

Structural effect of combined metakaolin and high-performance superplasticizers on the compressive behaviours of normal and high strength concrete

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Abstract

This study investigated the influences of metakaolin on the compressive strength and density of normal- and high-strength concrete. The metakaolin, sourced from a local kaolin mining site in Umuahia and calcined at 800 °C in the kiln at the University of Nigeria, Nsukka, was characterised using X-ray fluorescence. Its high silica (67.5 mol%) and alumina (26.5 mol%) contents confirmed strong pozzolanic activity, while particle-size analysis showed a sub-micron to low-micron distribution that enhances reactivity. Incorporating up to 10% metakaolin increased normal-strength concrete strength from 23.8 to 37.6 N/mm² at 7 days and from 32.8 to 48.1 N/mm² at 28 days. High-strength concrete also improved, with density rising from 2486 to 2575 kg/m³ and strength increasing from 50.9 to 72.6 N/mm² at 28 days. Ultracrete 61 superplasticiser further enhanced workability and compressive strength. Although chloride content (1.95 mol%) raises corrosion concerns, the findings underscore the need for careful proportioning and material evaluation to support more durable and sustainable concrete formulations.

Keywords: metakaolin, supplementary cementitious material (SCM), concrete compressive strength, concrete density, pozzolanic activity

Kulcsszavak: metakaolin, kiegészítő cementkötésű anyag (SCM), beton nyomószilárdság, beton sűrűség, pucolóanyag aktivitás

1. Introduction

Concrete remains fundamental to modern infrastructure due to its mechanical versatility and durability [1, 2, 3]. However, owing to the shortcomings of its primary binder, Portland cement, it is imperative to source an alternative material with binding properties. Cement production is among the most energy-intensive industrial processes, releasing significant quantities of CO₂, thus posing sustainability challenges that undermine the ecological viability of conventional concrete [4, 5, 23]. This dilemma has catalysed the integration of supplementary cementitious materials (SCM's) as partial cement replacements, a strategy that seeks to reconcile performance demands with environmental imperatives [6, 7, 8]. SCM's offer potential reductions in carbon emissions; their efficacy hinges on the balance between sustainability gains and the retention or enhancement of critical concrete properties such as strength and durability. Not all SCM's exhibit uniform pozzolanic reactivity or contribute equally to concrete performance, demanding rigorous characterisation and optimisation in mix design to prevent compromises in structural integrity [9]. Therefore, the deployment of SCM's embodies a complex trade-off, requiring a holistic evaluation that encompasses environmental, mechanical, and durability dimensions to ensure genuinely

sustainable construction practices. At the core is optimising concrete composition for sustainability, emphasising the need to create mixtures that reduce environmental impact while preserving structural integrity.

The pozzolanic reactivity of Metakaolin varies significantly with source purity, calcination, and particle morphology, causing inconsistent hydration and microstructure development in concrete [10, 22]. While its fine particles enhance early strength, they increase water demand, challenging workability, and require admixture optimisation [11, 12, 24]. Durability improvements, such as sulphate and chloride resistance, depend heavily on curing conditions and interactions with other SCM's, without uniform effectiveness [13, 14, 15, 16]. Environmentally, metakaolin reduces cement use and emissions, but requires energy-intensive production and limited raw materials, raising concerns about its sustainability and cost [17, 18, 25]. Thus, standardising metakaolin properties and integrating long-term performance data under varied exposures is essential to reliably harness the benefits in sustainable concrete production [19, 20].

The research aims to characterise the chemical composition and particle size distribution of metakaolin using advanced analytical techniques, which assess the influence of metakaolin incorporation on the compressive strength and density of

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both normal-strength and high-strength concrete at 7- and 28-day curing periods. It also establishes correlations between chemical and physical characteristics of metakaolin and the observed mechanical performance of concrete, which further provides insights and recommendations for the practical use of metakaolin in sustainable construction.

Despite extensive research on metakaolin's chemical and physical properties, a comprehensive understanding of how specific chemical compositions correlate with concrete's mechanical strength and durability remains limited. Most studies isolate either chemical characterisation or mechanical testing, lacking integrated analyses that link oxide profiles to strength and density evolution over time. Variability in metakaolin sources and processing further complicates the prediction of concrete behaviour, challenging the development of generalised performance models. Additionally, density changes and the influence of minor oxides and trace elements on hydration and microstructure are often overlooked. Few studies combine advanced characterisation techniques with systematic mechanical testing across curing ages, hindering a robust predictive framework.

Finally, despite the existence of extensive literature on metakaolin, no prior study has examined a locally sourced kaolin-based metakaolin from Umuahia, calcined under controlled conditions at 800 °C, with integrated chemical, particle-size, and mechanical performance characterisation across both normal- and high-strength concrete. This work therefore contributes new insights by directly linking oxide composition and particle-size distribution to strength and density evolution, quantifying the synergy between metakaolin and a high-performance superplasticiser, and identifying a chloride-related durability risk unique to this material source.

