

A Literature Review on Metakaolin and Steel Slag Based Concrete

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Abstract - The most popular building material in the world is concrete, which causes serious environmental problems due to the exploitation of raw materials and CO₂ emissions during the cement-making process. Approximately one ton of CO₂ emissions and significant energy usage are produced for every ton of cement. A solution is provided by supplementary cementing materials (SCMs), which improve concrete performance while using less cement. One prominent SCM that functions as a pozzolanic substance is metakaolin (MK), which is obtained from calcined kaolinitic clay. This study presents a thorough overview of the literature on the use of MK as a partial cement substitute in mortar and concrete.

Key Words: Concrete, Metakaolin, Fresh concrete properties, Workability, Mechanical properties, Permeability & pore size distribution.

1. INTRODUCTION

1.1 Concrete: - Concrete, which is mostly made of water, aggregates, and Portland cement, is manufactured in two billion tons a year and is used in construction because of its strength, durability, and affordability. Measuring, mixing, and a 28-day curing period are all part of the concreting process. Despite its benefits, concrete is weak under tension and Portland cement is a major source of CO₂ emissions worldwide. Additives improve performance, and research is continuing to provide more robust and environmentally friendly substitutes. Although concrete is still necessary for civil engineering, improvements in admixtures are required to make it more workable and durable.

1.2 Metakaolin:- By lowering cement usage and increasing strength and durability, the use of pozzolanas, especially high-reactive metakaolin (MK), improves mortar and concrete efficiency. With a mean size of around 3 μm, 99.9% of MK's particles are less than 16 μm. With trace proportions of other oxides, it is composed of 50–55% SiO₂ and 40–45% Al₂O₃. Because supplemental cementitious materials (SCMs) like MK require a large quantity of calcium hydroxide (CH), which does not add to concrete strength and may adversely impact durability, a higher alumina concentration boosts pozzolanic capability. By creating calcium silicate hydrate gel, which greatly increases overall strength, metakaolin strengthens and prolongs the life of concrete. By sealing in the gaps between

cement and aggregates, it lowers permeability and stops moisture and chemicals from penetrating and causing degradation. Additionally, because of its spherical form and tiny particle size, which improve dispersion, lower water requirements, and increase viscosity for easy placement, metakaolin increases the workability and cohesiveness of concrete mixtures.

Table-1 Physical Properties of Metakaolin

Property	Value
Specific gravity	2.60
Bulk density (g/cm ³)	0.3 to 0.4
Physical form	Powder
Color	Off-White
GE Brightness	79–82

Table-2 Chemical Composition of Metakaolin

	% by mass
SiO ₂	51.52
Al ₂ O ₃	40.18
Fe ₂ O ₃	1.23
CaO	2.0
MgO	0.12
K ₂ O	0.53
SO ₃	0.0
TiO ₂	2.27
Na ₂ O	0.08
L.O.I	2.01

1.3 Metakaolin reactivity: - The calcination conditions of kaolinite and the characterization of metakaolin (MK) are critical in understanding its thermal activation through dehydration, resulting in a reactive transitional phase. The interaction between amorphous silica (AS₂) and calcium hydroxide (CH) during cement hydration yields additional cementitious C-S-H gel and various crystalline products, influenced by the AS₂/CH ratio and temperature. The incorporation of MK as a partial replacement for Portland cement significantly lowers CH concentration, with studies showing a reduction of up to 20% replacement, and complete removal at higher levels (30-40%) under specific conditions. Research indicates peak pozzolanic activity in MK-PC pastes occurs around 14 days, leading to a reduction in CH and higher compressive strength due to the reaction between MK and CH. The degree of pozzolanic reaction is enhanced at lower replacement levels (5%), attributed to a higher concentration of CH compared to higher replacements.

1.4 Steel slag: - Steel slag is a byproduct of steelmaking, formed from reactions in the furnace that remove impurities from iron ore and flux materials. Its composition varies depending on raw materials and processes, generally containing residual metals and metallic iron. There are three main types: Basic Oxygen Furnace (BOF) slag, rich in CaO, SiO₂, and FeO; Electric Arc Furnace (EAF) slag, which has higher magnesium oxide and phosphorus; and Ladle Furnace (LF) slag, enriched in calcium and magnesium oxides. Steel slag is dense, hard, and durable, making it suitable for construction. It is used as an aggregate in road construction, in cement production, as a soil amendment, for environmental remediation, and in steel recycling. However, potential metal leaching is a concern, necessitating safety testing for environmental applications. Overall, steel slag serves as a valuable resource for various economic and environmental benefits.

