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Influence of water–binder ratio on the optimal percentage of metakaolin in metakaolin-blended cement concrete

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Abstract

The incorporation of metakaolin (MK) in blended cement concrete enhances mechanical and durability properties by refining the microstructure. However, the optimal MK content remains uncertain across studies. This research investigates the influence of water–binder ratio (w/b) on the ideal MK replacement level. Two concrete grades, with w/b ratios of 0.6 and 0.3, were designed for target strengths of 30 MPa and 50 MPa, respectively. Cement was replaced with MK at 5%, 10%, 15%, 20%, and 25% by weight. Mixes were evaluated for workability, compressive strength, tensile strength, and sulfate resistance. Each result represents the average of three specimens, with a total of 234 samples tested—90 for compressive strength, 90 for tensile strength, and 54 for sulfate resistance. Increasing MK content reduced workability due to its fine particle size and high surface area. Strength tests showed that optimal MK content depended on the w/b ratio: at 0.6, 5% MK gave the best performance, exceeding control strength by 8.0% at 28 days; at 0.3, 15% MK was optimal, surpassing the control by 19.4%. Microstructural analysis confirmed improved packing density and pore refinement. Sulfate resistance assessment showed that 5–15% MK replacement improved performance, with strength loss after 90 days of $MgSO_4$ exposure below 3.6%, compared to 4.1% for the control and 4.4% for 20–25% MK mixes. Furthermore, statistical analysis indicates that MK addition improves concrete strength and durability; highest compressive strength correlation was observed at 15% and 25% for samples with w/b of 0.6 and 0.3 respectively. This study provides new insight into the coupled effect of MK content and water–binder ratio, establishing a quantitative basis for optimizing MK use in performance-based concrete design.

Keywords Metakaolin, Mechanical properties, Durability, Blended, Water–binder ratio

1 Introduction

Concrete, as the most commonly used construction material worldwide, continues to evolve in response to increasing demands for sustainability, performance, and durability. Its affordability, better compressive strength, and versatile applications make it

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indispensable in contemporary civil engineering [1, 2]. However, traditional Cement, a major binding component in concrete, faces significant environmental challenges due to its high carbon footprint and energy-intensive production process. The cement production process contributes substantially to CO_2 emissions, mainly through the breakdown of limestone [3, 4]. According to Akinpelu et al. [5], cement production generates up to 5% of total human-caused CO_2 emissions in the world. Muhammed et al. [6] also reported that production of one ton of cement generates about one ton of CO_2. Additionally, the high heat energy required to produce cement from clinker (1450 °C) further emphasizes the need for sustainable practices in the construction industry.

To mitigate the impacts of global warming, research has focused on reducing CO_2 emissions from cement production and developing cost-effective, sustainable construction materials. Supplementary Cementitious Materials (SCMs) have appeared as a viable solution [7]. Derived from natural or industrial sources, SCMs improve concrete properties by boosting the effects of cement hydration reactions [8, 9]. SCMs including ground granulated blast furnace slag, fly ash, silica fume, and agricultural by-products, improve fresh and hardened properties of concrete, and reduce raw material costs. These materials, when incorporated as partial replacements or blended with cement, produce more calcium silicate hydrate through their interaction with calcium hydroxide from cement hydration, thus improving strength as well as the permeability properties of the concrete [10]. They also mitigate issues like sulfate attacks and alkali-silica reactions while lowering heat generation during curing [11].

Metakaolin, a high-performance pozzolanic material derived from heating kaolin clay at 500–800 °C [5], has gained prominence among SCMs due to its availability and superior pozzolanic properties, and more environmentally friendly compared to cement. The environmental advantage of using metakaolin (MK) as a supplementary cementitious material can be better appreciated through a quantitative comparison of carbon emissions. The production of Ordinary Portland Cement (OPC) typically results in approximately 800–900 kg of CO_2 emissions per ton of cement produced. In contrast, the manufacture of MK, derived from calcined kaolinite clays, emits significantly less—approximately 300–400 kg of CO_2 per ton—depending on the calcination temperature and the characteristics of the source clay [12, 13]. Therefore, replacing 1 ton of OPC with MK has the potential to reduce CO_2 emissions by about 500–600 kg. This substantial reduction highlights the role of MK in promoting sustainability and lowering the carbon footprint of cement-based materials.

Furthermore, numerous studies have highlighted the benefits of metakaolin in improving concrete workability, durability, microstructure, and mechanical properties. Meddah et al. [14] reported about 2 to 4% decrease in water demand with metakaolin owing to its high surface area. Hashim et al. [15] observed increased compressive and tensile strengths but reduced slump flow and L-box values when nano-metakaolin replaced cement partially. Similarly, Muduli and Mukharjee [16] found reduced workability in MK blended cement concrete utilizing recycled materials as aggregate. Chen et al. [17] noted improved flow properties and adhesion with 10–20% metakaolin, though benefits diminished at higher levels. Studies like those of Kannan [18] and Gill and Siddique [19] have demonstrated enhanced compressive strength at optimal metakaolin replacement levels of 15% and in ternary mixes with rice husk ash.

Durability studies have also confirmed metakaolin's effectiveness. The work of Joshaghani et al. [20] showed that blending cement with 10–15% MK at w/b ratios of 0.60 and 0.45 increased electrical resistivity by 2-1.5 times after 28–180 days. Similarly, Bucher et al. [21] observed a 20% reduction in gas permeability, while Bakera and Alexander [22] noted significant reductions in chloride conductivity, particularly at medium to high W/C ratios. Microstructurally, studies Jiang et al. [23] revealed that metakaolin reduces critical pore sizes and promotes uniform pore distribution, enhancing concrete's overall durability.

Despite the well-documented benefits of incorporating metakaolin (MK) as a supplementary cementitious material, the optimal replacement dosage remains a subject of debate. For instance, Pillay et al. [24] identified 5% replacement as optimal, while Xupeng et al. [25] and Akinpelu et al. (2) recommended 10%. Other researchers, such as Jagtap et al. [26] and Nanda et al. [27], suggested 15% and 20%, respectively. These variations in reported optimal values may be attributed to several factors, including differences in MK particle size, mineralogical composition, water-to-binder (w/b) ratio, calcination temperature, and cement content. While the individual influence of these parameters has been investigated in various studies, the interaction between w/b ratio and MK dosage remains poorly understood. This lack of clarity has contributed to inconsistent findings and limits the ability to draw generalised conclusions. Therefore, a systematic investigation into the combined effects of MK dosage and w/b ratio is necessary to establish more reliable performance guidelines and ensure consistent application in cement-based materials. The summary of past studies with their w/b ratios, MK percentages and its key findings are shown in Table 1.

