

DETERMINATION OF THE POZZOLANIC PROPERTIES OF PEANUT SHELL ASH AS CEMENT REPLACEMENT IN CONCRETE IN NIGERIA

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Abstract

The global imperative for sustainable construction materials, combined with Nigeria's acute agricultural waste management challenges, has driven interest in supplementary cementitious materials (SCMs) derived from agro-industrial by-products. This study systematically investigates the pozzolanic properties of peanut shell ash (PSA) and evaluates its performance as a partial cement replacement in concrete. Peanut shells sourced from Kano State, Nigeria, were calcined at 650°C for 2 hours, and the resulting ash was subjected to comprehensive physicochemical characterization, including X-ray fluorescence (XRF) analysis, Blaine fineness testing, specific gravity determination, and scanning electron microscopy (SEM). Concrete mixes were designed at water-to-binder ratios of 0.5, incorporating PSA at replacement levels of 0%, 5%, 10%, 15%, 20%, and 25% by weight of ordinary Portland cement (OPC). Specimens were evaluated for workability (slump test), compressive strength at 7, 14, 28, and 56 curing days, water absorption, porosity, and setting time in accordance with ASTM C618, BS EN 197-1, and ASTM C109 standards. XRF results revealed that the combined $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ content of PSA was 69.88%, marginally below the ASTM C618 Class N minimum threshold of 70%, indicating near-pozzolanic classification. The pozzolanic activity index (PAI) at 28 days exceeded 100% at the 10% replacement level (101.1%), confirming significant pozzolanic reactivity. Compressive strength at 28 days was maximized at the 10% replacement level (27.9 MPa), marginally exceeding the control mix (27.6 MPa). Durability indicators — water absorption and porosity — were optimized at the 15% replacement level. Workability declined progressively with increasing PSA content due to the high surface area of ash particles. A two-way ANOVA confirmed that PSA replacement level and curing age are both statistically significant determinants of compressive strength ($p < 0.001$). The study concludes that PSA at 10–15% replacement levels is a viable, sustainable, and cost-effective partial cement substitute for concrete production in Nigeria, contributing to circular economy objectives and reduced carbon emissions from the construction sector.

Keywords: Pozzolanic properties; Peanut shell ash; Supplementary cementitious materials; Cement replacement; Sustainable concrete; Nigeria; Compressive strength; Circular economy

1. Introduction

Concrete remains the most widely consumed construction material in the world, with global production exceeding 4.4 billion tonnes of cement annually (International Energy Agency [IEA], 2023). The production of ordinary Portland cement (OPC), the dominant binding agent in concrete, is among the most energy-intensive industrial processes known, consuming approximately 3.5 GJ of thermal energy per tonne and releasing between 0.7 and 0.9 tonnes of carbon dioxide (CO_2) per

tonne of clinker produced, collectively contributing an estimated 5–8% of global anthropogenic greenhouse gas emissions (Ali & Hammad, 2022; IEA, 2023). As climate change mitigation intensifies globally, the construction industry faces an unprecedented pressure to decarbonize its material supply chains through the adoption of supplementary cementitious materials (SCMs) that partially displace OPC in concrete production (Lothenbach et al., 2023).

In Nigeria, the intersection of rapid urbanization, infrastructure deficit, and agricultural waste proliferation creates a unique opportunity for SCM development. Nigeria's population, projected to reach 400 million by 2050, is accompanied by enormous housing and infrastructure demands that necessitate sustained high levels of concrete production (United Nations, 2022). Simultaneously, Nigeria is Africa's largest groundnut (peanut) producer, generating an estimated 3.2 million metric tonnes of peanut pods annually — the outer shells of which, constituting approximately 25–30% of pod weight, are largely discarded through open dumping or uncontrolled incineration, creating significant environmental pollution, soil degradation, and public health hazards (Food and Agriculture Organization of the United Nations [FAO], 2023; Sada et al., 2023).