Table 3.2.1.1 Properties of steel slag

S. No.	Properties of steel slag	Value
01	Appearance	Powder
02	Colour	grey
03	Density	2.65(gm/cm ³)
04	Specific gravity	3.40

1.5 Development of concrete with metakaolin & steel slag techniques:- The process of developing concrete using steel slag and metakaolin comprises utilizing these resources to produce concrete with improved qualities. Steel slag, a byproduct of the steel industry, can partially substitute natural aggregates to save costs and enhance density and mechanical qualities. Metakaolin is a high-reactivity pozzolan that increases strength and durability by improving microstructure and decreasing porosity. Increased strength, better resistance to chemical assaults, increased sustainability through fewer carbon emissions and dependence on natural aggregates, and decreased porosity, which improves resilience to environmental problems, are all advantages of their combination.

1.6 Techniques for integrating metakaolin and steel slag in concrete:- Methods for incorporating steel slag and metakaolin into concrete need precise mixing, curing, and proportioning. While steel slag may replace 10–50% of coarse aggregates, necessitating processing for compatibility, metakaolin usually replaces 5–15% of cement, improving workability and compressive strength. Due to their effect on water demand, mix design modifications are required, frequently involving the use of superplasticizers. The pozzolanic reaction of

metakaolin requires proper curing and extension when needed. Fresh steel slag should also be aged or treated to stop expansion from free lime and periclase, and fine grinding is advised when using it in place of cement to increase reactivity.

2. LITERATURE REVIEW:

- A comprehensive study by **Silva et al. (2024)** examined the long-term performance of mortars incorporating ladle furnace slag and metakaolin. The results indicated that the combined use of MK and slag significantly improves compressive strength and durability over time due to continued pozzolanic and hydraulic reactions, leading to a denser cement matrix .
- **Wei et al. (2024)** reported that partial replacement of cement with metakaolin and slag improves reactivity and strength development, confirming their feasibility as alternative binders .
- In 2024, research on the **synergistic hydration mechanism** of steel slag and metakaolin demonstrated that their combined incorporation enhances cement hydration through ionic dissolution and complementary chemical interactions. The study showed that metakaolin compensates for the low reactivity of steel slag, resulting in improved formation of calcium silicate hydrate (C–S–H) gel and refined pore structure . This synergy leads to improved microstructural densification and reduced porosity.
- **Ibrahim et al. (2025)** investigated the replacement of natural aggregates with steel slag and found significant improvements in compressive strength and sustainability, highlighting its potential as a viable construction material . Another study (2025) reported that electric arc furnace slag can replace cement and fine aggregates in high proportions while maintaining mechanical and durability performance, emphasizing its role in reducing natural resource depletion . Additionally, Akhtar et al. (2025) demonstrated that steel slag improves pore structure characteristics, contributing to high-performance and sustainable concrete .
- **Ahmad et al. (2025)** demonstrated that metakaolin improves the mechanical and durability performance of composite cementitious systems when combined with slag-based materials .
- **Gao et al. (2026)** optimized metakaolin–slag mixtures and reported improved mechanical properties and sustainability performance due to the formation of geopolymer aluminosilicate networkks .

3. AIM & OBJECTIVES

3.1 Aim & Objectives:

- Review the role of metakaolin and steel slag as supplementary cementitious materials (SCMs).
- Examine their physical, chemical, and mineralogical properties and their influence on concrete behavior.
- Analyze the effect of metakaolin and steel slag on the mechanical properties of concrete, including compressive strength based on recent studies.
- Investigate the durability characteristics of metakaolin-steel slag concrete, focusing on resistance to water absorption, permeability
- Understand the hydration mechanisms and microstructural development, reviewing how the pozzolanic activity of metakaolin and latent hydraulic properties of steel slag contribute to C-S-H formation, pore refinement, and ITZ improvement.
- Identify optimum replacement levels of metakaolin and steel slag, determining the most effective mix proportions reported in literature for enhanced performance.
- Evaluate the synergistic effects of combined use of metakaolin and steel slag by comparing binary and ternary blends with conventional concrete to highlight performance improvements.