Addressing these gaps is critical for optimising metakaolin use as a sustainable SCM and advancing durable concrete technologies.

2. Materials and methods

2.1 Materials

The materials employed in this study were carefully selected to ensure consistency and reliability in assessing the effects of metakaolin on concrete properties.

2.1.1 Limestone Portland cement

Grade 42.5N Lafarge Superset was used as the primary binder. The cement was characterised by its chemical composition, fineness, and setting times to establish baseline properties.

2.1.2 Metakaolin

The key supplementary cementitious material under investigation was procured from a kaolin mining site at Umuahia, Abia State, Nigeria, calcined to a temperature of 800 °C at the University of Nigeria, Nsukka, and subjected to preliminary characterisation to determine its chemical composition through XRF (X-ray Fluorescence) technology and physical properties tests. The metakaolin was produced through the controlled calcination of kaolin clay at 800 °C to achieve the amorphous

aluminosilicate phase critical for pozzolanic activity, as shown in Table 1, in comparison with ASTM C150 [28]. Table 2 shows the physical properties of aggregates used in line with BS EN 933-1 [29]. The particle size and molecular weight were measured by a Malvern Zetasizer, utilising Dynamic Light Scattering (DLS) and Electrophoretic Light Scattering (ELS) to analyse the metakaolin sample stability and characteristics.

S/ No	Parameter	Cement (Measured)	Meta-kaolin (Measured)	ASTM Standard Requirement	Compliance Assessment
1	Silicon Oxide (SiO ₂ , %)	21.03	67.48	C150[28]: No limit; C618[27]: SiO ₂ +Al ₂ O ₃ +Fe ₂ O ₃ ≥70%	Cement: Within typical OPC range; MK: Conforms
2	Calcium Oxide (CaO, %)	61.95	0.55	No limit in C150[28]; Not specified in C618[27]	Conforms
3	Aluminum Oxide (Al ₂ O ₃ , %)	3.4	26.54	C150[28]: 2–8% typical; in C618[27] total oxides	Conforms
4	Ferric Oxide (Fe ₂ O ₃ , %)	2.9	1.63	C150[28]: <6% typical; in C618[27] total oxides	Conforms
5	Magnesium Oxide (MgO, %)	2.8	0	C150[28]: ≤6.0%	Conforms
6	Sulphur Trioxide (SO ₃ , %)	3.1	0.61	C150 [28][28]: ≤3.5%; C618: ≤4.0%	Conforms
7	Loss on Ignition (LOI, %)	1.2	-	C150 [28]: ≤3%; C618: ≤10%	Cement: Conforms; MK: Requires measurement
8	Lime Saturation Factor (LSF, %)	94	-	Not in ASTM; typical OPC: 92–98	Cement: Acceptable
9	Chloride (Cl, %)	0.092	1.95	ACI 318 [30] durability <0.1%	Cement: OK; MK: Excessive chloride
10	Chromium (Cr ⁶⁺ , mg/cm ²)	2.75	0.01	≤3.0	Conforms

Table 1 Comparison of cement and metakaolin chemical properties against ASTM standards

1. táblázat A cement és a metakaolin kémiai tulajdonságainak összehasonlítása az ASTM szabványokkal

ASTM C150[28] applies to Portland cement; ASTM C618 [27] applies to pozzolans, including metakaolin. Limits shown are maximum allowable values unless otherwise stated.

2.1.3 Aggregates

The aggregates used in this study included both coarse and fine aggregates. The coarse aggregate was sourced from a crushed rock quarry at Akamkpa, Cross River State, Nigeria, while the fine aggregate was sourced from a natural Ogbogoro River, Rivers State, Nigeria. The aggregates were subjected to standard grading, cleanliness, and moisture content assessments to guarantee uniformity in particle size distribution and avoid extraneous influences on concrete behaviour.

2.1.4 Potable water complying

Potable water complying with standard specifications for concrete mixing obtained from the running tap of the Rivers State University, Port Harcourt, conforming to BS EN 1008 [26], was utilised throughout the experimental program to avoid contamination or variability in hydration.

S/No	Material/ Test	Chippings	Sand	Cement	Metakaolin
	Source	Akamkpa	Ogbogoro River	Lafarge Superset	Umuahia, Nigeria
1	Bulk Density (Kg/m ³)	1655.06	2121.45	1452.3	1215.5
2	Specific gravity	2.63	2.71	3.09	2.41
3	Finest Modulus	4.5	2.38		
4	Cc	0.57	1.03		
5	Cu	2.21	5		
6	Gradation	40mm Nominal Gradation curve	Zone 2		

Table 2 Physical properties of chippings, sand, cement, and metakaolin
2. táblázat A zúzottkő (chippings), homok, cement és metakaolin fizikai tulajdonságai

2.1.5 Ultracrete61

This is a high-range water reducer sourced from Purechem Industries Ltd, Lagos.

