they may arise intrinsically from the **concrete matrix** itself.

In **LC^3** concrete the **phases** that form during hydration and the resulting **microstructure** are **very similar** to those in **OPC**. Therefore, there is strong confidence that LC^3-based structures will exhibit **durability comparable** to that of **OPC** and that no surprises are expected in long-term behaviour.



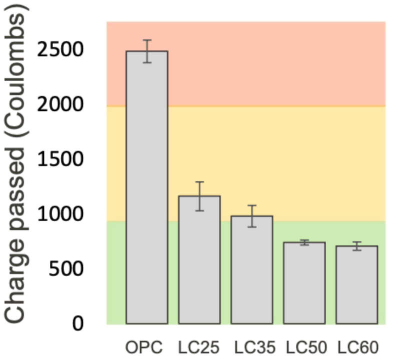
In sound concrete, the **high alkalinity** of the pore solution (pH > 12) ensures a **passive layer on the reinforcement**, **preventing corrosion**. Over time, however, the permeation of fluids from aggressive environments into the concrete can lead to depassivation of steel and subsequently corrosion.

Resistance to chloride ingress

The most **widespread** cause of **corrosion** is **chloride ingress**, where chloride ions penetrate the concrete cover and, upon reaching the reinforcement, locally destroy the passive film, initiating pitting corrosion. This reduces the tensile capacity of the steel and induces cracking and spalling of the concrete. Chloride exposure is common in marine structures, underground infrastructure, swimming pools and regions using de-icing salts.

LC^3 concrete **show** a **significantly lower chloride permeability compared to conventional OPC concrete**, with reductions in chloride ingress of up to fivefold in some cases. For an equivalent design and concrete quality, LC^3 therefore provides markedly improved resistance to corrosion, enhancing the service life of structures, with minimal maintenance related cost.

Rapid Chloride Penetration Test (ASTM C1202) for OPC and various LC^3 concrete



Durability of LC^3 concrete

Carbonation induced corrosion

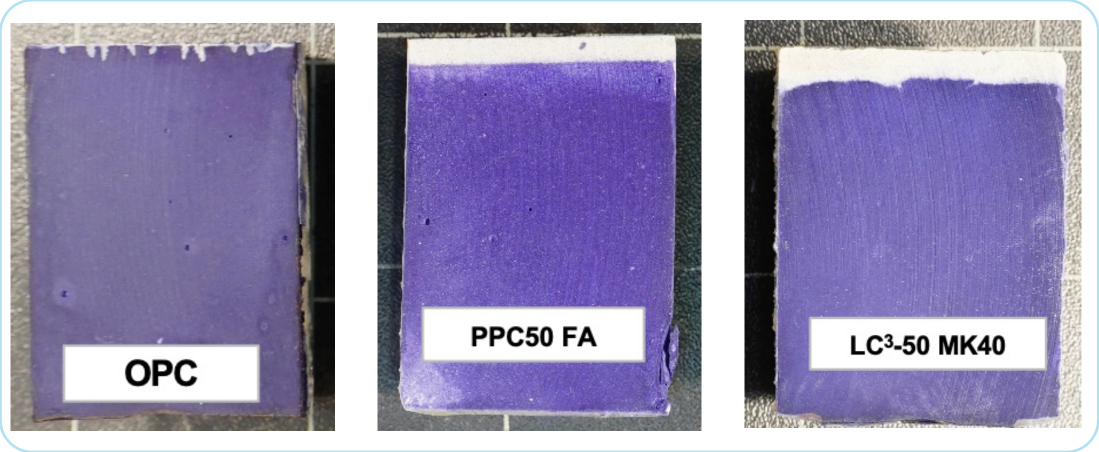
Carbonation occurs when **atmospheric CO_2 penetrates** the **concrete** and **reacts** with the **cement paste**, **lowering** the **alkalinity** of the pore solution. This highly alkaline environment normally **protects embedded steel reinforcement**. If the carbonation front reaches the reinforcement, the protective passivation layer on the steel can be compromised, creating conditions in which **corrosion may initiate**.

However, carbonation **alone** is **not sufficient** to cause **corrosion**, contrarily to chloride. Specific **additional conditions** — most importantly the presence of sufficient moisture — are **required** to enable the corrosion process. Interestingly, these conditions differ from those that favour carbonation, meaning that a **concrete** structure **can carbonate extensively without** necessarily **experiencing** significant reinforcement **corrosion**. Field studies in Japan and Switzerland indicate that more than 85% of carbonated structures show negligible corrosion damage, highlighting that carbonation is not a direct predictor of structural failure.

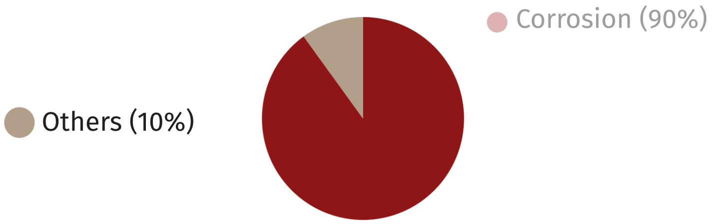
As is **typical for blended cements**, **carbonation** progresses **faster** in LC^3 than in OPC. Despite this, LC^3 concretes meet established durability standards.

Extensive **ongoing research** aims to deepen understanding of **carbonation mechanisms in LC^3 systems**, quantify the **risks of carbonation-induced corrosion** under different environmental exposures, and optimize mix design and curing practices to mitigate any potential effects. These efforts help reinforce the confidence of designers, engineers, and regulators in the long-term durability of LC^3-based structures.

