Advanced Low-Carbon Building Materials from Lime Sludge and Pozzolanic Additives: Review & Perspectives

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Abstract. This study critically explores the potential of lime sludge, a predominant byproduct from the pulp and paper industry, as a sustainable constituent in building materials. The literature reveals that thermally treated lime sludge demonstrates significant pozzolanic reactivity, making it a promising candidate for incorporation in cement, mortar, bricks, ceramics, and related composites. Integration of lime sludge not only addresses environmental challenges by reducing landfill disposal and conserving natural resources, but also directly mitigates the carbon intensity of conventional cementitious products. The findings indicate that lime sludge, either as a standalone substitute or blended with supplementary cementitious materials such as fly ash or metakaolin, can effectively replace up to 10–30% of cement by mass without detriment to the durability and strength characteristics of concrete and mortar, though excessive replacement can impair workability and strength. In brick and ceramic production, the use of lime sludge up to 40% by weight has been shown to lower sintering temperatures while preserving structural integrity. Beyond its role as a binder, lime sludge contributes to solid waste management and reduction of greenhouse gas emissions, with negligible leaching of harmful elements. The review highlights the necessity for ongoing research into chemical and alkali activation, geopolymer technology, and large-scale application, emphasizing life cycle assessments to establish lime sludge as a mainstream, low-carbon alternative in construction. Such advancements are pivotal for the sustainable transformation of the building sector, providing both ecological and economic benefits.

Keywords: lime sludge, metakaolin, pozzolans, performance, strength.

1. Introduction

Rapid population growth and accelerated urbanization, most notably in developing economies, have led to a substantial surge in demand for both housing and infrastructure. The pace of this transformation far exceeds historical trends. The construction sector has, over time, shown to produce greenhouse effect at large scale. By 2019, this sector was responsible for 38% of energy-related emissions worldwide, with construction materials alone accounting for nearly 10% of that figure [1]. Projections indicate

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that, by 2050, global annual cement production will escalate to 4 billion tonnes, rising from 2.8 billion tonnes at present, with China and India positioned as the primary drivers of this growth, and the Middle East and North Africa also experiencing notable expansion [2-4]. Cement manufacturing is inherently energy-intensive and carbon-emissive. Approximately one tonne of Portland cement releases between 730 and 990 kg of CO_2, which equates to about 8% of global CO_2 emissions [5-6]. Consequently, contemporary research has increasingly focused on developing alternative binders that are less demanding in terms of energy consumption and carbon footprint. One promising approach involves partially replacing cement with Supplementary Cementitious Materials (SCMs), which are predominantly sourced as by-products from diverse industrial processes. The viability of these materials hinges on their ability to deliver mechanical and durability properties comparable to, or better than, those of conventional Ordinary Portland Cement (OPC) concrete. The repurposing of such industrial by-products not only offers substantial cost reductions but, in some cases, also enhances material performance [7-8]. In recent years, considerable effort has been dedicated to transforming various categories of industrial waste into value-added construction resources [9-12], aligning with global priorities to employ waste materials as alternative resources to foster sustainable development [13-15].

Despite these advancements, challenges persist. The availability of widely used alternative materials is increasingly constrained [16-17], despite their well-documented benefits and extensive implementation in cement production [18-20]. As a result, attention is progressively shifting toward more accessible SCMs, including calcined clays and various industrial sludges generated from sectors such as papermaking, textiles, water treatment, and sewage management [21-22].

According to the 2018 Technology Roadmap published by the International Energy Agency (IEA) [3], there is a clear trend towards shifting the use of SCMs from traditional sources like fly ash and slag to less conventional options such as calcined clays and limestone by 2050 (see Fig. 1).

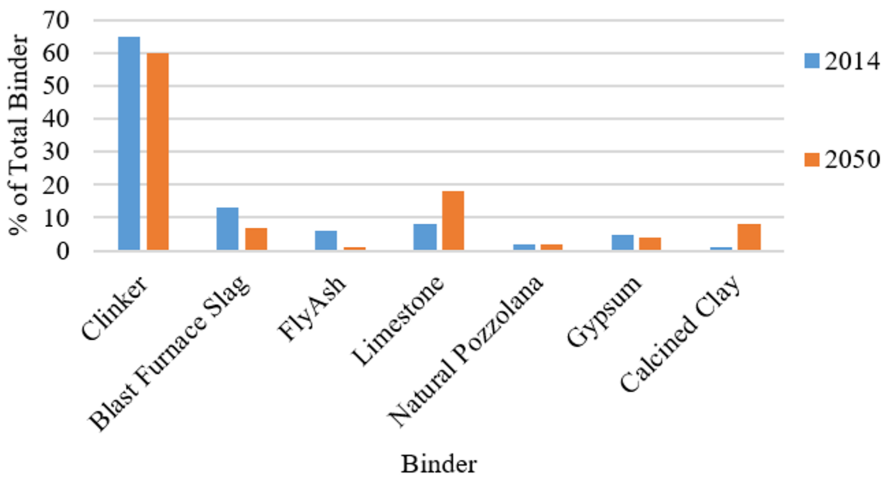

Figure 1. Global Average of Cement Composition as per IEA [19]