To address this gap, the present study investigates how variations in the water-to-binder ratio (w/b) influence the optimal metakaolin (MK) replacement level in cement-based concrete. By examining the effects of different w/b ratios on workability,

Table 1 Past studies on metakaolin in concrete with water–cement ratio considerations

Author	MK % tested	Optimum MK %	Water–cement ratio	Key findings
Agboola et al. [28]	5, 10, 15, 20, 25, 30	10%	0.5	10% MK gave highest strength (34.8 N/mm^2 at 90d vs. control 28.9 N/mm^2). Strength peaked at 10% (optimal replacement) (15% also showed late gains)
Amrane et al. [29]	5, 10, 15, 20	15%	0.5	15% MK gave maximum compressive strength. Beyond 15% strength declined (though still above control)
Dubey et al. [30]	5, 10, 15, 20, 25	15%	0.25, 0.30, 0.35	15% MK gave the largest strength gains (compressive + 33–46% vs. control, highest at 0.25 w/b)
Al-Hashem et al. [31]	5, 10, 15, 20	20%	0.55	20% MK achieved 33.43% higher compressive strength (90d) vs. control (strength increased with MK up to 20%)
Yin & Ma [32]	0, 1, 2, 3, 4	4%	0.18 (UHPC)	4% MK gave 136.78 MPa vs. 123.14 MPa for 0% MK (≈ + 11.08%). Compressive strength increased with MK up to 4%; w/b = 0.18
Liang et al. [33]	0, 10, 20, 30	10%	0.18	10% MK gave best 28d compressive strength (73.45 MPa; ≈6.35% > control). Flexural strength also peaked at 10% (≈ + 12.2% vs. control)
Pillay et al. [34]	0, 5, 10, 15, 20	10% (comp), 5% (flex)	0.54–0.61	10% MK yielded highest 28d compressive (49.8 MPa); flexural strength peaked at 5% MK (8.35 MPa). Strength and durability improved with MK (workability dropped)
Akinpelu et al. [35]	10, 20, 30, 40	10%	0.5	10% MK gave highest strength (compressive + 6.4–14.7% vs. control at 14–56d). Higher MK (≤ 30%) still outperformed control, but 10% was best

Table 2 Physical properties of materials

Physical property	Portland limestone cement	Fine aggregate	Coarse aggregate
Specific Gravity	2.7	2.7	2.62
Initial Setting Time (min)	46	–	–
Final Setting Time (min)	520	–	–
Fineness Test (%)	8.30	–	–
Standard Consistency	31	–	–
Fineness Modulus	–	4.17	8.1
Water Absorption Test (%)	–	2.56	0.99

Table 3 Chemical composition of Portland limestone cement

Oxides %	SiO_2	Al_2O_3	CaO	TiO_2	Fe_2O_3	Na_2O	MgO	TiO_2	MnO
Cement	20.62	5.35	61.79	0.12	3.07	0.2	1.93	0.12	0.06

Table 4 Mix proportions of concrete in kilogram per cubic meter (kg/m^3) for grades 30 (w/b = 0.6) and 50 (w/b = 0.3)

Specimens	Metakaolin (%)	Cement (kg/m^3)	Metakaolin (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)	w/b
Grade 30 (w/b = 0.6)							
MK0	0	392.0	0.0	620.7	1153.7	235.2	0.6
MK5	5	372.4	19.6	620.7	1153.7	235.2	0.6
MK10	10	352.8	39.2	620.7	1153.7	235.2	0.6
MK15	15	333.2	58.8	620.7	1153.7	235.2	0.6
MK20	20	313.6	78.4	620.7	1153.7	235.2	0.6
MK25	25	294.0	98.0	620.7	1153.7	235.2	0.6
Grade 50 (w/b = 0.3)							
MK0	0	550.0	0.0	560.0	1095.0	165.0	0.3
MK5	5	522.5	27.5	560.0	1095.0	165.0	0.3
MK10	10	495.0	55.0	560.0	1095.0	165.0	0.3
MK15	15	467.5	82.5	560.0	1095.0	165.0	0.3
MK20	20	440.0	110.0	560.0	1095.0	165.0	0.3
MK25	25	412.5	137.5	560.0	1095.0	165.0	0.3

compressive strength, and durability performance, the research seeks to identify the balance between fresh and hardened state properties. The outcomes provide an empirical model linking MK dosage to w/b ratio, offering practical guidance for optimizing MK content in both general-purpose and high-performance concretes. These insights contribute to the development of sustainable, durable, and performance-driven mix designs aligned with modern construction needs.

2 Materials and methods

2.1 Materials

Portland Limestone Cement (PLC) of grade 42.5R was used as the binder, purchased from Mohadis Construction Limited, Ilorin, Kwara state. River sand and crushed granite sourced from Ilorin were used as fine and coarse aggregates, respectively, while metakaolin (MK), supplied by the Nigerian Building & Road Research Institute (NBRRI), was also utilized as supplementary cementitious material. The physical properties of the cement, fine aggregate, and coarse aggregate used in the study are shown in the Table 2 while the chemical compositions of the cement are as shown in Table 4.

2.2 Methods

To explore the influence of the water–binder ratio on the optimal proportion of MK in metakaolin-blended cement concrete, two control concrete grades, 30 and 50, were designed at water–binder ratio of 0.6 and 0.3 respectively using the guidelines provided in the COREN Concrete Mix Design Manual [35]. A total of twelve concrete mixes were prepared—six for each grade—by partially replacing cement with metakaolin (MK) at intervals of 5%, ranging from 0 to 25%. The mixes were labelled as MK0 (control), MK5, MK10, MK15, MK20, and MK25, corresponding to 0%, 5%, 10%, 15%, 20%, and 25% MK replacement, respectively. The mix proportions are detailed in Table 4.

2.2.1 Materials characterization

The metakaolin was analyzed using three techniques: X-ray diffraction (XRD), X-ray fluorescence (XRF), and scanning electron microscopy (SEM). XRD identified the crystalline or amorphous nature of the particles using an Empyrean diffractometer, while XRF determined the chemical composition via a Thermo Scientific ARL QUANT'X EDXRF Spectrometer. SEM analysis was conducted using a JOEL-JSM 7600 F microscope to obtain high-resolution images of the particle morphology, serving two main purposes: to observe the morphological characteristics of the raw metakaolin and the hardened concrete microstructure after cement replacement, and to perform quantitative image analysis on selected SEM micrographs to estimate particle statistics such as D10, D50, D90, aspect ratio, circularity, and particle count.

2.2.2 Workability

The laboratory tests for concrete workability are conducted using various methods, including the compacting factor test, slump cone test, flow test, and Vee Bee consistometer. Among these methods, the slump test was chosen due to its widespread use as a standard workability test. The procedure for determining workability adhered to the guidelines specified in BS EN 12350-2 [36]. All the twelve mixes as detailed in Tables 2 and 4 were subjected to the workability test.

