

Application of Paper Mill Lime Sludge Waste in Building Construction Material: State of The Art Report

Arti Chouksey ¹, Nirendra Dev ², VVL Kantarao ³, Manvendra Verma ^{4,*}

Abstract

A Comprehensive Literature review is done to find various areas of application of Lime Sludge. Temperature-treated Lime sludge proves to be highly beneficial to be used as Building material. Lime Sludge has an application area in all types of Building materials such as bricks, Tiles, Cement etc. especially, in Cement it is highly beneficial in all the phases of cement from Clinker to, mortar and as a replacement in Concrete. As per the literature review, the application of Lime Sludge is limited to 10-20 % replacement when used alone, with a high replacement level of up to 30% observed in case of use with other SCMs such as Fly Ash, and Metakaolin. Lime Sludge is waste from the paper industry and can be effectively used in different building materials to reduce the depletion of natural resources and to reduce the carbon footprint of the product. There is a need to further investigate and enhance the utilization potential of Lime Sludge for Higher %ages for Sustainable construction practices.

Keywords: Sustainable construction material; Supplementary cementitious materials; Mechanical properties; Compressive strength; concrete composites

INTRODUCTION

Urbanization and rapid population growth especially in developing countries, escalate, housing, and infrastructure demand. It is at a much faster rate than is ever experienced. Global cement output has reached 2.8 billion tonnes annually and is anticipated to reach 4 billion tonnes annually by 2050. The epicentre of these growths is mainly China and India., with other developing regions like the Middle East and Northern Africa. [1, 2,3]

The process of cement manufacturing is highly carbon and energy-intensive. It is projected that the production of 1 ton of Portland cement generates 730-990 kg of CO₂, which is responsible for about 8% of total CO₂ Production. [4,5]. So, in recent years, the focus of the researcher shifted towards the

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production of new binders, which are less energy-intensive. Reduction in Co2 emission can be accomplished by partial replacement in a binder by Supplementary Cementitious Materials called as SCMs, mostly derived as unwanted by-products from other industries. This byproduct is viable only if it performs similarly to or better than concretes manufactured from OPC since these products are industrial waste so skillful utilization of this product reduces the cost of production significantly and also performance can be enhanced in case of some SCM.[6, 7] In recent years, there have been several attempts to use different types of industrial waste as substitute materials, but there is still room for improvement. Due to the limited supply of materials used to make typical cement constituents. Widely used alternate Materials, such as fly ash,

blast furnace slags, and other natural pozzolans, are available in much smaller quantities compared to the worldwide demand for ordinary Portland cement (OPC). [8,9] So, research interest has been shifted towards readily available sources of SCMs such as clays and Sludge from various industries such as paper mills, textile, water treatment, and sewage sludge [10,11].

The pulp and paper industries produced a huge amount of lime sludge. In India, During the white liquor recovery process, the paper companies produce about 4.9 million tonnes of lime sludge annually.[12,13], Because it is frequently dumped straight into landfills, lime sludge contributes to both anthropogenic and natural environmental impacts. this causes issues with the environment such as carbon breakdown, microbial activity, leaching, and ion exchange processes. This led to the contamination of the surface, groundwater, and soil.to reduce the risk of landfilling It is essential to use this waste material in applications like building materials such as cement and Aggregate [14](7). The major component in Lime sludge is Calcium Carbonate, while Silica and Alumina also present a small proportion [15]. The two primary crystalline phases in lime sludge are kaolinite ($\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$, 10–20%) and calcite (CaCO_3 , 60–90%). Reactive lime (CaO) and Metakaolin ($\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$) were produced during the thermal treatment of lime sludge, which accounts for their high reactivity when used as additional materials in cement [16,17,18]. Figure 1. shows the composition of cement at the global level.

Materials & Methods

Lime sludge is made up of very small precipitated CaCO_3 particles and leftover, unsettled green liquor clarifier dregs. Table 1 displays the typical Physicochemical characteristics of waste Lime Sludge. The Main mineralogical component of Lime Sludge is Calcite, Quartz, Hemihydrate [19,20]. Table 1 represents the main oxide components of raw lime sludge [21].