A significant quantity of lime sludge is produced as a byproduct in the pulp and paper industry. In India alone, this sector is responsible for generating around 4.9 million tonnes of lime sludge annually in the white liquor recovery phase [23-24]. Frequently, this lime sludge is dumped in landfills, which can worsen environmental issues caused by both human activities and natural factors. Problems such as carbon breakdown, changes in microbial activity, leaching, and ion exchange processes may lead to the contamination of surface water, groundwater, and soil. To minimize the negative impacts of landfill disposal, it is important to find alternative uses for this waste, such as incorporating it into construction materials like cement and aggregate [25, 8]. The main component found in lime sludge is calcium carbonate, with smaller amounts of silica and alumina also present [26]. The dominant crystalline structures in lime sludge include kaolinite (Al2O3·2SiO2·2H2O, 10–20%) and calcite (CaCO3, 60–90%). When lime sludge is subjected to heat treatment, it produces reactive lime (CaO) and metakaolin (Al2O3·2SiO2), which significantly boost its reactivity. This increased reactivity makes lime sludge a valuable supplementary material in cement applications [27-30].

2. Characteristics of Lime Sludge

Lime sludge mainly consists of fine particles of precipitated calcium carbonate ($CaCO_3$) along with residual materials from green liquor clarifiers. The characteristics of this waste material are detailed in Table 2. Its primary mineral phases include calcite, quartz, and hemihydrate [31-33]. The overall composition of various industrial waste products, including lime sludge, is illustrated using a ternary diagram in Fig. 2. Additionally, the X-ray diffraction (XRD) pattern of raw lime sludge is shown in Fig. 3, which highlights pronounced peaks corresponding to minerals such as calcite, talc, and kaolinite as the main components. The major oxide contents found in raw lime sludge are summarized in Table 1.

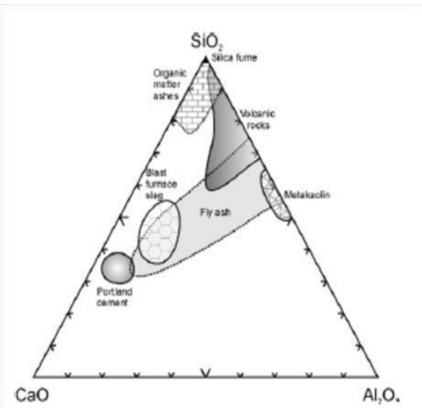

Figure 2. Ternary diagram showing position of different SCM [22.]

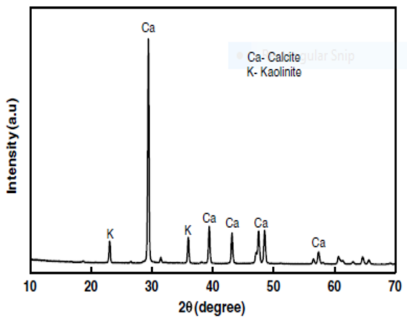

Figure3. XRD of Raw lime sludge [22.]

Table 1 : %Weight of different components in Raw Lime Sludge[22].

Element	O	Al	Si	S	Ca	Fe
Weight %	58.79	1.71	9.72	2.98	25.35	1.45
Atomic weight%	75.99	1.31	7.16	1.92	13.08	0.54

India produces about 13 million tonnes of paper, paperboard, and newsprint every year, accounting for roughly 3.18% of the world's total production, which is around 408 million tonnes annually [34]. The paper industry generates various types of waste during manufacturing, with 1.63 tonnes of lime residue produced for every tonne of paper made. Because of the vast amount of lime sludge generated, pulp and paper mills are considered among the most contaminating sectors [35]. Lime sludge is formed in the chemical recovery section of these mills. In India, all large, integrated paper manufacturing units are equipped with chemical recovery systems [36]. During the causticization process, green liquor is converted to white liquor. Most of the smelt, mainly soda ash (Na_2CO_3), reacts with calcium oxide (CaO) to form calcium carbonate ($CaCO_3$), also known as lime sludge, and caustic soda (NaOH). The lime sludge is then recycled in the lime kiln, where it can be reused multiple times as lime (CaO) in the causticization cycle. The lime recovery process in paper mills is energy-intensive, requiring between 1530 and 1830 kcal per kilogram of lime. Additionally, the high silica content (5–10%) in lime sludge leads to scaling problems in the lime kiln, making recycling difficult [33]. For this reason, many paper industries choose landfilling as their main disposal method. Traditionally, landfilling and land rectification have been used to manage lime sludge waste from paper mills [37]. However, increasing costs, stricter regulations, and limited space have made landfill disposal more expensive and less feasible. Because of its good quality, lime sludge holds significant promise for use in construction materials [38].

