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SUSTAINABLE USE OF LIME SLUDGE AND METAKAOLIN IN THE CONSTRUCTION INDUSTRY TO STRENGTHEN SUSTAINABLE DEVELOPMENT GOALS (SDGS): A REVIEW

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ABSTRACT

Construction is one of the most resource-intensive industries, requiring massive amounts of raw materials and causing greenhouse gas emissions, waste, and environmental destruction. With growing global pressure to adopt sustainable practices, reusing industrial byproducts like lime sludge and adding supplementary cementitious materials like metakaolin can reduce environmental footprints and improve construction material performance. Lime sludge, a high-calcium industrial waste from pulp and paper, chemical, and water treatment sectors, is volumetric and chemically reactive, making disposal difficult. In contrast, metakaolin, a highly reactive pozzolanic material made from thermally treated kaolinite clay, is suited for cement replacement due to its high surface area, amorphous silica concentration, and calcium hydroxide reactivity. This review study synthesises literature on lime sludge and metakaolin's chemical composition, mechanical behaviour, pozzolanic activity, and environmental effect to examine their synergistic potential in building. The review emphasises their function in compressive strength, permeability reduction, durability, and circular economy. The paper also links these materials to Sustainable Development Goals (SDGs) 9 (Industry, Innovation, and Infrastructure), 11 (Sustainable Cities and Communities), and 12 (Responsible Consumption and Production) to promote eco-efficiency, responsible waste management, and sustainable infrastructure. Discussing economic feasibility, environmental performance, and technical flexibility highlights their practical consequences for large-scale adoption. The review concludes by identifying challenges like material quality variability, lack of standardised guidelines, and awareness barriers and suggesting future research and policy development to mainstream these materials into sustainable construction practises.

Keywords: Lime Sludge, Metakaolin, Sustainable Construction, Supplementary Cementitious Materials, Circular Economy, Pozzolanic Reaction, SDGS, Industrial Waste Reuse, Green Concrete, Environmental Impact

1. INTRODUCTION

The building sector has been under fire for its unsustainable use of natural resources and environmental damage in recent decades. Traditional construction techniques, especially Portland cement manufacture, contribute to 8% of global CO_2 emissions, worsening climate change and straining ecosystems. The industry has been exploring ways to minimise carbon footprints and reuse industrial waste in response to environmental concerns and the push for sustainable growth. SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 12 (Responsible Consumption and Production) emphasise the need for innovative, eco-friendly materials that reduce environmental impact and support infrastructure growth. In this context, lime sludge and metakaolin are viable cement substitutes for concrete. Calcium carbonate-rich lime sludge, a byproduct of paper, chemical, and water treatment, is routinely dumped in landfills, posing environmental and health risks. Reusing it in construction is a sustainable industrial waste management strategy. Metakaolin, a pozzolanic substance made by thermally activating kaolinite clay, reacts well with calcium hydroxide and is a useful supplemental cementitious material. Both compounds improve concrete performance, including compressive strength, permeability, and chemical resistance, when used alone or together. This paper reviews the literature on lime sludge and metakaolin's physical, chemical, mechanical, and environmental qualities for construction applications. It also examines how these materials can reduce virgin raw material use and divert industrial waste from disposal to promote sustainable development. The paper also highlights material heterogeneity, lack of standard norms, and restricted field applications as research and implementation barriers and suggests future research topics. This study emphasises the need to use alternative materials like lime sludge and metakaolin in construction to create more sustainable, durable, and environmentally friendly buildings.

2. LIME SLUDGE: PROPERTIES AND USE IN CONSTRUCTION

Due to its bulk and chemical nature, lime sludge from industrial processes is a major environmental issue. Mostly produced in businesses using lime (CaO) or hydrated lime ($Ca(OH)_2$) for neutralisation, pH control, or clarifying. The pulp and paper industry, where lime is used in softening and coagulation, water treatment plants, and chemical manufacturers, particularly in alkali production and refining, are major contributors. Lime sludge is alkaline and usually contains more than 80% calcium carbonate, depending on its origin. It may contain trace amounts of magnesium oxide, silica, alumina, and trace metals. Before usage in construction, it must be dewatered or dried because it is semi-solid or sludge-like. Due of its high calcium content, lime sludge may be used in construction, especially in cementitious reactions. Lime sludge's calcium can engage in pozzolanic reactions with siliceous materials like fly ash, blast furnace slag, or metakaolin to generate calcium silicate hydrate (C-S-H) gels, which are essential for concrete strength. This enhances composite material structural performance and reduces Portland cement use, adding to sustainability goals. Lime sludge has several civil and geotechnical engineering uses. Early and popular uses include soil stabilisation, especially for clayey or expansive soils. Calcium ions flocculate tiny particles, increase bearing capacity, and raise the California Bearing Ratio (CBR), making treated soils better for foundations and subgrades. Several studies show that lime sludge-treated soils have increased shear strength, lower plasticity index, and cyclic loading durability. Lime sludge can replace 5% to 15% of cement in concrete. It improves compressive strength, permeability, and sulphate resistance at optimal doses. Replacement above acceptable levels may dilute cementitious phases, reducing strength. Lime sludge can also be used to bind and fill bricks and masonry blocks. This is useful for rural homes and non-load-bearing applications. It has also been used to stabilise sub-base layers in pavement construction, improving load-bearing and reducing deformation.