Comparison of carbonation fronts in paste specimens after 1 year of natural indoor carbonation: OPC, 50% fly ash blended cement, and LC^3-50



Durability of LC^3 concrete



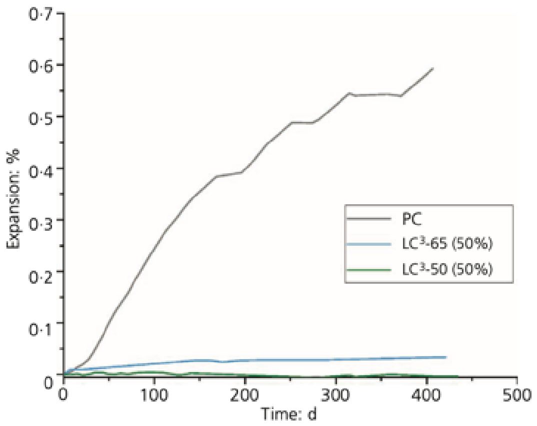
Beyond reinforcement corrosion, concrete may deteriorate due to **mechanisms inherent to the material**, including alkali–silica reaction and freeze–thaw cycles. Addressing these phenomena is key to ensuring robust and reliable long-term performance

Alkali-Silica Reaction (ASR)

An important degradation mechanism, particularly in mountainous regions, is **ASR**. Certain **aggregates contain reactive silica** which, in the presence of alkalis and moisture, forms an **expansive gel**. The resulting internal swelling leads to **cracking and long-term deterioration of concrete**. While reactive aggregates can sometimes be avoided, this is not always feasible, especially when local materials must be used for economic or logistical reasons.

LC^3 has suppresses **expansion due to ASR** even with clinkers of moderate to high alkali content. Its use therefore significantly limits ASR-related damage, again reducing the need for restrictive aggregate selection or structural adaptations.

OPC vs. LC^3-50 concrete ASR expansion over time



Sulphate attack

Sulphate attack occurs when sulphates (from internal or external source) **react** with the cement **paste**, forming **expansive products** that can ultimately lead to cracking of the concrete. Severity of the attacks mainly depend on the **paste** (and overall concrete) **quality**, as well as the **cement composition**. **LC^3** concrete **show an enhanced performance in tests designed to assess sulphate resistance.**

Freeze-thaw

Freeze–thaw damage **occurs** when water-saturated concrete is exposed to freezing temperatures, causing **internal stresses** that can lead to **cracking** and **surface scaling**. Mitigation is well established, primarily through air-entraining admixtures that create microscopic voids to accommodate ice expansion. **LC^3** concretes perform **comparably to OPC** and are **fully compatible with standard air-entraining admixtures**.

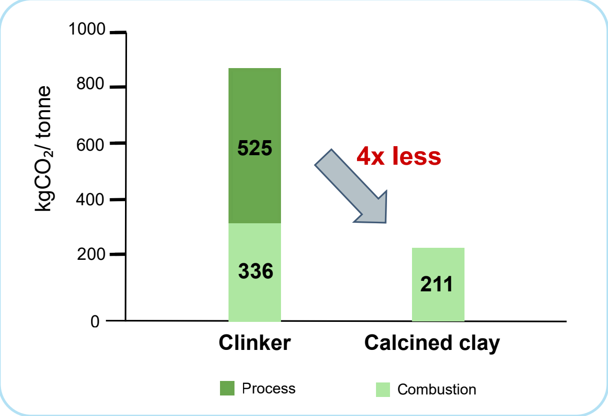
Environmental gains of LC³

Clinker substitution for fast emission cuts

Clinker alone accounts for roughly **85–90%** of the total emissions **footprint of concrete**. Consequently, reducing the clinker content in cement is the most effective lever for lowering its overall environmental impact. By replacing **50% of clinker** with a combination of uncalcined limestone and calcined clay, the **carbon footprint** per **kilogram** of **binder** can be **reduced** by up to **40%**. This is because calcined clay does not release chemical CO_2 during production and is calcined at a much lower temperature (~800 °C) than clinker (~1450 °C), reducing both chemical and fuel-related CO_2 emissions.

The **availability** of raw materials, reduced energy for calcination, **affordability** and **scalability** of this approach, makes it a practical solution for **immediate** environmental gains. In contrast, technologies such as Carbon Capture Utilisation & Storage (CCUS) are likely to yield measurable results only in 5–10 years. Furthermore, such technology could increase cement costs by 2–4 times — a major concern, especially as demand grows in countries where affordability is the top priority.

Comparison of CO_2 emissions: clinker vs. calcined clay



From binder to structure: unlocking emission savings in construction

These massive **reductions** can be further **amplified** depending on **choices** made at the **concrete** and **structural** applications **levels**. By combining low-impact binders with well-established engineering strategies at the concrete and structural levels — such as optimizing aggregate packing, using admixtures, and designing more efficient structures to avoid over-design — about **70%** of **emissions** related to **construction** could be **cut**. This can be achieved quickly through good practices, rather than waiting for the large-scale deployment of CCUS only.

Of course, achieving this requires **bold** investments and **decisions**, **coordinated efforts** across the entire **value chain** — from **cement producers to structural designers** — and supportive **policy** shifts. But global warming cannot wait.

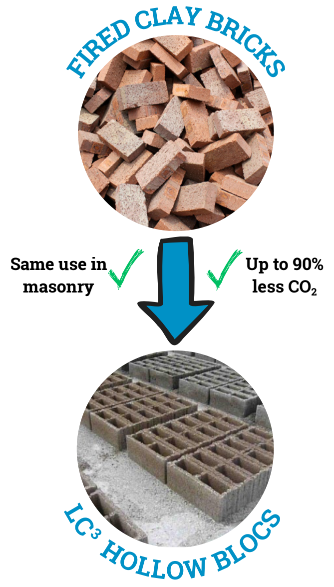
Non-reinforced concrete — The overlooked opportunity

The striking example of masonry

Many key **construction elements** do **not** require **steel reinforcement**, including **masonry walls**, **pavements**, **kerbs**, and most **precast elements**. Yet traditional solutions often have a high environmental impact.