Figure 4. Potential application areas of Lime Sludge.

The possible applications of lime sludge in various building construction products are illustrated in Fig. 4.

As the global population continues to grow, the demand for building materials is also increasing. This has created concerns in the construction industry about maintaining a balance between the supply and demand of these materials [39]. As a result, attention is shifting toward the development of sustainable alternatives to conventional supplementary cementitious materials (SCMs) to help meet demand and ensure a steady supply of construction resources [33]. One promising approach is to make use of waste products generated by various industries. Among these, lime sludge stands out for its significant potential as a raw material for building products [40]. Using lime sludge has become a new source of construction material but also offers an effective solution for solid waste management. Recently, researchers have explored the blending of lime sludge with other industrial byproducts to create alternative construction materials. While studies have examined paper mill waste [41-44], there has been little specific discussion on the application of lime sludge as a binder in construction materials like bricks, ceramics, cementitious binders, and concrete. Therefore, this review paper aims to fill this gap through analysis of recent trends in the use of lime sludge for building applications.

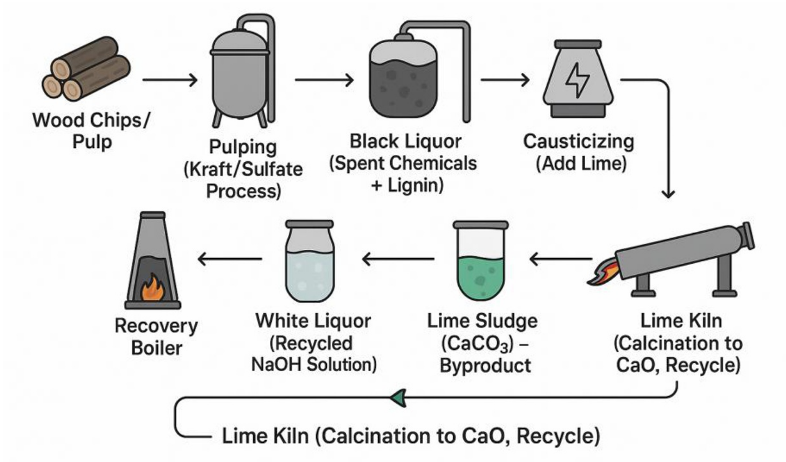

Figure 5. Manufacturing of Lime Sludge.

2.1. Cement Fabrication uses

The rapid growth in the demand for building materials is largely driven by the rising global population, with cement continuing to serve as a fundamental material for construction needs. However, the cement industry faces critical challenges, including resource depletion, increasing CO_2 emissions, and significant energy consumption. Sustainable use of alternative materials, especially industrial byproducts through energy-efficient processes, is now vital for the cement sector. Although progress has been made in adopting alternative materials, there is still considerable potential for further development in this field. Restrictions on the availability of conventional raw materials used in cement production highlight the need for exploring substitutes. In the future, new materials may increasingly replace traditional cement constituents. Studies have investigated blends of burnt clay pozzolanic cement with and without the addition of silica fume, finding that replacing around 10% of OPC with burnt clay enhanced compressive strength [45]. The study utilized XRD and DSC analyses to examine the reaction of calcium hydroxide (CH) with hydration products such as CASH and CSH, demonstrating that both components contribute positively to blended cement paste formation [46]. A comparable approach has also been used to investigate lime sludge as a raw material for cement. Lime sludge primarily contains calcium carbonate ($CaCO_3$) and silica (SiO_2), with the main crystalline phases being calcite and kaolinite. Kaolinite consists of hydrous aluminum silicate ($2H_2O{\cdot}Al_2O_3{\cdot}2SiO_2$), and metakaolin ($Al_2O_3{\cdot}2SiO_2$), a highly reactive product derived from the calcination of lime sludge, can be used as a cement ingredient. The reuse of lime sludge, therefore, presents opportunities for enhancing pozzolanic activity in the creation of cementitious binders, making it a practical solution for lime waste utilization. A study on using dried lime sludge in cement production and found that its inclusion improved the burning efficiency of clinker [47]. The presence of lime sludge helped to lower the temperatures required for the decomposition of calcium carbonate and the generation of the liquid phase. Phosphorus and other trace elements present in lime sludge also facilitated the formation of tricalcium silicate (C_3S) in cement clinker, enhancing the liquid phase and reducing viscosity. Additional research explored the synthesis of belite, a key cement clinker component, by reacting nano-silica with lime sludge at 850°C—a temperature lower than that needed for traditional cement production—using a lime sludge to nano-silica ratio of 2:1 [48]. Belite (β-dicalcium silicate, β-C_2S, Ca_2SiO_4) generally accounts for about 20% of Portland cement clinker, while alite makes up the majority.

