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Compressive Strength of Metakaolin Geopolymer Concrete Incorporating Palm Kernel Shell as Lightweight Coarse Aggregate

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Abstract

The global construction industry faces mounting pressure to reduce its environmental footprint, particularly through the elimination of Portland cement (PC), a major contributor to global CO_2 emissions. This study investigates the compressive strength of metakaolin (MK) geopolymer concrete having palm kernel shell (PKS) incorporated as a lightweight coarse aggregate, with the aim of establishing a PC-free, eco-efficient concrete system. Kankara kaolin from Katsina State, Nigeria, was calcined at 800°C to produce metakaolin, which was activated using a blend of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) at Si/Al molar ratios of 2.0, 2.5 and 3.0. PKS sourced from Ile Oluji, Ondo State, was used as the sole coarse aggregate. Specimens were cured under ambient laboratory conditions (27°C) and tested at 7, 14, 28 and 56 days. Results showed that the Si/Al ratio of 2.5 (Mix C_2) consistently yielded the best performance, achieving 15.60 N/mm² at 28 days and 16.80 N/mm² at 56 days, with a 80 mm slump and 90 minutes initial setting time. X-ray fluorescence (XRF) analysis confirmed 92.85 % pozzolanic oxides in metakaolin, exceeding ASTM C618-2022 requirements, while BET analysis revealed an ultrafine particle size (0.169 µm) and specific surface area of 14.2 m²/g up to 47 times greater than PC. The ambient-cured MK-PKS geopolymer concrete outperformed PKS-cement concrete by 9% at 28 days. Despite being 40-42% below the PC granite concrete benchmark (of 26 N/mm² at 28 days), these results establish a viable foundation for sustainable, PC free lightweight concrete using locally sourced Nigerian materials, with a projected potential for 50-55% CO_2 reduction compared to PC-based systems, in reference to established geopolymer emissions benchmarks in the literature, pending formal life-cycle assessment.

Keywords: Geopolymer Concrete, Metakaolin, Palm Kernel Shell, Si/Al Ratio, Lightweight Concrete.

Introduction

Concrete is the most widely used construction material globally, with production exceeding 30 billion tonnes annually (Adesina, 2020). however, its reliance on Portland cement (PC) contributes about 8% of global CO_2 emissions due to high-temperature calcination (1450 °C) and limestone decomposition (Andrew, 2018; Kumar *et al*., 2021). To reduce environmental impact, research has focused on supplementary cementitious materials such as Metakaolin (MK), a highly reactive pozzolan produced at 650-800 °C that enhances strength, durability, and pore structure (Amin *et al*., 2022; Raheem *et al*., 2024; Qader *et al*., 2025). Similarly, palm kernel shells (PKS), an abundant agro-waste, provide a sustainable lightweight aggregate supporting circular economy practices (Wang *et al*., 2020; Alengaram *et al*., 2013). despite their individual benefits, their combined use in fully PC-free systems remain limited (Pandey, 2023; Danso & Appiah-Agyei, 2021). A major gap exists in understanding the compressive behaviour of 100% MK-based geopolymer concrete with PKS aggregate, particularly due to PKS challenges such as high-water absorption, instability, and weak interfacial transition zone (ITZ) (John *et al*., 2023). Further validation is needed to confirm long-term structural reliability (Katte *et al*., 2023; Driouich *et al*., 2023). Most studies use metakaolin as a partial OPC replacement (5-30%) in PKS concrete, with limited work on 100% metakaolin binders combined with 100% PKS aggregate, especially under ambient curing (John *et al*., 2023; Mo *et al*., 2018). Additionally, the PKS geopolymer ITZ lacks detailed microstructural analysis (Biajawi *et al*., 2024). This study investigates MK geopolymer concrete with PKS aggregate by evaluating material properties, the effect of Si/Al ratio, compressive strength at 7-56 days, and the influence of PKS on geopolymerization.

Literature Review

Concept of geopolymer concrete

Geopolymer concrete is a sustainable alternative to PC-based concrete, formed by activating aluminosilicate materials with alkaline solutions to create a strong binder. The concept, introduced by Joseph Davidovits in the 1970s, describes inorganic polymers produced through alkaline activation (Saeed *et al*., 2022). Unlike PC production at ~1450°C, geopolymers form at ambient to 80°C, reducing CO_2 emissions by up to 80% (Davidovits, 2008; Andrew, 2018). The geopolymerization process involves three stages:

dissolution of aluminosilicates, reorganization into oligomers, and polycondensation into a three-dimensional N-A-S-H gel network with Si-O-Al-O bonds (Meskhi *et al.*, 2023). The chemical reaction can be represented as presented in equation 1.

Metakaolin as a geopolymer precursor

Metakaolin is a reactive pozzolan produced by calcining kaolinitic clay ($Al_2Si_2O_5(OH)_4$) at 650-800°C (Karthik & Mohan, 2021; Pandey, 2023). It typically contains 50-55% SiO_2 and 40-45% Al_2O_3, with total pozzolanic oxides exceeding the ASTM C618-2022 requirement of 70%, often reaching 90-95% (Raheem *et al.*, 2024). Reactivity depends on calcination temperature: below 600 °C leaves residual crystalline phases, while above 850-900 °C causes recrystallization and reduced amorphous content (Chaair, 2024; Qader *et al.*, 2025). Thus, 700-800 °C for 1-2 hours is optimal for producing highly reactive metakaolin for geopolymerization (Rashad, 2015; Dathe & Dehn, 2024; Xu & van Deventer, 2000).

Palm kernel shell as lightweight aggregate

Palm kernel shells (PKS) are agro-waste from palm oil production, with over 15 million tonnes generated annually, much of which is poorly disposed (Jagaba *et al.*, 2021). As lightweight aggregates (specific gravity 1.1-1.4, water absorption 12-25%), they support circular economy use in concrete (Alengaram *et al.*, 2013; Danso & Appiah-Agyei, 2021). However, high water absorption, irregular shape, and poor gradation reduce workability and packing efficiency. Despite these drawbacks, PKS concrete still achieves 15-28 N/mm² in both cement and geopolymer systems (John *et al.*, 2023; Mo *et al.*, 2018).

Si/Al ratio and activator optimization

The Si/Al molar ratio is a key factor controlling strength and microstructure in metakaolin geopolymers, influencing the degree of cross-linking in the N-A-S-H gel. Optimal values lie between 2.0-2.5; lower ratios limit cross-linking, while higher ratios increase viscosity and hinder dissolution (Duxson *et al.*, 2005; Provis & Bernal, 2014; Kwek *et al.*, 2021).

Activator composition also plays a critical role. A sodium silicate modulus of ~2.4 ensures balanced reactivity and durability, while the Na_2SiO_3/NaOH ratio (2.0-2.6) controls silicate availability and alkalinity, optimizing geopolymer performance in MK-PKS systems (Nath & Sarker, 2014; Kwek *et al.*, 2021; Hasnaoui *et al.*, 2019). Comparative properties of PC and Geopolymer concretes are presented in Table 1.

$$Si_2O_5 \cdot Al_2O_2 \text{ (MK)} + NaOH/Na_2SiO_3 \rightarrow Na(\text{-Si-O-Al-O-})_n \text{ (N-A-S-H gel)} + H_2O \qquad (1)$$

Table 1: Comparative Properties of PC Concrete and Geopolymer Concrete

Property	PC Concrete	Geopolymer Concrete	Reference
CO_2 emissions	High (900 kg CO_2/tonne)	Low (200 kg CO_2/tonne)	Andrew (2018)
28-day Compressive Strength	25-60 N/mm²	30-80 N/mm²	Salihu *et al.* (2021)
Acid resistance	Poor	Excellent	Tayeh *et al.* (2022)
Sulfate resistance	Moderate	High	Amin *et al.* (2022)
Fire resistance	Moderate (up to 400 °C)	Excellent (up to 800 °C)	Abdullah *et al.* (2024)
Curing requirement	Water curing	Heat or ambient curing	Driouich *et al.* (2023)
Workability	Good	Moderate (requires plasticisers)	Hasnaoui *et al.* (2019)

Materials and Methods

Materials

Metakaolin

Kaolin from the high-purity Kankara deposit (Katsina State, Nigeria) was processed by washing, milling, and calcining 100 kg at 800 °C for 2 hours using an electric muffle furnace at Ahmadu Bello University, Zaria. This temperature was selected based on its proven optimal pozzolanic reactivity within the 750-800 °C range (Aliyu *et al.*, 2020).

Palm kernel shell

Palm kernel shells were sourced locally from Ile Oluji, Ondo State, Nigeria. The shells were washed, air-dried, and sieved to a 5-14 mm size fraction. Their structural suitability was verified in line with ASTM C127-2021 and ASTM C131/C131M-2020 through tests on aggregate crushing value (ACV), water absorption, and specific gravity.

Fine aggregate

Natural river sand obtained from local suppliers in Minna was used as fine aggregate. Prior to use, the sand was air-dried and sieved to remove organic matter, dust, and other impurities, conforming to BS EN 12620:2013.

Alkaline activators

The alkaline activator comprised sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). NaOH was prepared from 99 % purity caustic soda pearls, while the sodium silicate solution contained 27 % SiO_2, 10.6 % Na_2O, and 62.4 % H_2O, with a silicate modulus of 2.5-3.3.

Their compositions are detailed in Tables 2 and 3.

Mix design and specimen preparation

A control PC concrete mix was designed per BS EN 206 to achieve 25 N/mm² (C20/25) at 28 days, serving as a benchmark for comparison. Using a water/cement ratio of 0.55 and 10 mm granite aggregate, a target mean strength of 31.56 N/mm² was obtained as specified by Neville (2012).

MK-PKS geopolymer concrete was designed using an alkaline-to-binder ratio of 2.0 and a liquid/binder (w/b) ratio of 0.50, with the liquid phase comprising NaOH and Na_2SiO_3 (Salihu et al., 2021). PKS was used in saturated surface dry (SSD) condition to prevent activator absorption. Three Si/Al ratios 2.0 (C_1), 2.5 (C_2), and 3.0 (C_3) were studied using 10 M NaOH.

The mix proportion (by mass) was fixed at 1:2.7:0.5 (MK: F.A: PKS), with only the activator composition adjusted to achieve target Si/Al ratios. Detailed proportions per cubic metre are presented in Table 4. The activator solution (prepared 24 hours in advance) was combined with metakaolin and mixed for 5 minutes at low speed until homogeneous. Fine aggregate was added and mixed for a further 3 minutes. PKS aggregate (at SSD condition) was introduced last and mixing continued for 2 minutes, giving a total mixing time of 10 minutes per batch.

Three replicate 100 mm cube specimens were cast for each mix-age combination as shown in Table 5 for compressive strength testing. Each layer was compacted manually with 25 tamping strokes. After casting, specimens were left in moulds for 24 hours before demoulding, then cured at ambient laboratory conditions at a temperature of 27 °C and relative humidity of 35-65 % until testing ages of 7, 14, 28, and 56 days. PKS-cement concrete specimens served as an additional benchmark.

Table 2: Chemical Composition of Sodium Hydroxide (NaOH)

Oxides	NaOH	Na	Cl	SiO_3	PO_4	SiO_2	N	Pb	Fe	K
Mass (%)	99	1	0.01	0.003	0.002	0.01	0.0005	0.0005	0.001	0.1

Source: Shanxi Jiahuang Chemical Industry Co., Ltd. (China)

Table 3: Chemical Composition of Sodium Silicate (Na_2SiO_3)

Component	SiO_2	Na_2O	H_2O	Fe_2O_3	Al_2O_3	CaO	Others (trace)
Mass (%)	27	10.6	62.4	0.02	0.01	0.01	<0.01

Source: Shanxi Jiahuang Chemical Industry Co., Ltd. (China)

Table 4: Volume of materials for metakaolin PKS geopolymer concrete

Specimen	Si/Al Ratio	MK (kg)	F.A (kg)	C.A (kg)	NaOH (Sol.) (kg)	Na_2SiO_3 (Sol.) (kg)	Water (kg)
MK-PKS C_2	2.0	0.47	1.26	0.23	0.08	0.16	0.24
MK-PKS C_3	2.5	0.47	1.26	0.23	0.07	0.17	0.24
MK-PKS C_4	3.0	0.47	1.26	0.23	0.24	0.00	0.24

Table 5: Specimen Matrix for Compressive Strength Testing (100 mm Cubes)

Property	Age (Days)	Replicates per test	Specimens	Si/Al:2.0, 10M	Si/Al:2.5, 10M	Si/Al:3.0, 10M
Compressive Strength	7, 14, 28, 56	3 each	Cubes	12	12	12

Characterisation methods

Material characterisation included XRF analysis (ASTM C168, 2012) to determine oxide composition, FTIR for functional groups and dehydroxylation, and BET for surface area and particle size. Aggregate grading and specific gravity were determined using

ASTM C136/C136M (2019) and ASTM D854-2000. Fresh properties were evaluated by slump test (ASTM C143/C143M-2020) and setting time using Vicat apparatus (ASTM C191-2021).

Compressive strength was measured per ASTM C39/C39M-03 and expressed as

$$f_c = P/A \qquad (2)$$

where f_c is compressive strength (N/mm²), P is the maximum applied load at failure (N), and A is the loaded surface area (mm²).

Results and Discussion

Material characterisation

Physical properties of aggregates and metakaolin

Table 6 shows that PKS is a lightweight aggregate (specific gravity = 1.20) with high water absorption (15%), exceeding ASTM C127 limits and affecting water demand and efficiency. It has adequate strength (ACV = 5.65 %) but poor gradation (C_u = 1.49, C_c = 0.93), leading to higher voids as pointed out in Danso & Appiah-Agyei (2021). Fine aggregate complied with BS EN 12620:2013 (specific gravity = 2.63, bulk density = 1,529 kg/m³, fineness modulus = 2.93), while metakaolin showed low density (SG = 2.54, bulk density = 603.6 kg/m³), consistent with its amorphous nature.

Table 6: Physical Properties of Palm Kernel Shell (PKS) and Fine Aggregate

Property	PKS	Fine Aggregate (Sand)	Standard Limit
Specific Gravity	1.20	2.63	2.4-2.9 (ASTM C127)
Bulk Density (kg/m³)	690	1,529	-
Water Absorption (%)	15.0	2.1	≤12 (ASTM C127)
ACV (%)	5.65	-	-
Fineness Modulus	-	2.93	2.3–3.1 (ASTM C33)
Coefficient of Uniformity (Cu)	1.49	-	>4 (well-graded)
Coefficient of Curvature (Cc)	0.93	-	1-3 (well-graded)

Table 7: XRF Chemical Composition of Metakaolin

Oxide	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	K_2O	Others
Content (%)	72.40	20.35	2.12	1.17	0.43	0.29	<2.5

Chemical composition of metakaolin

XRF analysis (Table 7) revealed that the metakaolin contains 72.4 % SiO_2 and 20.35 % Al_2O_3, giving a Si/Al molar ratio of 3.56 from the raw binder perspective. The total pozzolanic oxide content (SiO_2+ Fe_2O_3 + Fe_2O_3) was 92.85 %, well exceeding the 70 % minimum required by ASTM C618-2022 for reactive pozzolans. This high oxide content confirms the strong geopolymerization potential of the Kankara-derived metakaolin.

FTIR (Figure 1 and 2) confirmed complete de-hydroxylation by the absence of O-H bands (3690 cm⁻¹) and strong Si-O-Si/Si-O-Al peaks (950-1100 cm⁻¹), indicating a reactive amorphous structure from 800 °C calcination as opined by Amin *et al.* (2022). BET analysis showed ultrafine particles (0.169 µm) and high surface area (14.2 m²/g), about 35-47 times greater than PC, enhancing reactivity, dissolution, and N-A-S-H gel formation under ambient curing (Qader *et al.*, 2025).

Fresh properties of MK-PKS geopolymer concrete

The fresh properties of the three MK-PKS geopolymer concrete mixes are summarized in Table 8. Significant differences in workability and setting behaviour were observed across the three Si/Al ratios, primarily governed by the activator composition and Na_2SiO_3/NaOH ratio. Mix C_2 (Si/Al = 2.5) showed the best workability (80 mm slump, 90-minute setting time) due to a higher Na_2SiO_3/NaOH ratio (2.6), which improves dispersion and slows geopolymerization (Hasnaoui et al., 2019). Mix C1 had moderate performance (70 mm slump, 75 minutes), while Mix C3 (NaOH-only) showed the lowest workability (50 mm) and fastest setting (55 minutes) due to rapid reaction. PKS further reduced workability through high absorption of the alkaline solution (Saeed *et al.*, 2022; Alengaram *et al.*, 2010). Overall, the Na_2SiO_3/NaOH ratio controls fresh properties, with Si/Al = 2.5 and ratio 2.6 identified as optimal.

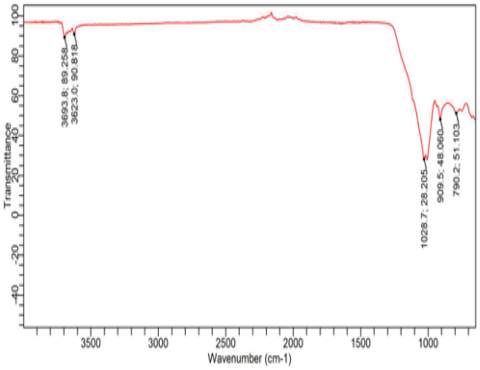
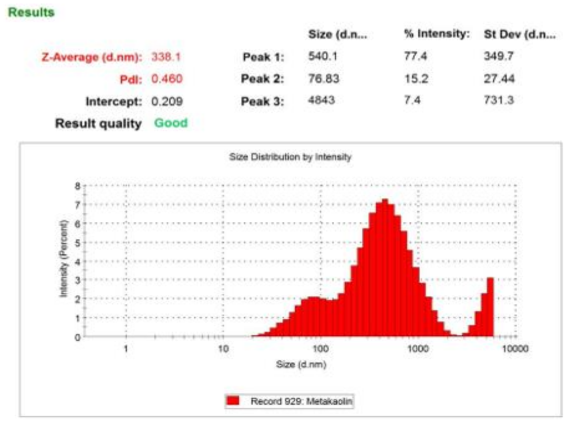


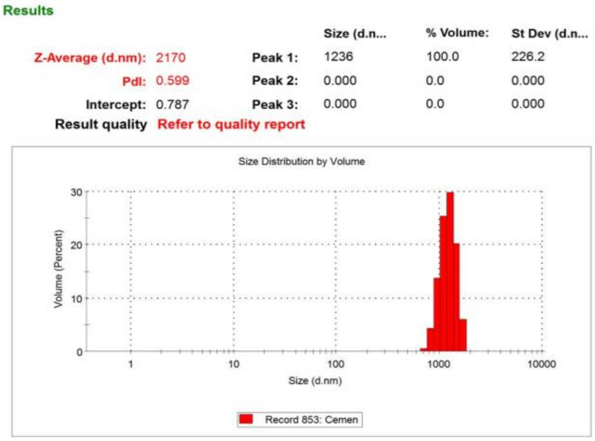
Figure 1: FTIR Spectrum of Metakaolin



Results

			Size (d.n...	% Intensity:	St Dev (d.n...
Z-Average (d.nm):	338.1	Peak 1:	540.1	77.4	349.7
PdI:	0.460	Peak 2:	76.83	15.2	27.44
Intercept:	0.209	Peak 3:	4843	7.4	731.3
Result quality	Good				

Figure 2: Particle Size Distribution of Metakaolin



Results

			Size (d.n...	% Volume:	St Dev (d.n...
Z-Average (d.nm):	2170	Peak 1:	1236	100.0	226.2
PdI:	0.599	Peak 2:	0.000	0.0	0.000
Intercept:	0.787	Peak 3:	0.000	0.0	0.000
Result quality	Refer to quality report				

Figure 3: Particle Size Distribution of cement

Table 8: Fresh Properties of MK-PKS Geopolymer Concrete at Different Si/Al Ratios

Mix ID	Si/Al Ratio	Na_2SiO_3/NaOH Ratio	Initial Setting Time (min)	Slump (mm)
MK-PKS C1	2.0	2.2	75	70
MK-PKS C2	2.5	2.6	90	80
MK-PKS C3	3.0	NaOH only	55	50
PC Control	-	-	-	30-60

Compressive strength development

MK-PKS geopolymer concrete

The compressive strength results of the MK-PKS geopolymer concrete, and reference concretes are presented in figure 4. All MK-PKS geopolymer mixes exhibited progressive strength development from 7 to 56 days, consistent with ongoing N-A-S-H gel formation and matrix densification under ambient curing conditions. The standard deviations reported in figure 4, ranging from 0.23 to 1.84 N/mm² across all test conditions, confirm satisfactory result reproducibility, with the higher variability observed in Mix C_3 (SD = 2.94 N/mm² at 7 days) attributable to the accelerated setting time of 55 minutes limiting uniform compaction. The strength development trajectory across curing ages demonstrates consistent gain from 7 to 56 days for all mixes, with the rate of gain decelerating progressively, reflecting the maturing N-A-S-H gel network characteristic of ambient-cured geopolymer systems.

Mix C_2 (Si/Al = 2.5) consistently outperformed both C_1 and C_3 at all curing ages, achieving compressive strengths of 11.07, 14.3, 15.6, and 16.8 N/mm² at 7, 14, 28, and 56 days, respectively. This superior performance is attributed to the optimal silica-to-alumina balance at Si/Al = 2.5, which promotes effective geopolymerization and the inferred formation of a denser, more continuous N-A-S-H gel network, consistent with the macroscopic strength advantage observed and supported by established geopolymer microstructure theory found in literature (Duxson *et al.*, 2005; 2007; Provis & Bernal, 2014), though direct microstructural verification via SEM and XRD is recommended in future work. The intermediate silicate content at this ratio provides sufficient reactive species for cross-linking without the viscosity-induced mixing challenges associated with higher ratios.

Mix C_1 (Si/Al = 2.0) showed moderate strength (10.13-16.1 N/mm²), while Mix C_3 (Si/Al = 3.0) had the lowest (6.85-12.83 N/mm²) due to excessive alkalinity, high viscosity, and poor gel formation, compounded by rapid setting (55 minutes) that reduced compaction quality (Salihu *et al.*, 2021). All mixes gained strength beyond 28 days under ambient curing (27°C), with 56-day values 7-11 % higher, reflecting continued N-A-S-H gel development as reported by Rangan (2008) and Davidovits (2008)

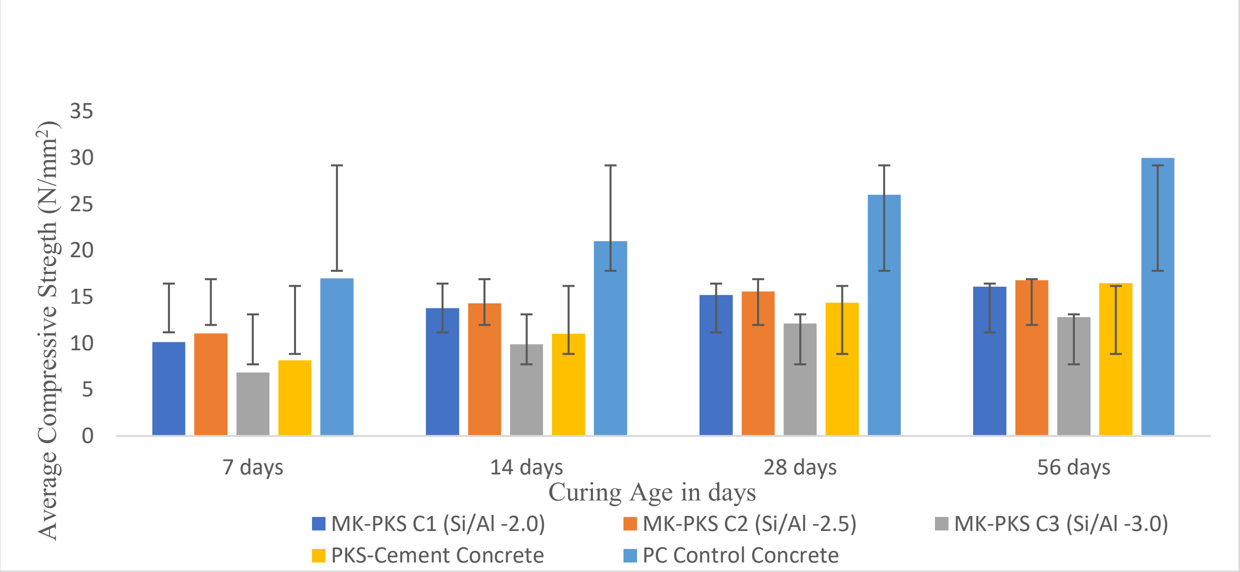


Figure 4: Effect of Si/Al ratio on compressive strength of MK-PKS geopolymer concrete

Comparative performance with reference concretes

The PC control achieved 26 N/mm² at 28 days, meeting the C20/25 target. PKS-cement concrete developed from 8.17 to 16.49 N/mm² (7-56 days), about 45% lower than PC at 28 days due to low density and weak bonding of PKS aggregates (Alengaram *et al.*, 2013).

Notably, the optimal MK-PKS mix (C_2) outperformed PKS-cement concrete by 9% at 28 days (15.60 vs. 14.37 N/mm²) and by 2% at 56 days (16.80 vs. 16.49 N/mm²), indicating superior compressive performance of the geopolymer binder under the tested conditions. This aligns with literature reports on the higher chemical stability and denser microstructure of N-A-S-H gels compared to C-S-H systems (Davidovits, 2008; Provis & Bernal, 2014; Duxson *et al.*, 2005), although direct microstructural verification was not conducted in this study.

This finding is particularly encouraging since the geopolymer system was cured entirely at ambient temperature without any heat treatment, conditions that typically disadvantage geopolymer concrete relative to heat-cured systems

Optimized mix design proposal

Based on experimental trends, a theoretical optimization framework is proposed for future validation. Key targets include increasing metakaolin content to 450 kg/m³, reducing PKS water absorption to 8-10% via surface treatment, improving PKS gradation (Cu > 2.5), maintaining an optimal Si/Al ratio of 2.5 with Na_2SiO_3/NaOH = 2.6, and adopting a mix ratio of 1:2.22:0.49 (MK:Sand:PKS). If validated, this formulation is expected to achieve structural-grade lightweight concrete (C20-C30) and a 50-55% reduction in embodied carbon due to full OPC elimination and ambient curing (Davidovits, 2008; Andrew, 2018). However, full carbon assessment requires life-cycle analysis.

Conclusion

This study confirms the feasibility of a fully PC-free geopolymer concrete using Kankara-derived metakaolin and palm kernel shell (PKS) aggregate under ambient curing, with four key conclusions. Metakaolin calcined at 800°C is a high-quality geopolymer precursor, with XRF showing pozzolanic oxides above the 70% ASTM C618-2022 limit, FTIR confirming complete dehydroxylation, and BET indicating a surface area up to 47× that of OPC, confirming high reactivity. The optimal mix (Si/Al = 2.5, Na_2SiO_3/NaOH = 2.6) achieved the best workability (80 mm slump, 90 min setting) and highest compressive strength across all ages, surpassing PKS-cement concrete at 28 days. Na_2SiO_3/NaOH ratio strongly controls fresh behaviour while NaOH only activation led to rapid setting and lower strength. PKS acts mainly as a diluting filler; However, PKS limitations (high water absorption, weak ITZ, poor gradation) reduced composite strength. Ambient curing at 27°C enabled continuous strength gain up to 56 days, with values exceeding 28-day strengths, confirming no need for heat curing. However, only compressive strength was evaluated, so tensile, flexural, modulus, and durability require further study, with microstructural validation (SEM, XRD, FTIR) recommended. The findings advance geopolymer theory by confirming that the Si/Al molar ratio governs N-A-S-H gel formation and compressive strength under ambient curing, while bio-aggregates act mainly as inert fillers, extending the framework for agro-waste use in alkali-activated systems. Practically, the study shows that fully OPC-free geopolymer concrete can be produced from locally available Nigerian materials at 27 °C without heat curing, achieving strengths comparable to PKS-cement concrete and supporting its use as a sustainable lightweight alternative in tropical regions. However, limitations include the focus on compressive strength alone, with tensile, flexural, and durability properties not evaluated; reliance on macroscopic data without SEM/XRD validation; and an optimized mix design that remains theoretical. Additionally, the projected 50-55% CO_2 reduction is literature-based and requires life-cycle assessment. Despite this, the elimination of Portland cement and use of PKS indicate strong potential for low-carbon construction, especially with improved aggregate treatment for structural applications.

Based on the findings of this study, the following directions for future research are recommended: (i) long-term monitoring of strength, shrinkage, creep, and dimensional stability beyond 56 days, including exposure to sulfate, chloride, acid, and elevated-temperature environments; (ii) determination of flexural, tensile, and elastic properties, and evaluation of reinforcement bond behaviour; (iii) SEM and XRD microstructural analysis to confirm N-A-S-H gel formation, characterize interfacial transition zones, and link microstructure to mechanical performance; (iv) investigation of supplementary binders (e.g., slag, fly ash) to improve ambient curing performance; (v) life cycle assessment to quantify the full environmental benefits; and (vi) development of standardized mix design guidelines and testing protocols for metakaolin-PKS geopolymer concrete systems.

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