Fired clay bricks are a striking example. In India alone, around **250 billion bricks** are produced **each year**. When manufactured in modern, well-controlled industrial kilns, brick production can achieve relatively high energy efficiency and controlled emissions. **However**, a **large share** of global **brick production** still takes place in low-efficiency, often **informal kilns**. In these cases, poor combustion control and outdated technologies lead to excessive fuel consumption and the release of significant amounts of harmful particulate matter, contributing to air pollution.

LC^3 hollow concrete blocks offer a clear sustainable alternative. They can use the same clays already employed in brickmaking, while maintaining performance, and have the potential to **cut the carbon footprint by up to 90%** compared to fired clay bricks. Importantly, their production can be adapted to small workshops, preserving local employment.



Versatile applications – Beyond blocks

Higher **clinker replacement levels of up to 65-75%** can often be used to produce **pavers**, **kerbs** and other **precast elements**, while **meeting** their **performance requirements** with consequent **massive environmental gains**. Additionally, due to the low-clinker levels, **carbonation** rates are significantly **higher** in these non-reinforced elements, thereby leading to the continuous **sequestration of carbon** throughout their lifecycle, without any risk of steel corrosion. Knowing such elements are widely used and **necessary in the Global South**, much research and industrial efforts should be directed in these areas for meaningful impact in the fight against climate change. Pilot **production projects** are ongoing in **Africa, India** and **Latin America**.

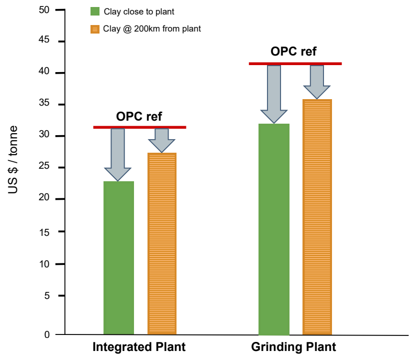
LC^3 unreinforced elements: pavement, concrete blocks, and pavers

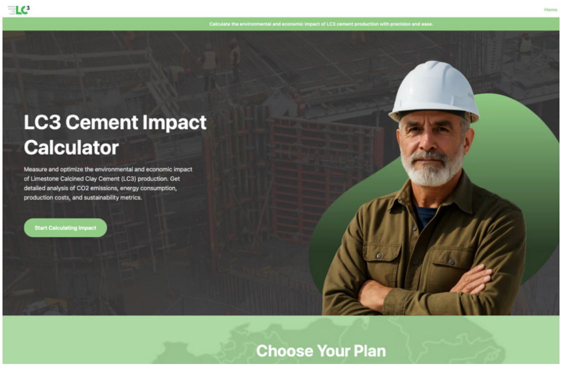
Economics of LC^3

Financial attractiveness of LC^3 – Cement producers and investors

From a **cement producer's perspective**, LC^3 can offer significant **economic advantages**, although the **performance varies** depending on several factors: the quality and distance of clay deposits, transport logistics, energy costs, and the selected production technology — whether retrofitting an existing rotary kiln or installing a dedicated flash calciner. Capital expenditure (**CAPEX**) requirements are substantially lower than those associated with new clinker production lines, particularly when existing infrastructure can be adapted. Operational expenditure (**OPEX**) is also significantly reduced, as LC^3 production typically requires less fuel than conventional OPC, with estimated savings of around 7.7 $/tonne of cement for LC^3-50 production. In addition, in regions with **CO_2 pricing** or **carbon taxes**, such as Europe, LC^3 offers further economic benefits through reduced emissions, with potential savings of approximately 25 €/tonne of cement for LC^3-50 compared to OPC. **The magnitude of these savings, however, is highly context dependent**.

Because these parameters differ from one location to another, a **dedicated assessment tool** has been developed to evaluate the technical and economic feasibility of potential LC^3 projects (https://test-tool.calclay.pt). By integrating variables such as raw material availability, transport distance, technology choice, energy costs, market conditions, and CO_2 pricing, this tool enables producers to determine the specific economic potential and return on investment for each individual scenario.


Financial attractiveness assessment for two scenarios of LC^3 production


Impact calculator tool: evaluate and optimize the environmental and economic impact of LC3 production for your specific scenario

Calculate the environmental and economic impact of LC3 cement production with precision and ease.

LC3 Cement Impact Calculator

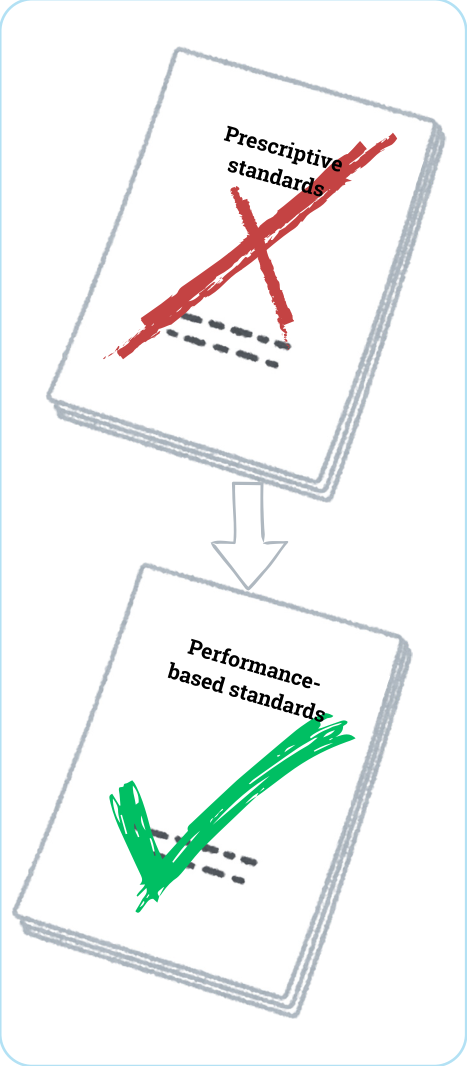
Measure and optimize the environmental and economic impact of Limestone Calcined Clay Cement (LC3) production. Get detailed analysis of CO2 emissions, energy consumption, production costs, and sustainability metrics.

