Metakaolin Blended with Lime Sludge in Concrete for Enhanced Performance and Eco-Efficient Infrastructure

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Abstract. The construction industry's ongoing quest for sustainable materials has directed attention toward the use of industrial by-products and natural pozzolans as alternatives to conventional cement. This study explores the combined effect of lime sludge and metakaolin, introduced as equal-proportion partial replacements for cement, on the fresh and hardened properties of M30 grade concrete. Replacement levels of 0%, 10%, 20%, and 30% were considered, designated as LM(0), LM(5), LM(10), and LM(15), respectively. Experimental evaluations included compressive strength, split tensile strength, flexural performance, and slump retention, conducted at multiple curing intervals up to 90 days.Results demonstrated that a 20% total replacement (LM10) yielded the most favorable outcomes, surpassing the control mix in all mechanical parameters. The enhanced performance was attributed to the fine particle size and high pozzolanic reactivity of metakaolin, complemented by the filler effect and latent hydraulic behavior of lime sludge. Notably, the LM(10) mix exhibited superior strength development without compromising structural reliability, making it suitable for both load-bearing and durability-critical applications.

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

1. Introduction

In the ongoing pursuit of sustainable and resource-efficient construction practices, the exploration of alternative materials that can partially replace conventional cement has gained significant traction. Among the many materials investigated for such roles, lime sludge and metakaolin have emerged as promising supplementary components due to their unique chemical compositions and beneficial reactivity with cementitious systems. Lime sludge, typically a by-product generated from industries such as paper manufacturing and water treatment plants, is rich in calcium-based compounds[1]–[3]. Its disposal poses a serious environmental challenge, often resulting in land and water contamination. However, its fine texture and high calcium oxide content make it a it a viable additive in concrete mixes, where it can participate in the hydration process

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and contribute to improved strength characteristics when carefully processed and blended[4], [5].On the other hand, metakaolin, derived through the calcination of purified kaolinite clay at moderate temperatures, is an amorphous aluminosilicate with a high pozzolanic activity. When incorporated into cementitious systems, it reacts with calcium hydroxide released during hydration to form additional calcium silicate hydrate (C–S–H) gel[6]–[8]. This reaction enhances the concrete's microstructure, leading to better mechanical performance, reduced permeability, and increased resistance to chemical attack.

Together, the incorporation of lime sludge and metakaolin not only aids in reducing the overall clinker content in cement-based composites but also supports the recycling of industrial by-products, contributing to a circular economy. The synergy between the pozzolanic and cementitious reactions offered by these materials makes them suitable candidates for developing durable and eco-friendly concrete tailored for modern infrastructure demands.

2. Materials used

The primary binder employed in this investigation was commercially available Ordinary Portland Cement of 43-grade, conforming to IS: 8112 specifications. It was sourced in sealed bags from a reputed manufacturer and stored in a dry environment to prevent moisture ingress. The cement was free from lumps and impurities, exhibiting a standard fineness and a typical light grey color. Well-graded natural river sand was used as the fine aggregate component. Prior to mixing, the sand was sieved to remove oversized particles and debris, then washed thoroughly to eliminate dust and clay particles. It fell within Zone II as per IS: 383 recommendations, ensuring proper workability and packing density in the concrete mix. Crushed angular stone with a nominal maximum size of 20 mm was employed as the coarse aggregate. The material was obtained from a local quarry and was cleaned of fines before usage. Its physical properties—including specific gravity, impact value and water absorption—were determined through standard laboratory procedures to confirm compliance with codalstandards. Industrial lime sludge was collected as a waste by-product from a paper manufacturing facility. This material was first sun-dried to remove excess moisture and then ground into a fine powder using a laboratory-grade ball mill. The powdered sludge, rich in calcium-based compounds, was passed through a 90-micron sieve to ensure uniformity and compatibility with cementitious components. Its potential for reactivity and filling capacity was noted as a key motivation for its inclusion. The metakaolin used in this study was procured from a certified supplier specializing in pozzolanic additives. Produced through the controlled calcination of pure kaolin clay, the material presented as a fine, off-white powder. The particle size was consistently below 45 microns, and its high silica and alumina content were essential in promoting secondary hydration reactions. It was stored in airtight containers to prevent exposure to atmospheric moisture. Each material was characterized prior to mix formulation through laboratory testing, including particle size analysis, specific gravity determination, and chemical composition assessment using appropriate methods. This rigorous approach ensured that all inputs met the quality standards necessary for reliable and reproducible concrete performance throughout the study.