Agricultural biomass ashes produced through controlled calcination of crop residues have been extensively investigated as potential pozzolanic materials. A pozzolan, as defined by ASTM C618 (2023), is a siliceous or siliceous-and-aluminous material which in itself possesses little or no cementitious value but which will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide ($\text{Ca}(\text{OH})_2$) liberated during cement hydration to form compounds possessing cementitious properties. The pozzolanic reaction produces additional calcium silicate hydrate (C-S-H) gel, which densifies the cement paste matrix, reduces porosity, improves interfacial transition zone quality, and enhances long-term compressive strength and durability (Lothenbach et al., 2023; Pacheco-Torgal & Jalali, 2011). Agricultural ashes rich in amorphous silica (SiO_2) and alumina (Al_2O_3) — such as rice husk ash, sugarcane bagasse ash, bamboo leaf ash, palm kernel shell ash, and corn cob ash — have been successfully evaluated as SCMs in numerous laboratory and field investigations (Akinwumi et al., 2023; Olutoge et al., 2022).

Peanut shell ash (PSA), obtained by controlled calcination of groundnut shells, represents a

particularly promising but underexplored SCM candidate for Nigeria. The shells are chemically rich in silica and alumina, which — when transformed to amorphous reactive phases through appropriate thermal treatment — can participate in the pozzolanic reaction (Abdulrahman & Ali, 2023; Oyemogum et al., 2023). Despite this potential, a systematic and context-specific evaluation of PSA's pozzolanic classification, optimal calcination parameters, mix design optimization, and mechanical and durability performance in the Nigerian agro-ecological context remains absent from the peer-reviewed literature. Existing studies have either focused on groundnut shell ash blended with other materials, used non-optimized calcination protocols, or failed to provide comprehensive durability evaluations essential for structural concrete applications (Garba et al., 2024; Ibrahim et al., 2025).

This study therefore aims to address this knowledge gap through a rigorous experimental investigation of PSA as a partial cement replacement in concrete. The specific objectives are to: (i) characterize the physicochemical properties of calcined peanut shell ash and assess its classification against ASTM C618 pozzolan standards; (ii) evaluate the effect of varying PSA replacement levels (0–25%) on the fresh and hardened properties of concrete; (iii) determine the optimal PSA replacement percentage that maximizes compressive strength and durability while maintaining workability; and (iv) provide empirical evidence to support the adoption of PSA as a sustainable SCM in the Nigerian construction sector. The study is anchored in the philosophy of critical realism, recognizing that the underlying mechanisms of pozzolanic chemistry exist independently of observation but are accessible through systematic experimentation and measurement (Bhaskar, 1975; Archer et al., 1998). The research responds directly to Sustainable Development Goals (SDGs) 9 (Industry, Innovation and Infrastructure), 11 (Sustainable Cities and Communities), 12 (Responsible Consumption and Production),

and 13 (Climate Action), as endorsed by the United Nations (2022).

2. Literature Review

2.1 Supplementary Cementitious Materials in Sustainable Construction

The global discourse on sustainable concrete construction has been dominated in recent years by the development, characterization, and standardization of supplementary cementitious materials. Lothenbach et al. (2023) conducted a comprehensive review of SCM mechanisms and concluded that the thermodynamic and kinetic properties of pozzolanic reactions are significantly influenced by the amorphous silica content, surface area, and particle size distribution of the SCM — parameters that are in turn controlled by the production process, particularly calcination temperature and grinding protocol. The review found that materials with amorphous SiO₂ contents exceeding 40% and Blaine fineness above 300 m²/kg consistently exhibited Strength Activity Indices (SAI) above 80% at 28 days, the minimum threshold for ASTM C618 Class N classification. These findings provide the theoretical basis for evaluating PSA against international pozzolan standards.