Affordability of LC^3 for end-users

For **end-users**, LC^3 is commercially available at a **price comparable to OPC**. It delivers durability equal to or superior to OPC — particularly in terms of chloride ingress — resulting in extended service-life at lower maintenance costs. This affordability enables economic and environmental sustainability to be achieved without compromising technical performance.

Policy as a catalyst

Adoption of LC³ — Tightly linked to regulatory frameworks



The **deployment of LC³ is strongly influenced by national cement standards**. In Colombia, for example, a combination of prescriptive and performance-based regulations has enabled the use of low-clinker cements across a wide range of structural applications — from residential buildings to major infrastructure. LC³ has been produced commercially in Colombia since early 2020, demonstrating that such cements can reliably meet performance requirements for strength, durability, and workability.

In regions where cement standards have traditionally emphasized fixed compositional limits, the adoption of innovative low-carbon cements has taken more time.

Recent developments, however, have shown once again that regulatory evolution can unlock significant opportunities. A **major milestone** was achieved in **Ghana** with the adoption of **GS PAS 5:2024**, allowing **clinker contents as low as 35%,** with similar implementation underway in **East Africa**. These advances illustrate that when regulations evolve in line with scientific evidence and practical experience, large-scale deployment of low-carbon cements becomes feasible.

Overall, LC³-type binders are currently reflected in **major international cement standards**. Within the European framework, they correspond to composite cements defined in **EN 197-5**, classified as **CEM II/C-M (Q-LL).** Similarly, in the ASTM system, LC³ compositions fall within ternary blended cements specified in **ASTM C595** (Type **IT**). These classifications illustrate that **LC³ is already recognised within the main cement standard frameworks worldwide**.

What is needed?

Looking forward, a broader **shift toward performance-based standards is essential for both cement and particularly concrete**. Instead of prescribing fixed clinker contents or minimum cement quantities, regulations could focus on measurable performance criteria such as compressive strength and durability. **This approach** would **avoid overdesign**, enable **further clinker reduction**, and **support cost-efficient decarbonization**. Extensive **collaboration** between **researchers**, **industry leaders**, and **public authorities** is already driving this transition, demonstrating that sustainable cement solutions like LC³ can be widely adopted when regulatory frameworks align with practical experience and scientific evidence.

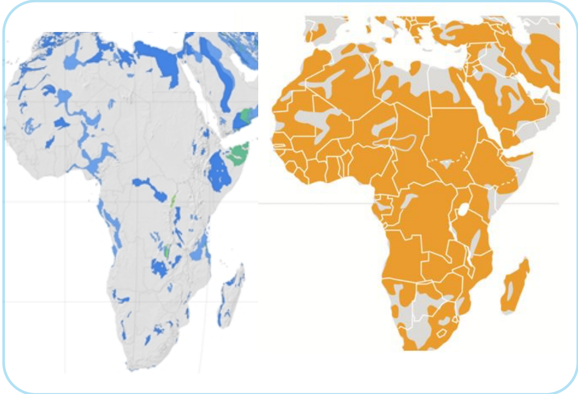
LC^3: an opportunity for Africa

The cement supply challenge in a growing Africa

Africa stands at the centre of the **next global construction boom**. Rapid **urbanization**, **infrastructure** expansion, and **demographic growth** are driving an unprecedented **demand for cement across the continent**.

Yet **conventional cement production faces a structural limitation**: high-quality **limestone deposits** are **unevenly distributed** and often located far from the regions where demand is rising fastest. As a result, significant volumes of cement or clinker are transported over long distances — frequently imported from Asia and North-Africa — increasing costs, supply vulnerability, and carbon emissions.

Comparison of limestone (left) and clay (right) deposits in Africa



LC^3: turning local resources into industrial advantage

LC^3 offers a **strategic reversal of this dynamic**. **Suitable clay** deposits are **abundant** and **widely distributed across the African continent**. By partially replacing clinker with locally produced calcined clay, dependency on imported clinker and limestone is significantly reduced, strengthening material sovereignty and supply security. By leveraging locally available clays for calcination, Africa can produce high-performance, lower-carbon cement domestically, unlocking **massive local value creation** and driving **industrialisation** at scale.

Moreover, as a **large share of housing** across the continent relies on **reinforced concrete frames** combined with **masonry infill**, transitioning both **structural concrete and masonry products to LC^3-based** solutions holds **tremendous potential for CO_2 reduction**. Such a transformation would not only preserve established construction traditions but also amplify local economic value creation.

Beyond meeting its internal cement demand sustainably, **Africa** can **become** a **competitive exporter of calcined clay materials** to regions such as Europe, where suitable raw materials are comparatively less accessible. LC^3 represents more than a technical innovation — it is a pathway for industrial empowerment and long-term economic transformation.

LC³: perspectives for Thailand

Thailand: a high potential for LC³ production

Thailand in Southeast Asia

Thailand provides another **excellent example** of a **region** where **suitable clays are widely distributed** and LC³ production could be readily implemented. As the country seeks to reduce industrial emissions and move toward a more sustainable economy, the integration of LC³ — incorporating locally produced calcined clays — offers a promising pathway. This transition could both strengthen local industrial activity and support economic growth, while enabling Thailand to produce lower-carbon cement and potentially expand exports to neighbouring markets in Southeast Asia.

