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INFLUENCE OF METAKAOLIN AND LIME SLUDGE ON RHEOLOGY, MECHANICAL PROPERTIES OF CONCRETE AND ITS SUSTAINABILITY ANALYSIS: A REVIEW

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ABSTRACT

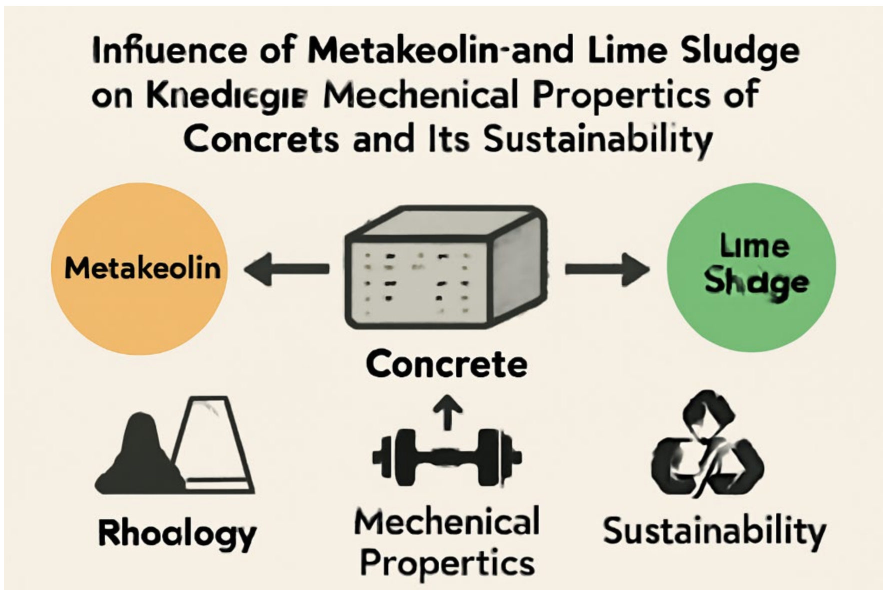
Researchers are exploring alternate cementitious materials to augment or partially replace Portland cement due to the increased need for sustainable infrastructure development and the push to minimise construction sector carbon emissions. Metakaolin, a highly reactive pozzolanic derivative of kaolin clay, and industrial lime sludge, a calcium-rich waste byproduct from paper, sugar, and water treatment industries, seem promising. This review study critically analyses and synthesises literature on metakaolin and lime sludge's impacts on concrete's rheology, mechanical performance, and sustainability. Metakaolin, with its high silica and alumina content, improves early strength gain, reduces permeability, and refines concrete microstructure through secondary pozzolanic reactions, while lime sludge, when used wisely, fills the concrete and helps develop long-term strength while reducing waste and cost. These compounds improve concrete's workability, viscosity, and flowability as well as its compressive, flexural, and split tensile strengths under conventional and aggressive exposure circumstances. Due to their pore-refining properties, these materials reduce chloride penetration, increase acid and sulphate resistance, and reduce shrinkage and cracking in concrete. Microstructural investigations like SEM, XRD, and TGA reveal that lime sludge and metakaolin interact with hydration products like CSH and CAH gels to densify the matrix and improve performance. On the sustainability front, lime sludge diverts a lot of industrial waste from landfills, while metakaolin lowers cement clinker, reducing carbon dioxide emissions by 25% or more depending on the replacement ratio. Cost-efficiency is crucial, especially in poor countries where lime sludge is abundant and cheap. Thus, improved concrete mixes are technically superior, economically viable, and environmentally friendly for large-scale infrastructure projects.