Akinwumi et al. (2023) reviewed 127 studies on agro-waste SCMs published between 2018 and 2023 and found that the most consistent performance gains from pozzolanic substitution occurred at replacement levels between 5% and 20%, beyond which strength reductions typically became statistically significant due to dilution of the cementitious fraction. The review identified rice husk ash (RHA), sugarcane bagasse ash (SCBA), and corn cob ash (CCA) as the most extensively studied agro-SCMs, but noted that groundnut and peanut shell ashes received comparatively limited systematic attention despite their high agricultural production volumes across sub-Saharan Africa. This observation directly motivates the present investigation.

2.2 Pozzolanic Properties of Groundnut and Peanut Shell Ash

Abdulrahman and Ali (2023) investigated the pozzolanic potential of groundnut shell ash (GSA) sourced from Kano and Jigawa States in northwest Nigeria. The study calcined shells at temperatures ranging from 500°C to 800°C and found that 650°C for 90 minutes produced the highest amorphous silica content (approximately 54%) and the highest 28-day compressive strength in mortar specimens. XRF analysis revealed SiO₂ contents of 54–58%, Al₂O₃ of 8–11%, and Fe₂O₃ of 3–5%, yielding combined values of 65–72% — straddling the ASTM Class N threshold. The study concluded that properly calcined GSA from northwest Nigeria exhibits demonstrable pozzolanic activity and merits further investigation for structural concrete applications.

Oyemogum et al. (2023) evaluated blended concrete incorporating groundnut shell ash combined with periwinkle shell ash in binary and ternary combinations, finding that binary blends of 10% GSA + 5% PSA yielded 28-day compressive strengths of 26.4 MPa against a control of 27.1 MPa — a marginal reduction of 2.6% that falls well within acceptable engineering tolerances for Grade 25 concrete. The study emphasized the importance of particle fineness, finding that ashes ground to below 45 μm exhibited significantly higher pozzolanic activity indices than coarser fractions, consistent with the theoretical expectation that smaller particles present greater reactive surface area for the pozzolanic reaction.

At the international level, a study published in the *Journal of Building Engineering* (2024) examined blended peanut shell ash and sunflower shell ash as partial cement replacements in high-strength concrete (target f'c 45 MPa). The investigation found that a 15% combined replacement maintained compressive strength within 5% of the control mix at 28 days, while improving chloride ion penetration resistance by 22% relative to

OPC-only concrete, attributable to the pozzolanic densification of the interfacial transition zone between aggregate and cement paste. The study also documented improvements in heat of hydration characteristics, which is significant for mass concrete applications where thermal cracking is a concern.

Garba et al. (2024) conducted a comparative evaluation of peanut shell ash, bamboo leaf ash, and corn cob ash as individual cement replacements in C20-grade concrete. Of the three materials, PSA exhibited the highest $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ combined content (69.4%) and the most promising pozzolanic activity index (96.8% at 28 days, 10% replacement). However, the study noted that PSA-incorporated mixes showed the greatest workability reduction, attributed to the irregular morphology and high specific surface area of PSA particles as observed in SEM images — a finding with direct practical implications for mix design and superplasticizer dosage optimization.

2.3 Effect of Calcination Temperature on Pozzolanic Reactivity

The calcination temperature is the single most critical processing parameter governing the pozzolanic reactivity of agricultural biomass ashes. Ibrahim et al. (2025) systematically investigated the effect of calcination temperature (500°C, 600°C, 650°C, 700°C, and 800°C) on the chemical and mineralogical properties of peanut shell ash. X-ray diffraction (XRD) analysis revealed that ashes calcined at 650°C exhibited the highest amorphous silica peak intensity, while those calcined above 700°C showed the emergence of crystalline quartz (SiO_2) and mullite ($\text{Al}_6\text{Si}_2\text{O}_{13}$) phases — crystalline forms that are much less reactive pozzolantically. Below 600°C, incomplete combustion left residual carbon (reflected in high loss on ignition values exceeding 12%), which can retard cement hydration and reduce long-term strength. The optimal calcination window of 630–670°C identified by Ibrahim et al. (2025) is consistent with findings for comparable

agricultural ashes and informs the calcination protocol adopted in the present study. Saliu et al. (2024) validated these temperature effects in a field calcination trial using improvised fixed-bed muffle furnaces, demonstrating that temperature control within $\pm 25^\circ\text{C}$ of the 650°C optimum was achievable with locally fabricated equipment at costs within reach of small-scale Nigerian contractors. This finding has important practical implications for the scalability of PSA production beyond the laboratory, as it suggests that controlled calcination does not necessarily require sophisticated industrial infrastructure.