2.2. Methods

2.2.1. Particle size distribution via laser diffraction

Laser diffraction with a Malvern Zetasizer was used to analyse particle size distribution of metakaolin, providing mean diameter and spread critical for understanding packing, surface area, and reactivity. Sand and chippings were also graded using BS EN 933-2:2020[29] standard British Standard Sieves for the determination of fineness modulus, coefficient of curvature (cc), coefficient of uniformity (cu), and gradation limits.

2.2.2 Characterisation of metakaolin using XRF

X-ray fluorescence (XRF) spectroscopy was used to quantify the oxide composition of metakaolin, including major and trace elements. Standardised pellet preparation ensured uniformity, with results used to confirm pozzolanic potential and interpret hydration effects.

2.2.3 Preparation of concrete mixes: normal strength and high strength with varying metakaolin content

Concrete mixes were designed to achieve both normal strength concrete (NSC) and high strength concrete (HSC) categories, with metakaolin incorporated as a partial replacement of cement at 0, 5, 7.5, 10, and 12.5% weights of cement at a constant water-binder ratio of 0.55 for normal strength concrete and 0.4 for high strength concrete. The admixture was also maintained at 1.5% of the weights of cementitious

material proportions as specified by the manufacturer. The mix design, concrete casting, and curing process adhered to ASTM C192/C192M-15[20] standard guidelines to achieve target compressive strengths reflective of typical structural applications. For each metakaolin replacement category, four concrete cylinders were prepared for 7 and 28-day compressive strength and density derivations, two samples for 7-day testing and two samples for 28-day testing.

From Table 3, mixes were batched on a weight basis, with no adjustments made to the water content to evaluate workability as influenced by the high surface area and fineness of metakaolin particles. Ultracrete61 superplasticiser was utilised to optimise the rheological properties of the fresh concrete without compromising the hydration process. Each mix batch is identified with a unique number, NS-0.55CM100MK0, with NS and HS signifying the nature of concrete, NS-Normal strength concrete, HS-High Strength Concrete. The first two letters are followed by a water-binder ratio (0.55 and 0.40), next to it is the cement content, CM 87.5 to CM 100. Numbers signify the percentage by weight of cement in the reference mix. The next number is the percentage by weight of Metakaolin in the mix. This ranges from MK 0 to MK 12.5 in the mixes. Finally, some mixes have the letter “A” after the mix specimen Identity. This signifies the mixes containing Admixture.

NORMAL STRENGTH CONCRETE							
S/ No	SPECIMEN ID	CE- MENT (kg/ m ³)	WATER (kg/ m ³)	META- KAOLIN (kg/m ³)	SAND (kg/ m ³)	CHIP- PINGS (kg/m ³)	AD- MIX (%)
1	NS-0.55CM100MK0	375.00	205	0.00	583.00	1239.00	0
2	NS-0.55CM95MK5	356.25	131.25	18.75	583.00	1239.00	0
3	NS-0.55CM92.5MK7.5	346.88	131.25	28.13	583.00	1239.00	0
4	NS-0.55CM90MK10	337.50	131.25	37.50	583.00	1239.00	0
5	NS-0.55CM87.5MK12.5	328.13	131.25	46.88	583.00	1239.00	0
6	NS-0.55CM100MK0 A	375.00	205	0.00	583.00	1239.00	1.5
7	NS-0.55CM95MK5 A	356.25	131.25	18.75	583.00	1239.00	1.5
8	NS-0.55CM92.5MK7.5 A	346.88	131.25	28.13	583.00	1239.00	1.5
9	NS-0.55CM90MK10 A	337.50	131.25	37.50	583.00	1239.00	1.5
10	NS-0.55CM87.5MK12.5 A	328.13	131.25	46.88	583.00	1239.00	1.5

HIGH STRENGTH CONCRETE							
S/ No	SPECIMEN ID	CE- MENT (kg/ m ³)	WATER (kg/ m ³)	META- KAOLIN (kg/m ³)	SAND (kg/ m ³)	CHIP- PINGS (kg/m ³)	AD- MIX (%)
1	HS-0.4CM100MK0	620	205	0	645.98	984.47	0
2	HS-0.4CM95MK5	589	155	31	645.98	984.47	0
3	HS-0.4CM92.5MK7.5	573.5	155	46.5	645.98	984.47	0
4	HS-0.4CM90MK10	558	155	62	645.98	984.47	0
5	HS-0.4CM87.5MK12.5	542.5	155	77.5	645.98	984.47	0
6	HS-0.4CM100MK0A	620	205	0	645.98	984.47	1.5
7	HS-0.4CM95MK5 A	589	155	31	645.98	984.47	1.5
8	HS-0.4CM92.5MK7.5 A	573.5	155	46.5	645.98	984.47	1.5
9	HS-0.4CM90MK10 A	558	155	62	645.98	984.47	1.5
10	HS-0.4CM87.5MK12.5 A	542.5	155	77.5	645.98	984.47	1.5