An estimated 13 million tonnes of paper, paperboard, and newsprint are produced in India annually, making up 3.18 % of the overall production (408 million tonnes annually) [22]. Paper production produces waste products. For every tonne of paper produced, a pulp and paper mill generate 1.63 tonnes of lime sludge. The pulp and paper industries are among the most polluting due to the enormous amounts of lime sludge they produce [23]. In the paper industries' chemical recovery division, lime sludge is produced. Chemical recovery systems are installed in every integrated large-scale paper manufacturing facility in India [24]. Chemicals are dissolved in water while they are still molten during the chemical recovery process to green liquor, make it. Through the causticization process, this green liquor is transformed into white liquor. The majority of the smelt, soda ash (Na_2CO_3), is converted to calcium carbonate (CaCO_3), or lime sludge, during the causticization process by combining with calcium oxide (CaO) to produce caustic soda (NaOH). Lime sludge can be recycled in the lime kiln and used once more as lime (CaO) during the causticization process. On the other hand, paper mills' lime recovery processes require a lot of energy (1530–1830 kcal/kg of lime). One problem brought on by high silica concentration (5–10% in lime sludge) is scaling in the lime kiln (22). This is the rationale behind why paper businesses typically prefer to landfills instead of recycling lime sludge. Landfilling and land Rectification are the preliminary measures taken to get rid of lime waste from paper mills [6 [25]]. However, as landfill sites become more expensive and limited due to taxes, strict regulations, and declining potential, the cost of land-filling is rising. Due to its high quality, lime sludge is therefore extremely important for usage in building construction materials [26]. The potential uses of lime sludge in different building applications are shown in Figure 2.

Table 1. %Weight of different components in Raw Lime Sludge

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

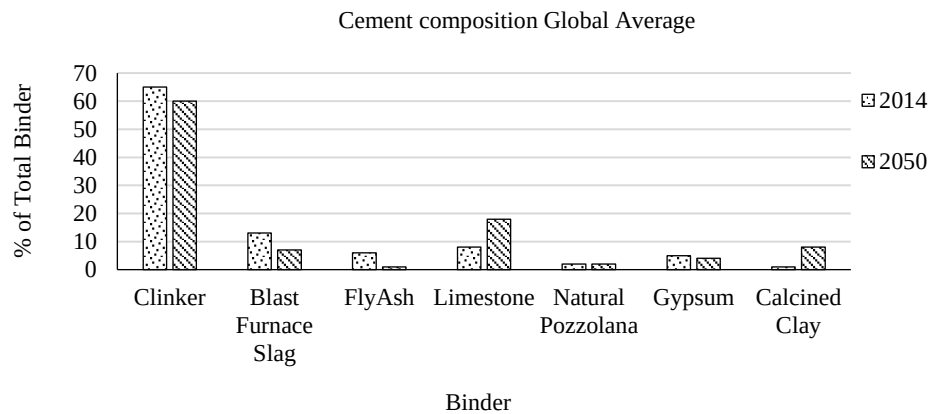


Figure 1. Global average of cement composition.

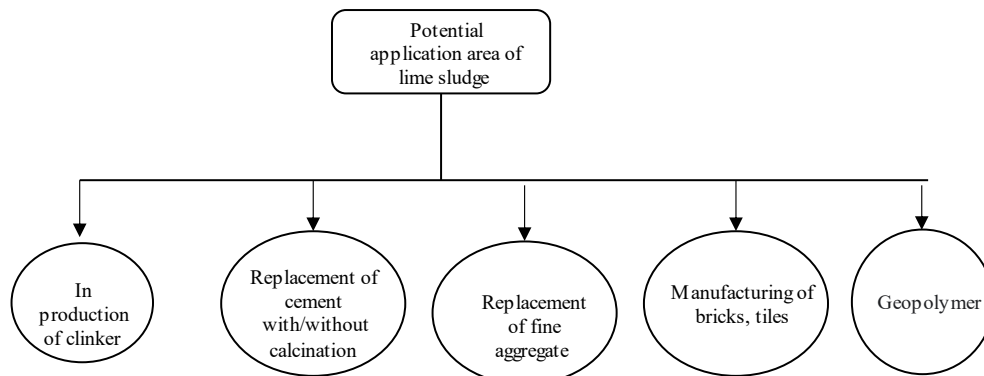


Figure 2. Potential application areas of lime sludge.