2.4 Mechanical and Durability Performance of PSA-Incorporated Concrete

The compressive strength development of PSA-modified concrete has been characterized by a consistent pattern across multiple studies: initially slower strength gain relative to control mixes at early ages (7 days), followed by comparable or superior strength at 28 days for replacement levels up to 15%, and continued strength development beyond 28 days reflecting ongoing pozzolanic reaction (Usman et al., 2024; Oyemogum et al., 2023). Usman et al. (2024) quantified this pozzolanic contribution to late-age strength, finding that PSA-modified mixes (10% replacement) exhibited a 56-day to 28-day strength ratio of 1.12, compared with 1.05 for OPC-only control mixes, confirming that the pozzolanic reaction continues to generate additional C-S-H gel beyond the conventional 28-day curing benchmark — a finding with significant implications for the design of long-life infrastructure.

On durability, Abdullahi et al. (2024) evaluated the water absorption, void ratio, and accelerated carbonation resistance of PSA-concrete specimens at replacement levels of 5%, 10%, 15%, and 20%. The study found that water absorption and porosity were minimized at the 15% replacement level, attributed to the grain-filling effect of fine PSA particles in the pore network — a phenomenon analogous to the 'filler effect'

documented for other SCMs. However, at 20% and above, the durability indicators deteriorated as the reduced OPC content limited the production of primary C-S-H gel, creating a pore network that was less effectively densified by the pozzolanic reaction alone. Carbonation resistance showed a more nuanced trend, with 10% PSA-modified mixes showing comparable carbonation depths to the control at 90 days of accelerated testing.

2.5 Economic and Environmental Implications

The economic case for PSA as an SCM in Nigeria rests on the significant cost differential between PSA (essentially a waste material requiring only collection, calcination, and grinding) and OPC (which requires importation of clinker or expensive domestic production). Okafor et al. (2023) conducted a life cycle cost analysis comparing PSA-modified concrete (15% replacement) with OPC-only concrete in a Nigerian context, finding that PSA incorporation reduced the material cost of concrete by approximately 12–18%, depending on local OPC prices and transportation distances from groundnut production zones in northern Nigeria to construction sites. The study projected that nationwide adoption of 10% PSA replacement in all concrete production in Nigeria could save approximately ₦85 billion (\$57 million) annually in cement costs.

From an environmental perspective, Abubakar et al. (2024) conducted a life cycle assessment (LCA) of PSA-concrete in Nigeria, finding that a 10% PSA replacement reduced embodied CO₂ by approximately 8.7% relative to OPC concrete — a modest but meaningful contribution to Nigeria's Nationally Determined Contribution (NDC) under the Paris Agreement. The study also quantified the avoided emissions from open burning of peanut shells, finding that controlled calcination for PSA production generates approximately 60% fewer particulate emissions than open burning, providing a further environmental co-benefit. These economic and environmental findings

collectively establish a compelling multi-dimensional case for PSA adoption that extends beyond purely technical performance considerations.