Table 3 Concrete mix design matrix for normal and high strength concrete
3. táblázat Beton összetétel-tervezési mátrix normál és nagy szilárdságú betonokhoz

2.2.4 Sample casting and curing procedures

Concrete samples were produced using a 100 mm diameter and 200 mm high cylinder following ASTM C31/C31M [21] procedures to ensure homogeneity and minimise variability in sample preparation. Concrete was mixed using a laboratory pan mixer to ensure thorough blending of all constituents. Fresh concrete was cast into cylindrical moulds for compressive strength testing. Each mould was subjected to vibration to eliminate entrapped air and ensure compaction.

Following casting, specimens were demoulded after 24 hours and transferred to a controlled curing environment maintained at standard temperature and humidity conditions. Curing periods of 7 and 28 days were adopted to evaluate both early and later-age properties. The curing regime was strictly monitored to prevent moisture loss and temperature fluctuations that could adversely affect hydration and microstructural development.

2.2.5 Compressive strength tests

Compressive strength, *f_{ck}*, was measured on multiple concrete cylindrical specimens at 7 and 28 days using a calibrated 2000KN hydraulic testing machine. The maximum load at failure was recorded, and the strength was calculated by dividing by the cross-sectional area. Average values ensured statistical reliability. Fig. 1 shows the production and testing of the cylindrical concrete specimen.

The compressive strength was calculated by

$$f_{ck} = \frac{\text{Failure load(KN)}}{\text{cross-sectional Area of sample(mm}^2\text{)}} \quad (1)$$



Fig. 1 Production and testing of metakaolin blended cement concrete specimen
1. ábra Metakaolinnal kevert cementbeton próbatestek gyártása és vizsgálata

2.2.6 Density measurements

The concrete density was determined at 7 and 28 days by measuring the mass and volume using a digital weighing balance and dividing the resulting mass by the volume of the concrete cylindrical sample. Density data complemented strength results to assess microstructural compactness and porosity influenced by metakaolin.

3. Data collection

Experimental data for particle size distributions, specific gravity, compressive strength, density, water binder ratio, admixture dosage, and workability were systematically

recorded; the compressive strength and densities of the concrete were recorded in two (2) replicates to capture variability. Statistical analyses were used to summarise results, while quality control measures, including equipment calibration and verification, ensured data validity, supporting subsequent correlation and interpretation.

3.1 Results

Fig. 2 presents the sieve analysis of metakaolin using the Malvern Zetasizer, revealing a finely graded particle size predominantly within the sub-micron to low-micron range. The sample is polydisperse, as indicated by the multiple peaks and the Polydispersity index (PDI) value. The Z-average provides an overall average size, but the distribution shows distinct particle populations.

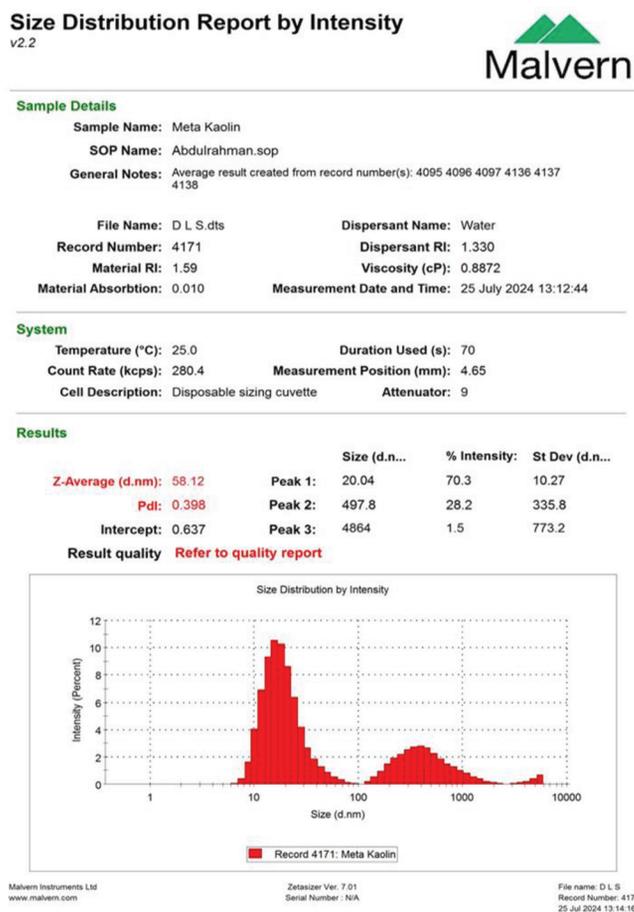


Fig. 2 Sieve Analysis of Metakaolin Using Malvern Zetasizer Laser Machine
2. ábra A metakaolin szitaelemzése (szemcseméret-eloszlása) Malvern Zetasizer lézeres berendezéssel

Peak Sizes and Intensities

Peak 1: Around 20.04 nm with an intensity of 70.3%. This is the dominant population.