Keywords: Metakaolin, Lime Sludge, Rheology, Mechanical Properties, Concrete Durability, Sustainable Construction, Supplementary Cementitious Materials (SCMS), Carbon Footprint, Waste Utilization, Pozzolanic Reaction

1. AN INTRODUCTION

Concrete is the most frequently used construction material due to its versatility, durability, and availability of constituent resources, however its production, especially OPC production, faces major environmental issues. Cement production accounts for about 8% of global carbon dioxide emissions, mostly from limestone calcination and fossil fuel burning, putting great pressure on the industry to adopt more sustainable methods. As urbanisation and infrastructure development increase worldwide, concrete consumption rises, making ecologically friendly construction methods essential. Given this, researchers, legislators, and industry stakeholders are focussing on incorporating sustainable and green elements into concrete mix design. These materials strive to lessen concrete's environmental impact by substituting or supplementing cement while preserving or improving performance. Supplementary Cementitious Materials (SCMs) are a realistic and well-researched eco-friendly option. Finely split SCMs have pozzolanic or latent hydraulic capabilities and react with calcium hydroxide in water to generate cementitious compounds. SCMs include fly ash, silica fume, ground granulated blast furnace slag, metakaolin, and lime sludge. These materials reduce cement content and improve concrete's strength, durability, chemical resistance, and long-term performance. Metakaolin, a highly reactive pozzolan made by calcining kaolin clay, improves early compressive strength, reduces permeability, and resists alkali-silica reaction and sulphate attack. However, calcium-rich lime sludge, produced in vast amounts by paper, sugar, and water treatment plants, has showed promise as a low-cost filler and binder extender. It helps manage solid waste and makes concrete cheaper and greener. Metakaolin and lime sludge as SCMs in concrete support circular economy, sustainability, and resource efficiency. This review examines how metakaolin and lime sludge affect concrete's rheology, mechanical performance, and environmental advantages. It critically assesses these materials as cement alternatives and their potential to cut carbon emissions, increase durability, and optimise resource use to support sustainable development. This study synthesises global research to demonstrate SCMs' revolutionary potential, especially in developing nations where material availability and affordability are key to sustainable infrastructure development. It also highlights the necessity for more study on standardising usage standards and understanding the long-term performance of modified concrete systems in real-world applications.

Figure 1 Influence of Metakaolin and Lime Sludge on Rheology, Mechanical Properties of Concrete, and Its Sustainability



2. REVIEW OF LITERATURE

Author(s) & Year	Title	Focus Area	Key Findings
Baker & Alexander (2019)	Use of Metakaolin as SCM in Concrete: Focus on Durability	Durability enhancement using metakaolin	MK reduces penetrability, improves ASR mitigation and carbonation resistance
Safiddine et al. (2021)	Effect of Quarry Waste Limestone Filler on Rheological Behavior	Limestone filler as rheology modifier	LF raises viscosity, affects flow depending on dosage
Sabir et al. (2001)	Metakaolin and pozzolanic materials	Metakaolin	Pozzolanic behavior, durability
Ahmed et al. (2021)	Compressive Strength of Sustainable Geopolymer Concrete Composites	Fly ash, Metakaolin, GGBFS	Compressive strength, mix design
UNDP (2023)	Sustainable Development Goals Report	General SDG-related materials	Sustainability context