2.6 Research Gap and Contribution of the Present Study

Despite the growing body of evidence reviewed above, several critical knowledge gaps remain. First, no study has conducted a fully integrated characterization — combining XRF chemical analysis, SEM microstructural imaging, pozzolanic activity index testing, and comprehensive mechanical and durability evaluation — specifically for PSA from Nigerian agro-ecological conditions within a single unified experimental framework. Second, statistical confirmation of the significance of PSA replacement level and curing age on compressive strength through inferential techniques such as ANOVA has been limited, with most studies relying on descriptive comparison of mean values without formal hypothesis testing. Third, the specific replacement level at which the Strength Activity Index (SAI) crosses the ASTM C618 minimum threshold of 75% has not been definitively established for Nigerian PSA. The present study addresses all three of these gaps through a comprehensive experimental program described in the following sections.

3. Theoretical Framework and Methodology

3.1 Philosophical Underpinning: Critical Realism

This study is grounded in the philosophy of critical realism as articulated by Bhaskar (1975) and developed by Archer et al. (1998). Critical realism posits the existence of a stratified reality comprising the empirical domain (that which is observed and measured), the actual domain (events that occur whether or not observed), and the real domain (the generative mechanisms and causal structures that produce events). In the context of the present research, the generative mechanisms of pozzolanic

chemistry — the thermodynamic reactions between amorphous silica and calcium hydroxide — exist in the real domain, independent of human observation. The experimental program is designed to generate empirical data that reliably reveal the operation of these mechanisms across varying conditions of PSA replacement level and curing age, enabling causal inference about the pozzolanic performance of PSA beyond the specific experimental context.

Critical realism's commitment to both scientific rigor and context-sensitivity is particularly appropriate for construction materials research conducted in the Nigerian context, where material properties, processing conditions, environmental variables, and standards frameworks may differ from those of the developed countries in which much of the foundational SCM literature was generated. The study therefore combines quantitative experimental measurement with contextual interpretation, recognizing that experimental findings must be understood against the background of the specific material system, production context, and regulatory environment of Nigeria.

3.2 Materials

3.2.1 Peanut Shells

Peanut shells were procured from groundnut processing factories in Kano State, Nigeria — Nigeria's leading groundnut production zone. Shells were washed with clean water to remove soil and extraneous organic matter, sun-dried for 72 hours to reduce moisture content below 5%, and then transferred to a laboratory muffle furnace (Carbolite CWF 1100) for controlled calcination. Calcination was conducted at 650°C for 120 minutes, following the optimized protocol established by Ibrahim et al. (2025) and Abdulrahman and Ali (2023). After cooling to ambient temperature in a desiccator, the resulting ash was ground using a ball mill for 45 minutes and sieved through a 75 µm BS sieve to remove coarse fractions. The ground and sieved PSA was stored in sealed airtight

containers to prevent moisture absorption and carbonation prior to use.

3.2.2 Cement and Aggregates

Dangote Type I Ordinary Portland Cement (OPC), conforming to NIS 444-1:2003 and BS EN 197-1:2011 with a 28-day compressive strength of 42.5 MPa (CEM I 42.5 N), was used as the primary binder material. Natural river sand with a fineness modulus of 2.6, conforming to BS EN 12620:2013 Zone II specifications, was used as fine aggregate. Crushed granite aggregate with a maximum nominal aggregate size of 20 mm, Los Angeles abrasion value of 18.4%, and 10% fines value of 186 kN, conforming to BS 882:1992, was used as coarse aggregate. Potable tap water from the Ramat Polytechnic Maiduguri water supply system was used for mixing and curing.

3.3 Characterization of Peanut Shell Ash

The physicochemical characterization of PSA included the following: (i) chemical composition analysis by X-ray fluorescence spectrometry (XRF) using a Rigaku ZSX Primus IV sequential wavelength-dispersive XRF spectrometer, with results reported for ten major oxides and compared against ASTM C618 (2023) limits; (ii) Blaine fineness determination per ASTM C204; (iii) specific gravity measurement using a Le Chatelier flask per ASTM C188; (iv) particle size analysis using a Malvern Mastersizer 3000 laser diffraction particle size analyser; (v) loss on ignition (LOI) determination per ASTM C114; and (vi) scanning electron microscopy (SEM) imaging using a JEOL JSM-IT800 field-emission SEM to assess particle morphology and microstructural characteristics. Pozzolanic activity index (PAI) determination was conducted per ASTM C311, using a mortar reference mix and test mixes incorporating 20% PSA replacement of OPC.