3. Methodology

The experimental procedures followed in this study were systematically designed to ensure the accurate evaluation of concrete performance when incorporating lime sludge and metakaolin as partial replacements for cement. Each phase of the methodology—from material preparation to testing—was conducted under controlled laboratory conditions with close attention to consistency, precision, and reproducibility. Concrete batches were prepared with varying replacement levels of lime sludge and metakaolin in place of Ordinary Portland Cement by weight. The control mix consisted solely of OPC, while modified mixes included 5%, 10%, 15%, and 20% combinations of the supplementary materials. The water-to-binder ratio was held constant for all mixes to isolate the influence of the binders. Proportions of fine and coarse aggregates remained unchanged throughout. Mixing was carried out in a mechanically driven pan mixer. Initially, dry constituents (cement, lime sludge, metakaolin, fine and coarse aggregates) were blended for a defined duration to ensure uniform distribution. Subsequently, measured quantities of water were introduced gradually, and the entire mixture was churned further to attain a homogenous, workable mass. Visual inspection ensured that no lumps or dry pockets remained. Freshly prepared concrete was poured into standard cube (150 mm × 150 mm × 150 mm) and cylinder (150 mm diameter × 300 mm height) moulds in three layers, each compacted using a table vibrator. The moulds were lightly tapped to expel entrapped air and produce dense specimens. Surface finishing was carried out using steel trowels.
After casting, the moulded specimens were covered with damp cloth and left undisturbed for 24 hours in ambient conditions. Upon demoulding, the specimens were transferred into a curing tank filled with clean water maintained at room temperature. Curing was performed for predefined durations—7, 14, and 28 days. At the end of each curing period, specimens were tested for compressive and split tensile strength using a calibrated universal testing machine. Testing procedures adhered to national standard practices. Each test was conducted on a minimum of three specimens, and the average value was reported. Observations related to appearance, density, and failure mode were also noted. All experimental data were systematically recorded in structured templates. Results were analyzed to identify performance trends, influence of binder replacement levels, and possible synergistic effects between lime sludge and metakaolin. Statistical treatment of the data ensured that the findings were both credible and reflective of the true behavior of the material combinations. This structured and replicable methodology forms the foundation for assessing the viability of industrial by-products and naturally occurring pozzolanic materials in reducing reliance on conventional cement, while maintaining or improving structural performance in concrete applications. Table 1 shows the mix design of the blends.

Table 1: Mix design of the blends.

Mix	OPC (kg/m^3)	Lime Sludge (kg/m^3)	Metakaolin (kg/m^3)	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	Water (kg/m^3)
L0M0	400	0	0	650	1200	180
LM(5)	360	20	20	650	1200	180
LM(10)	320	40	40	650	1200	180
LM(15)	260	60	60	650	1200	180

4. Results and Discussion

4.1. Workability

The slump retention behavior of M30 concrete mixes with lime sludge (L) and metakaolin (M) as partial replacements for cement was monitored at regular time intervals up to 80 minutes as shown in Figure 1. The mixes analyzed—LM(0), LM(5), LM(10), and LM(15)—represent 0%, 10%, 20%, and 30% total cement substitution respectively, using equal proportions of lime sludge and metakaolin. At the initial stage (0 minutes), all mixes exhibited relatively high slump values, with LM(0) (control) reaching the peak slump at approximately 175 mm, followed closely by LM(5) and LM(10), while LM(15) trailed at 145 mm. The reduction in initial slump with increasing replacement level is attributed to the finer particle size and higher surface area of metakaolin and lime sludge[6], [9]–[11]. These materials absorb more mixing water due to their porous and angular morphology, leaving less free water in the mix, which reduces the plasticity. As time progressed, slump values declined steadily across all mixes, but the rate of slump loss was more significant in mixes with higher replacement percentages. By the 80-minute mark, the slump for LM(0) remained relatively workable at around 130 mm, whereas LM(5) and LM(10) dropped to 115 mm and 105 mm respectively. LM(15), however, showed a substantial slump loss, declining to 80 mm, reflecting its reduced flowability over time. The accelerated slump loss in LM(10) and LM(15) can be directly linked to the high pozzolanic reactivity and water demand of metakaolin, which, while beneficial for long-term strength and microstructure, tends to absorb available moisture, accelerating stiffening of the mix rapidly. Additionally, lime sludge, though offering a filler effect, has a tendency to compact early due to its chalky nature, contributing further to reduced slump retention[8], [12], [13].

