TOWARD SUSTAINABLE CERAMIC-BASED INFRASTRUCTURE: CALCINED CLAYS, PARTICLE ENGINEERING, AND SANITARY APPLICATIONS

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Abstract: This work explores a multifaceted approach to advancing sustainability in cement and ceramic infrastructure. It examines the potential of calcined clay as clinker substitutes in Portland cement to reduce carbon dioxide (CO_2) emissions, supported by chemical mechanisms and implementation examples like LC3 cement. The role of particle size distribution is discussed in the context of cement hydration, strength development, and grinding energy efficiency. Nanomaterials, such as nano silica, offer novel ways to improve concrete performance while lowering processing energy. Additionally, the report expands into ceramic toilets, covering slip casting-based manufacturing processes, environmental challenges in production, and emerging innovations such as low-temperature firing and self-cleaning coatings. The study consolidates strategies for reducing emissions, energy use, and water consumption in ceramic-based construction materials.

Keywords: Portland cement; calcined clay; CO_2 emissions; ceramics; sustainability.

INTRODUCTION

Concrete is a ceramic matrix composite where both the binder (cement paste) and the reinforcement (aggregates) are ceramic in nature (Carter and Norton, 2013). Portland cement is the second most used material globally, with 4 billion tons produced in 2023 (USGS, 2024). The cement clinker, the main constituent of final cement powder, is produced by calcining limestone and clay in a rotating kiln at around 1400°C (Winter, 2013). This high-energy process also results in high carbon dioxide (CO_2) emissions, accounting for 7% of global industrial emissions (GCCA, 2021), primarily due to the decomposition of calcium carbonate ($CaCO_3$) into calcium oxide (CaO) at around 900°C, releasing approximately 0.6 tons of CO_2 per ton of cement (IEA, 2023).

Addressing this challenge requires a dual strategy: (chemical substation of clinker using reactive, low-emission materials such as calcined kaolinitic clays and (2) physical optimization of cement processing, particularly through particle size control. Beyond these, it is essential to consider the broader implications of ceramic manufacturing in household and infrastructure contexts, as ceramic-based components like sanitaryware also contribute significantly to environmental loads. This paper further includes an interdisciplinary view of sustainability in ceramics by examining the production of sanitaryware like ceramic toilets, which, despite being household essentials, contribute significantly to energy and water usage.

CALCINED CLAYS AS CLINKER SUBSTITUTES

When heated to 600°C, kaolinite ($Al_2Si_2O_5(OH)_4$) undergoes dihydroxylation, losing the hydroxyl group and becoming a semicrystalline material called metakaolin, which brings valuable reactivity when used as pozzolanic material (YESKIS et al. 1985). In the cement matrix, pozzolans react with calcium hydroxide ($Ca(OH)_2$) to form additional calcium silicate hydrate (C-S-H) (Figure 1), the main compound responsible for strength and durability in concrete (MCCARTHY; DYER, 2019).

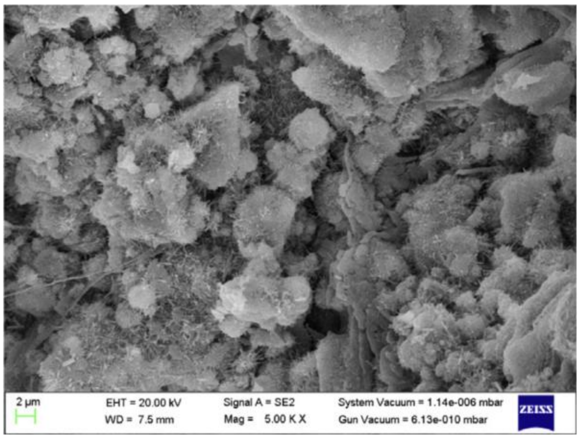

Figure 1 – Calcium silicate hydrate – Responsible for ultimate strength of concrete (Source: Das et al., 2020)

Calcining kaolinite emits less CO_2 than producing clinkers because it requires a lower temperature and does not involve carbonate decomposition which releases carbon dioxide from the raw material, only from fuel combustion. Commercial metakaolin is typically produced from high-purity kaolinite sources under strict process control, making it expensive and more common in high-performance applications like bridges and dams.

Alternatively, lower grade kaolinitic clays with reduced purity offer a more abundant and cost-effective option for widespread construction needs. These clays can be used where moderate performance is acceptable, such as in residential housing in rapidly urbanizing regions like India and China (LC3 Project).

An important application of calcined clay is in Limestone Calcined Clay Cement (LC3) which replaces 30% of Portland cement with calcined clay and 15% with limestone (Figure 2). Developed by Dr. Scrivener’s group at Ecole Polytechnique Fédérale de Lausanne (EPFL), LC3 has been used in pilot housing projects across India and Latin America, achieving up to 98% replacement of Portland cement and saving approximately 15 tons of CO2 per house constructed.