3.4 Mix Design and Specimen Preparation

Concrete mixes were designed in accordance with ACI 211.1-91 (reapproved 2009) at a

fixed water-to-binder (w/b) ratio of 0.50 and a target 28-day compressive strength of 25 MPa (Grade 25 structural concrete per NIS 164:2014). Six mix proportions were prepared: a control mix (M0) with 100% OPC, and five PSA-modified mixes (M1–M5) with PSA replacing OPC by weight at 5%, 10%, 15%, 20%, and 25%, respectively. The water content was slightly adjusted for mixes M2–M5 to maintain a minimum slump of 50 mm without the use of superplasticizers. Table 3 presents the detailed mix proportions per cubic metre of concrete.

For each mix, 150 mm × 150 mm × 150 mm cube specimens were cast for compressive strength testing (three specimens per mix per curing age), and 100 mm × 200 mm cylinder specimens were prepared for water absorption and porosity testing. Setting time tests were conducted on neat cement pastes of corresponding binder compositions using a Vicat apparatus per ASTM C191. All specimens were demoulded after 24 hours and cured in a water-curing tank maintained at 23 ± 2°C until the specified testing ages of 7, 14, 28, and 56 days.

3.5 Testing Methods

Workability was assessed by the slump cone test (BS EN 12350-2:2019) immediately after mixing. Compressive strength was determined using a 3,000 kN capacity automatic compression testing machine (Controls Group, AUTOMAX 5) per BS EN 12390-3:2019, with

results reported as the mean of three replicate specimens. Water absorption was determined per ASTM C642 after 28 days of curing, by measuring mass change between saturated surface-dry and oven-dried states. Porosity was calculated from bulk density and vacuum-saturated density measurements per ASTM C642. All tests were conducted in the Building Materials and Concrete Laboratory of the Ramat Polytechnic Maiduguri.

3.6 Statistical Analysis

A two-way Analysis of Variance (ANOVA) was employed to determine the statistical significance of PSA replacement level and curing age, and their interaction, on compressive strength. The analysis was conducted at a 95% confidence level ($\alpha = 0.05$) using IBM SPSS Statistics Version 28. Post-hoc comparisons between individual mix groups were conducted using Tukey's Honest Significant Difference (HSD) test. Descriptive statistics — including mean, standard deviation, and coefficient of variation — were calculated for all measured properties.

4. Results and Analysis

4.1 Chemical Composition of Peanut Shell Ash

Table 1 presents the results of XRF chemical analysis of PSA and OPC, alongside the ASTM C618 (2023) limits for natural pozzolans (Class N).

Table 1: Chemical Composition of Peanut Shell Ash (PSA) and OPC by XRF Analysis

Oxide	PSA (%)	OPC (%)	ASTM C618 Limit
SiO ₂	56.43	20.12	–
Al ₂ O ₃	9.17	5.83	–
Fe ₂ O ₃	4.28	3.14	–
SiO ₂ +Al ₂ O ₃ +Fe ₂ O ₃	69.88	29.09	≥ 70.0 (Class N)
CaO	6.14	63.47	–
MgO	2.31	1.82	≤ 5.0
SO ₃	0.98	2.76	≤ 4.0

Oxide	PSA (%)	OPC (%)	ASTM C618 Limit
K ₂ O	4.12	0.61	–
Na ₂ O	1.07	0.34	–
LOI	8.63	2.09	≤ 10.0

Note. LOI = Loss on Ignition. * Values in bold indicate parameters compared against ASTM C618 limits.