The demand for building materials is rising along with the global population. Therefore, the construction industry is now concerned about the imbalance between supply and demand for building materials [27]. Therefore, researchers are creating suitable alternative options for construction materials in order to close this gap and ensure the ongoing supply of building materials (21). Utilizing waste products from various sectors may be the way to close the supply-demand gap in the construction sector. Lime sludge, among other waste products, has excellent potential for use as building materials. Additionally, it is a successful strategy for reducing solid waste. Lime sludge has recently been combined with other wastes to produce a variety of materials used in construction. There have been numerous review papers and books written about paper mill waste [28–31], but none specifically discuss the use of lime sludge as a Binder in Construction and other building materials such as Bricks, Ceramics etc. cementitious binders, concrete, and ceramics. As a result, the current review paper has enormous potential for understanding how lime sludge consumption trends have evolved. Fig 3 depicts the process of manufacturing of lime sludge.

Cement Fabrication Uses

The demand for building materials is expanding exponentially, and cement remains the key component to meet these demands. As a result, it is crucial to address the expanding issues facing the cement business, such as resource conservation, CO₂ emissions, and energy use. The utilization of alternative materials mainly industrial waste and energy-efficient processes are the primary levers for the cement industries, according to the International Energy Agency. Although there have been recent efforts to promote the use of alternative materials, there is still room for growth in this area. There are consequently restrictions on the availability of the materials used to make typical cement constituents. As a result, in the upcoming years, new alternative materials might take the place of cement's component parts. Burnt clay pozzolanic cement blends with and without silica fume were examined by Amin et al. [19]. The 10% burnt clay with OPC exhibits improved compressive strength. The synthesis of CSH and

CASH with CH products was shown in the DSC and XRD tests. For the creation of blended cement paste, both silica fume and electric arc furnace slag were shown to be useful [20]. A similar strategy was also tested for making cement using lime sludge. The calcium carbonate, together with some silica and alumina, makes up the majority of the lime sludge. The calcium carbonate, together with some silica and alumina, makes up the majority of the lime sludge. Calcite and kaolinite are the two primary crystalline phases Table 1 found in lime sludge. While kaolinite is comprised of hydrous aluminium silicate ($2\text{H}_2\text{OAl}_2\text{O}_3 \cdot 2\text{SiO}_2$), Metakaolin ($\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$), a highly reactive byproduct of the calcination of lime sludge, can be employed as a cement ingredient. Reusing lime sludge demonstrates its potential as a source of pozzolanic activity for the creation of cementitious binders. The cementitious binder is thus the best material for utilizing lime waste.

A study on the utilisation of dried lime sludge in cement production was conducted by Wei et al. The result indicates that the addition of lime sludge enhanced the clinker's capacity to burn,[32] which in turn decreased the temperatures required for calcium carbonate decomposition and liquid phase production. Tricalcium silicate (C_3S) formation in cement clinker was also made possible by the presence of phosphorus and other trace elements, which enhanced the liquid phase and decreased the viscosity. [33] investigation into the manufacture of belite using nano-silica and paper mill lime waste. Alite is the primary component that makes up 80% of cement clinker, whereas belite, also known as b-dicalcium silicate ($\text{b-C}_2\text{S}$, Ca_2SiO_4), makes up 20% of Portland cement clinker.

But in this case, the elite was created via a solid-state reaction with lime sludge and nano-silica at a comparatively modest temperature of 850 °C. Additionally, the ratio of lime sludge to nano silica employed for the clinker preparation was 2 to 1. Lime sludge and silica fume were combined in[34] further study to create belite. The belite synthesis was carried out using the same experimental protocol but at a higher temperature. A study on the manufacturing of the binder from paper mill waste was conducted by [35]. To create belitic and Portland clinkers, various mixtures of lime sludge, biological sludge, and fly ash were made and then sintered at a temperature that was slightly lower than usual—1350 °C—for clinker synthesis. Additionally, it was determined that the mixture of 49 % lime sludge The largest quantity of belite synthesis was created using, 20% fly ash, and 30% biological sludge, which was also utilised to create the belite cement-based mortar, which provided adequate mechanical strength and exhibited no evidence of deterioration or durability flaws. (17) attempt to make eco-clinkers, lime sludge, coal biomass ash, and wastewater treatment process sludge were all utilised. In different quantities and configurations, the three fundamental materials were created and then burned at temperatures between 1350 and 1450 °C. According to the study, an eco-clinker formulation consisting of 69 % lime sludge, 29 % biomass ash, and 2 % wastewater process sludge at 1450 °C displayed the principal crystalline phases often present in commercial cement.