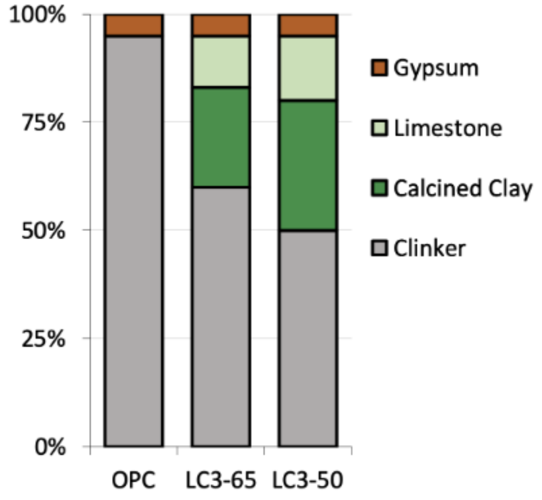

Figure 2 – Benchmark comparison Portland Cement vs. LC3 (Source: LC3 project)

The pozzolanic reactivity of calcined clays not only improves strength but also helps mitigate alkali-silica reactions and enhances long-term durability. When properly sourced and processed, these materials can perform like fly ash, especially in regions with limited industrial by-products. Additionally, calcined clays can offer benefits in terms of chemical resistance, reduced permeability, and compatibility with other supplementary cementitious materials (SCMs).

According to McCarthy and Dyer (2019), the term pozzolan is attributed to materials of natural origin from the Pozzuoli region, while pozzolanic materials refer to those inorganic materials of natural or artificial origin, both being hardened in contact with water and calcium hydroxide. Generally deficient in lime (Ca(OH)2), then the addition for the formation of hydrated calcium silicate (C-S-H) (WINTER, 2012).

According to the Global concrete and Cement Association, 40% of concrete production is dedicated to the residential market. If 20-30% of cement intended for housing projects were replaced by calcined clay, CO_2 emissions could be reduced by 0.12-0.18 tons per ton of cement (based on 0.6-ton CO_2 emitted per ton of cement and reduction due to $CaCO_3$ decomposition alone). This could result in global annual reductions of 480-720 million tons of CO_2 – comparable to removing 104-156 million passenger vehicles from the road, considering that each emits 4.6 tons of carbon dioxide per year (EPA).

Adopting calcined clay-based systems could be particularly beneficial in developing countries, where infrastructure needs are growing rapidly and local low-grade clays are abundant. Clays are formed through the weathering of all types of rocks, which makes them widely available near the surface in different geological settings. They’re mainly composed of silicon and aluminium oxides—two of the most common elements in the Earth's crust. Among the different types, kaolinite-rich clays are the most suitable for cement applications. These typically form in hot and humid environments, which explains their abundance in tropical and subtropical regions. Interestingly, these are also the same areas where cement demand is expected to grow the most in the coming decades (LC3 Project). The map below provides a global overview of geological zones. Clays are predominantly associated with Alfisols (light green) and Ultisols (yellow), highlighting their widespread presence—particularly across India and Southeast Asia (Figure 3).

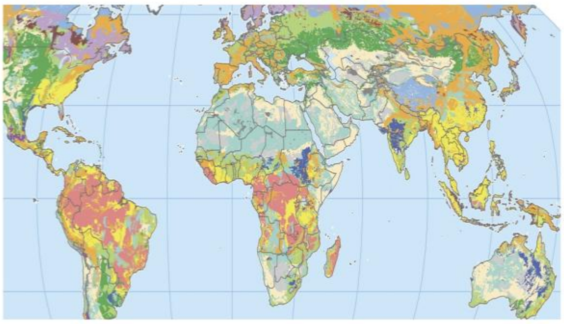

Figure 3 – Global map of available clays (Source: LC3 Project)

Government policies, construction codes, and performance-based specifications will play an important role in accelerating the use of these materials. Educational outreach and pilot-scale demonstrations could help overcome the conservative nature of the construction industry and facilitate widespread adoption of this technology.

PARTICLE SIZE ENGINEERING IN CEMENT PRODUCTION

Particle size distribution (PSD) critically influences cement hydration kinetics, strength development, and workability. ASTM C150 requires a minimum surface area of 260 m²/kg. Finer particles increase surface area, accelerating hydration and early strength gain in cement matrices. However, they also increase water demand, potentially leading to shrinkage or cracking (Mehta and Monteiro, 2006).

Rapid-hardening cement, for instance, is finely ground for higher early strength, while sulphate-resistant cement is coarser to reduce permeability due to high heat release. According to Taylor (1997), optimal PSD tuning is essential to tailor cement properties for specific environments. Particle size design not only affects mechanical properties but also impacts chemical shrinkage, hardening behaviour, and compatibility with admixtures. Even slight changes in particle gradation can influence workability, finishability, and setting time in real-world applications.