Further work combined lime sludge with silica fume to produce belite, following a similar experimental process but at higher temperatures [49]. Other studies focused on using mixtures of fly ash, lime sludge, and biological sludge to synthesize belite clinker at sintering temperatures of about 1350°C [50]. The most efficient belite synthesis was achieved with a mixture of 49% lime sludge, 20% fly ash, and 30% biological sludge, resulting in belite cement-based mortar with adequate strength and durability. Moreover, lime sludge has been utilized along with coal biomass ash and wastewater treatment sludge to produce eco-clinkers. These mixtures were burned at temperatures between 1350°C and 1450°C. One effective eco-clinker formulation included 69% lime sludge, 29% biomass ash, and 2% wastewater process sludge at 1450°C, exhibiting the main crystalline phases typically found in commercial cement [58]. This eco-clinker was then used to produce eco-cement (95% eco-clinker and 5% gypsum) [51]. Mortar prepared with this eco-cement showed a compressive strength of 21 MPa after 28 days of curing. Recent studies have also examined the role of lime sludge in geopolymer concrete. For example, research conducted by [52-53] involved using lime sludge as an activator for manufacturing geopolymer cement (CEM IIIC and type 32.5 N) in accordance with European Standards EN-197. In these cases, lime sludge was combined with blast furnace slag and sodium hydroxide to prepare the geopolymer cement, and additional unreacted lime sludge was used as filler. Increasing the lime sludge content improved the compressive strength of the cement, with 18% lime sludge yielding the highest strength (42 MPa) [54]. The mechanical properties of these mortars were assessed in terms of hydration heat and cement setting times, with results indicating that the total heat released by lime sludge cement was comparable to that of ordinary Portland cement [39]. Adopting lime sludge in cement production can help address the industry's waste disposal problems in both an environmentally friendly and economically sound manner. Its use reduces reliance on natural resources and cuts down on carbon emissions due to lower energy requirements [50, 55].

Table 2. Lime Sludge Use in Preparation of Clinker.

S.no.	Ref.	Parameter studies	Material used	Product
1	[38]	Mineralogicalstudies	Nanosilica	Clinker
2	[39]	Mineralogicalstudies	SilicaFume	Clinker
3	[40]	Mineralogical, hydration and compressive strength	Fly ash and biological Sludge	Clinker
4	[46]	The cement kiln's inclusion of lime sludge increased sintering.	Cement	Cement

5	[40]	Density and Compressive Strength	LM and gypsum	Clinker
6	[42]	Ground granulated blast furnace slag and sodium hydroxide	Compressive strength, heat of hydration, and mineralogy	Geopolymer binder

2.2. Lime sludge application in cement mortar

Masonry work involves the use of mortar, a malleable mixture made of cement and sand. As a substitute for cement and fine aggregates, lime sludge has been used in mortars. It is used in mortars in various configurations calcined, as received, and in mixtures with other substances. The work of some researchers on the impact of lime sludge in mortars is summarised in Table 2. The reactivity of lime sludge is increased by calcining it between 650 and 800^{0}C [57]. The lime produced by the breakdown of $CaCO_3$ is hydraulically reactive and stable for use in the production of binders.

Additionally, to create secondary CASH products, active CaO reacts with the SiO_2 that is present in matrices. However, an excessive amount of CaO may have a negative impact on durability. For the preparation of mortar, [58] employed burned lime sludge. In the preparation of mortars, 25% of the cement was replaced by lime sludge that had been heated to various degrees. The mortars' compressive strength was evaluated after 90 days with 25%, and it was found to be higher than that of regular Concrete [59-61]. The conversion of calcium carbonate from the lime sludge's calcium carbonate into calcium oxide during the heat treatment process may cause the subsequent development of compressive strength. When lime is used in mortar, it aids in the creation of additional calcium silicate hydrate, which leads to a late-stage enhancement in the strength qualities of the mortars.