Additionally, the eco-cement was made with this eco-clinker (95 wt % of eco-clinker and 5 wt. % of gypsum). [36] Additionally, eco mortar was made using the eco-cement that was generated. It was found that the functionalization of eco-cement in mortar demonstrated a compressive strength of 21 MPa after 28 days of curing. Researchers also studied the function of lime sludge in geopolymer concrete in light of recent developments. In an experimental investigation, [37,38] employed lime sludge as an activator in the manufacturing of geopolymer cement CEM III/C and type 32.5 N class in accordance with European Standards EN-197. To manufacture one part of geopolymer cement, the lime sludge was combined with blast furnace slag after being prepared with sodium hydroxide. In the mortar preparation, more lime sludge that hadn't yet reacted served as filler. By adding more lime sludge, cement demonstrated greater compressive strength. It was found that an application of 18 % lime sludge produced the highest compressive strength (42 MPa)[39]. the strength characteristics of the mortars are examined taking into account the heat of hydration and setting time of cement. The cumulative heat release from the lime sludge cement is found to be equal to the OPC cement in terms of the heat of hydration. (27) The industries' disposal issues may be resolved by using lime sludge in cement production in an environmentally and economically responsible way. When lime sludge is used in the process of making cement, less naturally natural resources are consumed, which also reduces carbon emissions because less energy is used. [35,40] Table 2 describes the lime sludge use in preparation of clinker.

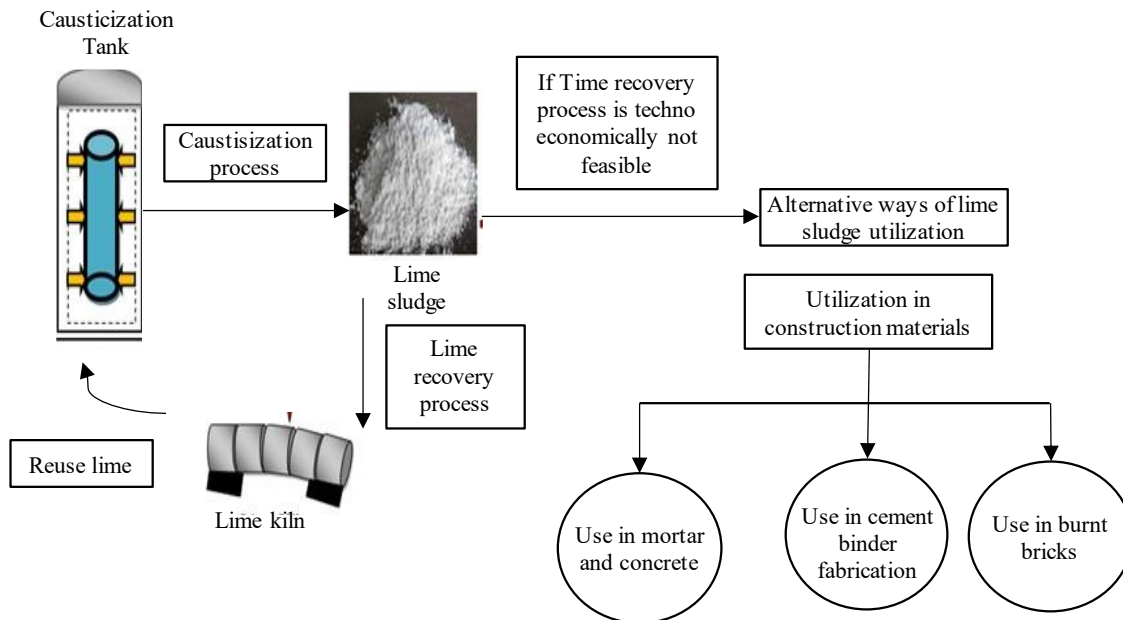


Figure 3. Manufacturing of lime sludge.