Figure 1

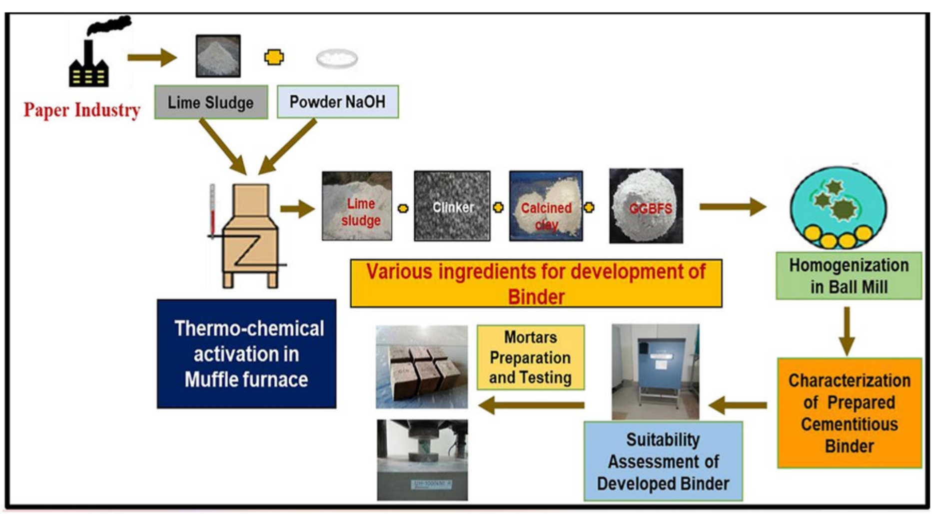

Figure1 Flowchart for Utilization of Lime Sludge in Construction

Source Prabhat Vashistha et al., "Valorization of paper mill lime sludge via application in building construction materials: A review," Construction and Building Materials, 2019.

Since lime sludge and other pozzolanic or industrial byproducts like fly ash or metakaolin boost strength and durability, their utilisation has garnered interest. These blended systems provide a circular construction economy and efficiently use trash. Reusing lime sludge reduces landfill disposal, conserves limestone, reduces cement production carbon emissions, and improves construction material life-cycle performance. Its usage is limited by chemical composition diversity, preprocessing, and lack of standardisation. Strong characterisation, quality control, and legislative incentives can make lime sludge a mainstream construction material, supporting environmental sustainability and cost efficiency.