Peak 2: Around 497.8 nm with an intensity of 28.2%.

Peak 3: Around 4864 nm with an intensity of 1.5%. This population has the lowest intensity.

Z-Average: The Z-average particle size is 58.12 nm. This is an intensity-weighted average and is heavily influenced by the larger particles. In a polydisperse sample, the Z-average may not accurately represent the typical particle size.

Polydispersity Index (Pdl): The Pdl is 0.398. A Pdl closer to 0 indicates a monodisperse sample (all particles are of similar size), while a value closer to 1 indicates a highly polydisperse sample. 0.398 suggests a moderately polydisperse distribution.

The analysis reveals that the Metakaolin sample contains particles ranging from approximately 20 nm to nearly 5000 nm, with a dominant population around 20 nm. The graph shows multiple peaks with three distinct peaks, indicating the presence of at least three different populations of particles. This fine particle size significantly enhances the pozzolanic reactivity by increasing the surface area available for reaction with calcium hydroxide, leading to improved microstructural density and, consequently, higher concrete strength and durability. However, the high fineness also tends to increase the water demand of the mix, which adversely affects workability without suitable admixtures. Therefore, controlling the particle size distribution is crucial for achieving an optimal balance between hardened mechanical performance and fresh properties of concrete.

S/ No	SPECIMEN ID	Slump (mm)	7 days				28 days			
			Density (kg/m ³)	Stress (N/mm ²)	AV. Stress (N/mm ²)	Density (kg/m ³)	Stress (N/mm ²)	AV. Stress (N/mm ²)		
1	NS-0.55CM100MK0	83	2431.57	22.92	23.23	2488.86	32.46	32.78		
				23.55		33.10				
2	NS-0.55CM95MK5	70	2444.30	24.19	24.19	2504.77	34.37	34.37		
				24.19		34.37				
3	NS-0.55CM92.5MK7.5	64	2460.22	24.82	24.70	2498.41	35.65	35.65		
				24.57		35.65				
4	NS-0.55CM90MK10	60	2466.58	26.73	26.42	2495.23	38.19	37.56		
				26.10		36.92				
5	NS-0.55CM87.5MK12.5	55	2482.50	23.55	23.87	2555.70	33.10	33.74		
				24.19		34.37				
6	NS-0.55CM100MK0 A	150	2492.04	28.64	28.33	2568.43	40.74	40.10		
				28.01		39.47				
7	NS-0.55CM95MK5 A	125	2517.50	29.28	29.92	2574.79	42.01	42.65		
				30.55		43.28				
8	NS-0.55CM92.5MK7.5 A	121	2517.50	31.83	32.15	2581.16	45.83	45.83		
				32.46		45.83				
9	NS-0.55CM90MK10 A	95	2555.70	33.10	32.78	2574.79	47.10	48.06		
				32.46		49.01				
10	NS-0.55CM87.5MK12.5 A	74	2565.25	29.28	28.96	2587.52	42.01	41.37		
				28.64		40.74				

Table 4 Fresh and hardened properties of normal strength concrete specimens with varying metakaolin content at 7 and 28 days

4. táblázat Különböző metakaolin-tartalmú normál szilárdságú betonpróbatetek friss és megszilárdult tulajdonságai 7 és 28 napos korban

Fig. 3 and Table 4 illustrates the impact of metakaolin (MK) replacement (0% to 12.5%) and Ultracrete 61 superplasticizer on the compressive strength of normal strength concrete (NSC) with a water binder (W/B) ratio of 0.55, showing strength increases from 23.83 N/mm² to 37.56 N/mm² at 7 days and 32.78 N/mm² to 48.06 N/mm² at 28 days without and with superplasticizer, respectively. The optimal MK replacement is 10%, yielding the highest strength (48.06 N/mm² at 28 days with superplasticiser), due to enhanced pozzolanic activity and

improved matrix density, though strength declines at 12.5% due to cement dilution. The superplasticiser improved the workability of the resulting concrete (Slump from 55 mm to 150 mm) in normal concrete mixes and strength by improving particle dispersion, suggesting its value in metakaolin-modified concrete.