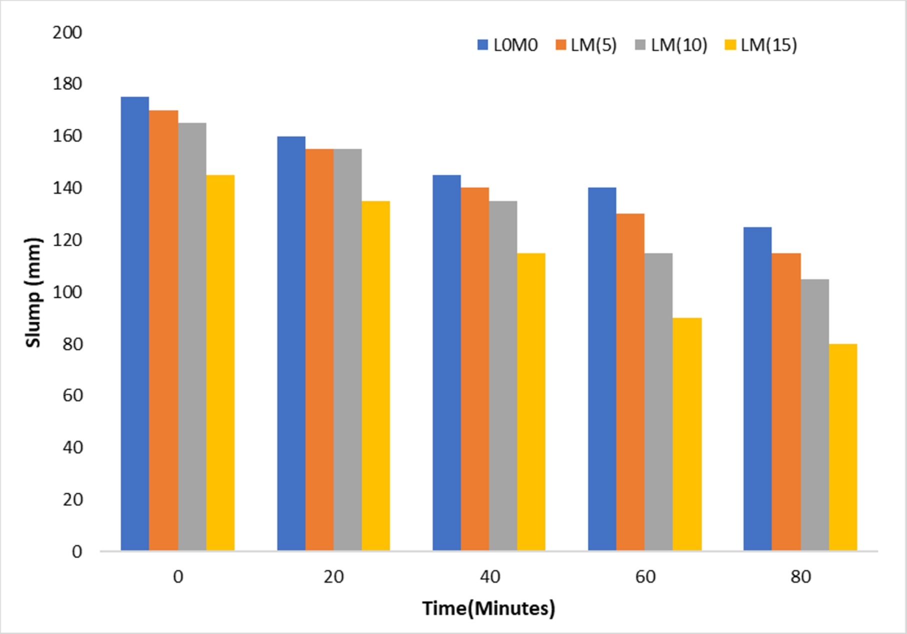

Figure 1: Slump values of blends

4.2. Compressive strength

The figure 2 of compressive strength development across different curing ages (7, 28, and 90 days) for M30 concrete mixes incorporating lime sludge (L) and metakaolin (M) highlights the distinct influence of increasing cement replacement levels on strength performance. Each LM(x) designation indicates a **combined replacement** of cement, where the value in parentheses reflects **equal proportions of lime sludge and metakaolin** (e.g., LM(10) = 10% L + 10% M = 20% total replacement).At**7 days**, all mixes demonstrate a reasonable gain in early strength, though with subtle differences. The control mix (LM0), composed entirely of OPC, registered a compressive strength of approximately 27 MPa. Both LM(5) and LM(10) slightly exceeded this, indicating the potential of the lime sludge–metakaolin blend to support early hydration. This enhancement is likely due to the filler effect and high surface reactivity of metakaolin, which can accelerate the nucleation of hydration products[1], [9], [14], [15]. However, LM(15), with 30% total replacement, showed a slight drop in strength compared to the control. This suggests that excessive substitution may initially hinder hydration due to reduced availability of primary clinker phases.The performance gap becomes more pronounced at **28 days**. The LM(10) mix exhibits the highest strength, surpassing even the control mix, which demonstrates the synergistic reactivity of metakaolin and the latent cementitious properties of lime sludge. The pozzolanic reaction between metakaolin and calcium hydroxide released during cement hydration results in the formation of additional calcium silicate hydrate (C–S–H) gel, which improves the concrete's microstructure and strength[16]–[18]. LM(5) also maintained strength comparable to the control. In contrast, LM(15), with a higher replacement level, showed a slight decline, indicating that the dilution of OPC beyond a certain threshold may reduce overall binder efficiency.At**90 days**, long-term strength development continued to follow a similar trajectory. LM(10) remained the most effective blend, yielding the highest compressive strength among all mixes. This result emphasizes the prolonged pozzolanic activity and densification of the matrix over time[19]–[22]. LM(5) and LM(15) also improved beyond their 28-day strengths, although LM(15) remained marginally below the control, reaffirming that while higher replacements continue to contribute to strength gain, the rate and extent of such gains diminish beyond 20% total substitution. This behaviour is due to the void free and compact matrix development by pozzolanic action of replacements used[23]–[27].