3. LITERATURE REVIEW

Author(s) & Year	Focus Area	Key Findings	Relevance to Study
Siddique, R. (2008)	Waste materials in concrete	Comprehensive review of various industrial wastes including lime sludge and fly ash in cementitious applications. Highlights strength and durability improvements.	Validates lime sludge as a viable SCM; encourages industrial waste utilization.
Sabir, B. B., Wild, S., & Bai, J. (2001)	Metakaolin and pozzolanic materials	Demonstrates the pozzolanic activity of metakaolin; improves early strength, permeability, and ASR resistance.	Supports the use of metakaolin for high-performance concrete and cement replacement.
Kumar, M., & Singh, B. (2019)	Lime sludge and fly ash in construction	Field and lab analysis show positive effects of blended lime sludge and fly ash on compressive strength and workability.	Supports combined use of lime sludge with other SCMs for sustainable construction.
BIS (2020)	IS 456: Code for Plain and Reinforced Concrete	Establishes guidelines for cement content, mix design, durability criteria, and use of SCMs.	Serves as the regulatory framework for incorporating alternative materials in concrete.
Laveglia & Laveglia (2013.)	Net-zero and carbon-negative transformations in lime-based construction materials	Demonstrated feasibility of net-zero and carbon-negative outcomes in lime-based masonry through advanced life-cycle assessment, circular economy integration, eco-friendly energy sources, and innovative kiln technologies; positioned CO_2 as a valuable resource for sustainable products within the 2050 European Action Plan.	Provides a strategic framework for decarbonizing lime-based materials, aligning with sustainability and carbon reduction goals relevant to eco-friendly construction.
Carlito Tabelin, Kyoungkeun Yoo & Jining Li (2013)	Sustainable mine tailings and acid mine drainage management	Highlighted climate change impacts from high atmospheric CO_2, N_2O, and CH_4 levels; emphasized the need for innovative mine waste management to mitigate environmental damage.	Offers insights into reducing industrial environmental impacts, complementing waste valorization approaches in construction.
Johnson, Napiah & Kamaruddin (2014)	Use of waste sludge in construction	Reviewed global attempts to recycle sludge from various plants into sustainable construction materials; assessed mechanical, physical, and environmental impacts, with recommendations for future research.	Supports circular economy in construction by exploring waste-to-resource conversion, reducing landfill and pollution.
Ayobami Busari (2020)	Subgrade stabilization using rice husk ash (RHA) and cement kiln dust (CKD)	Found CKD and RHA-based geopolymer improved soil mechanical strength; CKD alone performed best; optimum mix reduced pavement thickness and cost, saving ~$60,000; aligned with SDGs 9, 11, and 12.	Demonstrates economic and performance benefits of agricultural and industrial waste in geotechnical applications.
Habibi et al. (2020)	Recycled aggregate concrete with GGBFS and silica fume	Using RSM, optimized RAC mixes with GGBFS and SF improved mechanical and durability properties while addressing environmental issues of cement production; RA reduced early-age durability but had no effect at 90 days.	Provides a data-driven optimization approach for sustainable concrete incorporating industrial by-products.
Martins et al. (2021)	Use of medium/highly sulfidic mine tailings in construction	Reviewed technical and environmental barriers to using sulfidic tailings; identified calcium sulfoaluminate cement production as a promising valorization route.	Explores alternative raw material sources for low-CO_2 cements, relevant to sustainable binder development.

Muralidharan Raghav et al. (2021)	SCMs and chemical additives in hydraulic concrete	Summarized benefits of FA, GGBS, RHA, SBA, SF, and TDFA in enhancing strength and durability; highlighted roles of chemical additives in corrosion resistance and novel concrete types.	Broadens scope of sustainable material use in concrete, supporting waste valorization and performance improvement.
Muhammad M. Sadiq et al. (2021)	Ultra-high-performance cementitious composites with carbon-based nanomaterials	Functionalized carbon nanomaterials (<0.1% wt.) significantly enhanced UHPCM flexural strength, ductility, moisture resistance, and abrasion resistance at viable costs.	Shows potential for advanced material technology integration to improve performance and sustainability in cementitious systems.

4. SUSTAINABILITY ASPECTS AND SDG ALIGNMENT

The integration of lime sludge and metakaolin into construction practices presents a multidimensional opportunity to align the industry with the United Nations Sustainable Development Goals (SDGs). These materials not only serve as effective alternatives to traditional cement but also embody the principles of circular economy and green innovation. Their application addresses environmental, social, and economic dimensions of sustainability, making them highly relevant to several key SDGs.

The table below summarizes the primary contributions of lime sludge and metakaolin to selected SDGs:

Sustainable Development Goal (SDG)	Contribution from Lime Sludge and Metakaolin
SDG 9: Industry, Innovation, and Infrastructure	Use of innovative, high-performance, and locally available alternative materials
SDG 11: Sustainable Cities and Communities	Eco-friendly construction materials for resilient and low-impact urban development
SDG 12: Responsible Consumption and Production	Waste utilization, reduced extraction of virgin resources, industrial symbiosis
SDG 13: Climate Action	Reduced CO_2 emissions through partial cement replacement and low-energy processes
SDG 6: Clean Water and Sanitation	Beneficial reuse of water treatment by-products, reducing pollution and waste

Metakaolin and lime sludge promote material innovation and infrastructure resilience, supporting SDG 9. These compounds, especially when combined, increase compressive strength, reduce permeability, and lengthen concrete structural life, making infrastructure more sustainable. Partial cement replacement with these materials minimises energy-intensive clinker manufacture, a major source of industrial CO_2 emissions, supporting SDG 13: Climate Action. A 15–20% cement replacement with metakaolin reduces embodied carbon by 10–20%, according to studies.