The calcination of the lime sludge uses a tremendous amount of energy, which is wasteful. Lime sludge should be used exactly as it was received from an economic standpoint. In line with the aforementioned rationale, [62] Modolo et al. focused on the usage of received lime sludge. In order to compare mortars made with normal filler (commercial filler) application to those made using lime sludge as a filler material, the results were obtained. Following ball milling with smaller particle size, lime sludge was employed. Mortars were created by substituting lime sludge for 6, 12, and 18% of the total aggregates, respectively, increasing the compressive strength by 10%, 17%, and 23% compared to the reference mortar. Due to the presence of small, ball-milled particles in the concrete matrix, this effect may be linked to the filler and binder effects of lime sludge. Following this conclusion, some research has also concentrated on substituting fine aggregates with lime sludge. [35] Investigated two different mortar types with four different combinations of lime sludge binders. Binder 1 was created using lime sludge (30%) and fly ash (70%), while Binder 2 was created using the same proportions but with 1% gypsum. Due to an increased pozzolanic reaction, the inclusion of gypsum had a favorable influence on the compressive strength of mortars. Using fly ash and lime sludge from paper mills [63] research focused on creating environmentally friendly materials for construction purposes. Both lime sludge and fly ash were used to prepare the mortars. Maximum compressive and flexural strengths were attained by substituting lime sludge for 10% of the total cement; however, strength reduced if the percentage of lime sludge replacement exceeded 10%. Experimental research by [64] focused on the usage of fly ash and paper mill lime sludge in a mortar. The mortars with a 12.5% lime sludge and 12.5% fly ash replacement of the cement had the highest compressive strength of 25 KPa. The compressive strength of mortar made with more lime sludge and fly ash was significantly reduced. The mortars were grounded using cement pastes that contained a maximum of 20% lime sludge and fly ash [31]. In the preparation of the mortar, fluidized bed reactor sand was utilized in place of the fine aggregates. The study found that adding fly ash to lime sludge increased the cement paste's yield stress and viscosity. Mortars with a 10% fly ash and 10% lime sludge addition to cement paste demonstrated the highest compressive strength. According to study, lime sludge has a significant chance of taking the place of cement or fine aggregates in Concrete and mortar. Researchers studied various concrete grades, however it was found that the compressive strength of Concrete and mortars satisfy the requirement of strength upto replacement of 30% of total cement and then starts to drop with an exponential rate beyond that [65-66] a rise in the use of lime sludge in place of cement. This application limit for lime sludge has been increased in several studies to 10–20%. Up to a 25 to 30% application of lime sludge, replacing fine aggregates with it had no appreciable impact on the compressive strength of mortars and Concrete. Other industrial byproducts were applied along with lime sludge, improving the strength properties. Table 3 overviews various work done by researchers using Lime Sludge in Mortar application.

Table 3. Lime Sludge Application in Mortar

S.No.	Material Replaced	Material Added	% Replacement	Optimum Replacement	Parameters Studied	Impact	Reference
1	Cement	Fly Ash, Gypsum	89–100	80	Compressive Strength	+2.7% increase	[25]
2	Cement	Fly Ash	10–30	25	Compressive Strength	+3.1% increase	[53]
3	Fine Aggregate	Fly Ash	10–30	30	Compressive Strength	+1.34% increase	[52]
4	Cement and Fine Aggregate	Fly Ash	10	10	Compressive Strength	–37% decrease	[21]
5	Cement	Fly Ash	10–20	10	Compressive Strength	–6% decrease	[48]
6	Cement	Fly Ash	12.5	12.5	Flexural and Compressive Strength	–4.1% decrease	[54]

7	Cement	Fly Ash, Silica Fume	30–70	Not Specified	Not Specified	Not Specified	[29]
8	Cement and Fine Aggregate	Lime Sludge	0–20	15	Compressive and Flexural Strength	–7% decrease	[55]

2.3. Application in concrete

Concrete is a composite material that consists of cementitious binders holding fine and coarse particles together. Researchers from all over the world are attempting to use a variety of wastes from various industries, including fly ash, recycled aggregates, sugarcane bagasse ash, rubber waste, silica fume, ground granulated blast furnace slag, waste glass sludge, ceramic waste, hydrated lime and agro waste, to produce Concrete that is both affordable and sustainable. These components were used in the cement-based Concrete either as filler or as pozzolanic ingredients [66-72]. Manufacturing of cement-based building materials also uses various wastes from the pulp and paper industries, such as lime sludge, deinking Sludge, primary Sludge, and waste paper fiber sludge. Different application techniques for lime sludge in the creation of Concrete are shown in Table 4. Fig6 demonstrates the work of various researchers for different grades of Concrete, and it demonstrates that the influence of Lime Sludge is more at lower strengths but for higher strengths, the capability of lime sludge is limited [73-75]

Table 4. Lime Sludge Application in Concrete.