BIS (2020)	IS 456: Code of Practice for Plain and Reinforced Concrete	Concrete standards	Design and construction norms
Siddique (2008)	Waste materials and by-products in concrete	Lime sludge, Fly ash, Metakaolin	Use of industrial by-products
G. Saravanan et al., 2013	Flyash Based Geopolymer Concrete – A State of the Art Review	geopolymer concrete ingredients and technology; assessed fly ash utilization for CO_2 reduction and waste management.	Geopolymer concrete using fly ash can reduce OPC consumption, cut CO_2 emissions, and utilize industrial waste; shows potential as an eco-friendly binder.
R. Kalaignan & S. Siva Murthy Reddy, 2016	Impact of Metakaolin on the Properties of Concrete: A Literature Review	metakaolin as partial cement replacement in mortar and concrete; examined waste utilization and hazardous waste containment.	Metakaolin improves pore structure, increases resistance to harmful solutions, and enhances durability of concrete.
Suzan S. Ibrahim et al., 2018	Metakaolin as an Active Pozzolan for Cement That Improves Its Properties and Reduces Its Pollution Hazard	Prepared metakaolin by calcining kaolin at 750°C for 5 hrs; OPC replaced with 5%, 10%, 15% metakaolin; tested compressive strength, hydration kinetics, DSC, XRD, SEM over 1–28 days.	OPC-MK10 blend showed highest strength at all ages; reduced free CaO content; denser microstructure; increased C-S-H and C-A-S-H formation; improved overall durability.
Ayobami Busari & Joseph Akinmusuru, 2019	Strength and Durability Properties of Concrete Using Metakaolin as a Sustainable Material: Review of Literatures	mechanical strength, durability, cost-effectiveness, and sustainability aspects of metakaolin use in concrete.	Metakaolin increases strength by 10–20%, improves durability, reduces production cost; however, it decreases workability and increases heat of hydration.
Chandak & Pawade, 2020	Influence of Metakaolin in Concrete Mixture: A Review	Compilation of studies on various cementitious additives (fly ash, silica fume, metakaolin, slag); comparison of their effects.	Metakaolin improves various strengths and durability of concrete; gaining importance in modern concrete technology.

Vishojit Bahadur Thapa, 2020	Performance of Lime-Metakaolin Pastes Using Gravel Wash Mud (GWM)	Varied mixture proportions; tested raw materials and hardened pastes using PSD, XRF, XRD, compressive strength, STA, SEM; assessed reaction kinetics and microstructure.	Calcined GWM at 850°C enhanced compressive strength up to 18 MPa; hydrated lime-based pastes performed better than hydraulic lime-based ones.

3. BACKGROUND ON GLOBAL CEMENT USAGE AND ENVIRONMENTAL CONCERNS

Driving rapid urbanisation and population increase, the construction sector is one of the greatest consumers of natural resources and energy worldwide, with cement production being one of its most environmentally harmful components. Modern structures, bridges, dams, and roads are built with cement, a crucial constituent in concrete, produced in over 150 nations. However, it has major environmental impacts. The global cement industry accounts for 8% of anthropogenic carbon dioxide emissions, mostly from clinker calcination and high-temperature fossil fuel burning in kilns. Cement making uses a lot of limestone, clay, and other raw materials, degrading land and depleting natural resources. As worldwide concrete demand rises, especially in rising nations in Asia, Africa, and Latin America, worries about unsustainable resource exploitation, ecological footprint, and greenhouse gas emissions grow. The IPCC and other environmental groups have regularly targeted the cement industry for carbon reduction. The energy-intensive nature of cement manufacture complicates matters with shifting fuel prices and worldwide Paris Agreement commitments. Cement facilities release large amounts of NOx, SO_2, and particulate matter, worsening air pollution and public health risks. Traditional concrete has a high embodied energy, requiring a lot of energy for extraction, processing, shipping, and application, making it unsustainable unless other methods are used. Scientists, engineers, and policymakers are working to decarbonise the cement industry through technological innovation, process optimisation, renewable energy, and clinker-reducing materials as climate change mitigation becomes a global priority. Development and deployment of low-carbon cement alternatives, waste material utilisation, and SCM inclusion are promising. These methods attempt to reduce CO_2 emissions and enhance cementitious product performance and durability. Many countries have implemented carbon pricing and green procurement rules, increasing environmental, regulatory, and economic pressure to find alternatives. Thus, worldwide construction techniques are changing, and cement usage is being reassessed for lifetime and sustainability. Understanding cement production's environmental impacts is crucial to encouraging prudent infrastructure development. Green chemistry, circular economy principles, and waste valorisation must be integrated with concrete technology for sustainable urban expansion. Therefore, we must reassess conventional cement usage and develop new methods to reduce its environmental impact and meet future infrastructure needs.