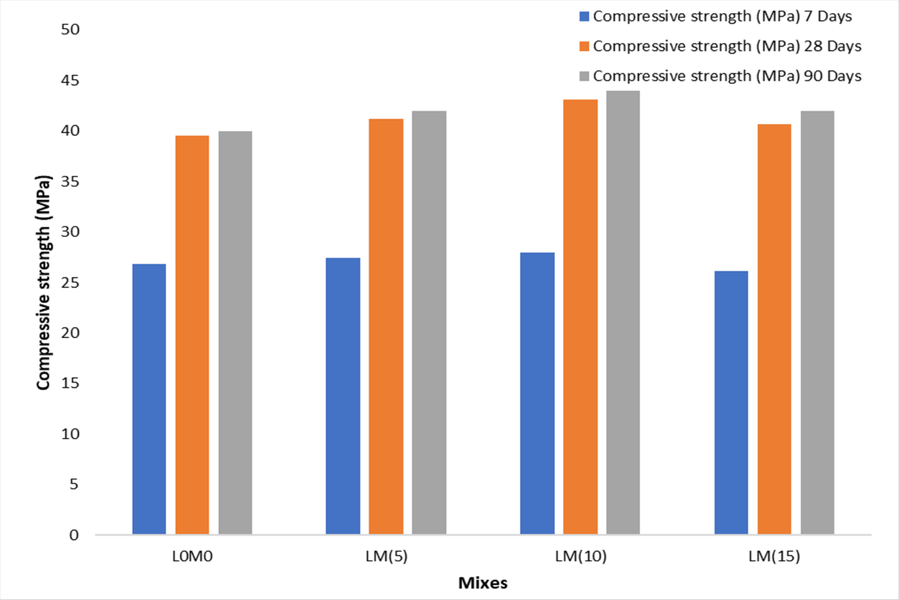

Figure 2: Compressive strength of the blends

4.3. Flexural strength

The flexural strength behavior of M30 concrete mixes incorporating lime sludge (L) and metakaolin (M) as supplementary cementitious materials was studied at three curing intervals: 7, 28, and 90 days is shown in Figure 3. The designations LM(0), LM(5), LM(10), and LM(15) represent total cement replacement levels of 0%, 10%, 20%, and 30%, respectively, with equal proportions of lime sludge and metakaolin.The**control mix (LM0)** recorded a flexural strength of around **3.8 MPa at 7 days**, which increased to **approximately 4.7 MPa at 28 days**, and further improved to **5.0 MPa at 90 days**. This gradual strength gain reflects the typical hydration pattern of conventional OPC-based concrete, providing a baseline for evaluating the influence of SCMs[28]–[32].Upon incorporating a **10% total replacement** in the LM(5) mix (5% L + 5% M), a marginal improvement was observed across all curing periods. The 7-day strength increased slightly to **4.0 MPa**, while 28- and 90-day values reached **4.9 MPa** and **5.2 MPa**, respectively. The enhancement can be attributed to the combined benefits of the fine lime sludge particles filling microvoids and the highly reactive metakaolin triggering early pozzolanic reactions, leading to a denser and more cohesive matrix[33]–[35].The most remarkable performance was observed in **LM(10)**, where **20% total cement replacement** (10% L + 10% M) resulted in superior flexural strength development across all time frames. The 7-day strength rose to **4.7 MPa**, reflecting strong early-age matrix formation. By 28 days, the mix attained a strength of **5.1 MPa**, and at 90 days, it peaked at **5.5 MPa**.