S.No.	Replaced By	% Replaced	Optimum % Obtained	Parameters Studied	Effect	Reference	Grade
1	Cement	10–70	30	Compressive Strength	Decrease 4%	Srinivasan et al., 2010	M30
2	Cement	10–30	30	Modulus of Elasticity, Viscosity, Cohesion	Decrease 1.34%	Modolo et al., 2011	M30
3	Cement	10–40	10	Fluidity, Compressive Strength	Increase	Pitroda et al., 2013	M40
4	Cement	10–40	15	Compressive Strength, Modulus of Elasticity	Increase 16%	Yousuf et al., 2014	M15

5	Cement	10–20	30	Compressive Strength	Increase 8%	Manchriyal et al., 2016	M20
6	Cement	10–40	30	Compressive Strength	Increase 6%	Abhishek et al., 2017	M20
7	Cement	10–30	30	Compressive Strength	Decrease 6.2%	Alam et al., 2015	M20
8	Fine Aggregate	10–25	25	Compressive Strength	Decrease 5%	Soni et al., 2015	M25
9	Fine Aggregate	10–40	20	Compressive Strength	Increase 3.7%	Shermale et al., 2015	M30

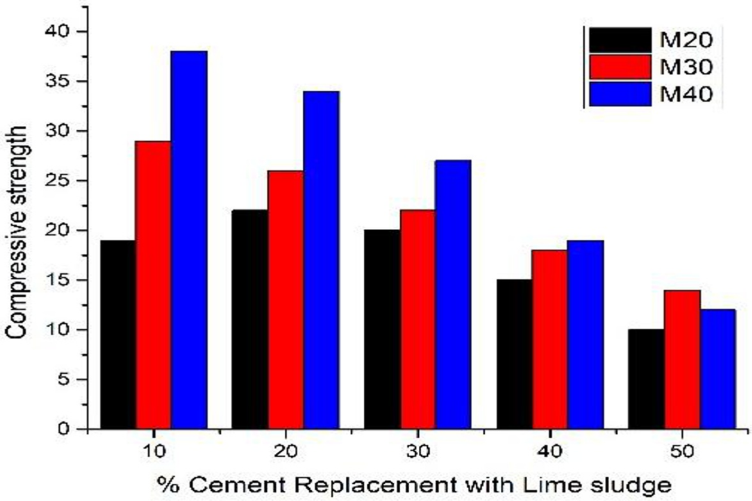

Figure 6. Variation of compressive strength with various Design Mixes.

2.3.1. Effect on compressive strength of Concrete

Many researchers have examined how lime sludge affects the properties of concrete. Table 6 provides a summary of multiple studies evaluating the impact of lime sludge on different grades of concrete after 28 days of curing. In these studies, lime sludge was used as a partial replacement for cement in various concrete mixes. For M20 grade concrete, replacing 10–20% of the cement with lime sludge led to a slight improvement in compressive strength compared to standard concrete. However, when the replacement percentage exceeded this range, the compressive strength began to decrease. Interestingly, at a 30% replacement level, lime sludge still produced compressive strengths similar to those of conventional M20 concrete [76-77]. This suggests that excessive lime sludge may saturate the matrix, weakening its binding effect, and thus, high percentages of lime sludge are not recommended for M20 grade concrete.

In higher-grade concretes like M30, researchers aimed to use larger amounts of lime sludge. Despite these efforts, the same positive trend seen in M20 grade concrete was not observed. For example, one study reported that, for M30 concrete, compressive strength dropped when lime sludge content surpassed 30% of the total cement, and beyond this limit, significant strength losses occurred [76]. Similarly, [78] found that using more than 20% lime sludge as a replacement for cement in M30 grade concrete resulted in a reduction in compressive strength. According to this study, lime sludge mainly acts as a filler material, and exceeding 20% replacement can negatively affect the final strength. Currently, there is little research explaining why these differences in strength occur between M20 and M30 grade concretes.

For M40 grade concrete, [79] recommended that lime sludge could replace up to 10% of cement without any reduction in strength. Some studies also investigated using lime sludge as a replacement for fine aggregates in concrete mixes. One such study [64] observed that substituting fine aggregate with lime sludge reduced compressive strength, but the loss was not as significant up to a 25% replacement level. This decline in strength may be attributed to decreased workability caused by the finer particles of lime sludge. As lime sludge replaces finer aggregate, the mix's overall workability decreases due to higher water demand, which can lead to lower compressive strength.

Lime sludge also influences the rheological (flow) properties of concrete, including fluidity, yield stress, plastic viscosity, and cohesion between particles [37], [62], [79]. With increased lime sludge content, yield stress and particle cohesion increased, but fluidity and plastic viscosity decreased. At about 30% replacement, the apparent porosity of the concrete was found to be 6% lower than that of standard concrete. Based on rheological tests, up to 30% lime sludge replacement was found to be feasible. In another investigation, [80] observed that a higher proportion of lime sludge increased the yield stress and cohesiveness of mortar but reduced its fluidity and plastic viscosity. This means the mortar became stiffer and less workable as lime sludge content increased.

Beyond a certain point, the addition of lime sludge reduced the elasticity of the concrete mix, but for M40 grade, the modulus of elasticity remained comparable to that of standard concrete. The changes in rheological behavior are mainly due to the fine particle size of lime sludge, which reduces the amount of free water in the mix. This leads to decreased workability and elastic modulus, while increasing the mix's viscosity, cohesiveness, and yield stress [77].