2.2.3 Mechanical properties

The mechanical properties of metakaolin-blended cement concrete were evaluated through compressive and split tensile strength tests at the Concrete Laboratory of the Department of Civil Engineering, University of Ilorin. A total of 12 concrete mixes were prepared and tested after 7, 14, 28, 56, and 90 days of curing. For each test (compressive and split tensile strength), three specimens were tested at each curing age, and the average result was recorded. This amounted to 15 specimens per mix for each test type, resulting in a total of 180 specimens, 90 for compressive strength and 90 for split tensile strength.

The compressive strength test was conducted on 100 mm cube specimens in accordance with BS EN 12390-3 [37]. A 1560 kN capacity machine was used to apply a gradual load at a rate of 140 kg/cm^2 per minute until failure, with the compressive strength calculated as the failure load divided by the cross-sectional area of the specimen.

The split tensile strength test followed the procedure outlined in BS EN 12390-6 [38], using cylindrical specimens measuring 100 mm in diameter and 200 mm in height. After removing the specimens from water and drying them, a gradual load was applied at a

rate between 0.7 and 1.4 MPa/min until the specimen fractured, and the load at failure was recorded.as applied until fracture, and the load at failure was recorded.

2.2.4 Sulfate resistance property

The durability of the blended cement concrete was evaluated based on its resistance to structural degradation under magnesium sulfate attack. The assessment involved immersing concrete specimens in a 10% magnesium sulfate solution (specifically magnesium sulfate heptahydrate, $MgSO_4 \cdot 7\ H_2O$, commonly known as Epsom salt) and monitoring their performance over time. Control specimens were also prepared for comparison. Following initial curing in water for 28 days, the samples were further exposed to the sulfate solution for 30, 60, and 90 days, after which their compressive strengths were determined through crushing tests. For each mix and exposure period, three specimens were tested, and the reported results represent the average of these three values. This test followed the guidelines of ASTM C452 [39].

3 Result and discussions

3.1 Characterization of metakaolin

Table 5 presents the chemical composition of the metakaolin (MK). The combined oxide content of SiO_2, Al_2O_3, and Fe_2O_3 in the metakaolin used for this study is 91.52%. The silica (SiO_2) being the most abundant at 63.64%, followed by alumina (Al_2O_3) at 23.35% and ferric oxide (Fe_2O_3) at 4.53%. This total surpasses the ASTM C618 [40] minimum requirement of 70% for supplementary cementitious materials, thus verifying the suitability of the MK as a pozzolan.

Figure 1 illustrates the XRD analysis of the metakaolin, showcasing a distinct and prominent silica peak at a 2θ angle of 26.97°. This result corroborates the XRF analysis, which confirmed an elevated silica content, and aligns with the findings reported by Caballero et al. [41] and Mendes et al. [42]. The presence of broad humps in the pattern indicates the amorphous characteristics of the metakaolin, consistent with observations by Akinpelu et al. [2].

The SEM image in Fig. 2 highlights the distinct morphological features of metakaolin (MK) particles. In contrast to cement particles, which are typically smoother and more rounded, MK particles appear highly angular, jagged, and irregularly shaped. These characteristics result in a polygonal geometry with sharp edges that increase the surface texture. Table 6 presents supporting particle size and shape parameters: a fine median particle size (D_{50} = 12.9 μm), a broad particle size distribution (D_{10}–D_{90} ≈ 10–36 μm), and shape descriptors indicating low circularity (0.33) and a relatively high aspect ratio (2.1). These features suggest a large specific surface area and irregular packing geometry. While this section focuses on material characterisation, such particle features generally imply increased interparticle friction and higher water demand, which may influence flowability. Conversely, the high surface reactivity and fine particle size are expected to contribute positively to particle packing and may promote pozzolanic activity, with potential implications for strength development.

Table 5 Chemical composition of metakaolin

Oxides %	SiO_2	Al_2O_3	CaO	TiO_2	Fe_2O_3	K_2O	Cl	SO_3	MnO
Metakaolin	63.64	23.35	2.01	3.83	4.53	0.66	0.57	0.45	0.06

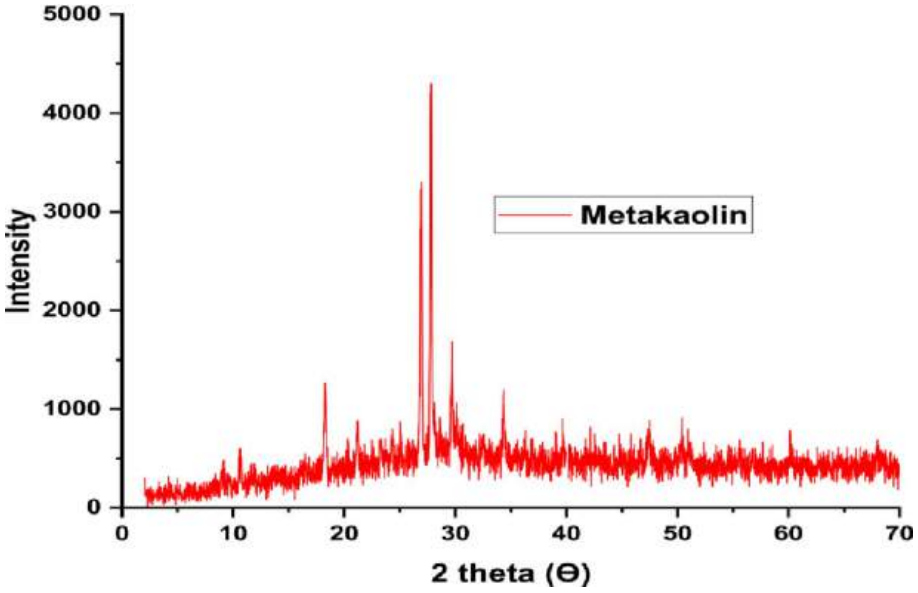


Fig. 1 Diffractogram of metakaolin

3.2 Workability

Figure 3 presents slump results for Grade 30 (w/c = 0.6) and Grade 50 (w/c = 0.3) concretes. The control mixes record slumps of 100 mm (Grade 30) and 89 mm (Grade 50), indicating good workability. Slump decreases steadily with increasing metakaolin content, reaching 7 mm and 5 mm at 25% replacement for Grades 30 and 50, respectively. The reduction is attributed to metakaolin's fine, angular particles and high surface area (aspect ratio = 2.1), which increase water demand, while its pozzolanic activity further stiffens the mix. The results align with findings by Al-Hashem et al. [31] and Pillay et al. [43], which also reported reduced flowability with higher metakaolin content.