4. IMPORTANCE OF SUSTAINABLE AND GREEN MATERIALS IN CONSTRUCTION

As the global population reaches 9 billion and urban expansion continues at an unprecedented rate, the construction sector is challenged to build faster, more efficiently, and sustainably. Traditional construction practices, which employ non-renewable resources like cement, sand, gravel, and steel, have caused deforestation, biodiversity loss, greenhouse gas emissions, and water pollution. These negative effects highlight the urgent need to switch to sustainable and green construction materials that reduce environmental impact, conserve energy and resources, and promote ecological equilibrium. By improving indoor air quality, resource utilisation, energy efficiency, and waste reduction, green construction materials lessen the built environment's impact on human health and nature. Bamboo, recycled aggregates, fly ash, blast furnace slag, silica fume, metakaolin, rice husk ash, lime sludge, and geopolymer-based binders are examples. These options lessen dependence on virgin resources and reuse industrial waste that would pollute the environment. Sustainable construction materials also support the UN Sustainable Development Goals (SDGs), particularly Goal 11 (Sustainable Cities and Communities), Goal 12 (Responsible Consumption and Production), and Goal 13 (Climate Action). Concrete, a common construction material, offers many sustainability potential. Green materials increase mechanical and durability, reduce cement use, and cut carbon emissions in concrete mixes. Sustainable construction approaches also improve thermal efficiency, life-cycle costs, and resilience to climatic disasters like floods and heatwaves. Green certifications like LEED, BREEAM, and GRIHA, which emphasise eco-friendly materials, are becoming more important to architects, engineers, and developers. Governments worldwide are also promoting green development with tax subsidies, green building rules, and waste reduction mandates. Prefabricated and modular construction techniques have increased material economy and reduced on-site waste.

Figure 2 Sustainable and Green Materials in Construction: Benefits and Impact on the Built Environment

Source Adapted from various industry reports and visualized concepts related to sustainable construction practices (BigRentz, Claris Design Build).

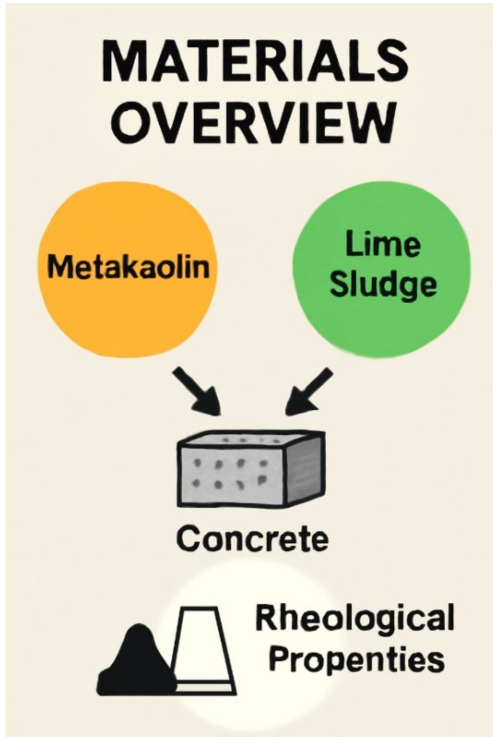
Although breakthroughs have been made, high initial costs, low knowledge, material quality heterogeneity, and lack of standardised codes still prevent widespread usage. However, continual innovation, rigorous testing, stakeholder collaboration, and supporting policy frameworks can expedite green material incorporation into mainstream building. In the long run, using sustainable materials is ethical, economic, and environmental. By using low-impact, renewable, and recycled materials, the construction industry can reduce its carbon footprint, promote circular economy principles, and meet current and future infrastructure needs without harming the environment.