2.4. Application with other waste materials

To enhance the overall quality of concrete, lime sludge has also been combined with other pozzolanic supplementary cementitious materials. When pozzolanic materials—such as those that are rich in silica or both silica and alumina—react with calcium hydroxide, they form additional cementitious compounds. Incorporating pozzolanic elements into lime sludge-based binders has been shown to significantly increase their durability and resistance to degradation, especially in challenging environmental conditions. Studies have found that both conventional and air-cured concretes made with binary blends of cement, pulverized fly ash, and metakaolin, as well as various other cementitious systems, show improved strength and greater durability. The dense microstructure created in these mixes also helps reduce the penetration of chloride ions. Compared to standard concrete, ternary mixes containing cement, fly ash, and silica fume have displayed superior strength and higher durability. Additionally, these ternary blended concretes have demonstrated outstanding long-term chemical resistance, particularly against sulphate attack [32], [81-83].

Durability is a key property of lime sludge-based concrete and mortar. Multiple investigations have established that using specific ratios of fly ash and silica fume with lime sludge as a partial replacement enhances the concrete's long-term performance. A variety of supplementary cementitious materials—including fly ash, slag cement, rice husk ash, metakaolin, palm oil fuel ash, and silica fume—are commonly used to achieve these benefits [84-86]. For example, to assess chemical resistance, [64] exposed lime sludge-based cement concrete to 5% hydrochloric acid (HCl) and 5% sulfuric acid (H2SO4). The results showed a greater mass loss in sulfuric acid, indicating higher vulnerability to sulphate attack.

Similar beneficial effects have been observed when using fly ash and quarry dust with lime sludge. In these cases, the addition of lime sludge improved the compressive strength of concrete [75]. For M30 grade concrete, studies that replaced fine aggregates with lime sludge and cement with silica fume demonstrated that, after 28 days, a mix containing 20% lime sludge (as a fine aggregate substitute) and 20% silica fume (as a cement substitute) achieved compressive strength comparable to conventional concrete. In another experiment, [83] replaced cement with nano-silica and paper mill lime sludge, and found that a mix with 4% nano-silica and 30% dried, crushed lime sludge produced compressive strength similar to standard M30 concrete. The nano-silica used in this study was derived from boiler ash and featured a specific surface area of 450 m^2/g, with particle sizes ranging from 10 to 25 nm.

The inclusion of silica fume and nano-silica in lime sludge-based mixes has led to noticeable strength gains, although the economic aspects of this approach still need evaluation. In another study, [64] used jute and glass fibers, together with deinking and repulping-derived lime sludge, to create fiber-reinforced M30 concrete. Lime sludge and other sludges were combined as partial cement replacements. However, only moderate compressive strength was achieved, and just 10% substitution was found suitable when combined with jute and glass fibers [87]. In addition, some researchers have combined lime sludge with wood ash in concrete mixes. This practice has been recommended as a way to reduce lime sludge disposal and lower emissions of carbon dioxide and other greenhouse gases.

Table 5. Other material used with Lime Sludge.

S.no.	Added material	Material replaced	Optimum % replacement	Grade	Change in Strength	Ref.
1	Jute and Glass Fibers	Cement	30%	M30	Increase	[54]
2	Nano Silica	Cement	30%	M20	Decrease 1.37%	[73]
3	Quarry Sand	Cement	20%	M20	Decrease	[65]

					12.5%	
4	Silica Fume	Fine aggregate	20%	M30	Decrease 6.09%	[68]
5	FlyAsh	Cement	10%	M20	Increase 8.91%	[63]

2.5. Application in bricks and ceramics

Burnt clay bricks are among the most commonly used construction materials in India. The clay needed to make high-quality bricks, owing to its plasticity and molding properties, is often sourced from riverbeds, ponds, and coastal regions. However, the increasing demand for clay bricks has resulted in the rapid depletion of alluvial soils that are best suited for brick production. This situation is particularly concerning because these same alluvial soils are essential for agricultural productivity in the country.

Researchers have investigated the potential of various industrial and urban waste materials—such as recycled paper mill waste, kraft pulp residue, marble industry sludge, rice industry by-products, sugarcane waste, waste glass sludge, sawdust, and even municipal waste—in the manufacturing of burnt bricks [41], [88-91]. The effects of adding lime sludge to burnt clay bricks and ceramics have been summarized in Table 6. The reaction mechanism between the calcium and silicate phases during the brick firing process has been explored in detail by [92]. X-ray diffraction (XRD) studies have shown that the firing temperature is the most significant factor influencing both the formation and strength development of bricks. Major phase changes that improve brick quality occur at temperatures above 1000°C.