Table 2. Lime Sludge Use in Preparation of Clinker.

S.no.	Author	Parameter studies	Material used	Product
1	(33)	Mineralogical studies	Nano silica	Clinker
2	(34)	Mineralogical studies	Silica Fume	Clinker
3	(35)	Mineralogical, hydration and compressive strength	Fly ash and biological sludge	Clinker
4	(41)	The cement kiln's inclusion of lime sludge increased sintering.	Cement	Cement
5.	(35)	Density and Compressive Strength	LM and gypsum	Clinker
6	(37)	Ground granulated blast furnace slag and sodium hydroxide	Compressive strength, heat of hydration, and mineralogy	Geopolymer binder

RESULTS & DISCUSSION

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 and as received and mixtures with other substances. The research of many researchers on the impact of lime sludge in mortars is summarised in Table 3. The reactivity of lime sludge is increased by calcining it between 650 and 800 degrees Celsius[42]. 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 harm durability. For the preparation of mortar, [43] 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 % lime sludge, and it was found to be higher than that of regular concrete[19,44–46]. The conversion of calcium carbonate from the lime sludge calcium carbonate into calcium oxide during the heat treatment process may be the cause of 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, [47]Modolo et al. focused on the usage of received lime sludge. 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 a 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. (23) 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 favourable influence on the compressive strength of mortars. By using fly ash and lime sludge from paper mills that had already been received. [48] 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 was reduced if the %age of lime sludge replacement exceeded 10%. Experimental research by [49]. 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. Lime sludge, fly ash, and Portland cement were used to create a cement adhesive by. The mortars were grounded using cement pastes that contained a maximum of 20% lime sludge and fly ash(19). In the preparation of the mortar, fluidized bed reactor sand was utilised 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 the 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 up to replacement of 30% of total cement and then starts to drop with an exponential rate beyond that[50,51]. 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 by-products were applied along with lime sludge, and this improved the strength properties

Table 3. Lime Sludge Application in Mortar.

S. no.	Material replaced	Material added	% replacement	Optimum replacement	Parameters studies	Impact	Reference
1	Cement	Fly Ash, Gypsum	89-100	80	Compressive Strength	+2.7% (increase)	(23)
2	Cement		10-30	25	Compressive Strength	+3.1% Increase	(48)
3	Fine Aggregate		10-30	30	Compressive Strength	+1.34% (Increase)	(47)
4	Cement and Fine Aggregate	FlyAsh	10	10	Compressive strength	-37% (Decrease)	(19)
5	Cement	FlyAsh	10-20	10	Compressive Strength	-6% Decrease	43
6	Cement	FlyAsh	12.5	12.5	Flexural and Compressive Strength	-4.1% Decrease	(49)
7	Cement	Flyash, Silica Fume	30-70				(27)
8	CementFine aggregate		0-20	15	Compressive and Flexural strength,	-7% decrease	(50)

Application In Concretes

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 [51–57]. The manufacturing of cement-based building materials also uses wastes from the pulp and paper industries, such as lime sludge, deinking sludge, primary sludge, and waste paper fibre sludge. Different application techniques for lime sludge in the creation of concrete are shown in Table 4. Fig 4 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 [49,58–60].

Table 4. Lime sludge application in concrete.

S.no.	Replaced by	% replaced	Optimum % obtained	Parameter studies	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	Increases 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