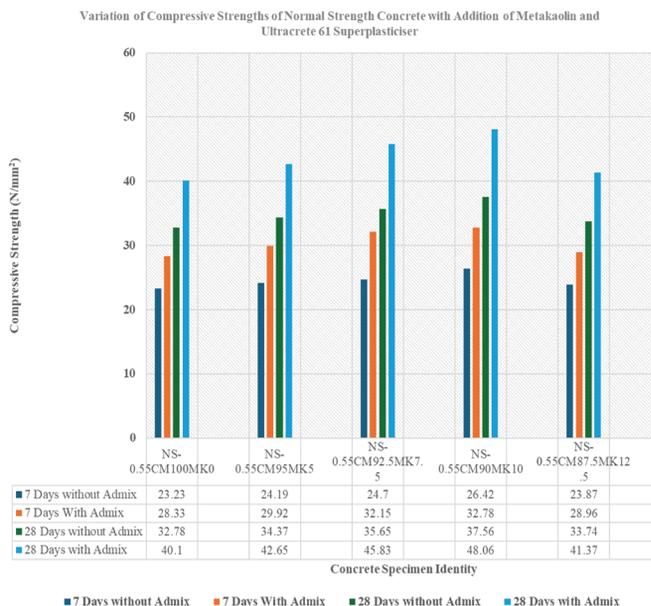


Fig. 3 Variation of compressive strength of normal concrete with addition of metakaolin and Ultracrete 61 superplasticiser

3. ábra A normál beton nyomószilárdságának változása metakaolin és Ultracrete 61 szuperfolyósító hozzáadásával

S/ No	SPECIMEN ID	Slump (mm)	7 Days				28 Days			
			Density (kg/m ³)	Stress (N/mm ²)	AV. Stress (N/mm ²)	Density (kg/m ³)	Stress (N/mm ²)	AV. Stress (N/mm ²)		
1	HS-0.40CM100MK0	87	2486.03	35.65	36.28	2511.14	50.92	51.56		
				36.92		52.20				
2	HS-0.40CM95MK5	80	2498.63	40.74	40.42	2523.87	58.56	57.92		
				40.10		57.29				
3	HS-0.40CM92.5MK7.5	70	2501.78	42.01	42.65	2527.05	59.83	61.11		
				43.28		62.38				
4	HS-0.40CM90MK10	65	2508.08	44.56	44.88	2533.42	63.65	64.29		
				45.19		64.93				
5	HS-0.40CM87.5MK12.5	60	2545.89	38.83	38.51	2571.61	56.02	55.38		
				38.19		54.74				
6	HS-0.40CM100MK0 A	150	2567.95	40.74	41.37	2593.89	58.56	59.20		
				42.01		59.83				
7	HS-0.40CM95MK5 A	135	2574.25	44.56	44.56	2600.25	63.65	63.65		
				44.56		63.65				
8	HS-0.40CM92.5MK7.5 A	120	2580.55	46.47	46.15	2606.62	66.20	65.56		
				45.83		64.93				
9	HS-0.40CM90MK10 A	100	2574.25	47.74	47.42	2600.25	72.57	70.02		
				47.10		67.47				
10	HS-0.40CM87.5MK12.5 A	85	2586.86	43.28	43.60	2612.99	62.38	62.70		
				43.92		63.02				

Table 5 Fresh and hardened properties of high-strength concrete specimens with varying metakaolin content at 7 and 28 days

5. táblázat Különböző metakaolin-tartalmú nagy szilárdságú betonpróbatetek friss és megszilárdult tulajdonságai 7 és 28 napos korban

Table 5 presents the density and compressive strength results of high-strength concrete specimens with varying metakaolin contents, tested at 7 and 28 days. The data show a consistent increase in both density and compressive strength over time, reflecting the ongoing hydration and pozzolanic reactions facilitated by metakaolin. Specimens labelled with “A” generally exhibit higher densities and strengths compared to their non-“A” counterparts, indicating enhanced performance due to Ultracrete 61 superplasticiser additions. This trend suggests that increasing metakaolin content up to certain levels improves microstructural densification, which directly contributes to higher compressive strength. Notably, the densest specimens correspond to the highest strength values at both curing ages, supporting the strong positive correlation between these parameters. However, some variation in strength at similar densities hints at the complex interactions of metakaolin with other mix components, emphasising the need for precise control of replacement levels and curing practices to maximise concrete performance.

Fig. 4 illustrates that the addition of Ultracrete 61 superplasticiser significantly enhances the compressive strength of high-strength concrete specimens at both 7 and 28 days. The strength gains are more pronounced at 28 days, indicating that the superplasticiser effectively improves particle dispersion and hydration, thereby densifying the concrete matrix and boosting long-term mechanical performance.