Both items demonstrate resource circularity and industrial symbiosis for SDG 12. Construction reuses lime sludge, which is frequently dumped, minimising waste and environmental impact. Compared to clinker, metakaolin, made from natural kaolinite, consumes less thermal energy and produces less CO_2 from carbonate decomposition, making it a cleaner choice.

According to SDG 11, using eco-materials in urban infrastructure including pavements, masonry blocks, and concrete parts helps create greener, more environmentally friendly cities. Reusing water treatment sludge reduces waste and improves water sector sustainability, supporting SDG 6.

Lime sludge and metakaolin in building show how material innovation can assist global sustainability by reducing virgin limestone use, industrial waste, and greenhouse gas emissions. Standardisation, incentives, and construction stakeholder knowledge are needed for mainstream adoption.

5. PERFORMANCE ANALYSIS: MECHANICAL AND DURABILITY PROPERTIES

The integration of lime sludge and metakaolin into concrete and mortar systems has demonstrated significant improvements in both mechanical strength and long-term durability. Numerous experimental studies have validated their potential as supplementary cementitious materials, either individually or in combination. The performance enhancements are largely attributed to their chemical reactivity, filler effect, and the refinement of the concrete microstructure, which together contribute to better engineering properties and environmental resilience of the composite material.

Figure 2

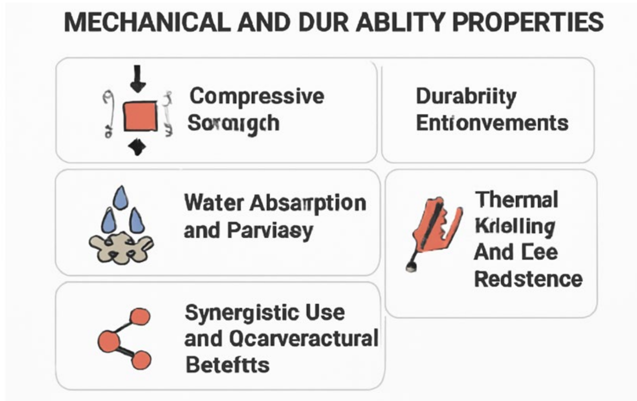

Figure 2 Mechanical and Durability Properties

5.1. COMPRESSIVE STRENGTH

One of the most widely reported benefits is the increase in compressive strength, particularly when metakaolin is used as a partial cement replacement. Studies have consistently shown that replacing 10–15% of ordinary Portland cement (OPC) with metakaolin results in a **10–20% improvement** in compressive strength over control concrete. This enhancement is attributed to the high pozzolanic activity of metakaolin, which reacts with calcium hydroxide (CH) produced during cement hydration to form additional calcium silicate hydrate (C-S-H), a primary binder that densifies the matrix. When lime sludge is used along with metakaolin, the calcium-rich sludge activates the latent pozzolanicity of metakaolin more effectively, further accelerating early-age strength development. However, lime sludge alone shows mixed results; while it can marginally contribute to early strength due to its high calcium content, excessive dosages may lead to strength dilution unless optimized with other reactive components.

5.2. DURABILITY ENHANCEMENTS

Durability is a critical parameter for sustainable construction, especially in aggressive environmental conditions. The inclusion of metakaolin improves resistance to **acid attack**, **sulfate exposure**, and **chloride ingress**, owing to its ability to reduce free CH and refine the pore structure. The denser microstructure reduces the pathways for moisture and ions, thereby limiting degradation mechanisms. Lime sludge, when finely processed and used in optimal proportions, also contributes to pore refinement and chemical resistance, especially when combined with other pozzolanic materials. The blended use of both metakaolin and lime sludge has been found to increase resistance to **alkali-silica reaction (ASR)**, a major cause of concrete deterioration in reactive aggregate environments.

5.3. WATER ABSORPTION AND POROSITY

Concrete mixes incorporating metakaolin typically exhibit **reduced water absorption and capillary porosity**, leading to enhanced waterproofing characteristics. This is primarily due to the packing effect of ultrafine metakaolin particles and the increased formation of secondary C-S-H, which fills the voids within the matrix. Lime sludge, when adequately ground, also functions as a filler, helping to reduce the overall porosity. Lower porosity contributes not only to improved durability but also to better thermal insulation performance in certain applications.