5. SCOPE OF SUPPLEMENTARY CEMENTITIOUS MATERIALS (SCMS)

Sustainable concrete technology relies on Supplementary Cementitious Materials (SCMs) to improve concrete performance and reduce cement production's environmental impact. Finely split SCMs can be naturally or industrially created and have pozzolanic or latent hydraulic activity. SCMs react with calcium hydroxide produced during cement hydration to form calcium-silicate-hydrate (C-S-H), which strengthens and prolongs concrete. SCMs reduce clinker and carbon dioxide emissions by partially replacing Portland cement (OPC). This substitution technique supports global sustainability goals and construction sector efforts to reduce infrastructure's environmental impact. SCMs include fly ash, GGBS, silica fume, rice husk ash, metakaolin, volcanic ash, and industrial lime sludge. Fly ash improves workability and long-term strength, GGBS reduces heat of hydration and sulphate resistance, silica fume increases strength and impermeability, metakaolin improves early strength and chemical resistance, and lime sludge uses waste to benefit the environment and economy. SCMs allow engineers and material scientists to customise concrete compositions for structural, durability, and environmental performance in various applications. They also help make high-performance concrete (HPC), self-compacting concrete (SCC), and durable constructions in harsh environments. In instance, ternary or quaternary SCM blends can optimise concrete's mechanical and sustainability. Circular economy concepts have extended SCMs by encouraging industrial by-products and agro-waste to be reused as building materials. SEM, XRD, and TGA have improved material characterisation, revealing more about SCM-based concretes' hydration behaviour and microstructural evolution. SCMs have several benefits, but material quality, standards, transportation constraints, and regional availability affect their widespread implementation. Optimising mix designs, standardising testing methodologies, and measuring long-term performance under real-world situations are continuing research topics. Modern digital tools and machine learning are being utilised to forecast appropriate SCM proportions and performance outcomes, expanding the breadth and usefulness of these materials. As the building sector becomes more sustainable, SCMs' significance in lowering cement usage, improving concrete qualities, and minimising environmental effect grows. They reduce concrete's carbon footprint while addressing modern infrastructure's structural and functional needs in a realistic and scalable way.

6. MATERIALS OVERVIEW

Figure 3 Materials Overview: Metakaolin, Lime Sludge, and Rheological Properties of Concrete



Source Adapted from the research on sustainable concrete materials and their impact on concrete properties.

Metakaolin

Metakaolin, a highly reactive pozzolanic material, is made by calcining kaolinite clay, an alumina-silica mineral. Heating purified kaolin clay between 650°C and 850°C removes the hydroxyl ions from the kaolinite structure, creating an amorphous, disordered aluminosilicate structure with high surface area and reactivity. Thermal activation creates a cementitious material with excellent pozzolanic properties but no crystalline phases. Chemically, metakaolin contains high amounts of silica (SiO_2) and alumina (Al_2O_3), typically 45-55% and 35-40%, respectively. This fine, off-white powder has a particle size finer than cement, contributing to its filler effect and high reactivity. Its specific surface area and pozzolanic activity index are higher than fly ash, so it can modify concrete properties at low replacement levels (5–15% by weight of cement). The pozzolanic properties of metakaolin allow it to react with calcium hydroxide ($Ca(OH)_2$), a byproduct of cement hydration, to form C-S-H and C-A-H gels. These additional hydration products fill voids, reduce porosity, and improve the cement paste-aggregate interfacial transition zone (ITZ), improving strength, impermeability, and chemical resistance. Metakaolin boosts early and later-age compressive strength, decreasing permeability, heat of hydration, and sulphate and chloride penetration. It also improves workability, shrinkage, and durability in harsh environments. It is well-established in high-performance and self-consolidating concrete, especially in structural applications that require long service life and low maintenance. Despite its higher cost than industrial by-product SCMs, its technical advantages and lower replacement dosage often justify its use in sustainable concrete design.