The grinding of clinker is energy intensive. Rotary kilns heat raw materials up to 1450°C (Figure 4), and clinker is then ground in multi-chamber ball mills (Figure 5). These processed consume large energy quantities (Winter, 2012).

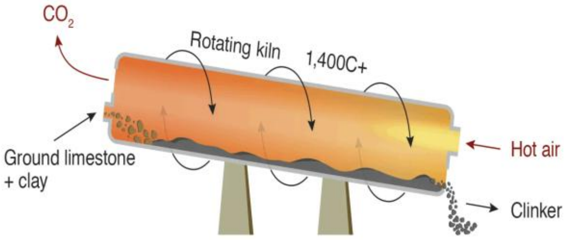

Figure 4 – Rotating Kiln (Source: Carbon Brief, Chatham House)

Figure 5 – Inside of ball mill (Source: Winter, 2012)

The U.S. Energy information Administration reports cement as the most energy-intensive manufacturing sector (EIA, 2024). Reducing this energy demand is a crucial step toward achieving more sustainable cement production.

Increasing the grinding time does not always produce a material with greater fineness, since very fine particles tend to form agglomerates, in addition to requiring larger amounts of water. Therefore, excessively long grindings should be avoided (XU et al., 2015). Therefore, grinding should be carried out at an ideal time, capable of reducing the size of cement particles to an optimized extent.

A promising strategy is the integration of nanomaterials such as nano silica, which improves particle packing and nucleation, enabling better performance at coarser PSDs cement. This reduces the need for fine grinding, lowering energy demands while maintaining strength and durability in the concrete production. Moreover, by reducing porosity and improving microstructure densification, nanomaterials contribute to both mechanical performance and long-term durability, making them an ideal addition for high-performance applications.

Continued research in this area could explore combining various mineral admixtures with optimized particle gradations to develop next-generation blended cements. By tailoring surface chemistry and fineness, it is possible to design cements that are both high-performing and energy efficient. Advances in grinding technologies and predictive modelling tools could also play an important role in optimizing the production of customized particle blends. These strategies could be particularly useful in precast and infrastructure applications where high performance and durability are essential.

CERAMIC TOILETS: MANUFACTURING AND SUSTAINABILITY

The global ceramic toilet market size was valued at approximately USD 5.8 billion in 2023 and is projected to reach USD 8.6 billion by 2032. The sector is driven by increasing housing demand, and sanitation initiatives, especially in developing regions. Leading companies include Toto, Kohler, Roca Group, and American Standard, with China as the largest exporter and the US a major importer.

The production of ceramic toilets follows a structured process designed to ensure durability and quality. It begins with the preparation of raw materials, including kaolin clay, plastic clay, feldspar, and silica, which are mixed with water to create a slurry or slip. Shaping is primarily done through slip casting (Figure 6), where the liquid slip is poured into plaster molds to form the toilet's structure. Excess slip is drained, and the mold is dried. Other methods, such as extrusion for components and high-pressure mold pressing for uniformity, are also employed. After shaping, the pieces undergo drying to remove moisture. A vitreous glaze is then applied, and the toilets are fired at high temperatures in kilns for forty hours, vitrifying the product and creating a stain-resistant finish. Finally, the products are inspected and finished.

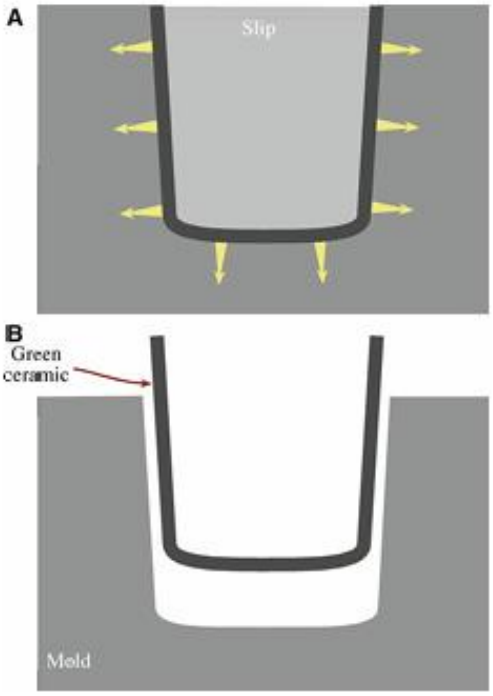

Figure 6 – Slip casting process: (a) Fill mold with slip. Mold extracts liquid, forming compact along the mold's walls. (b) After excess slip is drained, the dried green ceramic is removed. (Source: Carter and Norton, 2013)

To meet industry standards, toilets undergo ASTM C373 (water absorption), ASTM C648 (breaking strength), ASME A112.19.2/CSA B45.1 (flushing performance), and ISO 9001 (quality management). These standards ensure durability, functionality, and consumer safety while promoting industry-wide consistency. The compliance with multiple regional and international norms also facilitates global trade and technological standardization.