5.4. THERMAL STABILITY AND FIRE RESISTANCE

The presence of metakaolin enhances the **thermal resistance** of concrete, making it more stable under high-temperature conditions. This is due to the ceramic nature of metakaolin and the reduction in CH, which decomposes under heat and weakens conventional OPC concrete. Studies have noted improved **residual strength retention** after exposure to elevated temperatures (600–800°C) in metakaolin-modified mixes. Although limited literature is available on the thermal performance of lime sludge-based systems, its high calcium carbonate content can act as a thermal buffer up to certain temperature thresholds.

5.5. SYNERGISTIC USE AND MICROSTRUCTURAL BENEFITS

The synergy between lime sludge and metakaolin could lead to enhanced cementitious composites. Metakaolin provides reactive silica and alumina, whereas lime sludge provides calcium. Their combination enhances pozzolanic reactions, binder efficiency, and microstructure compactness and chemical stability. Recent SEM and XRD measurements show denser C-S-H networks and lower portlandite content in mixed systems.
In conclusion, optimising lime sludge and metakaolin use, alone or together, improves concrete mechanical and durability. These improvements lengthen concrete structure life, reduce resource use, reduce maintenance, and improve environmental resilience.

6. ENVIRONMENTAL IMPACT

The environmental effects of using lime sludge and metakaolin in construction materials are important for sustainable development and carbon reduction. Lime sludge accumulation and disposal are major challenges. Large amounts of untreated lime sludge from pulp and paper, water treatment, and chemical manufacturing factories are thrown in landfills, degrading land, contaminating groundwater, and causing odours. Limesludge can be utilised as a supplemental cementitious material (SCM) in concrete or mortar, decreasing landfill congestion and environmental risks. Its high calcium carbonate concentration makes it a good binder or filler for cementitious composites, helping waste valorisation and circular economy.

Metakaolin, made from plentiful kaolinite clay, is a low-carbon Portland cement substitute. In contrast to clinker manufacturing, metakaolin is made at 650-800°C without emitting CO_2 via carbonate decomposition, which occurs at temperatures above 1400°C. Metakaolin may be found locally in many areas, reducing long-distance transportation and construction material embodied energy. LCA studies show that replacing 15-20% cement with metakaolin can reduce CO_2 emissions by 10-25%, depending on base mix, curing conditions, and transport variables. Lime sludge and metakaolin in blended cement formulas reduce waste and increase energy efficiency.
Metakaolin- and lime sludge-based concretes' resistance to chloride ingress, acid attack, and thermal damage extends infrastructure service life and reduces maintenance. This helps sustainability by lowering the frequency of repairs and material use across the duration of developed assets, reducing the environmental effect of construction operations.

7. ENVIRONMENTAL AND ECONOMIC ASSESSMENT

Figure 3

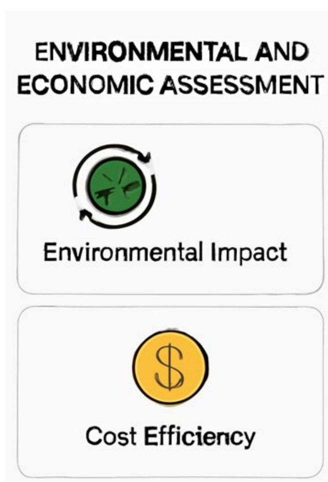

Figure 3 Environmental and Economic Assessment of Lime Sludge and Metakaolin in Construction Materials

8. COST EFFICIENCY

Economic viability is as essential as environmental concerns in determining lime sludge and metakaolin usage in building. Construction firms can often get lime sludge for free from industrial plants looking for cost-effective disposal. While drying and grinding may entail modest expenditures, lime sludge is much cheaper than virgin materials, making it an economical SCM alternative for low-cost housing and rural infrastructure projects. However, metakaolin costs more than cement or other SCMs like fly ash. Calcination energy and production quality control make this necessary. However, metakaolin improves concrete matrix performance by increasing early and long-term strength, reducing permeability, and increasing chemical durability. Marine buildings, bridges, and water tanks are significantly affected by these benefits, which reduce lifecycle costs. Metakaolin-enhanced concrete pays up in longer service life and less maintenance.

Several industrial-scale pilot investigations and field testing have shown that lime sludge-metakaolin blended systems are economically viable. These investigations show increased material performance and cost–benefit outcomes over structure lifetimes. As sustainability becomes a legislative and economic requirement, green construction materials' market value will rise, making them more financially desirable.

Overall, lime sludge and metakaolin provide a strong argument for environmental sustainability and economic viability. These materials can be scaled up in construction to minimise costs, emissions, and resource dependency with proper processing, mix optimisation, and regulatory support.

CONFLICT OF INTERESTS

None.

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