Lime Sludge

Lime sludge is a byproduct of the paper and pulp industry, sugar refining, and water or wastewater treatment plants, where lime is used for neutralisation, clarification, or chemical precipitation. The sludge, primarily calcium carbonate ($CaCO_3$) or calcium hydroxide ($Ca(OH)_2$), is a large, alkaline residue that is difficult to dispose of. Depending on its industrial origin, lime sludge contains 40% to 70% CaO and minor impurities like silica, alumina, iron oxide, and trace heavy metals. Unless thermally treated, it is a fine powder or slurry with high water retention and low cementitious reactivity. Pre-treatment, drying, and sieving before adding it to cement or concrete mixes is necessary due to composition and moisture variability. The environmental impact of landfilling lime sludge includes land degradation, leaching, and groundwater contamination. Thus, reuse reduces cement production's carbon footprint and provides a sustainable waste management solution. As a filler or weak pozzolan, lime sludge can improve particle packing density, reduce water demand, and slightly increase strength, especially in later curing stages, when blended with cement. While lime sludge lacks intrinsic pozzolanic reactivity, its synergistic interaction with other SCMs like metakaolin or fly ash can improve composite cementitious systems. At optimal replacement levels of 10–20% of cement weight, it improves concrete compressive strength, water absorption, and durability. Lime sludge use supports the circular economy by recovering resources and reducing dependence on virgin materials. Free availability makes it economically attractive, especially for large-scale infrastructure projects in developing countries. However, inconsistent quality, regulatory restrictions, and lack of awareness prevent widespread adoption. Standardising processing methods and optimising mix design parameters for lime sludge-incorporated concretes is being researched to improve structural performance and sustainability.

7. RHEOLOGICAL PROPERTIES OF CONCRETE

Rheology studies material flow and deformation, especially under stress, and it governs concrete's fresh-state properties like workability, consistency, viscosity, yield stress, and thixotropy. In complex structural elements or under restricted site conditions, concrete mixing, pumping, placing, and compaction depend on rheological behaviour. Water-cement ratio, particle size distribution, admixtures, and SCMs like metakaolin and lime sludge affect concrete's rheology. Due to its fine particle size, high surface area, and angular particle morphology, metakaolin changes fresh properties. Addition of metakaolin to concrete reduces slump and increases viscosity and yield stress. Its high water absorption capacity and cement particle surface interaction increase water demand. This may reduce workability in conventional mixes, but it helps make cohesive mixes in self-consolidating concrete (SCC) or high-performance concrete (HPC), where segregation resistance is crucial. Metakaolin reduces bleeding and improves paste cohesiveness, enhancing flow stability under shear stress. High-range water-reducing admixtures (HRWRs) or superplasticizers are often used to reduce slump. Lime sludge, rich in calcium hydroxide or carbonate, affects rheology differently. Its irregular, fluffy particle morphology increases water retention and fills between particles to reduce interstitial voids. Due to its filler effect, lime sludge can slightly improve workability at low replacement levels (10–15%), but excessive addition often reduces slump and flow due to higher water demand and poor particle interaction with cement hydrates. Pre-treatment, moisture, and fineness affect lime sludge behaviour. In a cementitious matrix, metakaolin and lime sludge synergise. Metakaolin increases viscosity and strength, while lime sludge improves workability through dilution and particle packing. The mix proportions affect this synergy, and improper balancing can cause stiff mixes, segregation, or bleeding. Studies suggest that optimised ternary blends with 5–10% metakaolin and 10–15% lime sludge can balance flowability and cohesiveness if water content and superplasticizer dosage are adjusted. Rheological behaviour in modified concretes must be understood to create pumpable, durable, and high-quality mixes for advanced applications like precast elements, mass pours, and marine structures. Despite the potential, raw material properties and lack of mix design guidelines make rheological behaviour prediction difficult. Modern research uses advanced rheometers and models like the Bingham model to better characterise yield stress and plastic viscosity, enabling better prediction and control over fresh-state behaviour in SCM-rich concretes.