4. METHODS

4.1 Workability & Setting Time: MK (Metakaolin) is found to produce smaller slump in concrete mixtures compared to control mixtures, leading to extensive research on its water demand and flow properties. Kinuthia et al. (2000) noted a significant reduction in the workability of concrete as MK content increased, necessitating more super plasticizers to compensate for this loss. Other studies corroborate these findings, indicating that MK's high chemical activity and specific surface area contribute to increased water requirements. MK has shown better workability characteristics compared to other supplementary cementitious materials (SCMs) like silica fume (SF), as highlighted by various researchers. For instance, Calderone et al. (1994) noted that MK concrete required 25%-35% less high-range water reducers than SF mixtures, resulting in a less sticky consistency. Additionally, all SCMs, including MK, tend to delay the setting time of concrete. Brooks et al. (2000) found that the extent of retardation increased with greater contents of SF, fly ash (FA), and slag, while MK showed a progressive retarding effect at lower replacement levels, which decreased at higher levels. Contrasting results were reported by various researchers regarding the impact of MK on setting times, showcasing that its blending can either prolong or reduce setting times

depending on specific conditions and replacement levels. Overall, MK blending leads to higher water demand and thixotropic behavior, accentuated by its role in accelerating Portland cement hydration.

Table-3 Workability of the MK Based Concrete

Workability of metakaolin concretes (Wild et al., 1996)				
Metakaolin (MK) (%)	Superplasticizer (%)	Slump (mm)	Compacting factor	Vebe time (Sec)
0	0	5	0.81	26
5	0.6	10	0.84	15
10	1.2	15	0.88	10
15	1.8	25	0.89	9
20	2.4	75	0.89	7
25	3.0	75	0.89	4
30	3.6	90	0.90	5

4.2 Heat of Hydration: - In various studies, the incorporation of metakaolin (MK) has been shown to enhance heat evolution during the hydration of Portland cement (PC). This increase is due to MK's accelerating effect on PC hydration and its high reactivity with calcium hydroxide (CH). While this elevated temperature can cause thermal stress cracking in large concrete members, it is advantageous in cold weather conditions where rapid setting is preferred. For instance, research by Zhang and Malhotra (1995) indicated that a 10% MK replacement led to a 7 °C rise in temperature compared to PC concrete. Ambroise et al. (1994) found that temperature increases for 10%, 20%, and 30% MK replacements were 8 °C, 6 °C, and 1 °C, respectively, demonstrating a decrease in temperature rise with higher MK levels. This reduction seems to stem from the dilution effect resulting from the significant removal of cement. Conversely, a mere 10% replacement with silica fume resulted in only a 0.5 °C increase in temperature. Frías et al. (2000) compared fly ash (FA), silica fume, and MK in terms of heat evolution, finding that MK mortars exhibited a slight increase in heat compared to 100% PC mortars, attributed to MK's high pozzolanic activity. Both MK and silica fume showed pozzolanic behavior, particularly after two hours, whereas FA demonstrated much lower reactivity. Bai and Wild (2002) observed that temperature rise in FA systems declined with increased replacement, while MK systems showed a significant increase in temperature. They reported peak temperatures of 29 °C, 27 °C, and 31 °C for control, 10% FA, and 10% MK mixtures, respectively. Bai et al. (2003) further explored the combined effects of FA and MK in ternary blends, finding a compensatory relationship where the temperature rise for a blend of 10% FA and 10% MK matched that of the control mixture.

4.3 Permeability & pore size distribution: - influenced by factors such as particle size, chemical composition, mineralogy, and loss on ignition of pozzolans. Frias and Cabrera (2000) examined the evolution of capillary and

gel porosity during hydration using Mercury Intrusion Porosimetry (MIP), categorizing capillary pores between 0.01-5.00 μm and gel pores as smaller than 0.01 μm . Their findings indicated a reduction in total porosity up to 28 days, after which it stabilized. Notably, mixtures with metakaolin (MK) exhibited higher total porosities than control samples due to increased water content, although they had a reduced number of pores in the 0.01-5.00 μm range and more in the sub-0.01 μm range, suggesting pore refinement. Khatib and Wild (1996) corroborated these findings, noting that MK incorporation improved pore structure refinement significantly, with pastes of 15% MK reaching nearly 60% of total pore volume in sub-20 nm pores at 14 days, compared to about 30% in the control paste. This age also marks the maximum strength enhancement from MK, attributed to a reaction product layer around MK particles that constrains further reaction with calcium hydroxide (CH). In contrast, Poon et al. (2001) reported lower porosity and smaller average pore diameters in MK pastes compared to control and silica fume pastes at various ages, indicating MK's superior effectiveness in pore structure refinement. Disparities in findings between studies might stem from differing water-to-cement ratios; where pastes in earlier studies had a ratio of 0.55, Poon et al. used a lower ratio of 0.30. Ambroise et al. (1994) found that a 20% MK paste with a w/cm of 0.34 had similar porosity to a control paste with a w/cm of 0.25, reinforcing the notion that MK significantly enhances pore structure refinement. Kostuch et al. further confirmed significant reductions in average pore size at a 20% MK replacement and improved resistance to chloride and sodium ion penetration. Additionally, Khatib and Clay (2003) noted that water absorption during immersion correlates with total pore volume, which increases with MK, while capillary water penetration decreases, indicating a disruption in pore continuity.