For example, [89] developed a technique for making burnt clay bricks using textile mill effluent combined with red, white, and black soils. They also experimented with blending sludge into the soils to enhance the physical and mechanical properties of the bricks, while maintaining the required silica and mineral content. The study determined that a firing temperature of 800°C for 24 hours was optimal for achieving the best compressive strength. Bricks containing up to 15% lime sludge attained an acceptable compressive strength of 4.5 N/mm², but increasing the lime sludge content beyond this level led to strengths dropping below the minimum standard of 3.5 N/mm² for burnt clay bricks [93].

Lime sludge has also been used in pottery and ceramics. According to [94], combining lime sludge with fly ash from the paper industry can produce anorthite ceramics through solid-state reactions. Researchers tested different mixtures of lime sludge and fly ash at various sintering temperatures. The anorthite phase was mainly formed in samples containing 36% lime sludge, though it appeared in all compositions at 1100°C. Further research also examined the synthesis of ceramic materials by directly blending lime sludge with fly ash and additives such as sawdust, shale, diatomite, and perlite.

Table 6. Lime sludge application in bricks.

S.No.	Material	% Replacement	Prepared Material	Parameter Studied	Effect on Strength	Reference
1	Clay, Fly	40	Bricks	Compressive	Decrease	[85]

	Ash			Strength	4.1%	
2	Fly Ash	36	Anorthitic Ceramic	Compressive Strength and Mineralogy	Decrease 5.1%	[45]
3	Fly Ash	60	Bricks	Compressive Strength and Mineralogy	Decrease 2.3%	[86]
4	Fly Ash	20	Tiles	Compressive Strength	Not Spec-ified	[50]
5	Fly Ash	40	Bricks	Compressive Strength	Not Spec-ified	[87]

3. Environmental advantages of lime sludge utilization as building material

Due to the need of a vast amount of primary and non-renewable resources and the flexibility/variety of products available, the building materials are an ideal target for the usage of lime sludge (Cement, Concrete, aggregates, ceramics, etc.). The desire for the supply of raw materials in appropriate quantities and quality, as well as cost related to energy supply, are some of the issues the cement industry is currently dealing with. By lowering the amount of cement used in the Concrete, the use of lime sludge in cement-based construction can address these difficulties.

Sludge from paper mills is often disposed of in landfills. Natural and man-made environmental changes greatly impact how metallic contaminants, if any, behave in Sludge because they can modify how they appear. The redox potential, pH, temperature, leaching, ion exchange procedures, and microbiological activity are a few examples of such external influences. Paper mill sludge when compacted it has very low hydraulic conductivity. It can serve as a natural hydraulic barrier having permeability value in the range of $4.00*10^{-6}$ and $6.00*10^{-10}$ m/s. As a result, paper mill sludge can replace the use of natural clay as natural hydraulic binder in the construction of the landfill hydraulic barrier layer, which can save disposal costs and also be a great alternative in locations without access to clay resources locally. The finding by demonstrated that the percentage of leachable trace elements was extremely low, which was advantageous for using lime sludge.

4. Conclusions

The replacement of cementitious binder or fine aggregates in Concrete and mortar by lime sludge has a substantial potential. According to several published works, the compressive strength of Concrete and mortars doesn't change until 30 percent of the cement is replaced by lime sludge, after which the compressive strength starts to decline. Nevertheless, some studies have improved this cap on lime sludge use to 10- 20 percent. Up to a 25–30% application, there was no discernible difference in the compressive strength of mortars and concrete when fine particles were replaced with lime sludge. Better strength properties were obtained in mortar and Concrete when lime sludge and fly ash or metakaolin were combined. Lime sludge, however, alters the rheological characteristics of mortar and Concrete, causing a drop in plastic viscosity and an increase in yield stress.

The issue of topsoil being used extensively in the manufacturing of burnt bricks and ceramics could be resolved by using lime sludge instead. Up to 20% of lime sludge can be used to make bricks, and 40% can be used to make ceramics. Utilizing lime sludge in the manufacture of bricks and ceramics can save energy because it requires a lower sintering temperature than the standard procedure while maintaining the same compressive strength. Since lime sludge produces eco-clinker at relatively lower temperatures and with substance usage of lime sludge, lime sludge has enormous potential as a raw material for the manufacture of cement (up to 70 percent). Since calcium carbonate serves as the calcium phase during clinker synthesis it can be used directly in the production of cement clinker. In cement industries, its synthesis can be increased to large-scale production. Therefore, the tonnes of uncontrolled waste created by the pulp and paper sector each year might be replaced by using lime sludge in construction materials. Use of Lime Sludge in the production of Clinker also Limits the overusing the lime's natural resource.

Application of lime sludge in concrete may yield more significant benefits if it is chemically activated before being applied to various grades of concrete. Future opportunities for the researchers may lie in their efforts to better understand the process of lime sludge in concrete, especially in alkali activated, one-part geopolymer concrete.

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