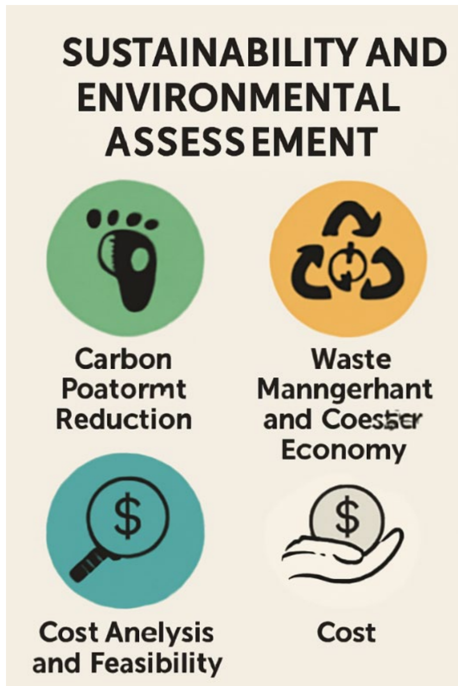
Summary of Rheological Effects from Comparative Studies

Study	**SCM Used**	**Replacement %**	**Effect on Slump**	**Effect on Viscosity**	**Key Observations**

Siddique (2008)	Metakaolin	10%	↓ Significant reduction	↑ Increased	Requires superplasticizer for workability
Kumar & Singh (2019)	Lime Sludge	15%	↓ Moderate reduction	↑ Slight increase	Filler effect; improved cohesion
Sabir et al. (2001)	Metakaolin	15%	↓ High	↑ High	Recommended for SCC and HPC

Sustainability and Environmental Assessment

Figure 4 Sustainability and Environmental Assessment: Key Concepts in Carbon Footprint Reduction, Waste Management, and Cost Feasibility



Source Adapted from sustainability and environmental assessment frameworks in construction and waste management studies.

8. CARBON FOOTPRINT REDUCTION

Adding metakaolin and lime sludge to concrete reduces the carbon footprint of conventional cement production. Ordinary Portland cement production is highly carbon-intensive, emitting 0.9 tonnes of CO_2 per tonne of cement produced. This emission comes from limestone calcination and fossil fuel combustion in rotary kilns. These emissions can be reduced by replacing cement with SCMs like metakaolin and lime sludge. Metakaolin, produced at lower temperatures (650-850°C) than clinker (~1450°C), has a lower carbon footprint. Although some energy is used in calcination, the net CO_2 released is significantly less, especially when used in optimised proportions (10-15%). As a waste byproduct, lime sludge does not require thermal processing and is often considered carbon-neutral in life cycle analyses because it diverts industrial waste from disposal and offsets the use of virgin raw materials. LCA comparisons of conventional concrete and modified concrete with metakaolin and lime sludge show significant sustainability gains. Studies indicate that replacing 20% cement with metakaolin and lime sludge can reduce embodied CO_2 by 15-25%, depending on transportation distance, mix design, and processing method. LCA also considers energy savings, durability, and downstream benefits like lower maintenance and repair costs. When considering raw material extraction, processing, transportation, application, and end-of-life reuse or recycling, SCM-based concrete's sustainability advantage is even greater.

9. WASTE MANAGEMENT AND CIRCULAR ECONOMY

Concrete made with lime sludge and other industrial byproducts supports circular economy and sustainable waste management. The paper and pulp industry, sugar refineries, and water treatment plants generate a lot of lime sludge for pH adjustment, deinking, and chemical precipitation. Water contamination, land use issues, and atmospheric particulate dispersion are all risks from landfilling this sludge. The construction industry can use lime sludge in concrete to divert high-volume waste from landfills and create value. This reduces the environmental impact of sludge disposal and conserves resources by replacing virgin cement. Lime sludge reuse with high-reactivity SCMs like metakaolin promotes industrial symbiosis, where one industry's waste becomes another's input. This idea supports sustainable production chains and waste valorisation and circular manufacturing encouraged by national and international sustainability frameworks. Additionally, it reduces pressure on natural limestone reserves and high-temperature calcination. Using lime sludge in a blended system encourages construction and manufacturing companies to work together on environmental solutions. The variability in chemical composition and moisture content of lime sludge requires pre-treatment, testing, and classification before use, which requires clear standards and regulatory support for widespread adoption.