Thailand is **rich in clay resources** and is one of the **leading producers and exporters** of **kaolin-type clays** in Southeast Asia, primarily **used in the ceramics** and **paper** industries. However, the **clays required for supplementary cementitious material** applications in LC³ do **not need to meet such high purity standards**, meaning there is **little** direct **competition** with existing industrial uses. Geological maps and surveys across the country indicate that **suitable medium-grade clays are widely available**, particularly in **the central and southern regions.** Importantly, these areas closely **coincide with the highest concentration of cement plants**, creating highly **favourable logistics** for the integration of calcined clay into existing production systems.

Clay calcination also presents additional advantages. **Biomass** derived from **abundant agricultural residues** — widely **available in Thailand**, such as **rice husks** — can be used as an **alternative fuel** for the calcination process. This approach avoids the inefficiencies and risks of over-calcination associated with traditional fuels like coal or petcoke, while delivering significant environmental benefits by lowering CO_2 emissions and promoting the circular use of agricultural waste.

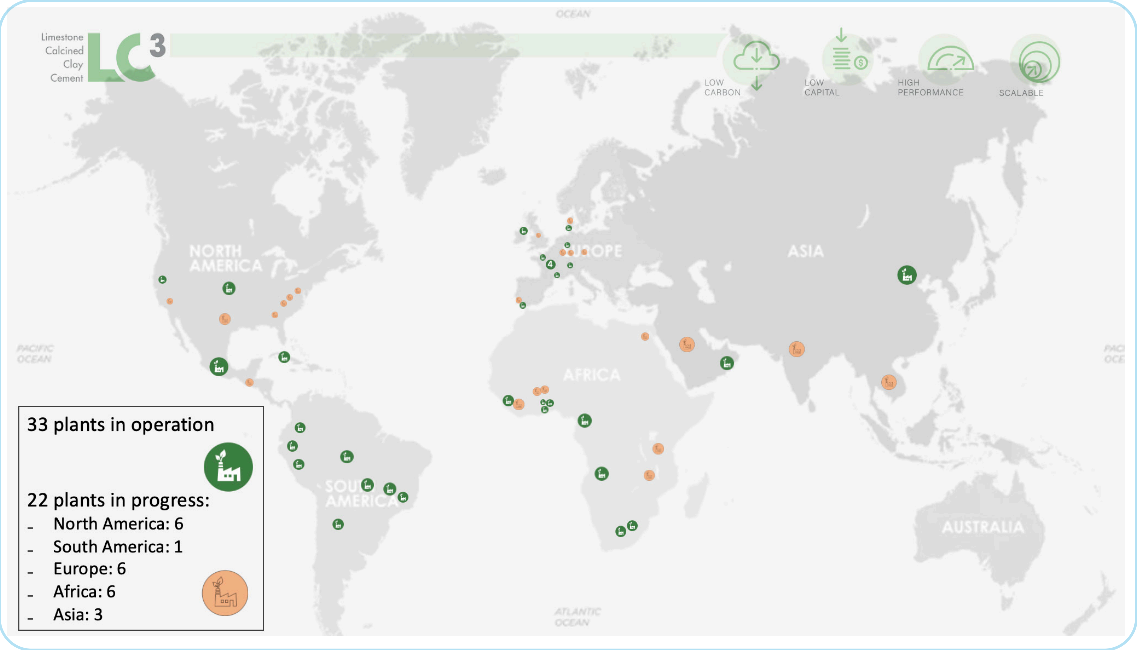
Applying global LC³ experience in Thailand

Thailand can **build on** the extensive global **experience** built **with LC³** — from **research teams** to **industrial producers** worldwide — to transition toward lower-carbon cement production. Across multiple markets, LC³ has proven robust, with performance validated from clay assessment and calcination to final concrete properties, giving confidence to producers, concrete makers, and end users. In Thailand, a **key consideration** is the prevalent use of **traditional water-reducing admixtures** (lignosulfonates and SNF), which are **less compatible with LC³**. However, **switching to modern polycarboxylate ethers** (PCEs) is **straightforward**, involves **little or no additional costs**, and improves cement performance. By adopting this shift alongside established LC³ knowledge, Thailand can implement high-performance, lower-carbon cement while fully leveraging local production systems, material availability, and concrete practices.

Unlocking the next level of LC³ production

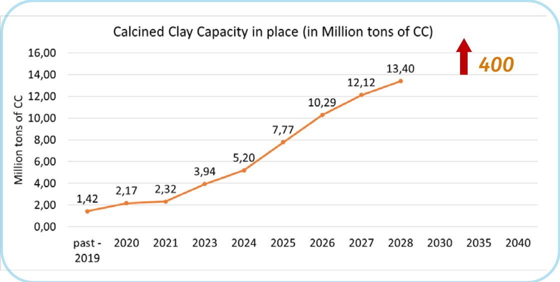
Calcined clay is already being produced at industrial scale worldwide in around **35 plants**, with about the same number under construction. These plants give an installed capacity of **15 million tonnes per year**, but the potential worldwide is over **1 billion tonnes**. Countries including (but not limited to) **Colombia, Ghana, Ivory Coast, India, Oman** and **Switzerland** already have **commercial LC³ on the market**.

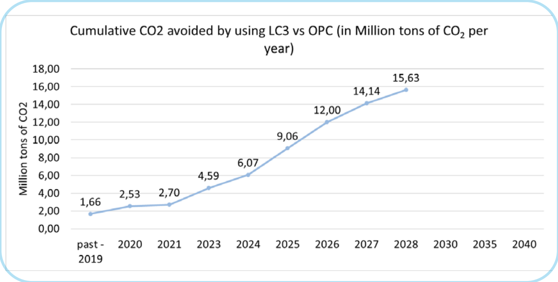
Map of operational and planned LC³ plants worldwide



Environmental benefits of LC³: current results and future potential

With **current LC³ production capacity**, around **10 million tonnes of CO_2 have** already **been** cumulatively **avoided** since its implementation. If **deployed at scale**, **LC³** could **reduce emissions by 400 to 800 million tonnes of CO_2 per year** — comparable to the annual emissions of a country like Germany.