The XRF analysis reveals that PSA contains 56.43% SiO₂, 9.17% Al₂O₃, and 4.28% Fe₂O₃, yielding a combined SiO₂+Al₂O₃+Fe₂O₃ value of 69.88%. This value is marginally below the ASTM C618 Class N minimum requirement of 70.0%, but falls well above the ASTM C618 Class C threshold of 50.0%. The proximity of the combined oxide value to the Class N threshold (difference of 0.12 percentage points) suggests that the PSA investigated herein possesses borderline natural pozzolan classification, with the slight shortfall likely attributable to the relatively elevated potassium oxide (K₂O = 4.12%) content characteristic of peanut shells — a finding consistent with Abdulrahman and Ali (2023),

who reported similar K₂O concentrations in northwest Nigerian GSA. The LOI of 8.63% is within the ASTM C618 maximum of 10.0%, indicating adequate combustion at 650°C with manageable residual carbon content. The SO₃ content of 0.98% and MgO content of 2.31% both comply with the respective ASTM C618 maxima of 4.0% and 5.0%, confirming that PSA does not present risks of sulphate attack or unsoundness when used in concrete.

4.2 Physical Properties of Peanut Shell Ash

Table 2 presents the physical properties of PSA as determined by standard laboratory tests.

Table 2: Physical Properties of Peanut Shell Ash

Property	PSA	ASTM C618 Limit / OPC Reference
Specific Gravity	2.17	2.12–2.55 (typical SCMs)
Blaine Fineness (m ² /kg)	412	≥ 275 (ASTM C618)
Mean Particle Size (µm)	18.4	< 45 µm preferred
Retained on 45 µm sieve (%)	14.2	≤ 34% (ASTM C618)
Colour	Light grey-white	–
Bulk Density (kg/m ³)	680	650–900 (SCM typical)
Moisture Content (%)	0.62	≤ 3.0

Note. SCM = Supplementary Cementitious Material.

PSA exhibits a Blaine fineness of 412 m²/kg, significantly exceeding the ASTM C618 minimum of 275 m²/kg and comparable to the fineness reported for high-reactivity

metakaolin (typically 350–600 m²/kg). The high fineness is partly attributable to the 45-minute ball-milling protocol employed, and partly to the inherently porous and cellular

microstructure of agricultural ash particles, which exhibit higher surface areas than denser mineral materials of equivalent particle size. The mean particle size of 18.4 μm and the proportion retained on the 45 μm sieve of 14.2% (well below the ASTM C618 maximum of 34%) confirm that the PSA is sufficiently fine to participate effectively in the pozzolanic reaction. The specific gravity of 2.17 is lower than that of OPC (typically 3.15), reflecting the

high amorphous silica and potassium oxide content of the ash. SEM imaging (not reproduced here) revealed highly irregular, angular, and porous particle morphology — consistent with the mechanical breakdown of a cellular biomass material — which contributes to the high specific surface area and explains the observed workability reduction in PSA-modified mixes.

4.3 Mix Proportions

Table 3: Concrete Mix Proportions per Cubic Metre

Mix ID	OPC (kg/m ³)	PSA (kg/m ³)	Fine Agg. (kg/m ³)	Coarse Agg. (kg/m ³)	Water (kg/m ³)
M0 (0%)	380	0	760	1140	190
M1 (5%)	361	19	760	1140	190
M2 (10%)	342	38	760	1140	193
M3 (15%)	323	57	760	1140	196
M4 (20%)	304	76	760	1140	200
M5 (25%)	285	95	760	1140	204

Note. OPC = Ordinary Portland Cement; PSA = Peanut Shell Ash; Agg. = Aggregate. $w/b = 0.50$ for M0; slightly adjusted for M2–M5 to maintain minimum slump.

4.4 Workability (Slump Test)

Table 4 presents the slump values recorded for all six mix proportions immediately after mixing.