10. COST ANALYSIS AND FEASIBILITY

Beyond environmental benefits, metakaolin and lime sludge must be economically viable for infrastructure and commercial construction projects. Metakaolin is a highly effective pozzolanic material, but purification and thermal activation make it more expensive than fly ash or GGBS. High reactivity and effectiveness at lower replacement levels (5–15%) increase early strength, reduce curing time, and reduce the need for durability-enhancing admixtures, offsetting its initial cost. In structures like precast elements, marine structures, and urban high-rises that need durability or fast turnover, its performance benefits can lead to long-term economic gains. Lime sludge, on the other hand, is often free, especially when sourced directly from industries looking to reduce waste disposal. The only costs of lime sludge are drying, grinding (if needed), and transportation. This makes lime sludge an economical filler or partial replacement material, especially in areas with high sludge availability and limited access to conventional SCMs. Regional metakaolin and lime sludge availability affects scalability. India, China, and Brazil have large kaolin deposits that can be used to make metakaolin. However, lime sludge is produced near industrial zones and abundant in regions with paper, sugar, or water treatment facilities. Without local supply chains, these materials' transportation costs may outweigh their economic benefits for rural construction sites. Public sector engagement, policy incentives, and green procurement can provide cost subsidies, tax rebates, or mandatory green building standards to make SCM-blended concretes more feasible. In conclusion, metakaolin requires a careful cost-performance analysis, especially for large-scale applications, but lime sludge is an economical and sustainable alternative with quality control. These materials make greener construction economically and technically feasible, supporting environmental goals and circular economy principles.

11. RESEARCH GAPS AND FUTURE DIRECTIONS

Metakaolin and lime sludge are promising partial cement replacements, but they must be studied further before they can be used in mainstream construction. Understanding the long-term durability of concrete incorporating metakaolin and lime sludge in marine, freeze-thaw, or aggressive chemical-laden industrial environments is difficult. Laboratory studies have shown improvements in compressive strength, microstructure refinement, and chloride and sulphate resistance, but field data is lacking to determine how these materials perform over 20–30 years. Long-term structural performance monitoring, especially with different environmental stressors, is essential for engineer and policymaker confidence. Lime sludge in concrete is not standardised, another research gap. Lime sludge's chemical composition, particle size, and moisture content vary by industrial source, making quality benchmarks difficult to set. Contractors and concrete manufacturers are wary of lime sludge because it lacks classification systems, processing guidelines, and codal provisions like fly ash and slag. Consistent lime sludge pre-treatment, grinding, and blending protocols require extensive research. Only a few experiments have combined lime sludge with other SCMs like fly ash, ground granulated blast furnace slag (GGBS), or silica fume. Multi-component (ternary or quaternary) blends may improve mechanical and durability while reducing cement demand, but microstructural synergy, optimal replacement ratios, and combined rheological effects are poorly studied. Turning lab results into real-world applications requires pilot studies and field-scale validation. Current research is limited to small-scale samples, and there is little data on how these materials perform in large structural elements like beams, pavements, and precast components under different site conditions. Field trials with actual structural loads, curing practices, and environmental exposures would illuminate practical challenges, workability adjustments, and lifecycle performance.

12. CONCLUSION

that using metakaolin and lime sludge as supplementary cementitious materials can improve the rheology, mechanical properties, and durability of concrete in a sustainable and effective manner. Metakaolin's high pozzolanic reactivity improves strength and durability, while lime sludge reduces cement and industrial waste cost-effectively. Their use reduces carbon footprints, promotes circular economy, and supports green construction. Standardisation, field validation, and digital mix optimisation are needed to maximise performance and maintain environmental and economic feasibility for widespread use.

CONFLICT OF INTERESTS

None.

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None.

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