LC³ frontrunner producers — Summarized insights and lessons from early adopters

Suitable clay identification

Successful LC³ production starts with identifying suitable clays within roughly 100 km of cement plants or target markets to ensure low logistic costs. The LC³ team defined key suitability parameters based on years of experience, using thermal analysis to determine clay reactivity for cement applications. Field verification confirms both volume and quality consistency, while medium-grade clays — sufficient for LC³ — are often underreported in national geological databases. Early assessment of deposits strengthens the commercial case and reassures producers and investors. Governments and geological services can support this by updating databases, considering lower-grade clays, and encouraging the use of low-quality limestone as a complementary resource.

Commercialization and market adoption experience

Market adoption of LC³ requires addressing both technical factors and market perception. Concrete mix adjustments are minor, but modern poly carboxylate ether (PCE) admixtures are recommended, especially in regions like Thailand where lignosulfonates are common. Early industrial trials, field demonstrations, and visible projects help build trust among producers, contractors, and end users. Visual aspects such as cement colour and product consistency are critical for acceptance in informal and formal markets alike. Strategic engagement with local standards, regulators, and green building initiatives further ensures market confidence and smooth commercialization, supporting both sustainable construction and industrial growth.

Calcination technologies and process insights

Clay calcination is a key step for LC³ production and should be implemented on a case-by-case scenario. Existing kiln systems can be retrofitted for calcined clay production, or new rotary or flash kilns can be installed depending on local conditions and production scale. Rotary kilns offer more flexibility for different scales and slightly more humid clays, while flash calciners typically produce finer particles but involve higher capital cost. Calcination requires relatively low energy, making it possible to use biomass or alternative fuels. This provides significant environmental benefits. Overall, LC³ calcination can be efficiently integrated with moderate investment and operational adjustments, ensuring technical feasibility, cost-effectiveness, and sustainability.

LC³ production and grinding: strategic choices

Grinding LC³ components requires careful attention due to their varying hardness. To optimize operations, clay and limestone are often pre-ground before final blending, reducing under-grinding or coating issues while ensuring consistent quality. Different grinding systems have distinct advantages. Closed-circuit ball mills with recirculation handle LC³ effectively, ensuring proper clinker grinding and uniform mixing. Vertical roller mills (VRMs) can be adapted with minor adjustments and grinding aids, though fine clay particles need careful airflow management. Roller press systems combined with ball mills produce uniform particle sizes and good blending, provided sequencing is correct for clay integration. The choice of grinding system should be evaluated on a case-by-case basis, considering plant layout, production scale, and energy efficiency. Only minor modifications are usually required.

The following examples were shared by the companies involved

Calcined Clay – The Experience of Cementos Argos

Since 2020, Cementos Argos has produced more than 7 million tons of cement incorporating calcined clay as a supplementary cementitious material (SCM) at its Rioclaro plant in Colombia. This facility supplies major urban centers such as Bogotá and Medellín.

The company invested in a dedicated calcined clay production line to expand the plant's cement capacity. Alternative SCMs, such as fly ash and slag, were not locally available, and the construction of a third clinker line was considered a less attractive option, both economically and environmentally. The calcined clay solution not only increased production capacity but also enabled a significant reduction in CO_2 emissions.

At Rioclaro, the plant produces UG (General Use) and HE (High Early Strength) cements in compliance with ASTM C1157. The proportion of calcined clay in each cement type has been optimized to meet market performance requirements while enhancing cost efficiency. As a result, the clinker factor has been reduced by 11.5 and 6.2 percentage points in UG and HE cements, respectively.

These cements are widely used by customers in a broad range of structural applications, confirming not only the technical viability and industrial scalability of calcined clay as a lowcarbon SCM solution, but also the importance of effective management of material variability, process optimization, and knowledge transfer across the value chain. Key challenges such as water demand, color control, and raw clay handling were addressed through continuous improvement, supplier collaboration, and the use of tailored admixtures. Crucially, early and sustained customer engagement enabled product refinement under real construction conditions, strengthening market confidence and positioning calcined clays as a platform for cocreating performance, sustainability, and economic value.

CIMPOR's Journey to Low-Carbon Cement Leadership

CIMPOR Global, part of TCC Group Holdings, represents the group's global vision for innovative and environmentally responsible building material solutions. TCC Group Holdings is a green environmental engineering company dedicated to addressing the complex relation- ship between human civilization and nature. The group focuses on low-carbon building materials, resource recycling, and green energy, positioning itself as an eco-solution provider committed to sustainability and becoming a "Best Earth Helper." With a cement production capacity of 112 million tons, TCC is one of the world's largest international cement producers.

Advancing low-carbon cement

CIMPOR Global is an industrial pioneer in calcined clay technologies, implementing several first-of-a-kind solutions through its proprietary deOHclay technology and know-how. One of CIMPOR's key decarbonization pathways is the reduction of clinker factor using calcined clay. As traditional supplementary cementitious materials such as fly ash and blast furnace slag become increasingly scarce due to industrial decarbonization, the cement industry requires a widely available and scalable alternative. Calcined clay provides this solution. It is globally abundant, low in carbon footprint, and enables significant clinker reduction. Through technologies such as LC^3 (limestone calcined clay cement), blending calcined clay and limestone with clinker can reduce the CO_2 footprint of cement by 40% or more. Building on this concept, CIMPOR has developed deOHclay, a next-generation calcined clay binder that can be produced with less than 100 kg net CO_2 per ton and can replace up to 40% of clinker in cement formulations. As deOHclay has nearly 90% lower CO_2 emissions compared to conventional OPC clinker, its use enables significant cement decarbonization.

From innovation to industrial scale

Key milestones include:

2020
Abidjan (Côte d'Ivoire)

World's first greenfield calcined clay cement facility.

2023
Kribi (Cameroon)

World's first industrial flash calciner for clay.