3.3 Mechanical properties

3.3.1 Compressive strength result

Figure 4 illustrates the compressive strength development of Grade 30 concrete (w/b = 0.6) with varying MK contents. While the control mix gained about 35% strength from 7 to 90 days, MK addition further enhanced strength and microstructure (Fig. 5). The control mix shows a porous matrix with weak bonding, consistent with its moderate aspect ratio (2.49), low particle count (14), and narrow size distribution (D90 = 0.112 μm), resulting in lower strength. In contrast, MK-modified mixes exhibit denser, more homogeneous microstructures due to finer, angular particles that improve packing, pore refinement, and pozzolanic reactivity. Mixes with 5–15% MK show optimal dispersion and additional C–S–H formation, leading to notable strength gains. The 5% MK mix performed best, exceeding the control by 16–17.5% at early ages and by 8–10% up to 90 days, reflecting its favourable aspect ratio (2.18) and particle distribution. At 20–25% MK, unreacted MK clusters indicate CH depletion and dilution effects, limiting further gains. Nevertheless, the 25% MK mix still surpassed the control by 3.3% at 90 days, confirming sustained long-term pozzolanic benefits (Table 7).

Figure 6 illustrates the compressive strength development of grade 50 concrete with metakaolin (MK) at a w/b of 0.3, measured over different curing durations. The control

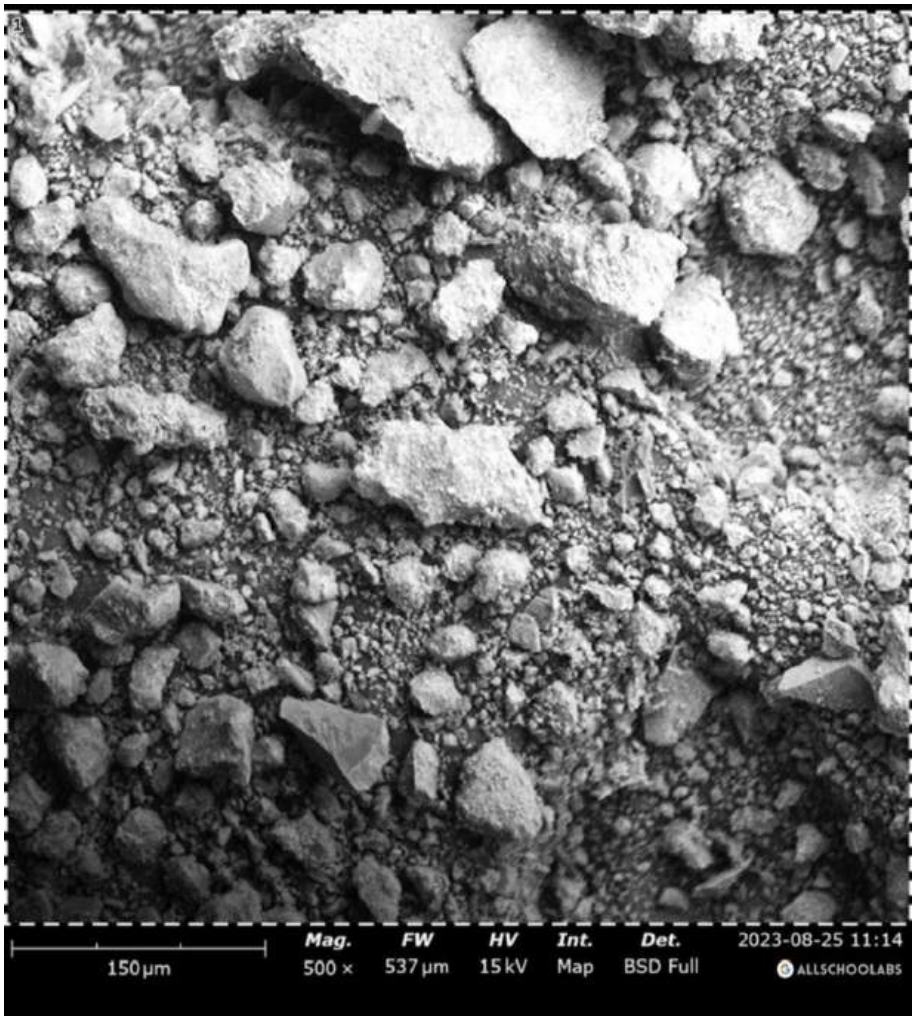


Fig. 2 SEM micrographs of MK particles at 500x magnification

Table 6 Particle-size and shape metrics

Sample	D10 (µm)	D50 (µm)	D90 (µm)	Mean aspect ratio	Mean circularity	Particle count
MK	10.41	12.92	36.39	2.13	0.33	27

mix (0% MK) exhibits a notable strength increase of approximately 33.5% from 7 days to 90 days, rising from 42.0 to 56.0 N/mm², reflecting the strong impact of curing on strength enhancement. Concrete mixes with MK replacement (5 to 25%) generally surpassed the control at most curing ages, though the degree of improvement depended on the MK content. Unlike grade 30 concrete (w/b = 0.6), where 5% MK yielded the best results, the 15% MK mix achieved remarkable early-age strength, reaching 50.0 N/mm² at 7 days. The improved early strength development could only be linked to filler effect.

The 15% MK mix also demonstrated superior long-term strength, outperforming the control mix by 19.4%, 14.4%, and 3.6% at 28, 56, and 90 days, respectively. However, the extent of improvement declined over time. At MK replacement levels exceeding 15% (e.g., MK20 and MK25), the strength was negatively affected, emphasizing the importance of optimizing MK content for high-performance concrete.

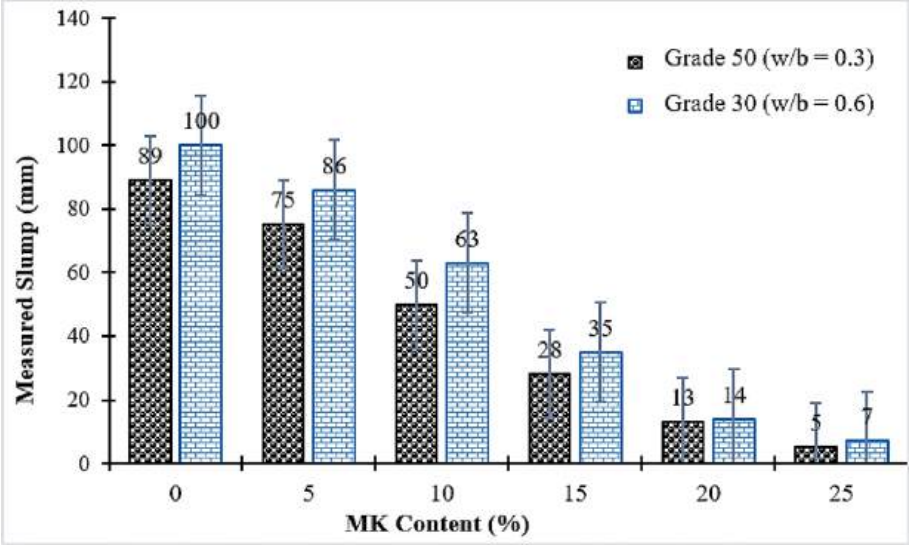


Fig. 3 Slump heights of concrete Incorporating metakaolin

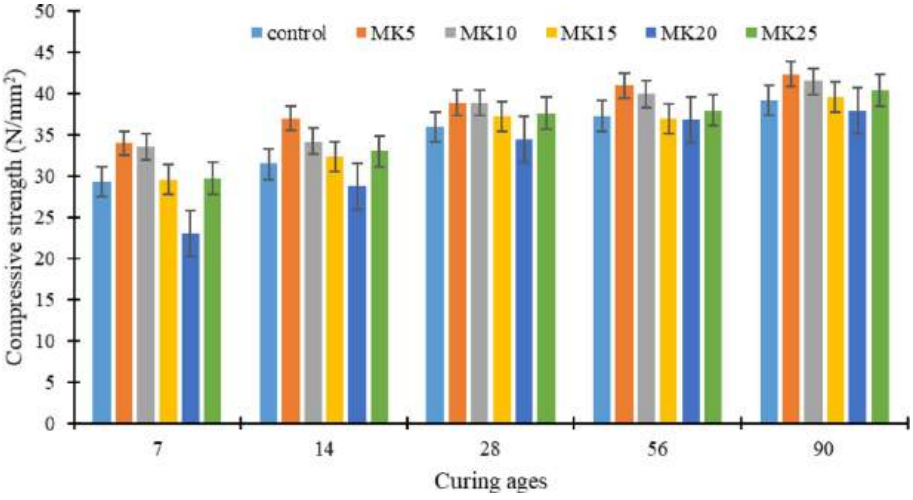


Fig. 4 Compressive strength of concrete incorporating metakaolin at w/b = of 0.6 (Grade 30)

Table 8 presents SEM-based particle metrics obtained from ImageJ analysis, reflecting morphological characteristics rather than laser PSD. The control mix shows a coarse, porous matrix (D50 = 0.30 μm; 16 particles). Incorporating 5–10% MK increases particle count and refines distribution, improving packing (Fig. 7). At 15% MK, the mix with highest strength, larger hydration products (D90 = 5.21 μm) indicate enhanced densification. Higher MK contents (20–25%) show irregular distributions and higher counts, suggesting unreacted MK and reduced cohesion due to CH depletion. Overall, the findings confirm that 15% MK gives optimal pozzolanic reactivity and structural densification, while higher replacements lead to diminishing returns. These findings align with previous research by Wang [30] and Wang et al. [31], reinforcing the benefits of MK as a pozzolanic material in high-strength concrete.

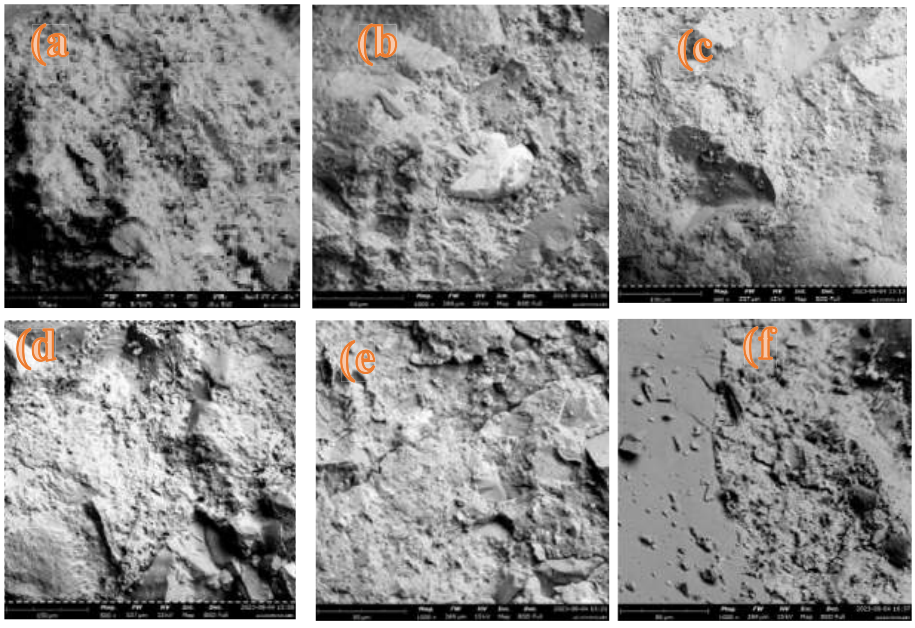


Fig. 5 SEM images of concrete with w/b ratio of 0.3 (**a**) control (**b**) MK-5 (**c**) MK-10 (**d**) MK-15 (**e**) MK-20 (**f**) MK-25 at the 28-day

Table 7 SEM data (w/b = 0.6, grade 30)

Sample	D10 (μm)	D50 (μm)	D90 (μm)	Mean Aspect Ratio	Mean Circularity	Particle Count
Control	0.055	0.081	0.112	2.49	0.45	14
MK5	0.059	0.081	0.199	2.18	0.45	16
MK10	0.054	0.084	0.142	2.89	0.4	14
MK15	0.053	0.062	0.195	5.87	0.45	18
MK20	0.055	0.093	0.253	4.63	0.45	26
MK25	0.056	0.098	0.278	5.25	0.44	30

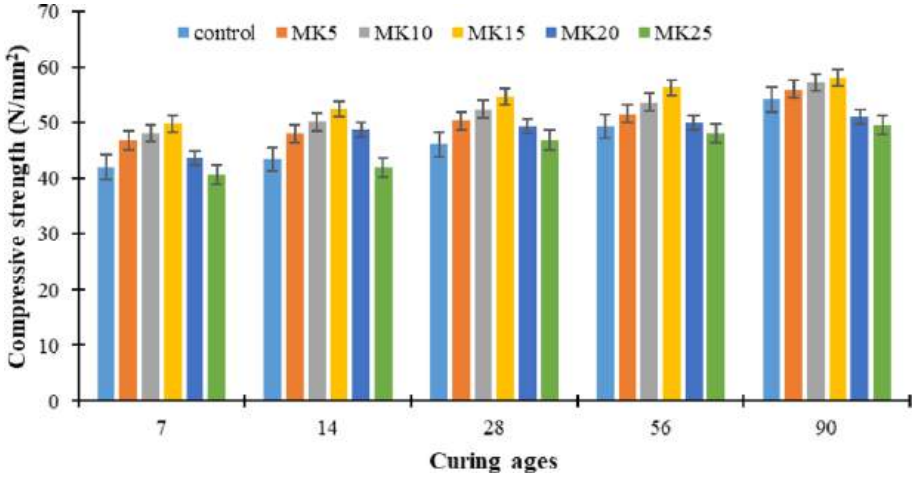


Fig. 6 Compressive strength of concrete incorporating metakaolin at w/b = of 0.3 (Grade 50)

Table 8 SEM data for MK series (w/b = 0.3, grade 50)

Panel	D10 (μm)	D50 (μm)	D90 (μm)	Mean aspect ratio	Mean circularity	Particle count
a	0.23	0.3	1.09	1.83	0.45	16
b	0.25	0.51	1.03	2.3	0.48	22
c	0.23	0.37	0.73	2.13	0.46	25
d	0.33	0.79	5.21	1.79	0.42	6
e	0.25	0.39	1.78	2.24	0.44	32
f	0.24	0.36	1.05	2.15	0.44	24

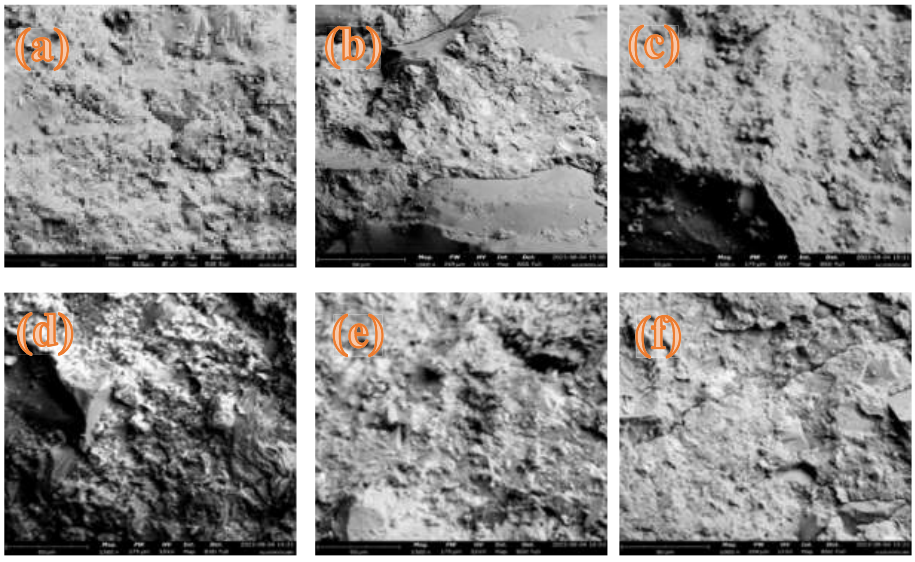


Fig. 7 SEM images of concrete with a w/b of 0.3 (**a**) control (**b**) MK5 (**c**) MK10 (**d**) MK15 (**e**) M20 (**f**) MK25

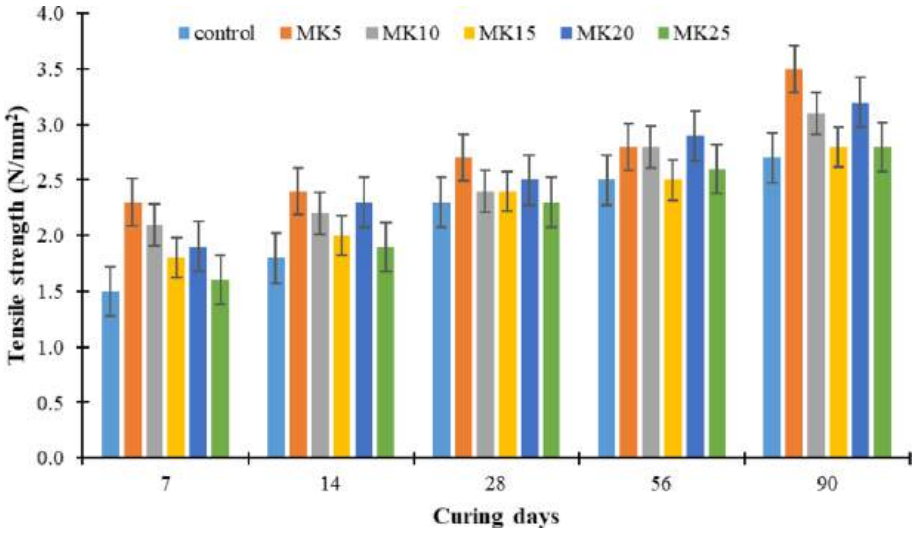


Fig. 8 Tensile strength of concrete incorporating metakaolin at w/b of 0.6 (Grade 30)

3.3.2 Tensile strength result

Figure 8 illustrates the tensile strength development of MK-blended cement concrete, produced with a w/b ratio of 0.6 (Grade 30), over different curing periods up to 90 days. Among all the mixes, the 5% metakaolin blend also exhibited superior performance

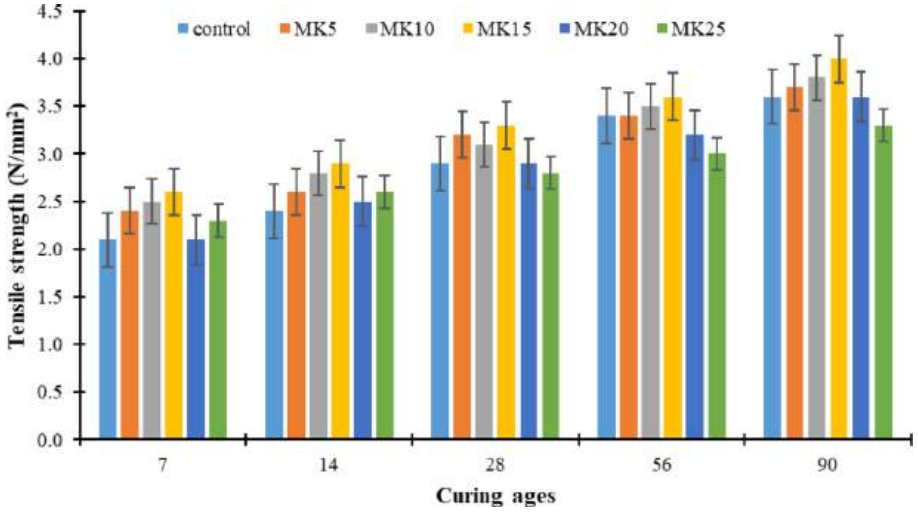


Fig. 9 Tensile strength of Grade 50 concrete incorporating metakaolin (w/b = 0.3)

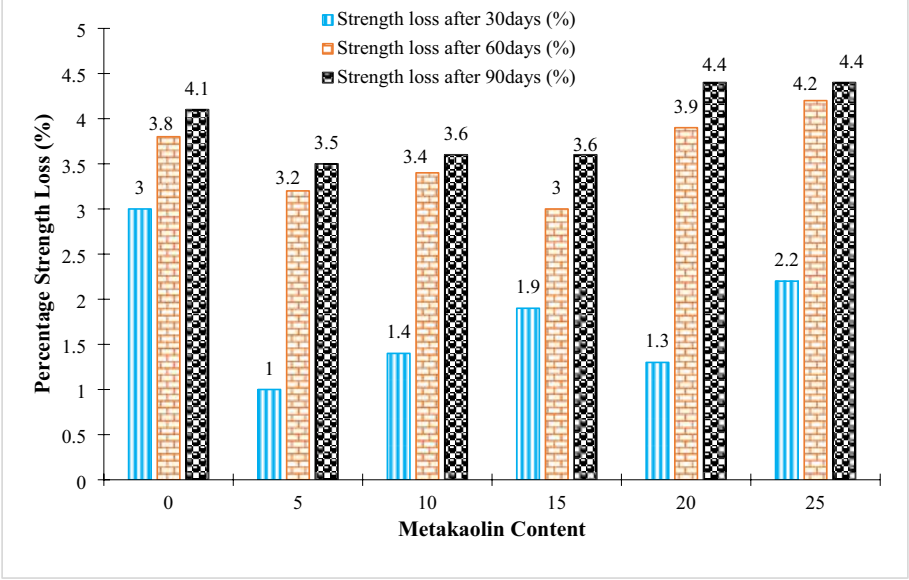


Fig. 10 Strength loss comparison for Grade 50: concrete exposed to $MgSO_4$ vs. concrete soaked in water

across all curing ages, surpassing the control by 53.3% at 7 days and 29.6% at 90 days. Other replacement levels (10%, 15%, 20%, and 25%) also achieved tensile strengths higher or comparable to the control, even though the strength generally decreased with increasing metakaolin content. Overall, the addition of MK significantly enhanced the tensile strength, with the 5% mix demonstrating the greatest strength enhancement across all curing durations. These results also align with the findings of Narmatha and Felixkala [32].

Figure 9 presents the tensile strength performance of metakaolin (MK) blended concrete samples produced with a water–binder ratio of 0.3 (Grade 50) across multiple curing periods (7, 14, 28, 56, and 90 days). The results follow a trend similar to that observed in compressive strength, where replacing cement with 5% to 15% MK consistently resulted in strength enhancement across all curing durations. However, beyond a 15%

replacement level, further substitution with MK led to a decline in tensile strength at 28, 56, and 90 days. Therefore, limiting the metakaolin content to 15% is recommended to achieve optimal performance in high-grade concrete with a water–binder ratio of 0.3. These observations are consistent with the findings of Bright Singh and Murugan [44].

3.4 Sulfate resistance test result

Figure 10 shows strength loss of MK concrete after exposure to 10% $MgSO_4$ for 30–90 days following 28 days of water curing. Strength reduction was minor at 30 days, with the control showing the highest loss (3%). After 60 days, deterioration increased slightly, with MK25 (4.2%) and MK20 (3.9%) experiencing the greatest losses, while mixes with up to 15% MK consistently showed lower strength reductions. The improved sulfate resistance at 5–15% MK is attributed to pozzolanic consumption of CH and pore refinement, which limit sulfate ingress and formation of expansive products, thereby enhancing durability. These microstructural refinements limit sulfate ion ingress and associated expansion damage, thereby improving long-term durability (Muduli and Mukharjee, 2021) [45]. However, beyond 15% MK, durability improvements plateau or slightly decline. This is primarily due to excessive CH consumption, leading to an underdeveloped C–S–H network and localized porosity, as observed in the SEM micrographs. The higher MK contents thus yield a more porous and less cohesive matrix, which weakens the internal microstructure and increases susceptibility to sulfate-induced deterioration. This trend aligns with the compressive strength results, confirming that higher matrix density and well-formed C–S–H structures are critical to improved sulfate resistance.

3.5 Mechanism of MK–CH interaction

The reaction between metakaolin and calcium hydroxide ($Ca(OH)_2$) occurs primarily through a dissolution–precipitation mechanism in the pore solution, rather than a direct solid–solid reaction. In the highly alkaline pore environment (pH > 12.5), $Ca(OH)_2$ partially dissolves, releasing Ca^{2+} and OH^- ions, while reactive amorphous aluminosilicate phases in MK simultaneously dissolve to release Si^{4+} and Al^{3+} species. These ions subsequently recombine in the aqueous phase to form secondary C–S–H and C–A–S–H gels that refine the microstructure and improve strength and durability. At higher MK contents, however, insufficient $Ca(OH)_2$ remains available to sustain these reactions, leaving unreacted MK and resulting in a less cohesive matrix.

4 Statistical analysis

The study evaluated correlations between control strengths and strengths at 5–25% MK replacement for compressive and tensile properties. Pearson correlation matrices for Grades 30 and 50 (Tables 9, 10, 11 and 12) were computed at a 95% confidence level and

Table 9 Correlation matrix for the compressive strengths

Variables	f_{cu}0%	f_{cu}5%	f_{cu}10%	f_{cu}15%	f_{cu}20%	f_{cu}25%
f_{cu}0%	1					
f_{cu}5%	0.56	1				
f_{cu}10%	0.89	0.56	1			
f_{cu}15%	**0.93**	0.62	0.87	1		
f_{cu}20%	0.90	0.48	0.84	0.88	1	
f_{cu}25%	0.38	0.23	0.22	0.32	0.31	1

Table 10 Correlation matrix for the tensile strengths

Variables	f_t0%	f_t5%	f_t10%	f_t15%	f_t20%	f_t25%
f_t0%	1					
f_t5%	− **0.58**	1				
f_t10%	0.47	− 0.80	1			
f_t15%	− 0.17	0.31	− 0.07	1		
f_t20%	− 0.28	− 0.28	0.20	− 0.27	1	
f_t25%	0.39	0.00	0.06	− 0.44	− 0.52	1

Table 11 Correlation matrix for the compressive strengths

Variables	f_{cu}0%	f_{cu}5%	f_{cu}10%	f_{cu}15%	f_{cu}20%	f_{cu}25%
f_{cu}0%	1					
f_{cu}5%	0.51	1				
f_{cu}10%	0.46	0.33	1			
f_{cu}15%	0.43	0.28	0.45	1		
f_{cu}20%	0.57	0.33	− 0.05	0.28	1	
f_{cu}25%	**0.67**	0.74	0.25	0.52	0.61	1

Table 12 Correlation matrix for the tensile strengths

Variables	f_t0%	f_t5%	f_t10%	f_t15%	f_t20%	f_t25%
f_t0%	1					
f_t5%	**0.72**	1				
f_t10%	0.06	0.25	1			
f_t15%	0.23	0.27	− 0.46	1		
f_t20%	0.58	0.60	0.15	0.02	1	
f_t25%	− 0.08	0.25	0.05	0.17	− 0.04	1

0.05 significance. Correlation strength was classified using Guilford's rule, ranging from negligible (r < 20%) to very high (r > 90%) [46–49].

Grade 30 (w/b = 0.6)

A very high positive correlation (> 90%) exists between control compressive strength and that at 15% MK (Table 5). In contrast, control tensile strength shows a moderate negative correlation with 5% MK (– 40% < r < – 70%) (Table 6). The negative and weaker tensile correlations indicate a divergence from control behavior, likely due to tensile strength's higher sensitivity to microcracking, interfacial bonding, and material variability. Unlike compressive strength, which tends to be more consistent and bulk-dependent, tensile strength is influenced by localised and heterogeneous factors, resulting in more scatter in the data [50].

Grade 50 (w/b = 0.3)

Tables 11 and 12 present correlation matrices for compressive and tensile strengths of MK-modified concretes at a low w/b ratio of 0.3. Compressive strength correlations are generally weak to moderate, indicating higher variability at low water content. The control mix shows moderate correlation with 5% and 20% MK, but weaker correlation with the 15% MK mix, despite the latter achieving the highest strength. This suggests distinct hydration and densification behaviour at 15% MK, likely due to an optimal balance between MK reactivity and $Ca(OH)_2$ availability. Weak correlations between the 15% mix and other MK levels further support this unique performance, while the highest correlation (r = 0.74) occurs between 5% and 25% MK, neither of which reached peak strength.

Tensile strength correlations are similarly irregular, with the 15% MK mix showing very weak association with the control and other mixes, reflecting tensile strength's sensitivity to microcracking and interfacial bonding. The strongest tensile correlation is between the control and 5% MK ($r = 0.72$), despite the latter not achieving maximum strength. Overall, the analysis highlights the distinct and optimal performance of the 15% MK mix at low w/b ratio. The weak correlations, especially in tensile strength, indicate that high linear association does not necessarily imply optimal mechanical performance, underscoring the nonlinear nature of MK pozzolanic reactions and the need to interpret correlation results alongside microstructural evidence.

5 Conclusions

The following conclusions drawn are:

i. The characterization tests revealed that the metakaolin is amorphous and meets the ASTM C618 standards required for pozzolana.
ii. Increasing MK content consistently reduced slump due to its high fineness and angular particle shape, resulting in increased water demand. While this reduction in workability was more pronounced at higher MK contents, strength improvements were notable up to a certain threshold. The optimum MK replacement level for compressive and tensile strength was found to be 15% for Grade 50 concrete (w/b = 0.3) and 5% for Grade 30 (w/b = 0.6). These results suggest that the optimal MK dosage is inversely related to the water–binder ratio, and a simplified empirical model—Optimal MK (%) ≈ 60 – 150 × (w/b)—is proposed to aid practitioners in selecting MK content based on mix water demand.
iii. However, the improvements in strength come with trade-offs. At higher MK levels (above 15%), workability losses became significant, and strength gains began to plateau or even decline. This highlights the need for a balanced mix design approach that considers both fresh and hardened state performance. In practical terms, admixtures may be required to compensate for the reduced workability when targeting high MK dosages.
iv. Durability assessments showed that MK improved resistance to magnesium sulfate attack up to 15% replacement, beyond which mass loss increased notably—by up to 16% compared to the 15% mix. This suggests that while MK refines pore structure and reduces calcium hydroxide through pozzolanic activity, excessive dosages may introduce microstructural weaknesses or incomplete hydration. Therefore, 15% MK appears to be the upper threshold for enhanced sulfate resistance under the tested conditions.
v. Statistical analysis further reinforced the experimental findings. Pearson correlation results indicated strong positive relationships ($r > 0.94$) between MK content and compressive strength up to optimal dosage levels, and strong negative correlations ($r \approx$ -0.83) with workability. These insights could serve as the basis for predictive tools or algorithms that help engineers identify optimal MK percentages for specific performance targets.
vi. In conclusion, MK is an effective partial cement replacement material, particularly when used judiciously based on mix water content and performance priorities. For practical applications, MK contents between 5% and 15% are recommended, with 15% serving as an upper limit for both mechanical enhancement and sulfate durability.

Specifically, lower MK contents (≈5%) are most suitable for general-purpose and mass concrete applications where workability and ease of placement are crucial, while higher MK contents (≈15%) are ideal for high-performance, structural, or durability-focused concretes—such as those used in marine, sulfate-exposed, or aggressive environments. The statistical relationships and proposed model offer a foundation for more data-driven and performance-optimized concrete mix design involving metakaolin.

5.1 Limitations and future work

This study was limited to evaluating the mechanical, microstructural, and sulphate resistance performance of metakaolin (MK) blended concrete without the use of chemical admixtures. The absence of superplasticizers or water-reducing agents may have influenced the workability and strength development, and thus, future studies should incorporate these admixtures to simulate realistic field conditions. The durability scope was confined to magnesium sulphate ($MgSO_4$) exposure, which provides a case-specific insight rather than a comprehensive durability evaluation. Additional durability tests—such as chloride ingress, carbonation, and freeze–thaw resistance—are recommended to establish a more holistic understanding of MK-blended concrete under diverse environmental exposures.

Furthermore, while the study quantified CO_2 emission reduction due to partial cement replacement, a full life cycle assessment (LCA) and cost analysis were not conducted. Therefore, the sustainability claims should be interpreted as preliminary estimates, and future work should include detailed LCA and economic analyses to validate the environmental and economic benefits of MK incorporation. Lastly, future investigations should explore multi-objective optimization of MK dosage and water–binder ratio, integrate machine learning or AI-based modeling for performance prediction, and examine long-term field performance to translate laboratory findings into practical design guidelines for sustainable and durable concrete.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s44416-026-00044-w.

Supplementary Material 1

Author contributions

MAA: Conceptualization, experimental design, supervision, and correction of the final drafts. AA: Methodology, investigation and review of literatures. A.S: Co-supervision and revision of the initial and final drafts. M.A.: Preparation of the initial draft. DG: Final draft preparation and editing of figures. HS: Statistical analysis.

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Data availability

All data supporting the findings of this study are available within the paper and its Supplementary Information.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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