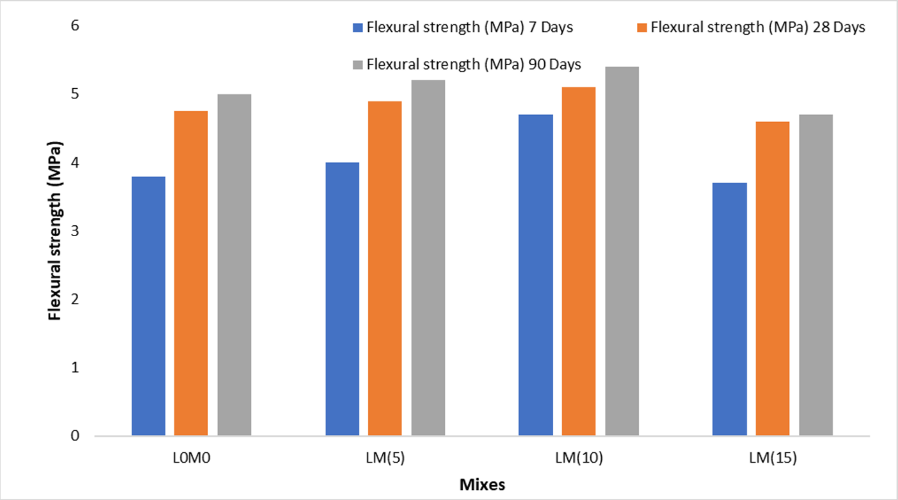

Figure 3: Flexural strength of the blends

These results highlight the effective synergy between the high surface reactivity of metakaolin and the calcium-rich character of lime sludge. Their interaction likely promotes secondary hydration products and microstructural refinement, leading to improved tensile stress distribution and crack-bridging capability under flexural loading[36]–[38].However, at the **30% total replacement level** in LM(15), a slight decline in performance was evident. The 7-day strength dropped back to **3.7 MPa**, and the trend continued modestly with values of **4.6 MPa** at 28 days and **4.7 MPa** at 90 days. This suggests that beyond a certain threshold, the replacement of OPC leads to reduced binder efficiency, possibly due to insufficient calcium hydroxide for complete pozzolanic reaction and a decrease in the cementitious phase needed to form primary hydration compounds. The resulting paste may become leaner, affecting the ability of the concrete to resist tensile stresses along the beam's lower fiber under bending[19], [39], [40].

4.4. Split tensile strength

The split tensile strength results for M30 concrete incorporating lime sludge (L) and metakaolin (M) in varying proportions were evaluated over three curing periods: 7, 28, and 90 days as shown in Figure 4. The mixes—LM(0), LM(5), LM(10), and LM(15)—correspond to 0%, 10%, 20%, and 30% total replacement of cement, respectively, with equal portions of lime sludge and metakaolin.From the graphical data, a clear and coherent trend emerges across all mixes and curing durations. The **control mix (LM0)**, composed entirely of OPC, exhibited a 7-day split tensile strength of approximately **2.3 MPa**, which steadily increased to about **3.4 MPa** by 90 days. This serves as a benchmark for comparing the modified mixes. With a **10% replacement** (LM5), there was a notable improvement in strength across all ages. The 7-day strength rose to nearly **3.0 MPa**, while the 28- and 90-day results were consistently above the control, indicating enhanced early bonding and progressive microstructural development.