2026
Souselas (Portugal)

World's biggest flagship calcined clay line. Capacity of 1,500 tons per day.

2026
Ghana (Africa)

Largest flash calciner capacity with 1280 tpd and the latest technology.

By early 2026, CIMPOR aims to reach...

1.5 million
tons/year of **calcined clay capacity**

UP TO 6 million
tons/year of
low-carbon cement

1.2 million
Potential **avoidance** of tons of **CO_2** annually

Activated clay – The experience of the Vicat group

Vicat is a long-standing family-run company founded in 1853 with operations in 12 countries and 16 integrated cement plants with a production capacity of 40 million tonnes of cement per year. The Group ambitions to reach carbon neutrality by 2050 on its full value chain.

Activated clays constitute a fast track to lower-CO_2 cements. Activated clays are widely available, performant, and their impact is proven at industrial scale. The Vicat group has three industrial productions of limestone activated clay cements (also called LC^3): Brazil, France and in the U.S. Different clay activation technologies are used: rotary kiln, flash calciner and the conversion of existing kiln.

Illustration of clay calcination using rotary kiln (left – Ciplan Brazil) and flash calcination (right – Vicat France).

A recent achievement is the certification of the first cement from the production in France. The cement type is a CEM II/C, with a clinker content close to 50%, while the performance class is 52,5 MPa. This is evidence that any standard performance class can be reached with activated clay, allowing higher clinker substitution and lower CO_2 footprint. Once adjusted via different strategies, adequate workability can be achieved. The range of applications of such cements is the same as conventional cements, from small scale working site to massive structures.

Illustration of applications of activated clay cements. Construction site in France with adequate concrete pumpability (left) and the national stadium of Brasilia (right).

Activated clay – The experience of Heidelberg Materials

Heidelberg Materials is one of the world's largest integrated manufacturers of heavy building materials and solutions with leading market positions in cement, aggregates, and ready-mixed concrete. Around 50,000 employees in almost 50 countries shape our growth path. As the industry's frontrunner on the path to Net Zero, Heidelberg Materials has officially committed to reducing its CO_2 emissions to below 400kgCO_2/tonne of cementitious material until 2030. This represents a 47% emission reduction compared to 1990. Additionally, Heidelberg Materials is the first company to offer carbon captured near-zero cement at scale under its evoZero® brand.

One essential lever to achieve Heidelberg Materials' ambitious sustainability targets is to reduce the clinker incorporation rate in cements. For more than 50 years, the construction industry mainly relied on granulated blast furnace slag and fly ashes as substitute for clinker. But the broader industrial transformation toward decarbonisation, combined with an increasing demand for construction materials, requires alternative solutions as well. An interesting opportunity lies in the use of calcined clay. When exposed to a well-controlled thermal process, natural clays of suitable composition develop pozzolanic properties and can successfully replace clinker and other constituents in cement compositions. The advantage of calcined clay is that clays are widely available, allowing local integration of calcined clay towards industrial sovereignty. Heidelberg Materials has already launched the production and integration of calcined clay across several regions, including:

- In NorthWestern France, the Ranville cement plant has been using local clay resources to produce and market limestone calcined clay cements since the end of 2025.
- Building on this momentum, the Benelux region is accelerating its decarbonization with the deployment of several calcined-clay-based cements in 2025. Supported by production at its cement plants in Belgium and the Netherlands, Heidelberg Materials Benelux ensures a controlled and efficient supply chain with a fully local calcined clay production.
- Calcined clay is also a solution in African markets, where clinker is imported due to a lack of local limestone. These regions often have abundant supplies of high-quality clays. One example is the commissioning of the world's largest flash calciner in Ghana in 2025 – as part of a joint venture between Heidelberg Materials and CBI Ghana Ltd. This is an important milestone that underlines Heidelberg Materials' commitment to accelerate decarbonization globally.

World's largest flash calciner (400kT of calcined clay per year), Ghana

Calcined Clay ready to be milled (produced in Ranville cement plant, North of France)

Calcined clay production by Heidelberg Materials Benelux

Holcim's Calcined Clay: Driving Sustainable Construction

Holcim is the leading partner for sustainable construction creating value across the built environment from infrastructure and industry to buildings. Active in 44 attractive markets, we offer high-value end-to-end Building Materials and Building Solutions, from foundations and flooring to roofing and walling. Our ECOPlanet range delivers 100% performance starting at 30% lower CO_2 emissions and is already available in 31 markets.

Calcined clay is a key driver for developing ECOPlanet low-carbon cements. As of 2025, worldwide volumes of calcined clay cement for Holcim reached 1.1 million tons, encompassing 12 products on the market, including LC^3. Holcim's calcined clay-based cements are already in use at construction sites globally. The performance of these cements is comparable to that of conventional cements, and can be utilized across all construction types, including housing and infrastructure, and for various applications like ready-mix and precast concrete.

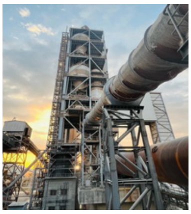
Woha Tower, Cancun, Mexico ECOPact with calcined-clay based cement achieving a 30% CO_2 reduction

Le Clos Saint-Joseph residential development, Orléans, France Calcined clay-based ECOPlanet cement with a 36% CO_2 reduction used for precast concrete

Stade Nautique du Roucas Blanc for 2024 Paris Olympic Games, Marseille, France. ECOPact concrete with a 40% lower CO_2 footprint made from calcined clay-based ECOPlanet cement

Holcim is rapidly expanding global production of calcined clay-based cement, with technology already deployed across Europe and Latin America. Key efforts include Europe's first dedicated line in France, a new facility under construction in the Czech Republic, and completed kiln retrofits in France, Mexico, Ecuador, and Spain, with more scheduled for 2026. The largest of these retrofits is at the Guayaquil, Ecuador plant, which was commissioned in the second half of 2025.