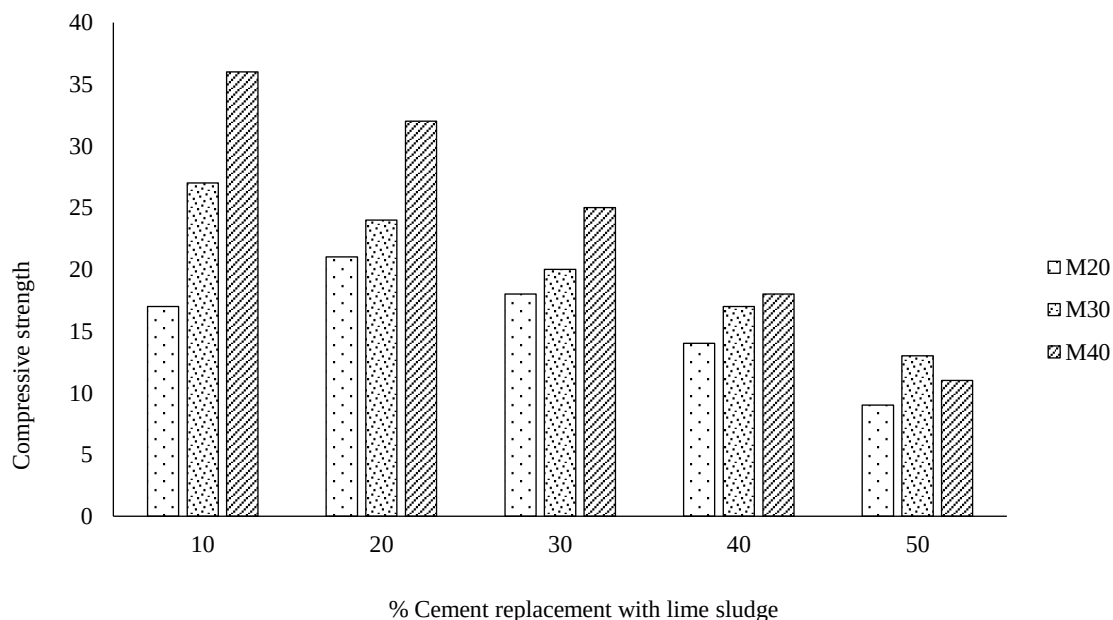


Figure 4. Variation of compressive strength with various design mixes.

Effect on compressive strength of concrete

The impact of lime sludge on concrete has been the subject of numerous investigations. Table 5 summarises the findings of numerous studies on the effects of applying lime sludge to different concrete grades after 28 days of curing. Researchers have used lime sludge to prepare various concrete grades. According to research on the concrete of the M20 grade, lime sludge replaced cement 10–20 % of the time, slightly increasing compressive strength compared to reference concrete. However, the compressive strength was reduced as a replacement was further increased. Furthermore, lime sludge demonstrates comparable compressive strength to conventional M20 grade concrete at a 30 % cement substitution level [59,61,62]. It's possible that the saturation of lime sludge binding in the matrix is what is having a detrimental effect on the larger %age of lime sludge. This limits the use of lime sludge in concrete in large quantities. The researchers used lime sludge in the higher grade of concrete since it was necessary to use lime sludge in large quantities. Numerous researchers attempted to increase the use of lime sludge in concrete blocks of the M30 grade. However, no researcher has identified a pattern akin to the one identified in the instance of M20 concrete. According to (61), lime sludge reduced compressive strength and only allowed a 30 % replacement of total cement. Since the compressive strength substantially reduced below the M30 grade of concrete beyond this limit of replacement. Similarly, [63] noted a decline in compressive strength. According to the study, lime sludge acts as a filler and only 20% of cement replacement is permissible in concrete of the M30 grade. There is no literature discussing the root cause and mechanism of these discrepant compressive strengths of M20 and M30 grade concrete. [64] advised replacing up to 10% of the cement with lime sludge without reducing the strength of the concrete in terms of the impact of lime sludge on the compressive strength of M40-grade concrete. Some investigations have concentrated on replacing fine aggregates with lime sludge in addition to replacing cement with the substance. In a study that contributed to the novelties in lime sludge utilisation, (49) found that concrete strength decreases when fine aggregate is replaced with lime sludge, but that this decrease is not equal to a 25 per cent replacement of fine aggregate. The claimed decline in compressive strength may be caused by the concrete's decreased workability. When lime sludge replaces fine aggregate with equivalently smaller particle size, the workability of the concrete matrix is maintained thanks to the coarser fine aggregate. The concrete matrix's reduced compressive strength is ultimately caused by the extra water present.