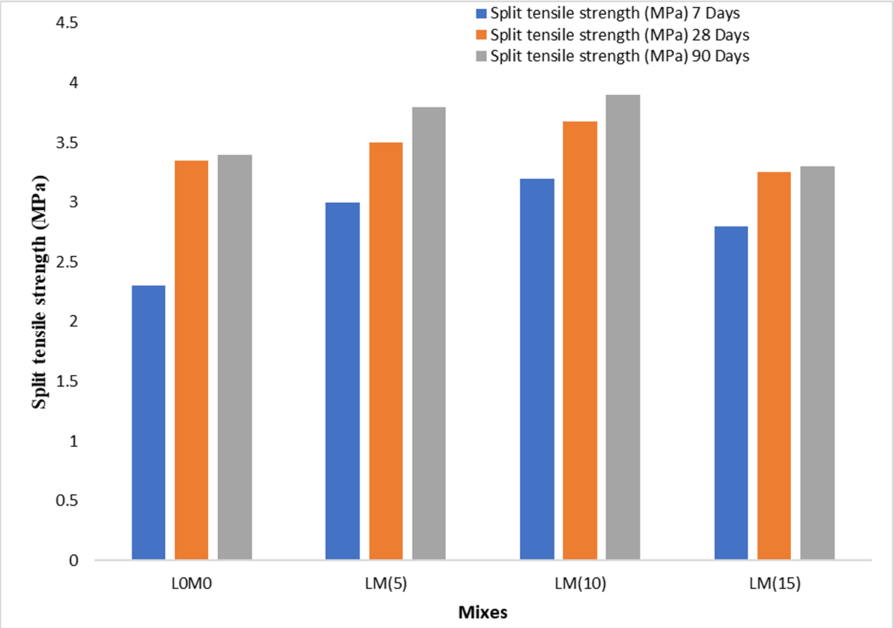

Figure 4: Split tensile strength.

This performance enhancement can be linked to the **fine particle size and reactivity of metakaolin**, which promotes the formation of additional calcium silicate hydrate (C–S–H) gel, while lime sludge contributes to matrix densification through its filler effect[36], [41], [42]. The **peak performance** was observed with the LM(10) mix, involving **20% total replacement** (10% L + 10% M). Here, the strength at 7 days exceeded **3.2 MPa**, progressing to nearly **4.0 MPa** at 90 days. This demonstrates a strong pozzolanic synergy between lime sludge and metakaolin. The improvement is particularly significant at 28 and 90 days, where long-term hydration and pozzolanic reactions intensify, leading to a more cohesive and refined microstructure. Additionally, the lime sludge's calcium content likely supplements the ongoing reactions, compensating for the reduced OPC content[2], [3], [43].However, as the replacement level increased to **30% in LM(15)**, a decline in tensile strength was observed, though the values still remained within structurally acceptable ranges. The 7-day strength dropped to around **2.8 MPa**, while 90-day strength plateaued just below **3.5 MPa**. This reduction suggests that beyond a certain threshold, the dilution of OPC and insufficient availability of free calcium hydroxide may limit pozzolanic activity, resulting in a less cohesive matrix and weaker bond development[6], [44], [45].For sustainable development further research could be enhanced using modern AI and ML techniques[46-51].Further optimizations could also be done through statistical methods like Taguchi and Response Surface Methodology (RSM) [52-55].

5. Conclusion

This experimental investigation examined the influence of lime sludge and metakaolin, used as partial replacements for Ordinary Portland Cement in equal proportions, on the fresh and hardened properties of M30 grade concrete. Four mix variants were studied, with total cement replacement levels of 0%, 10%, 20%, and 30%, designated as LM(0), LM(5), LM(10), and LM(15), respectively. The results clearly indicate that a balanced substitution of 20% (LM10) provided the **optimum performance across all mechanical properties**. This mix consistently outperformed the control in compressive, split tensile, and flexural strength at all curing ages, including up to 90 days. The improvement was attributed to the synergistic behaviour of metakaolin's high pozzolanic reactivity and lime sludge's dense filler effect, which collectively contributed to enhanced matrix formation, better packing density, and reduced porosity. In terms of **split tensile and flexural strength**, LM(10) again emerged as the best-performing mix, offering higher resistance to cracking and bending stresses due to improved interfacial bonding and the formation of supplementary calcium silicate hydrate. These enhancements were sustained over time, confirming the long-term benefits of the hybrid binder system. However, the study also observed a **progressive decline in workability and slump retention** as the replacement percentage increased. The highest replacement mix, LM(15), while still within acceptable strength limits, exhibited rapid slump loss, reduced initial flowability, and early stiffening tendencies. This reinforces the understanding that higher levels of SCMs, though beneficial in terms of strength and durability, require careful water management and possible admixture adjustments for practical field applications.

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