However, manufacturing poses environmental challenges: high kiln energy consumption, material waste during slip casting, and limited ceramic recyclability. Low-temperature firing methods and automation may reduce these impacts. Further, new coating based on hydrophobic and antimicrobial materials such as silver nanoparticles are being explored to create self-cleaning surfaces, lowering the need for harsh chemical and excessive flushing (Biolin Scientific; ACS).

These surface technologies use different mechanisms: hydrophobic coatings repel water and dirt; photocatalytic surfaces break down organic matter under UV light, and antimicrobial agents disrupt bacterial growth. The integration of these technologies into ceramic toilets not only improves hygiene but also reduces maintenance, cleaning labour, and chemical usage – extending product lifespan and reducing environmental impact.

Toilets also represent a major source of water use: 30% of household consumption. WaterSense-certified toilets can save up to 50000 liters of water/year per home and 150 billion liters of water in the USA per year if fully adopted in residential and commercial buildings (EPA). Beyond water savings, these products can reduce wastewater treatment loads and help municipalities meet conservation targets. Moreover, pressure-assisted and dual-flush designs are being combined with ceramic innovation to further lower water usage without sacrificing performance.

Advancing sustainability in this area will depend on increased adoption of water-savings designs, recycling of ceramic water, and broader use of smart materials and coatings. Collaboration between manufacturers, policy makers, and researchers is essential to bring these improvements to scale. The ceramic toilet, often overlooked in sustainability conversations, thus becomes a site of innovation intersecting materials engineering, policy, and behaviour change.

DISCUSSION

The ceramic and cement industries play a significant role in modern infrastructure, yet both remain contributors to carbon emission and resource consumption. The convergence of sustainable chemistry, process engineering, and materials science provides a critical opportunity to transform these sectors. The preceding sections demonstrate how calcined clay use, optimization of particle size, and sanitary ceramics innovation offer a coherent strategy for long-term improvements in sustainability.

The incorporation of calcined clays like metakaolin as partial clinker replacements presents a direct reduction in process-based CO_2 emissions. This approach is strengthened by its scalability, local availability of clay materials, and chemical compatibility with existing Portland cement systems. Its inclusion in formulas like LC3 not only enhances environmental performance but also promotes durability through pozzolanic reactions, which refine pore structure and mitigate deleterious reactions in concrete.

Likewise, particle size engineering, though sometimes underestimated in sustainability discussion, emerges as a powerful tool. By balancing the fineness of ground clinker with significant energy savings in grinding operation. Moreover, tailored particle gradations influence early strength development, permeability, and chemical reactivity – all factors critical to life-cycle performance.

Ceramic toilets, though not traditionally linked with infrastructure sustainability, reveal a new frontier when considered through the lens of resource efficiency. By applying advanced surface technologies and refining slip casting and firing processes, manufacturers can reduce energy usage, extend product lifetime, and conserve water. These efforts are amplified when combined with water-saving mechanisms and innovation in hydrophobic and antimicrobial coatings.

Taking them together, these threads illustrate how a holistic view of ceramic and cement-based systems can yield measurable environmental benefits. Governments and international agencies can play a central role in supporting these transitions through updated buildings codes, incentives for low-CO_2 materials, and procurement policies that prioritize life-cycle performance.

CONCLUSION

The path toward sustainable cement and ceramic lies in holistic innovation – adopting reactive clays, refining particle engineering, and transforming high-energy processes into more efficient and environmentally responsible systems. Initiatives like LC3 cement, nano-enhanced mixtures, and water saving sanitary features with durable coatings demonstrate that ceramics can remain central to global development without compromising the environment.

The integration of chemistry, processing control, and

Sustainability science opens up opportunities to rethink materials that have been traditionally high impact. As the demand for affordable housing, sanitation, and infrastructure grows, especially in developing countries, these strategies present a timely and feasible contribution to a lower-carbon future.

Promoting education, technical capacity, and awareness around sustainable ceramic materials will be essential to translate scientific progress into widespread industry practice and benefits to society. Clear policy guidelines, incentives for green certifications, and integration into the academic curriculum can support long-term transformation of the cement and ceramics industries. Additionally, investment in pilot projects, local supply chain development, and interdisciplinary collaborations will enhance feasibility, performance, and scalability of these solutions.

Ultimately, the synergy between research, industry, and policy will define the pace at which sustainable ceramic technologies are adopted globally. With continued innovation, these materials will not only reduce emissions and resource use but also support resilient, equitable infrastructure development worldwide.

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