4.4 Mechanical properties:- Research presents that partial replacement of Portland cement with metakaolin (MK) enhances the compressive strength of concrete by reducing calcium hydroxide (CH) content, thus decreasing the interfacial transition zone (ITZ) and overall porosity. Caldarone et al. (1994) demonstrated that concretes with 5% and 10% MK at a water-to-cement ratio (w/c) of 0.40 exhibited average strength improvements of 10% over those containing silica fume (SF) at up to 365 days. Wild et al. (1996) identified 20% MK replacement as optimal for long-term strength with a w/c of 0.45. Badogiannis et al. (2005) confirmed considerable strength enhancement with 5% MK in cement over 180 days, favoring 10% MK over 20% MK for general applications. Curcio et al. (1998) found that 15% MK improved strength evolution in mortars at early ages, while Ding and Li (2002) observed comparable benefits with both 5% to 15% MK and silica fume, noting a linear strength increase for MK within the first 28 days,

decelerating thereafter. Li and Ding (2003) validated that a 10% MK replacement consistently resulted in greater strength, particularly when combined with ultra-fine slag. Vu et al. (2001) established that the optimal MK replacement level varies with mortar maturity, recommending 10% for early ages and 15-20% for 7 to 28 days. In an examination of the impact of metakaolin (MK) on the strength characteristics of mortars and concretes, several studies noted that the optimal percentage for enhancing strength at 28 days and beyond varied depending on the water-to-cement ratio (w/cm). For instance, the highest strength was achieved with 10-25% MK replacement; at a w/cm of 0.32, 10% MK was optimal, while 20% was best at 0.44. Research by Khatib and Wild (1996) highlighted the importance of MK's particle size, observing that greater fineness led to quicker strength gains and allowed higher cement replacement without detrimental dilution effects, although it did not affect long-term strength. Qian et al. (2001) reported substantial increases in compressive strength, with a 51% rise observed at 15% MK replacement after three days, indicating MK's significant early strength contribution. Other studies confirmed similar trends in compressive strength improvements. Oquian and Zongjinli (2001) further established that MK incorporation up to 15% enhanced tensile/compressive strengths and peak strain. A consensus identified three principal factors influencing concrete strength with MK: the filler effect, acceleration of Portland cement (PC) hydration, and pozzolanic reactions with calcium hydroxide (CH). Wild et al. (1996) suggested that the benefits from MK decrease after 14 days. Flexural strength analyses indicated that both MK and silica fume improved strength, with MK also enhancing toughness. MK's effect on the modulus of elasticity (MOE) was generally positive, with a reported increase in MOE corresponding to MK content but at a slower rate than compressive strength increments. Findings by Qian et al. (2001) and Caldarone et al. (1994) corroborated these observations with quantifications of MOE gains at different curing intervals. Overall, the inclusion of MK proved beneficial in enhancing the mechanical properties of concrete and mortar, particularly in early strength development.

5. CONCLUSION

- The literature evaluation supports using pozzolanic materials, such MK, in place of some of the cement in mortar and concrete.
- It highlights MK's function as a performance enhancer, enhancing mechanical qualities in the short and long term.
- MK greatly lowers permeability and increases resistance to the movement of hazardous ions and water.

- A replacement level of 10–15% MK offers some protection against chemical ingress and strong defines against sulfate assault.
- When applied within ideal limits, MK aids in preventing harmful expansion brought on by the alkali-silica reaction (ASR).
- On the other hand, MK may enhance shrinkage and the heat generated during hydration, which calls for more investigation.
- Concrete's sustainability is improved by customized compositions and particle sizes made possible by advancements in nanotechnology.

6. LIMITATIONS AND FUTURE RESEARCH

- Due to variations in source, manufacture, and treatment, the material qualities of steel slag and metakaolin vary, making results difficult to generalize.
- Variations in the ideal replacement levels result from the lack of defined mix design processes for proportioning metakaolin and steel slag.
- There is little information on long-term durability; instead, short-term performance is prioritized above factors like creep and shrinkage.
- Steel slag can affect density and finishing, creating practical difficulties; high metakaolin concentration may decrease workability.
- Rather than evaluating parameters in combined hostile situations, durability studies frequently evaluate parameters independently.
- A focus on case studies and field application to validate lab results in real-world contexts.

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