Calcined clay production line at Saint-Pierre-la-Cour, France



Calcined clay production line at Guayaquil, Ecuador

These projects are just the beginning. The shift to calcined clay-based formulations is a fundamental means by which sustainability will drive profitable growth for Holcim, as we fulfil our NextGen Growth 2030 strategy as the leading partner for sustainable construction.

Middle East Calcined Clay – First Calcined Clay factory in the region

Middle East Calcined Clay L.L.C (MECC) is an Omani company established in Sohar - Oman as a joint venture between local Omani individuals (60% ownership) and an international expert in calcined clay technology, Kaolin Group International (40% ownership), who built its first Calcined Clay Plant in South Africa over a decade ago. The company's foundation represents the strategic merger of two development paths. The first was a national initiative to modernize "Omani Sarooj," a traditional building material. Funded by the Ministry of Heritage and Tourism and developed in cooperation with the Industrial Innovation Academy, this project successfully transformed the material from an inconsistently produced, low-quality item made by open-air burning into a standardized, high-quality product. Key outcomes included a patented initial mixture, formal intellectual property registration, and an approved Omani standard specification. MECC was subsequently granted an exclusive license from Ministry of Heritage and Tourism in Oman to commercially manufacture and distribute this heritage product by MECC.

Illustration of MECC Factory in Oman, two production lines, 1st line under commissioning, each line capacity of 120,000 Ton annually, 2nd line expected to be commissioned end 2026

Illustration of Omani Sarooj® packed in 10kg paper bag which is registered trademark owned by Ministry of Heritage & Tourism Oman and licensed to MECC for production and sales.

Simultaneously, global research, notably from institutions like EPFL in Switzerland highlighted the industrial significance of calcined clay as a high-performance pozzolanic material. Its use in cement, particularly in Limestone Calcined Clay Cement (LC^3) formulations, significantly enhances performance while reducing the carbon footprint of production by up to 40% by drastically cutting clinker content to below 50%. The convergence of these two initiatives – heritage product commercialization and green construction material innovation – led to the establishment of the integrated MECC factory in Oman. Financed through a combination of Development Bank funding and foreign investment (60%:40%), the facility features an advanced production chain. The process involves receiving and preparing raw materials, processing them in a dual-stage rotary kiln (for drying and high-temperature calcination 750 to 900°C in a closed system), followed by cooling, storage, and final grinding. From this core calcination process, MECC produces three strategic products: 1) High-Performance Calcined Clay: a premium raw material serving as a local substitute for imported silica fume; 2) Limestone Calcined Clay (LC2): a key blend for producing environmentally friendly "green" cement (LC^3), replacing imported fly ash and GGBS; and 3) Omani Sarooj®: a modernized, quality assured version of the traditional heritage product

Supporting this operation in Mazoon Lab (www.mazoon-lab.com), an in-house, state-of-the-art testing facility equipped with advanced instruments like XRF and XRD analyzers. The lab conducts specialized testing on raw materials, minerals, cement, clinker, concrete and aggregates, functioning both as a quality assurance hub for production and a research and development center. The lab is certified ISO 14001 and ISO 9001.

References and Important Links

References

International Energy Agency (IEA). (2009). *Cement technology roadmap 2009.*

Architecture 2030. *Architecture 2030 initiative.* https://www.architecture2030.org

Global Alliance for Buildings and Construction (GlobalABC). (2017). *Global Status Report 2017: Towards a zero-emission, efficient and resilient buildings and construction sector.* United Nations Environment Programme (UNEP).

EPFL. (2024) *Engineering a more sustainable skyscraper.* https://www.epfl.ch/labs/lmc/engineering-a-more-sustainable-skyscraper/

Hewlett, P., & Liska, M. (Eds.). (2019). *Lea's Chemistry of Cement and Concrete* (5th ed.). Elsevier. Figure (page 6) based on ThyssenKrupp AG.

Avet, F., Snellings, R., Alujas Diaz, A., Ben Haha, M., & Scrivener, K. (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

Chen, Z., Goldscheider, N., Auler, A. S., Bakalowicz, M., Broda, S., Drew, D., Hartmann, J., Jiang, G., Moosdorf, N., Richts, A., Stevanovic, Z., Veni, G., Dumont, A., Aureli, A., Clos, P., & Krombholz, M. (2017). *World Karst Aquifer Map (WHYMAP WOKAM).* BGR, IAH, KIT, UNESCO. https://doi.org/10.25928/b2.21_sfkq-r406

Zunino, F., & Scrivener, K. L. (2020). Processing of calcined clays for applications in cementitious materials: The use of grinding aids and particle classification after grinding. In J. Martirena-Hernandez, A. Alujas-Díaz, & M. Amador-Hernandez (Eds.), *Proceedings of the International Conference of Sustainable Production and Use of Cement and Concrete* (RILEM Bookseries, Vol. 22). Springer. https://doi.org/10.1007/978-3-030-22034-1_11

Scrivener, K., Avet, F., Maraghechi, H., Zunino, F., Ston, J., Hanpongpun, W., & Favier, A. (2019). Impacting factors and properties of limestone calcined clay cements (LC3). *Green Materials*, 7(1), 3–14. https://doi.org/10.1680/jgrma.18.00029

Scrivener, K., Dekeukelaere, A., Avet, F., & Grimmeissen, L. (2019). *Financial attractiveness of LC^3.* LC^3-Project, École Polytechnique Fédérale de Lausanne. https://lc^3.ch/financial-attractiveness-of-lc^3/

Additional links

- https://lc3.ch
- https://cwsc.epfl.ch
- https://gbdi.io
- https://test-tool.calclay.pt

Vienna International Centre
Wagramerstr. 5, P.O. Box 300,
A-1400 Vienna, Austria

☎ +43 1 26026-0

www.unido.org

unido@unido.org

UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION