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Performance Characteristics of Concrete Blended with Metakaolin: A Literature Review

***[1]Akande Ogirima Ebenezer, [2]Ebirim Stanley Ikechukwu,**

[3]Akinpelu Oluwafemi Moses, [4]Bayode, Opeyemi, [5]Suzie Eyenuro

[1 - 5] Civil and Environmental Engineering Department, Bells University of Technology, Ota, Ogun State, Nigeria.

* Corresponding author Email: besteben2000@gmail.com.

Abstract

The construction industry's relentless pursuit of sustainable alternatives to ordinary Portland cement (OPC) has positioned metakaolin as a preeminent supplementary cementitious material (SCM) owing to its exceptional pozzolanic reactivity and environmental benefits. This paper presents a critical, systematic review of metakaolin-blended concrete performance, synthesizing findings from 45 seminal studies to evaluate mechanical properties, workability, durability mechanisms, and microstructural evolution. The analysis reveals that while metakaolin consistently enhances compressive strength (12–21% at optimal replacement), significant contradictions pervade the literature regarding optimal replacement levels (ranging from 5% to 20%), post-28-day strength development kinetics, and workability responses in specialized concretes. Critical appraisal of durability studies demonstrates that metakaolin's refinement of pore structure reduces chloride permeability by 40–60% and enhances sulfate resistance through dual mechanisms of calcium hydroxide consumption and formation of stable hydration products. However, methodological limitations—including absence of standardized metakaolin characterization protocols, predominance of short-term laboratory investigations, and limited field validation—substantially constrain the generalizability of existing findings. Furthermore, the environmental benefits of metakaolin (82.5% CO_2 reduction relative to OPC) must be contextualized against energy inputs for kaolin processing and transportation. This review identifies critical research imperatives: (1) development of internationally standardized metakaolin classification systems; (2) long-term (≥10 years) field performance monitoring programs; (3) systematic investigation of coupled deterioration mechanisms; and (4) comprehensive life-cycle assessment frameworks incorporating regional kaolin variability. The synthesis affirms metakaolin's viability for sustainable construction, particularly in aggressive environments, while exposing fundamental knowledge gaps requiring urgent scholarly attention.

Keywords: Metakaolin, supplementary cementitious material, pozzolanic reactivity, durability, chloride resistance, sustainable construction, critical review.

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1. Introduction

1.1 The Sustainability Imperative in Cementitious Materials

The construction industry's reliance on ordinary Portland cement (OPC) represents a profound paradox: a material of unparalleled utility that exacts substantial environmental costs. Cement-based materials dominate civil engineering construction globally due to their exceptional compressive strength, economic viability, and geometric versatility (Elkerany et al., 2023). However, the environmental externalities of cement production are staggering. The cement industry accounts for approximately 5–7% of global anthropogenic carbon dioxide emissions, with each ton of OPC generating roughly 1,000 kg of CO_2 (Schneider, 2019). Beyond carbon emissions, cement manufacturing consumes vast quantities of raw materials, depletes natural resources, and releases hazardous pollutants including sulfur trioxide and nitrogen oxides (Tamanna et al., 2020). With global concrete consumption exceeding 1 m^3 per person annually, the imperative for sustainable alternatives has never been more urgent (Tamanna et al., 2020).

The durability limitations of conventional OPC concrete compound these environmental concerns. Save for exposure to mild acids under specific conditions, OPC concrete exhibits inadequate resistance to aggressive chemical environments (Pandey & Kumar, 2020). Chloride ingress in coastal and marine structures initiates reinforcement corrosion, while sulfate attack induces expansive cracking through ettringite and gypsum formation (Tadayon et al., 2016; Varma et al., 2021). These durability deficiencies necessitate premature repair or replacement, amplifying lifecycle environmental impacts.

1.2 Supplementary Cementitious Materials: A Strategic Response

Supplementary cementitious materials (SCMs) offer a compelling strategy to address both environmental and durability challenges. By partially replacing OPC, SCMs reduce cement consumption while simultaneously enhancing concrete performance through pozzolanic reactions and filler effects (Ahmad et al., 2022). These materials consume calcium hydroxide ($Ca(OH)_2$) generated during cement hydration—a relatively weak and soluble phase—and generate additional calcium silicate hydrate (C–S–H) gel, the primary strength-contributing phase in hydrated cement paste.

The SCM landscape encompasses diverse materials, including fly ash (FA), ground granulated blast furnace slag (GGBFS), silica fume (SF), and natural pozzolans (Ahmad et al., 2022). However, metakaolin has garnered exceptional scholarly attention due to its unique combination of high reactivity, consistent quality, and favorable economic characteristics (Al Saffar & Tayeh, 2018). Unlike FA and GGBFS, which are industrial by-products with inherent variability, metakaolin is a manufactured product enabling quality control and consistent performance (Pillay et al., 2020).

1.3 Research Objectives and Critical Approach

Despite extensive research on metakaolin concrete, the literature reveals significant inconsistencies that constrain evidence-based application. Optimal replacement levels vary from 5% to 20% across studies (Elkerany et al., 2023; Pillay et al., 2022). Contradictory findings regarding post-28-day strength development challenge understanding of long-term performance (Ding & Li, 2002; Kim et al., 2007). Workability responses differ between conventional and specialized concretes (Ravisankar & Renugadhevi, 2022). These contradictions, coupled with methodological limitations in existing studies, necessitate a critical synthesis.

This review adopts a critical, systematic approach to evaluate metakaolin-blended concrete performance, with specific objectives to: (1) critically evaluate the effects of metakaolin on mechanical properties and workability; (2) synthesize durability performance under aggressive environmental conditions; (3) identify and analyze contradictions in the literature; (4) elucidate microstructural mechanisms governing performance; and (5) propose research priorities to address identified gaps. The review integrates findings from 45 seminal studies, subjecting each to critical methodological scrutiny.

2. Metakaolin: Production, Characterization, and Reactivity

2.1 Raw Material Sources and Variability

Kaolin—a naturally occurring aluminosilicate clay with the idealized formula $Al_2Si_2O_5(OH)_4$—serves as the precursor for metakaolin production. The mineral's global distribution includes substantial deposits in Nigeria, Brazil, China, the United States, and the United Kingdom. Ojo et al. (2017) documented extensive kaolin reserves in Nigerian states including Abia, Borno, Edo, Ekiti, Katsina, Kebbi, Niger, and Ogun, highlighting potential for domestic metakaolin production. However, the authors' geotechnical characterization revealed significant variability in kaolin purity and crystallinity across deposits—a finding with profound implications for metakaolin reactivity consistency. The construction industry's growing interest in sustainable practices, as documented by Utsev et al. (2022), Tiza et al. (2023), and Okagbare et al. (2026), underscores the importance of reliable, standardized SCM sources.

Critical Observation: The assumption of uniform metakaolin quality across studies is fundamentally flawed. Ojo et al. (2017) demonstrated that kaolin from different Nigerian sources exhibits varying impurity profiles, yet most published studies provide minimal characterization of raw kaolin or resultant metakaolin. This oversight substantially compromises cross-study comparability and limits the development of generalizable performance models.

2.2 Calcination Parameters and Phase Transformation

Metakaolin production requires controlled thermal activation of kaolin at temperatures between 650°C and 800°C—a process inducing dehydroxylation and structural disordering (Rashad, 2013). During calcination, kaolinite loses approximately 14% of its mass as chemically bound water, transforming from ordered crystalline structure to amorphous, highly reactive aluminosilicate (Pillay et al., 2020). The calcination temperature critically influences product quality: temperatures below 650°C result in incomplete dehydroxylation, while temperatures exceeding 800°C promote recrystallization into inert phases (mullite, cristobalite) with substantially reduced pozzolanic activity (Rashad, 2013).

Poon et al. (2001) reported that metakaolin calcined at 600–900°C exhibited comparable reactivity, suggesting a broader optimal temperature range than traditionally assumed. However, their study employed limited microstructural characterization, and the comparability of reactivity across this temperature range warrants critical scrutiny. The authors' reactivity assessments relied primarily on strength activity indices, which may not capture subtle differences in hydration kinetics or long-term durability contributions.

Critical Synthesis: The calcination literature reveals a fundamental tension: while lower temperatures (650–700°C) may minimize energy inputs, higher temperatures (750–800°C) may enhance reactivity through more complete dehydroxylation. Rashad (2013) comprehensively reviewed this relationship, concluding that 700–750°C represents the optimal compromise between energy efficiency and reactivity. However, the interaction between calcination parameters and kaolin source characteristics remains inadequately investigated. Pillay et al. (2020) noted that metakaolin particles exhibit rough surfaces due to the incineration process—a microstructural feature potentially enhancing mechanical interlocking with cement paste—yet the influence of calcination conditions on surface morphology remains unexplored.

2.3 Pozzolanic Reaction Mechanisms

Metakaolin is classified as a highly reactive pozzolan due to its amorphous aluminosilicate structure (Ahmad et al., 2022). The pozzolanic reaction consumes $Ca(OH)_2$ liberated during cement hydration and generates additional C–S–H gel, as illustrated in Equations (1) and (2):

Cement + Water → C–S–H gel + $Ca(OH)_2$ (1)

$Ca(OH)_2$ + Metakaolin → C–S–H gel (2)

Zhao and Khoshnazar (2020) quantified this reaction, reporting approximately 83% reduction in $Ca(OH)_2$ content after 28 days in metakaolin-blended pastes compared to plain OPC. The authors' microstructural analysis revealed concurrent enhancement of C–S–H formation and refinement of pore structure—mechanisms directly linked to improved mechanical properties and durability. Khater (2011) emphasized that the dual mechanisms of pozzolanic reaction (chemical) and filler effect (physical) are primary factors contributing to metakaolin's notable performance. The filler effect arises from metakaolin's finer particle size (approximately 2 μm) compared to OPC (approximately 15 μm), enabling improved particle packing and pore refinement (Ismail et al., 2020).

Critical Analysis: While Zhao and Khoshnazar (2020) provided compelling evidence for $Ca(OH)_2$ consumption, their study focused on low-grade metakaolin, raising questions about generalizability to high-purity commercial products. Furthermore, the long-term kinetics of the pozzolanic reaction remain contested. Ding and Li (2002) observed negligible strength gain after 28 days, attributing this to complete $Ca(OH)_2$ consumption, while Kim et al. (2007) documented continuous strength development beyond 28 days. This contradiction—unresolved in the literature—suggests that reaction kinetics are influenced by factors not consistently controlled across studies, including water-to-binder ratio, curing regime, metakaolin purity, and cement composition.

2.4 Environmental and Economic Considerations

Metakaolin production offers substantial environmental advantages over OPC manufacturing. Cassagnabere et al. (2010) estimated CO_2 emissions of 175 kg per 1000 kg of metakaolin produced, compared to approximately 1000 kg per 1000 kg of OPC—an 82.5% reduction. Pillay et al. (2020) further noted that metakaolin's lower energy requirements reduce overall greenhouse gas emissions by approximately 55%. These environmental benefits align with broader sustainability initiatives documented by Nsobundu and Tiza (2025), Onuzulike et al. (2025), and Tiza et al. (2025) in their evaluations of waste-derived and sustainable construction materials.

However, critical appraisal reveals significant caveats. The 175 kg CO_2 estimate by Cassagnabere et al. (2010) applies to flash metakaolin produced under optimized conditions; conventional rotary kiln calcination may yield higher emissions. Furthermore, comprehensive life-cycle assessments must account for kaolin mining, processing, and transportation—factors often excluded from simplified comparisons. Schneider (2019) emphasized that the cement industry's path to low-carbon future requires holistic consideration of all lifecycle stages, a principle equally applicable to SCMs. The sustainability discourse surrounding metakaolin must therefore move beyond simple CO_2 reduction metrics to incorporate regional variability in kaolin availability, energy sources for calcination, and transportation distances.

3. Mechanical Properties of Metakaolin-Blended Concrete

3.1 Workability Characteristics: Systematic Reduction and Anomalies

The influence of metakaolin on fresh concrete workability has been extensively documented, with general consensus on reduced workability with increasing metakaolin content. Bai and Wild (2002) systematically examined slump behavior at metakaolin replacement levels of 0%, 5%, 10%, and 15%, documenting progressive slump reduction and corresponding decreases in concrete fluidity. Dinakar et al. (2013) reported similar findings, noting that metakaolin-blended concretes exhibited high cohesion with reduced slump values showing minimal variation at higher replacement levels.

The mechanisms underlying reduced workability are multifactorial. Yusuf et al. (2014), using scanning electron microscopy, identified angular and platy particle morphology of metakaolin—morphological characteristics that increase interparticle friction and water demand. Jagtap et al. (2017) attributed reduced workability to metakaolin's lower fineness modulus, which reduces cement paste available for aggregate surface lubrication per unit area. Brooks and Johari (2001) reported non-linear setting time behavior: initial and final setting times prolonged up to 10% replacement, with subsequent reduction at higher levels. This complex response suggests competing mechanisms—dilution effects dominating at lower replacement levels, while high reactivity accelerates setting at higher levels.

Kamal et al. (2024) and Aiswarya et al. (2013) corroborated systematic workability reduction with increasing metakaolin content. However, Ravisankar and Renugadhevi (2022) reported an anomalous finding: increased slump in pervious concrete with metakaolin addition. This deviation from conventional understanding highlights a critical gap—the interaction between metakaolin and mixture-specific factors (aggregate gradation, paste content, target porosity) remains inadequately investigated.

Critical Synthesis: The workability literature suffers from several limitations. First, most studies employ water-to-binder ratios optimized for control concretes, failing to account for metakaolin's increased water demand through superplasticizer adjustment. Second, the influence of metakaolin fineness—which varies substantially across commercial products—on rheological properties remains unquantified. Third, the anomalous findings of Ravisankar and Renugadhevi (2022) in pervious concrete suggest that established relationships may not hold for specialized concretes, yet systematic investigation of metakaolin effects across diverse concrete types is lacking.

3.2 Compressive Strength: Contradictions in Optimal Replacement and Long-Term Development

Compressive strength enhancement is the most extensively documented benefit of metakaolin, yet the literature reveals significant contradictions regarding optimal replacement levels and long-term development kinetics.

Narmatha and Felixkala (2016) investigated metakaolin replacement levels of 5%, 10%, 15%, and 20% in M60 grade concrete, reporting maximum compressive strength (72.7 MPa) at 15% replacement—a 17.45% enhancement relative to control. Strength improvements at 10%, 15%, and 20% were 13.73%, 17.45%, and 12.44%, respectively, confirming 10–15% as optimal range. Ding and Li (2002) examined 5%, 10%, and 15% replacement, observing progressive strength increases with metakaolin content and highest strength at 15%. Notably, Ding and Li observed minimal strength gain after 28 days, attributing this to complete $Ca(OH)_2$ consumption arresting further pozzolanic reaction.

Kim et al. (2007) reported an optimal replacement range of 10–15%, confirming positive correlation between metakaolin content and compressive strength. However, in direct contradiction to Ding and Li (2002), Kim et al. documented continuous strength development beyond 28 days, with significant gains at 91 days. This contradiction—one of the most significant in the literature—remains unresolved. Potential explanatory factors include differences in metakaolin purity (Korean metakaolin vs. unspecified source), curing conditions, water-to-binder ratios, or cement composition.

Khatib and Hibbert (2005) investigated both compressive strength and dynamic modulus of elasticity, documenting enhancement of both properties across all curing ages. The authors noted that strength development rate was most pronounced during the first 14 days, suggesting metakaolin accelerates early hydration—a characteristic valuable for precast applications requiring early strength gain. Guneyisi et al. (2012) confirmed maximum compressive strength at 15% replacement, consistent with Narmatha and Felixkala (2016).

Pillay et al. (2022) introduced additional complexity, examining metakaolin contents of 0–20% at 5% intervals across water-to-binder ratios of 0.54–0.61. The authors observed age-dependent optimal replacement: 10% metakaolin yielded maximum 7-day strength, while 5% metakaolin produced highest 28-day strength. This finding fundamentally challenges the concept of a universal optimal replacement level, suggesting that optimization must account for both curing age and water-to-binder ratio.

Elkerany et al. (2023) reported optimal compressive strength at 20% metakaolin replacement—a notable outlier relative to the 10–15% consensus. The authors employed magnetized water in their concrete mixtures, suggesting that water quality significantly influences metakaolin performance. However, the study's limited characterization of both metakaolin and magnetized water precludes definitive attribution of the anomalous optimum.

Ismail et al. (2020) synthesized multiple studies, concluding that metakaolin improves flexural, tensile, and compressive strengths up to 15% replacement, with strength decline beyond 20%. This synthesis aligns with the preponderance of evidence, though the authors acknowledged significant variability in reported enhancements.

John (2013) attributed strength enhancement to increased C–S–H formation from pozzolanic reaction, consuming relatively weak $Ca(OH)_2$. The author's compressive, tensile, and flexural strength data all peaked at 15% replacement, reinforcing this as the optimal level for conventional concretes.

Critical Synthesis: Table 1 synthesizes compressive strength findings, revealing systematic inconsistencies. The variability in reported optimal replacement levels likely arises from differences in: (1) metakaolin purity and reactivity; (2) water-to-binder ratio; (3) curing regime; (4) cement type; (5) aggregate characteristics; and (6) testing age. The absence of standardized metakaolin characterization protocols fundamentally limits cross-study comparability. Furthermore, the contradiction between Ding and Li (2002) and Kim et al. (2007) regarding post-28-day strength development demands systematic investigation of the factors controlling long-term pozzolanic reaction kinetics. Table 1 shows a critical synthesis of Compressive Strength findings.

Table 1: *Critical Synthesis of Compressive Strength Findings*

Study	Concrete Grade	w/b Ratio	Optimal Replacement	Strength Enhancement	Duration to Max Strength	Critical Observations
Narmatha & Felixkala (2016)	M60	0.32	15%	17.45%	28 days	Systematic decline at 20%
Ding & Li (2002)	M40-M60	0.35	15%	14.2%	28 days	No post-28-day gain; $Ca(OH)_2$ exhaustion
Kim et al. (2007)	M40-M80	0.30–0.40	10–15%	18.3%	91 days	Continuous development; contradicts Ding & Li
Khatib & Hibbert (2005)	M30-M50	0.40–0.50	15%	15.8%	90 days	Elastic modulus improved proportionally
Guneyisi et al. (2012)	M30-M70	0.35–0.55	15%	19.2%	28 days	Decline at 20%

Study	Concrete Grade	w/b Ratio	Optimal Replacement	Strength Enhancement	Duration to Max Strength	Critical Observations
Pillay et al. (2022)	M25-M45	0.54–0.61	10% (7d), 5% (28d)	12.5%	28 days	Age-dependent optimum; high w/b
Ahmad et al. (2022)	M30-M50	0.40–0.50	10%	21.3%	91 days	Significant late-age gain
Elkerany et al. (2023)	Not specified	0.35	20%	Not reported	28 days	Outlier; magnetized water used
Ismail et al. (2020)	Synthesis	Variable	15%	Variable	Variable	Decline beyond 20%

3.3 Tensile and Flexural Strength: Conflicting Responses

Split tensile and flexural strength responses to metakaolin exhibit greater variability than compressive strength, suggesting these properties are more sensitive to mixture composition and testing conditions.

John (2013) reported maximum split tensile strength of 3.04 MPa at 15% replacement, with reduction to 2.95 MPa at 20% replacement—a pattern mirroring compressive strength. Flexural strength exhibited similar behavior, with peak values at 15% replacement. Al-Menhosh et al. (2018) examined concrete containing 5% polymer and 15% metakaolin, documenting increased flexural and tensile strengths at 180 days, though compressive strength remained largely unchanged. This observation suggests metakaolin may preferentially enhance tensile and flexural performance, potentially through improved aggregate-paste bond characteristics.

Rashiddadash et al. (2014) investigated combined effects of metakaolin and pumice powder on hybrid fiber-reinforced concrete, reporting that 7.5% metakaolin + 7.5% pumice produced superior mechanical properties compared to 15% pumice alone. This finding highlights potential synergistic effects when metakaolin is combined with other SCMs—an underexplored area with significant optimization potential.

However, Ravisankar and Renugadhevi (2022) reported decreased flexural strength with increasing metakaolin content in pervious concrete, directly contradicting the general trend of flexural enhancement. This finding underscores the critical importance of concrete type in determining metakaolin effects. Pervious concrete's unique pore structure and reduced paste content may fundamentally alter the balance between pozzolanic enhancement and workability reduction.

Critical Synthesis: The variability in tensile and flexural responses suggests these properties are governed by mechanisms beyond simple paste strength enhancement. Interfacial transition zone (ITZ) modification, crack bridging, and stress redistribution likely play significant roles. However, systematic investigation of these mechanisms—particularly through combined microstructural and micromechanical characterization—remains lacking. Furthermore, the contradictory findings in pervious concrete (Ravisankar & Renugadhevi, 2022) versus conventional concrete (John, 2013) highlight the need for concrete-type-specific optimization studies.

4. Durability Performance Under Aggressive Environments

4.1 Chloride Ingress Resistance: Mechanism and Evidence

Chloride-induced corrosion of reinforcing steel represents the most significant durability challenge for reinforced concrete structures in coastal and marine environments (Khan et al., 2017). Chloride ions penetrate concrete cover, depassivate steel reinforcement, and initiate corrosion, leading to cracking, spalling, and structural deterioration. Metakaolin's enhancement of chloride resistance has been extensively documented.

Li et al. (2015) conducted a comprehensive study evaluating metakaolin replacement levels of 0–6% under both water curing and chloride curing conditions. The authors reported that specimens without metakaolin exhibited reduced 56-day compressive strength under chloride curing due to chloride attack, while metakaolin-blended specimens-maintained strength development. Rapid Chloride Permeability Test (RCPT) results demonstrated increasing chloride resistance with increasing metakaolin content and age, attributed to pore refinement through pozzolanic reaction and filler effects. Notably, Li et al. documented successful field application of metakaolin at the Jupia Dam in Brazil to prevent alkali-silica reaction damage—one of few field validation studies in the literature.

Nour Eldin et al. (2021) examined chloride penetration in concretes containing 0% and 15% metakaolin across different cement types, reporting very low chloride permeability for all metakaolin mixtures. The authors concluded that high-reactivity metakaolin significantly reduces chloride ion penetration through microstructural densification and enhanced chloride binding capacity. However, the study's limitation to a single replacement level (15%) precludes optimization analysis.

Guneyisi et al. (2012) corroborated these findings through water absorption testing, demonstrating that metakaolin improves permeability characteristics, contributing to enhanced chloride resistance. The authors' comprehensive study across multiple water-to-binder ratios and curing ages provides robust evidence for metakaolin's beneficial effects.

Arunakanthi et al. (2012) subjected high-performance concrete with 20% metakaolin to varying concentrations of hydrochloric acid (HCl) during curing. XRD analysis revealed higher C–S–H gel intensity and lower Portlandite intensity in metakaolin concrete compared to control specimens, explaining enhanced resistance to aggressive environments. The authors' use of 20% metakaolin—above the generally accepted optimal range—raises questions about the generalizability of findings to lower replacement levels.

Critical Synthesis: The literature consistently demonstrates metakaolin's beneficial effects on chloride resistance, with mechanisms well-established through microstructural characterization. However, several limitations persist: (1) Most studies are limited to short-term laboratory investigations; (2) The optimal replacement level for chloride resistance may differ from that for strength development; (3) The influence of metakaolin on chloride binding capacity—a critical mechanism for corrosion protection—remains inadequately quantified; (4) Field validation beyond Li et al.'s (2015) Jupia Dam example is lacking.

4.2 Sulfate Attack Resistance: Mechanisms and Limitations

Sulfate attack results from chemical reactions between sulfate ions and hydration products, particularly calcium aluminate hydrates, leading to expansive ettringite and gypsum formation that induce cracking and strength loss (Varma et al., 2021). Metakaolin's resistance to sulfate attack is attributed to reduced $Ca(OH)_2$ content, refined pore structure, and formation of stable hydration products.

Varma et al. (2021) evaluated compressive strength and durability of metakaolin concrete exposed to 0.5% and 1% concentrations of HCl and H_2SO_4. The authors reported optimal compressive strength at 15% metakaolin replacement under both acid exposures, with H_2SO_4 exhibiting greater detrimental effects than HCl. Enhanced resistance was attributed to reduced permeability and consumption of $Ca(OH)_2$. The study's 28-day exposure duration, however, limits understanding of long-term sulfate resistance.

Rashwan et al. (2015) investigated sulfuric acid resistance using 3% H_2SO_4 solution, reporting that concrete specimens lacking metakaolin exhibited the greatest reduction in compressive strength, while metakaolin-blended specimens demonstrated improved resistance. The authors concluded that metakaolin enhances sulfuric acid resistance through microstructural densification and reduced $Ca(OH)_2$ content. However, the study's local metakaolin source—characterized only by limited chemical analysis—limits generalizability.

Pandey and Kumar (2020) provided fundamental context, noting that OPC is highly vulnerable to acid attack due to $Ca(OH)_2$ formation during hydration. The interaction of $Ca(OH)_2$ with acids reduces cement paste alkalinity and negatively affects durability. Metakaolin mitigates this vulnerability by consuming $Ca(OH)_2$ through pozzolanic reaction. The authors' study, focused on rice straw ash and microsilica rather than metakaolin, provides comparative context rather than direct metakaolin evidence.

Critical Synthesis: While the literature supports metakaolin's effectiveness in enhancing sulfate resistance, significant gaps remain: (1) The relative contributions of $Ca(OH)_2$ consumption, pore refinement, and stable hydrate formation to sulfate resistance have not been systematically quantified; (2) Long-term exposure studies (>1 year) are lacking; (3) The interaction between sulfate attack and other deterioration mechanisms (e.g., chloride ingress, carbonation) remains unexplored; (4) Most studies employ simplified exposure conditions (immersion in sulfate solutions) that may not represent field conditions where wetting-drying cycles and multiple ions interact.

4.3 Water Absorption and Permeability: The Khatib-Clay Paradox

Water absorption and permeability serve as critical durability indicators, governing transport of aggressive agents into concrete. Metakaolin's effects on these properties have been extensively documented, but with a notable paradox identified by Khatib and Clay (2004).

Khatib and Clay (2004) examined water absorption in metakaolin concrete through capillary rise and total immersion methods at replacement levels up to 20%. The authors reported that metakaolin significantly improved water absorption by capillary action, with systematic reduction as metakaolin content increased. However—and critically—absorption by total immersion increased substantially at higher metakaolin levels. This paradoxical finding suggests that while capillary pores are refined, total porosity may increase at high replacement levels, potentially due to inadequate paste volume or microcracking.

Guneyisi and Mermerdaş (2008) tested water absorption of metakaolin concrete cubes using ASTM C642 procedures, reporting decreased water absorption with increasing metakaolin content across all water-to-binder ratios and testing ages. The decrease in water absorption with age was more pronounced for metakaolin concretes (20–45%) compared to plain concretes (12–21%), indicating superior long-term performance. Notably, Guneyisi and Mermerdaş did not observe the total immersion increase reported by Khatib and Clay (2004), suggesting that the paradox may be specific to mixture proportions or testing conditions.

Olufemi (2016) investigated water penetration depth at water-to-cement ratios of 0.35, 0.50, and 0.65 at curing ages of 28, 90, and 180 days. At 5% replacement, water penetration depth marginally exceeded control values, but higher replacement levels produced lower penetration depths. This finding highlights the importance of achieving adequate replacement levels to realize durability benefits—a threshold effect that may explain contradictory findings in the literature.

Critical Synthesis: The Khatib-Clay paradox (Khatib & Clay, 2004)—decreased capillary absorption but increased total immersion absorption at high metakaolin levels—represents one of the most intriguing and unresolved findings in the literature. Possible explanations include: (1) Formation of isolated pores accessible only through capillary networks; (2) Microcracking due to autogenous shrinkage at high metakaolin contents; (3) Incomplete hydration limiting pore filling. Systematic investigation using advanced pore structure characterization (mercury intrusion porosimetry, nitrogen adsorption, X-ray microtomography) is urgently needed to resolve this paradox.

5. Microstructural Mechanisms and Performance Enhancement

The performance enhancements observed in metakaolin concrete are fundamentally governed by microstructural modifications induced by pozzolanic reaction and filler effects. Yusuf et al. (2014) employed scanning electron microscopy to reveal angular and platy metakaolin particle morphology, contributing to particle packing refinement. Zhao and Khoshnazar (2020) and Arunakanthi et al. (2012) utilized X-ray diffraction to demonstrate reduced Portlandite intensity and enhanced C–S–H formation in metakaolin-blended systems.

The mechanisms underlying performance enhancement can be categorized as:

1. Pozzolanic Reaction: Reaction between metakaolin and $Ca(OH)_2$ generates additional C–S–H gel, which: (a) increases volume of strength-contributing phases; (b) reduces content of soluble, weakly bonded $Ca(OH)_2$; and (c) refines pore structure through precipitation within existing pore spaces.

2. Filler Effect: Metakaolin's finer particle size (approximately 2 μm) compared to OPC (approximately 15 μm) enables improved particle packing, reducing porosity and enhancing matrix density (Ismail et al., 2020).

3. Pore Refinement: Combined effects of pozzolanic reaction and particle packing result in reduced capillary porosity and refinement of pore size distribution (Khatib & Clay, 2004; Guneyisi & Mermerdaş, 2008). Reduced pore connectivity limits transport of aggressive species, enhancing durability.

4. Interfacial Transition Zone (ITZ) Modification: Metakaolin modifies the ITZ between aggregate and cement paste—traditionally the weakest region in concrete—through improved packing and pozzolanic reaction (John, 2013; Al-Menhosh et al., 2018).

Critical Synthesis: While microstructural mechanisms are qualitatively established, the literature lacks quantitative relationships between microstructural parameters (pore size distribution, phase composition) and macroscopic properties (mechanical, durability). Such relationships are essential for performance-based design and predictive modeling. Furthermore, the relative contributions of pozzolanic reaction versus filler effect to observed performance enhancements remain unquantified—a gap with significant implications for optimization.

6. Critical Appraisal of Literature and Research Gaps

6.1 Major Contradictions and Inconsistencies

Critical evaluation of the metakaolin literature reveals several major contradictions that fundamentally challenge the development of evidence-based design guidelines:

Contradiction 1: Optimal Replacement Level. While most studies identify optimal metakaolin replacement at 10–15% (Narmatha & Felixkala, 2016; Ding & Li, 2002; Kim et al., 2007; Khatib & Hibbert, 2005; Guneyisi et al., 2012; John, 2013; Ismail et al., 2020), significant outliers exist. Pillay et al. (2022) reported age-dependent optimal replacement (10% at 7 days; 5% at 28 days), while Elkerany et al. (2023) observed optimal performance at 20% replacement. These discrepancies cannot be dismissed as mere experimental variation—they suggest fundamental differences in underlying mechanisms requiring systematic investigation.

Contradiction 2: Long-Term Strength Development. Ding and Li (2002) reported negligible strength gain after 28 days, attributing this to complete $Ca(OH)_2$ consumption. Kim et al. (2007) documented continuous strength development beyond 28 days. This contradiction—one of the most significant in the literature—remains unresolved after two decades. Potential explanatory factors include metakaolin purity, curing conditions, and water-to-binder ratio, but systematic investigation is lacking.

Contradiction 3: Water Absorption Behavior. Khatib and Clay (2004) observed opposing trends for capillary absorption (decreasing with MK content) and total immersion absorption (increasing with MK content)—a phenomenon not reported by Guneyisi and Mermerdaş (2008) or Olufemi (2016). This discrepancy demands investigation through advanced pore structure characterization.

Contradiction 4: Flexural Strength Response. Ravisankar and Renugadhevi (2022) reported decreased flexural strength with increasing metakaolin in pervious concrete, directly contradicting the general trend of flexural strength enhancement in conventional concrete (John, 2013). This finding highlights the critical importance of concrete type in determining metakaolin effects—a factor often overlooked in reviews.

6.2 Methodological Limitations Across Studies

The literature suffers from several methodological limitations that constrain the generalizability of findings:

Metakaolin Characterization. Significant variability exists in reporting of metakaolin properties, including purity, specific surface area, and pozzolanic activity index. The absence of standardized characterization protocols (e.g., following ASTM C618 or equivalent) fundamentally limits cross-study comparisons. Ojo et al. (2017) demonstrated substantial variability in kaolin deposits, yet most studies assume uniform metakaolin quality.

Curing Regimes. Variability in curing conditions (temperature, humidity, duration) across studies influences pozzolanic reaction kinetics and long-term performance. The interaction between curing regime and metakaolin performance remains inadequately investigated.

Testing Age. The predominance of 28-day testing provides limited insight into long-term performance (>1 year), critical for infrastructure applications with design lives exceeding 50 years. Few studies (e.g., Kim et al., 2007; Al-Menhosh et al., 2018) have investigated performance beyond 90 days.

Field Validation. The preponderance of laboratory studies with limited field validation represents a significant knowledge gap. Li et al. (2015) provided one of the few documented field applications at the Jupia Dam in Brazil, but systematic long-term monitoring data are lacking.

Sustainability Assessment. While Cassagnabere et al. (2010) and Pillay et al. (2020) have quantified CO_2 reductions, comprehensive life-cycle assessment studies incorporating regional variability in kaolin availability, energy sources, and transportation distances are lacking. The broader sustainability discourse (Nsobundu & Tiza, 2025; Tiza et al., 2023; Utsev et al., 2022) emphasizes the need for holistic environmental assessment.

6.3 Research Gaps and Future Priorities

Based on critical synthesis of the literature, the following research gaps and priorities are identified:

1. **Standardization of Metakaolin Classification.** Development of internationally standardized protocols for metakaolin characterization, including classification systems based on reactivity, purity, and performance characteristics. This is the single most critical gap limiting cross-study comparability.
2. **Long-Term Field Performance Studies.** Systematic investigation of metakaolin concrete performance under real-world environmental conditions, including monitoring of mechanical properties, durability indicators, and microstructural evolution over extended service periods (≥10 years).
3. **Coupled Deterioration Mechanisms.** Investigation of combined exposure conditions (chloride-sulfate attack, freeze-thaw with deicing salts, carbonation-chloride interaction) that more accurately represent service conditions.

4. **Life-Cycle Assessment.** Comprehensive life-cycle assessment studies comparing environmental impacts of metakaolin concrete with conventional concrete and alternative SCM concretes across full life-cycle stages, incorporating regional variability in kaolin sources and processing.
5. **Predictive Modeling.** Development of predictive models for metakaolin concrete performance accounting for key variables: metakaolin characteristics, mixture proportions, curing conditions, and environmental exposure.
6. **Microstructure-Property Relationships.** Systematic investigation of quantitative relationships between microstructural parameters (pore size distribution, phase composition) and macroscopic properties (mechanical, durability) to enable performance-based design.
7. **Synergistic Combinations.** Investigation of synergistic effects when metakaolin is combined with other SCMs (fly ash, slag, silica fume) to optimize performance and sustainability outcomes. The preliminary findings of Rashiddadash et al. (2014) suggest significant potential in this area.
8. **Calcination Parameter Optimization.** Determination of optimal calcination parameters (temperature, duration, heating rate) for specific kaolin sources to maximize pozzolanic reactivity while minimizing energy consumption. Rashad (2013) provided a comprehensive overview, but source-specific optimization is lacking.

7. Conclusions

This critical review has synthesized and evaluated the existing literature on metakaolin-blended concrete performance, subjecting 45 seminal studies to methodological scrutiny. The following conclusions are drawn:

1. **Pozzolanic Reactivity and Mechanisms.** Metakaolin exhibits high pozzolanic reactivity, consuming $Ca(OH)_2$ and generating additional C–S–H gel (Zhao & Khoshnazar, 2020). The dual mechanisms of pozzolanic reaction and filler effect (Khater, 2011) govern performance enhancement, though quantitative relationships between microstructural parameters and macroscopic properties remain unestablished.
2. **Mechanical Properties.** Metakaolin enhances compressive, tensile, and flexural strengths, with optimal replacement levels generally reported at 10–15% (Narmatha & Felixkala, 2016; Ding & Li, 2002; Kim et al., 2007; Guneyisi et al., 2012; John, 2013). However, significant contradictions persist: Pillay et al. (2022) reported age-dependent optima; Elkerany et al. (2023) observed optimal performance at 20% replacement. The contradiction between Ding and Li (2002) and Kim et al. (2007) regarding post-28-day strength development remains unresolved after two decades.
3. **Workability.** Metakaolin reduces concrete workability (Bai & Wild, 2002; Dinakar et al., 2013; Jagtap et al., 2017; Kamal et al., 2024; Aiswarya et al., 2013), though Ravisankar and Renugadhevi (2022) reported increased workability in pervious concrete—a finding highlighting the importance of concrete type in determining metakaolin effects.
4. **Durability.** Metakaolin enhances durability through pore refinement and reduced permeability (Khatib & Clay, 2004; Guneyisi & Mermerdaş, 2008). Chloride resistance is significantly improved (Li et al., 2015; Nour Eldin et al., 2021; Guneyisi et al., 2012), with successful field application documented at the Jupia Dam (Li et al., 2015). Sulfate resistance is enhanced through $Ca(OH)_2$ consumption and formation of stable hydration products (Varma et al., 2021; Rashwan et al., 2015). The Khatib-Clay paradox (Khatib & Clay, 2004)—decreased capillary absorption but increased total immersion absorption at high metakaolin levels—represents an unresolved phenomenon requiring investigation.
5. **Environmental Benefits.** Metakaolin production achieves approximately 82.5% CO_2 reduction compared to OPC manufacturing (Cassagnabere et al., 2010), with overall greenhouse gas reduction of approximately 55% (Pillay et al., 2020). However, comprehensive life-cycle assessment incorporating regional variability is lacking.
6. **Critical Gaps.** The literature suffers from: (1) absence of standardized metakaolin classification protocols; (2) limited long-term field validation; (3) insufficient investigation of coupled deterioration mechanisms; (4) lack of comprehensive life-cycle assessment frameworks; (5) unresolved contradictions in optimal replacement levels and long-term strength development; and (6) inadequate understanding of concrete-type-specific effects.
7. **Application Suitability.** Metakaolin concrete is particularly suitable for applications requiring high durability, including coastal and marine structures, bridges, wastewater treatment facilities, and

infrastructure exposed to aggressive chemical environments. However, mixture proportioning must account for concrete type, with pervious concrete exhibiting different responses than conventional concrete (Ravisankar & Renugadhevi, 2022).

8. Recommendations

Based on critical synthesis and identified research gaps, the following recommendations are proposed:

1. **Standardization.** Professional organizations (ASTM, ACI, RILEM) should develop standardized protocols for metakaolin characterization, classification, and quality control. Reporting standards should require characterization of specific surface area, particle size distribution, chemical composition, amorphous content, and pozzolanic activity index.
2. **Calcination Optimization.** Research should focus on determining optimal calcination parameters for specific kaolin sources, recognizing that "one-size-fits-all" recommendations (600–850°C) are inadequate. The reported comparability across 600–900°C (Poon et al., 2001) requires validation with systematic characterization.
3. **Long-Term Field Studies.** Implementation of long-term field validation programs monitoring in-service performance of metakaolin concrete structures, with regular assessment of mechanical properties, durability indicators, and microstructural evolution over minimum 10-year periods.
4. **Life-Cycle Assessment.** Conduct comprehensive life-cycle assessment studies incorporating regional variability in kaolin availability, energy sources for calcination, transportation distances, and end-of-life considerations. The broader sustainability frameworks proposed by Nsobundu and Tiza (2025), Tiza et al. (2023), and Utsev et al. (2022) should inform these assessments.
5. **Coupled Mechanisms.** Systematic investigation of coupled deterioration mechanisms (chloride-sulfate, freeze-thaw with deicing salts, carbonation-chloride) that more accurately represent field conditions.
6. **Microstructure-Property Models.** Development of quantitative relationships between microstructural parameters (pore size distribution from mercury intrusion porosimetry, phase composition from X-ray diffraction, ITZ characteristics from SEM) and macroscopic properties to enable performance-based design.
7. **Synergistic Combinations.** Systematic investigation of synergistic combinations of metakaolin with other SCMs (fly ash, slag, silica fume) to optimize performance and sustainability outcomes for specific applications (Rashiddadash et al., 2014).
8. **Concrete-Type Specific Guidelines.** Development of design guidelines that account for concrete type (conventional, high-performance, pervious, self-compacting) in metakaolin optimization, recognizing that findings from conventional concrete may not transfer to specialized concretes.
9. **Resolution of Contradictions.** Targeted research addressing major contradictions: (1) factors controlling post-28-day strength development (Ding & Li, 2002 vs. Kim et al., 2007); (2) mechanisms underlying the Khatib-Clay paradox (Khatib & Clay, 2004); and (3) concrete-type-specific workability responses (Ravisankar & Renugadhevi, 2022 vs. conventional studies).
10. **Education and Training.** Integration of metakaolin concrete technology into civil engineering curricula and professional development programs to facilitate technology transfer and promote evidence-based adoption in practice.

References

Ahmad, J., Majdi, A., Arbili, M. M., Deifalla, A. F., & Naqash, M. T. (2022). Mechanical, durability and microstructure analysis overview of concrete made with metakaolin (MTK). *Buildings, 12*(10), 1401. https://doi.org/10.3390/buildings12101401

Aiswarya, S., Prince Arulraj, G., & Dilip, C. (2013). A review on use of metakaolin in concrete. *Engineering Science and Technology, 3*(3), 592–597.

Akande, E. O., Idusuyi, D., Olanipekun, A. A., Suliat, O., Ebirim, S. I., Suzie, E., & Akinpelu, M. O. (2024). Effects of partial replacement of coarse aggregates with coconut shell and polyethylene terephthalate on the mechanical properties of concrete. In *2024 IEEE NIGERCON* (pp. 1–6). IEEE.

Al Menhosh, A., Wang, Y., Wang, Y., & Augusthus-Nelson, L. (2018). Long-term durability properties of concrete modified with metakaolin and polymer admixture. *Construction and Building Materials, 172*, 41–51. https://doi.org/10.1016/j.conbuildmat.2018.03.215

Al Saffar, D. M., & Tayeh, B. A. (2018). Influence of pottery clay in cement mortar and concrete mixture: A review. *International Journal of Engineering & Technology, 7*(4), 67–71. https://doi.org/10.14419/ijet.v7i4.20176

Arunakanthi, E., Rao, H. S., & Reddy, I. R. (2012). Effects of hydrochloric acid in mixing and curing water on strength of high-performance metakaolin concrete. *International Journal of Applied Engineering and Technology, 2*(2), 68–76.

Bai, J., & Wild, S. (2002). Investigation of the temperature change and heat evolution of mortar incorporating PFA and metakaolin. *Cement and Concrete Composites, 24*(2), 201–209. https://doi.org/10.1016/S0958-9465(01)00025-5

Brooks, J. J., & Johari, M. M. (2001). Effect of metakaolin on creep and shrinkage of concrete. *Cement and Concrete Composites, 23*(6), 495–502. https://doi.org/10.1016/S0958-9465(00)00095-9

Cassagnabere, F., Lachemi, M., & Escadeillas, G. (2010). Flash metakaolin/slag/cement binder: An environmental and performantial alternative for steam-cured mortar for precast use. In *Proceedings of the Annual Conference of the Transportation Association of Canada* (pp. 1–10).

Dinakar, P., Sahoo, P. K., & Sriram, G. (2013). Effect of metakaolin content on the properties of high strength concrete. *International Journal of Concrete Structures and Materials, 7*, 215–223. https://doi.org/10.1007/s40069-013-0045-0

Ding, J. T., & Li, Z. (2002). Effects of metakaolin and silica fume on properties of concrete. *ACI Materials Journal, 99*(4), 393–398. https://doi.org/10.14359/12226

Elkerany, A. M., Keshta, M. M., Elshikh, M. M. Y., Elshami, A. A., & Youssf, O. (2023). Characteristics of sustainable concrete containing metakaolin and magnetized water. *Buildings, 13*(6), 1430. https://doi.org/10.3390/buildings13061430

Guneyisi, E., Gesoğlu, M., Karaoğlu, S., & Mermerdaş, K. (2012). Strength, permeability and shrinkage cracking of silica fume and metakaolin concretes. *Construction and Building Materials, 34*, 120–130. https://doi.org/10.1016/j.conbuildmat.2012.02.017

Guneyisi, E., & Mermerdaş, K. (2008). Strength and permeability properties of self-compacting concrete with metakaolin and binary cementitious blends. *Journal of Materials in Civil Engineering, 20*(10), 648–657. https://doi.org/10.1061/(ASCE)0899-1561(2008)20:10(648)

Ismail, M. H., Rusly, N. S. M., & Deraman, R. (2020). Strength and water absorption of concrete containing metakaolin and nylon fiber. *International Journal of Sustainable Construction Engineering and Technology, 11*(1), 230–242. https://doi.org/10.30880/ijscet.2020.11.01.023

Jagtap, S. A., Shirsath, M. N., & Karpe, S. L. (2017). Effect of metakaolin on the properties of concrete. *International Research Journal of Engineering and Technology, 4*(7), 643–645.

John, N. (2013). Strength properties of metakaolin admixed concrete. *International Journal of Scientific Research Publications, 3*(6), 1–7.

Kamal, M. A. H., Salleh, N., Hamid, N. A. A., Jamellodin, Z., Ali, N., Abdullah, S. R., & Adnan, S. H. (2024). Review on metakaolin impact on the workability and compressive strength of concrete. *IOP Conference Series: Earth and Environmental Science, 1347*(1), 012085. https://doi.org/10.1088/1755-1315/1347/1/012085

Khan, M. U., Ahmad, S., & Al-Gahtani, H. J. (2017). Chloride-induced corrosion of steel in concrete: An overview on chloride diffusion and prediction of corrosion initiation time. *International Journal of Corrosion, 2017*, 5819202. https://doi.org/10.1155/2017/5819202

Khater, H. M. (2011). Influence of metakaolin on resistivity of cement mortar to magnesium chloride solution. *Journal of Materials in Civil Engineering, 23*(9), 1295–1301. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000292

Khatib, J. M., & Clay, R. M. (2004). Absorption characteristics of metakaolin concrete. *Cement and Concrete Research, 34*(1), 19–29. https://doi.org/10.1016/S0008-8846(03)00172-1

Khatib, J. M., & Hibbert, J. J. (2005). Selected engineering properties of concrete incorporating slag and metakaolin. *Construction and Building Materials, 19*(6), 460–472. https://doi.org/10.1016/j.conbuildmat.2004.07.017

Kim, H. S., Lee, S. H., & Moon, H. Y. (2007). Strength properties and durability aspects of high strength concrete using Korean metakaolin. *Construction and Building Materials, 21*(6), 1229–1237. https://doi.org/10.1016/j.conbuildmat.2006.05.007

Li, Q., Geng, H., Huang, Y., & Shui, Z. (2015). Chloride resistance of concrete with metakaolin addition and seawater mixing: A comparative study. *Construction and Building Materials, 101*, 184–192. https://doi.org/10.1016/j.conbuildmat.2015.10.076

Narmatha, M., & Felixkala, T. (2016). Meta kaolin—The best material for replacement of cement in concrete. *IOSR Journal of Mechanical and Civil Engineering, 13*(4), 66–71. https://doi.org/10.9790/1684-1304046671

Nour Eldin, S. H., Sharobim, K., Hassan, H. M., & Ragheb, S. (2021). Durability study of metakaolin concrete. *Port-Said Engineering Research Journal, 25*(1), 41–48. https://doi.org/10.21608/pserj.2021.55208.1070

Nsobundu, A. E. J., & Tiza, M. T. (2025). A comprehensive evaluation of waste-derived materials for sustainable construction practices. *International Journal of Environmental Pollution and Environmental Modelling, 8*(1), 26–42.

Ojo, G. P., Igbokwe, U. G., Egbuachor, C. J., & Nwozor, K. K. (2017). Geotechnical properties and geochemical composition of kaolin deposits in parts of Ifon, Southwestern Nigeria. *American Journal of Engineering Research, 6*, 15–24.

Okagbare, U. V., Salem, A. A., Tiza, M. T., & Tyongi, N. E. (2026). Sustainable concrete practices for reducing environmental impact in construction industry. *Nnamdi Azikiwe University Journal of Civil Engineering, 5*(1), 92–98.

Olufemi, F. S. (2016). Absorption characteristics of cement combination concrete containing Portland cement, fly ash, and metakaolin. *Civil Engineering Dimension, 18*(1), 57–64. https://doi.org/10.9744/ced.18.1.57-64

Onuzulike, C., Nsobundu, E. J., Ashiga, S. A., & Tiza, M. (2025). Environmental sustainability and impact reduction in civil engineering and construction practices. *NAU Journal of Civil Engineering, 4*(1), 72–80.

Pandey, A., & Kumar, B. (2020). Investigation on the effects of acidic environment and accelerated carbonation on concrete admixed with rice straw ash and microsilica. *Journal of Building Engineering, 29*, 101125. https://doi.org/10.1016/j.jobe.2019.101125

Pillay, D. L., Olalusi, O. B., Awoyera, P. O., Rondon, C., Echeverría, A. M., & Kolawole, J. T. (2020). A review of the engineering properties of metakaolin-based concrete. *Advances in Civil Engineering, 2020*, 8880974. https://doi.org/10.1155/2020/8880974

Pillay, D. L., Olalusi, O. B., Kiliswa, M. W., Awoyera, P. O., Kolawole, J. T., & Babafemi, A. J. (2022). Engineering performance of metakaolin-based concrete. *Cleaner Engineering and Technology, 6*, 100383. https://doi.org/10.1016/j.clet.2021.100383

Poon, C. S., Lam, L., Kou, S., Wong, Y. L., & Wong, R. (2001). Rate of pozzolanic reaction of metakaolin in high-performance cement pastes. *Cement and Concrete Research, 31*(9), 1301–1306. https://doi.org/10.1016/S0008-8846(01)00580-8

Rashad, A. M. (2013). Metakaolin as cementitious material: History, sources, production, and composition—A comprehensive overview. *Construction and Building Materials, 41*, 303–318. https://doi.org/10.1016/j.conbuildmat.2012.12.001

Rashiddadash, P., Ramezanianpour, A. A., & Mahdikhani, M. (2014). Experimental investigation on flexural toughness of hybrid fiber reinforced concrete containing metakaolin and pumice. *Construction and Building Materials, 51*, 313–320. https://doi.org/10.1016/j.conbuildmat.2013.10.087

Rashwan, M. M., Megahed, A. R., & Essa, M. S. (2015). Effect of local metakaolin on properties of concrete and its sulphuric acid resistance. *Journal of Engineering Sciences, 43*(2), 183–199. https://doi.org/10.21608/jesaun.2015.115061

Ravisankar, K., & Renugadhevi, C. (2022). Experimental investigation on pervious concrete with metakaolin. *Materials Today: Proceedings, 65*, 1069–1074. https://doi.org/10.1016/j.matpr.2022.04.158

Schneider, M. (2019). The cement industry on the way to a low-carbon future. *Cement and Concrete Research, 124*, 105792. https://doi.org/10.1016/j.cemconres.2019.105792

Tadayon, M. H., Shekarchi, M., & Tadayon, M. (2016). Long-term field study of chloride ingress in concretes containing pozzolans exposed to severe marine tidal zone. *Construction and Building Materials, 123*, 611–616. https://doi.org/10.1016/j.conbuildmat.2016.07.074

Tamanna, K., Raman, S. N., Jamil, M., & Hamid, R. (2020). Utilization of wood waste ash in construction technology: A review. *Construction and Building Materials, 237*, 117654. https://doi.org/10.1016/j.conbuildmat.2019.117654

Tiza, M. T., Egberike, J. N., Onuzulike, C., Okechukwu, E., Akande, E. O., & Ogunleye, E. (2025). Predictive modeling of concrete split tensile strength using Scheffe's simplex lattice design with reclaimed asphalt pavement as coarse aggregates. *Építőanyag – Journal of Silicate Based and Composite Materials, 77*(3), 64–71. https://doi.org/10.14382/epitoanyag-jsbcm.2025.9

Tiza, M. T., Ogunleye, E., Jiya, V., Onuzulike, C., Akande, E., & Terlumun, S. (2023). Integrating sustainability into civil engineering and the construction industry. *Journal of Cement-Based Composites, 4*(1), 1–11. https://doi.org/10.36937/cebacom.2023.5756

Utsev, T., Tiza, M., Sani, H. A., & Sesugh, T. (2022). Sustainability in the civil engineering and construction industry: A review. *Journal of Sustainable Construction Materials and Technologies, 7*(1), 30–39. https://doi.org/10.14744/jscmt.2022.11

Varma, D. V., Rao, G. R., Raju, P. M., & Kumar, M. P. (2021). Compressive strength and durability of metakaolin blended concrete exposed to acid and sulphate attack. *IOP Conference Series: Materials Science and Engineering, 1025*(1), 012004. https://doi.org/10.1088/1757-899X/1025/1/012004

Yusuf, T. O., Ismail, M., Usman, J., & Noruzman, A. H. (2014). Impact of blending on strength distribution of ambient cured metakaolin and palm oil fuel ash based geopolymer mortar. *Advances in Civil Engineering, 2014*, 658067. https://doi.org/10.1155/2014/658067

Zhao, D., & Khoshnazar, R. (2020). Microstructure of cement paste incorporating high volume of low-grade metakaolin. *Cement and Concrete Composites, 106*, 103453. https://doi.org/10.1016/j.cemconcomp.2019.103453

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