The slump also improved from 87 mm for mixes without admixture to 150 mm for the same mixture produced with Ultracrete 61 admixture, as shown in Table 5.

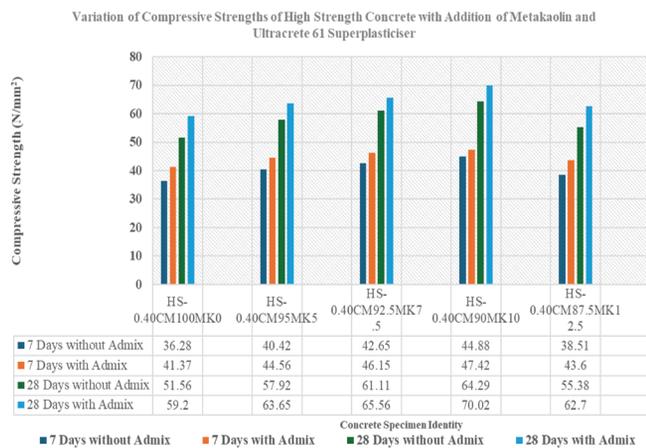


Fig. 4 Variation of compressive strength on high-strength concrete with addition of Ultracrete61 superplasticizer

4. ábra A nagy szilárdságú beton nyomószilárdságának változása Ultracrete 61 szuperfolyósító hozzáadásával

Table 6 presents the detailed oxide composition analysis of metakaolin using X-ray fluorescence (XRF) spectroscopy. The data show that the primary components are silica (SiO₂) at 55.614 mg/cm² (67.483 mol%) and alumina (Al₂O₃) at 37.119 mg/cm² (26.542 mol%), which together constitute most of the material and are critical for its pozzolanic activity. Minor oxides such as Fe₂O₃, TiO₂, SO₃, and K₂O are present in smaller quantities, potentially influencing hydration kinetics and durability. Trace elements like V₂O₅, Cr₂O₃, MnO, and others are detected at very low levels, typically under 0.1 mg/cm².

The absence or negligible amounts of oxides like WO₃ and MgO suggest minimal interference with pozzolanic reactions. The presence of chlorine (Cl) at 0.95 mg/cm² (1.954 mol%) could have implications for corrosion resistance and needs to be monitored in mix designs. This comprehensive chemical profile is essential for understanding the reactivity and performance potential of the metakaolin in cementitious systems

S/No	Sample Layer	Component	Component (mg/cm ²)	Moles (%)
1	1	SiO ₂	55.614	67.483
2	1	V ₂ O ₅	0.034	0.013
3	1	Cr ₂ O ₃	0.026	0.013
4	1	MnO	0.055	0.056
5	1	Fe ₂ O ₃	3.561	1.626
6	1	CoO	0.009	0.005
7	1	NiO	0.01	0.01
8	1	CuO	0.043	0.04
9	1	Nb ₂ O ₅	0.017	0.005
10	1	WO ₃	0.0	0.0
11	1	P ₂ O ₅	0.126	0.065
12	1	SO ₃	0.674	0.613
13	1	CaO	0.423	0.55
14	1	MgO	0.0	0.0
15	1	K ₂ O	0.859	0.665
16	1	BaO	0.039	0.018
17	1	Al ₂ O ₃	37.119	26.542
18	1	Ta ₂ O ₅	0.041	0.007
19	1	TiO ₂	0.309	0.282
20	1	ZnO	0.015	0.013
21	1	Ag ₂ O	0.01	0.003
22	1	Cl	0.95	1.954
23	1	ZrO ₂	0.049	0.029
24	1	SnO ₂	0.0	0.0
25	1	SrO	0.004	0.003
26	1	Rb ₂ O	0.009	0.003
27	1	Y ₂ O ₃	0.009	0.003

Table 6 Metakaolin oxide composition analysis (XRF method)
6. táblázat A metakaolin oxidösszetétel-elemzése (XRF módszer)

3.2 Interpretation and synthesis of metakaolin chemical composition and its implications for concrete performance

The XRF analysis showed that metakaolin is composed high percentage of silica (SiO₂) and alumina (Al₂O₃), over 94% by mole, confirming strong pozzolanic activity essential for forming strength-enhancing hydration products like C-S-H and calcium aluminate hydrate. Minor oxides such as Fe₂O₃, TiO₂, SO₃, and K₂O may aid hydration and microstructure refinement of the resulting concrete. Negligible harmful oxides like MgO and WO₃ reduce risks of expansion or instability. Elevated chlorine content signals potential corrosion risks in reinforced concrete, requiring careful mix design. Trace elements are present in low amounts, with minimal direct

impact but possible subtle effects on durability. Overall, this composition supports metakaolin's role in enhancing concrete strength and durability, provided chloride levels are controlled for long-term performance.

4. Conclusion and recommendations

The structural effects of utilising metakaolin and high-performance superplasticizer on the compressive response and density evolution of normal- and high-strength concretes were quantitatively evaluated in this study. The metakaolin used had a Z-average of 58.12 nm with multimodal peaks at roughly 20 nm, 498 nm, and 4864 nm, and a chemical profile dominated by SiO₂ (67.48 mol%) and Al₂O₃ (26.54 mol%), totalling 94% reactive oxides. Strong pozzolanic potential was established by this nanostructured fineness and high aluminosilicate content, which had a direct impact on microstructural densification and hydration kinetics.

In normal-strength concrete (NSC), metakaolin replacement from 0 to 10% resulted in clear strength gains. At 7 days, compressive strength increased from 23.23 N/mm² (control) to 26.42 N/mm² at 10% MK, representing a 13.7% improvement. At 28 days, strength increased from 32.78 N/mm² to 37.56 N/mm² (14.6% increase). Density also increased from 2488.86 to 2495.23 kg/m³ over the same replacement range, indicating reduced pore volume and enhanced binder packing. With Ultracrete 61, the 28-day compressive strength rose further to 48.06 N/mm², representing a 46.7% improvement relative to the unmodified control. The slump improved from 83 mm to 150 mm, demonstrating that the admixture effectively counteracted metakaolin's high water demand and enabled full reactivity.

High-strength concrete (HSC) exhibited similar quantitatively significant responses. At 7 days, strength increased from 36.28 N/mm² to 44.88 N/mm² at 10% MK (23.7% gain). At 28 days, strength increased from 51.56 N/mm² to 64.29 N/mm² (24.7% gain). For mixes containing Ultracrete 61, 28-day strength reached 72.57 N/mm², equivalent to a 40.8% increase over the control and a 12.9% increase over the 10% MK mix without admixture. Density rose from 2511.14 kg/m³ (control) to 2533.42 kg/m³ at 10% MK and further to 2600.25 kg/m³ with admixture incorporation. These density increments (up to +3.5%) strongly correlate with the observed strength development, reinforcing the mechanistic link between metakaolin-induced refinement of the pore structure and compressive resistance.

Despite these mechanical advantages, XRF analysis revealed a chloride content of 1.95 mol%, significantly higher than the 0.1% limit recommended for reinforced concrete under ACI 318. This concentration necessitates a cautious approach regarding durability and demands source-specific mitigation strategies. Nevertheless, the favourable oxide composition, minimal deleterious impurities, and the demonstrated strength enhancements confirm the technical viability of this metakaolin for structural-grade concrete, provided durability safeguards are adopted. Overall, the study establishes a clear quantitative performance envelope: 0–10% metakaolin maximises strength, density, and

workability (with admixture) for both NSC and HSC, while greater than 10% replacement leads to cement dilution and mechanical decline. The synergy between fine metakaolin particles and superplasticiser action was shown to be indispensable for achieving optimal dispersion, hydration, and matrix consolidation.

4.1 Recommendations

1. The ideal replacement level for structural concrete is 10% metakaolin, which results in strength gains of 14–25% without admixture and up to 46% with Ultracrete 61 in NSC and 40% in HSC. Because clinker availability is gradually decreasing and mechanical response is deteriorating, replacement levels higher than 10% should be avoided.
2. Require all locally sourced metakaolin to undergo oxide and impurity profiling. Remedial measures such as washing, blending with low-chloride SCMs, or limiting use in reinforced members should be included in quality control and mix design procedures, given the measured chloride content of 1.95 mol%.
3. Choose high-performance water reducers at levels of less than or equal to 1.5%. The results exhibit substantial enhancements in strength (up to +46.7% in NSC) and workability (up to +81% slump increase), confirming their crucial role in overcoming water demand from sub-micron metakaolin.
4. Extend mechanical evaluation to durability indices, such as sulphate resistance, sorptivity, carbonation depth, and chloride diffusion coefficients. These measurements are crucial for creating predictive models that relate oxide chemistry, particle fineness, and material durability.
5. Advocate regional investment in metakaolin processing, considering the study demonstrated that, when properly processed and characterised, locally sourced metakaolin, even with impurities, can achieve structural-grade performance comparable to imported alternatives.
6. To standardise metakaolin quality for commercial concrete, establish performance-based specifications that incorporate quantitative thresholds, oxide indices (greater than 70% for SiO₂+Al₂O₃), chloride limit (<0.1%), target particle fineness (<1 µm median size), and mechanical benchmarks (≥20% strength enhancement at 28 days).

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Author contributions

Justin Egbebike: Conceptualization, Methodology, Field study, **Fidelis Okafor:** Reviewing -Original draft preparation, Validation, **Chijioke Ikeagwuani:** Visualization, Investigation, Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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