The presence of lime sludge affects the rheological characteristics of concrete, including fluidity, yield stress, plastic viscosity and cohesion between particles. (25,47,64). While raising the yield stress and cohesion between particles in the fresh state, adding more lime sludge decreased the matrix's fluidity and plastic viscosity. As lime sludge application increased, the apparent porosity of concrete decreased; at around 30%, compared to the reference concrete, the apparent porosity was reduced by 6%. The study recommended up to 30% replacement of the lime sludge based on the results of rheological experiments. In a study, [65]. found that, as the proportion of lime sludge grew, the yield stress of mortar increased and the plastic viscosity dropped. Additionally, it was found that applying lime sludge reduced the fluidity of mortar and increased the cohesiveness between particles and water.

After this point, the concrete's elasticity significantly decreased. The M40 grade of concrete provided the same modulus of elasticity as regular concrete. This influence on the rheology of concrete is generally attributed to the small particle size of the lime sludge, which lowers the free water content. As a result, the concrete loses workability and elastic modulus while increasing cohesiveness, viscosity, and yield stress.

Application With Other Waste Materials

To keep the concrete's desirable quality, lime sludge has also been used in conjunction with other pozzolanic supplementary cementitious materials. When combined with calcium hydroxide, pozzolanic materials—which are either siliceous or siliceous and aluminous—form cement. Pozzolanic elements were successfully included in lime sludge-based binders, greatly improving their resistance to deterioration in harsh environments and increasing their durability. In both conventional curing and air curing, binary blended cement concrete with pulverised fly ash and metakaolin and various

combinations of cementitious systems demonstrated increased strength and durability. According to reports, the reduction in chloride ions intrusion resulted in the reinforcement of safety measures. In comparison to the control mix, the ternary mixed concrete with cement, fly ash, and silica fume offers increased strength and greater durability. For ternary blended concrete, long-term resistance to sulphate attack revealed very strong chemical resistance. [20,66–68]

One of the most important characteristics of lime sludge-based concrete and mortar is durability. Numerous studies show that using fly ash and silica fume in particular ratios with lime sludge as a partial replacement improves the durability of concrete. Numerous supplementary cementitious materials (SCMs) are utilised widely, such as fly ash, slag cement, rice husk ash, metakaolin, palm oil fuel ash, and silica fume [49,69–71]. In order to study the chemical resistance of lime sludge-based cement concrete, (49) subjected it to 5% HCl and 5% H₂SO₄. The acid mass loss factor for H₂SO₄ was higher than for HCl, indicating that concretes are more vulnerable to sulphate attack.

Due to the similar effects of quarry dust and fly ash on concrete, the application of lime sludge along with fly ash and quarry dust had a favourable impact on compressive strength (60). In their study of the mechanical characteristics of concrete with a strength of 30 MPa, substituted lime sludge for fine aggregates and silica fumes for cement, respectively. (33)The investigations were also conducted using a mixture of silica fume and lime sludge. At 28 days, it was found that replacing 20% of the fine aggregate with lime sludge and 20% of the cement with silica fume produced concrete with a similar compressive strength to the control concrete. (68) replaced cement with nano-silica and paper mill lime sludge and found that the compressive strength remained the same as that of traditional concrete of M30 grade at 4% nano-silica and 30% dried and crushed lime sludge. The boiler ash employed in the procedure was used to create the nano silica, which had a specific surface area of 450 m²/g with particle sizes ranging from 10 to 25 nm.

The strength of the concrete was increased by adding silica fume and nano-silica to lime sludge, but this procedure also has to be evaluated for its economic viability. Jute and glass fibres were used by(49) in addition to drinking and repulping generated paper mill lime sludge. For the M30 grade of concrete, lime sludge and sludge were combined in place of cement. Concrete only attained a modest amount of compressive strength, and only a 10% application of sludge was suitable when combined with jute and glass fibre. [72] Lime sludge and wood ash were applied together for the manufacture of concrete, this study recommended using lime sludge in concrete to minimize sludge disposal and to cut back on carbon dioxide and other greenhouse gases[73–77].

Table 5. Other materials used with Lime Sludge.

S.no.	Added material	Material replaced	Optimum % replacement	Grade	Parameter studies	Chang in strength	Reference
1	Jute and Glass Fibers	Cement	30%	M30	Compressive Strength	Increase	(49)
2	Nano Silica	Cement	30%	M20		Decrease 1.37%	(68)
3	Quarry Sand	Cement	20%	M20		Decrease 12.5%	(60)
4	Silica Fume	Fine aggregate	20%	M30		Decrease 6.09%	(63)
5	Fly Ash	Cement	10%	M20	Flexural Strength, Workability	Increase 8.91%	(58)

Application In Bricks and Ceramics

In India, burned clay bricks are widely used. Due to its great plasticity and appropriateness for moulding, river basins, ponds, and coastal locations are where the clay scrap is typically found when

creating high-quality burnt clay bricks. Due to the nation's expanding need for clay-based bricks, alluvial soil supplies that are ideal for building bricks are being used up more quickly than they can be replenished. It also raises more issues because alluvial soil accounts for the majority of India's agricultural production.

There have been several studies on the use of recycled paper mill waste, craft pulp residue, sludge from the marble business, trash from the rice industry, waste from the sugarcane industry, waste glass sludge, sawdust, and urban garbage in the manufacturing of burnt bricks [28,78–81].

The completed work of the Researcher on the impact of lime sludge in burnt clay bricks and ceramics is compiled in Table 6. The mechanism of the reaction between the calcium and silicate phases during brick firing was put out by [82]. Furthermore, XRD (X-ray diffraction spectroscopy) investigations came to the conclusion that the most important aspect in brick creation and the development of strength in the bricks is the firing temperature. Better brick manufacture results from significant phase shifts caused by temperatures more than 1000 °C. A technique for producing burnt clay bricks using textile mill effluent that contains red, white, and black soil was devised by (79). Additionally, sludge was combined with soils for brick manufacture to get superior physical and mechanical characteristics while still meeting the requisite amount of silica and other minerals in the soils. For the best compressive strength of the bricks, a firing temperature of 800 °C and a firing time of 24 hours were determined to be ideal. Compressive strength of 4.5 N/mm² was acceptable for bricks containing 15% lime sludge, while bricks containing more than 15% lime sludge were found to have a compressive strength that was less than the minimal permissible level of 3.5 N/mm² for burnt clay bricks [83]

Studies on the utilisation of lime sludge also demonstrate its application in the creation of pottery. According to a study by [84], lime sludge and fly ash from the paper industry can be used to create anorthite ceramic through the process of solid-state reaction. Additionally, studies were conducted to test various mixtures of lime sludge and fly ash under various sintering temperatures. The anorthite phase was found to be primarily synthesised in the sample containing 36% lime sludge, however, it was mostly present in all samples at 1100 °C. Further research on the synthesis of ceramic material by direct mixing of already-received lime mud, fly ash, and other additives (sawdust, shale, diatomite, and perlite) was done by the author.

Table 6. Lime sludge application in bricks.

S.no.	Material	% replacement	Prepared material	Parameter studied	Effect on strength	Reference
1	Clay, Fly ash	40	Bricks	Compressive strength	Decrease 4.1%	(85)
2	Fly Ash	36	Artistic Ceramic	Compressive Strength and Mineralogy	Decrease 5.1%	(40)
3	Fly Ash	60	Bricks	Compressive strength and Mineralogy	Decrease 2.3%	(86)
4	Flay Ash	20	Tiles	Compressive strength		(45)
5	Fly Ash	40	Bricks	Compressive strength		(87)

ENVIRONMENTAL ADVANTAGES OF LIME SLUDGE UTILIZATION AS A BUILDING MATERIAL

Due to the need for vast amounts 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 increases 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 have a big impact on 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 [88]. Paper mill sludge when compacted 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 a 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 [89]. demonstrated that the %age of leachable trace elements was extremely low, which was advantageous for the utilization of lime sludge.

CONCLUSIONS

The replacement of cementitious binder or fine aggregates in concrete and mortar with lime sludge has substantial potential. According to several published works, the compressive strength of concrete and mortars doesn't change until 30 % 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 %. 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 %). 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.

The study is beneficial to a lot of resource persons who are involved in using used lime sludge to make sustainable building materials.

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