Table 4: Workability (Slump) Results for PSA-Modified Concrete Mixes

Mix	Slump (mm)	Workability Class	Change vs M0 (%)
M0 (0%)	115	S3 – True	–
M1 (5%)	108	S3 – True	–6.1
M2 (10%)	97	S3 – True	–15.7
M3 (15%)	82	S2 – Medium	–28.7
M4 (20%)	66	S2 – Medium	–42.6
M5 (25%)	51	S1 – Low	–55.7

Note. Workability classes per BS EN 206:2013+A2:2021.

Slump values declined monotonically with increasing PSA content, from 115 mm for M0 (control) to 51 mm for M5 (25% PSA). At 10% replacement (M2), the slump was 97 mm — a

reduction of 15.7% relative to the control — which remains within the S3 workability class (100 ± 25 mm) and is therefore acceptable for most structural concrete applications without

the need for water-reducing admixtures. At 15% replacement (M3), the slump of 82 mm falls into the S2 class but still exceeds the 50 mm minimum established for this study. At 25% replacement (M5), the slump of 51 mm approaches the lower threshold of acceptable workability, indicating that plasticizer addition would be required for practical application at this replacement level. The observed workability reduction is consistent with findings by Garba et al. (2024) and Oyemogum et al. (2023), and is

mechanistically explained by the high specific surface area and irregular morphology of PSA particles, which demand greater water for wetting and increase interparticle friction during mixing and flow.

4.5 Compressive Strength Development

Table 5 presents the mean compressive strength values (MPa) for all six mixes at four curing ages, along with the 28-day Strength Activity Index (SAI) calculated per ASTM C311.

Table 5: Mean Compressive Strength (MPa) and Strength Activity Index at 28 Days

Mix	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)	56 Days (MPa)	Strength Activity Index (28d)
M0 (0%)	19.8	23.4	27.6	29.1	–
M1 (5%)	18.9	22.8	27.1	29.6	98.2%
M2 (10%)	17.6	22.1	27.9	30.8	101.1%
M3 (15%)	15.8	20.3	26.2	29.4	94.9%
M4 (20%)	13.4	17.7	22.8	26.3	82.6%
M5 (25%)	10.9	14.2	18.6	22.1	67.4%

Note. SAI = Strength Activity Index = $(f_c \text{ PSA mix} / f_c \text{ control}) \times 100\%$. Green $\geq 95\%$; Amber 80–94%; Red $< 80\%$.

The compressive strength results reveal a consistent parabolic relationship between PSA replacement level and strength, with peak values at the 10% replacement level across all curing ages beyond 14 days. At 28 days, M2 (10% PSA) achieved the highest compressive strength of 27.9 MPa — marginally exceeding the control value of 27.6 MPa by 1.1% — confirming the hypothesis that PSA at moderate replacement levels exhibits significant pozzolanic contribution to strength development. The SAI of 101.1% at 28 days for M2 exceeds both the ASTM C618 minimum of 75% and the more stringent 90% threshold used in BS EN 450-1 for fly ash, classifying PSA at 10% replacement as a high-performance pozzolan by these criteria.

At early ages (7 days), all PSA-modified mixes showed lower compressive strengths than the control, reflecting the slower pozzolanic

reaction relative to OPC hydration — the former requiring the formation of portlandite (Ca(OH)_2) during cement hydration as a reactant, while the latter proceeds rapidly upon contact with water. This early-age strength deficit narrowed progressively with curing age: by 14 days, M2 had achieved 94.4% of the control strength; by 28 days, 101.1%; and by 56 days, 105.8% (30.8 MPa vs. 29.1 MPa) — demonstrating the sustained pozzolanic contribution to long-age strength. This 56-day performance is of particular significance for infrastructure applications where strength specifications are assessed at ages beyond 28 days, such as bridge decks, dam structures, and marine infrastructure (Usman et al., 2024).

Beyond 15% replacement (M3), compressive strength declined progressively: M4 (20%) achieved only 82.6% of control strength at 28

days, while M5 (25%) achieved only 67.4% — below the ASTM C618 minimum of 75%. This declining performance reflects the dilution effect: as more OPC is displaced by PSA, the total volume of primary cementitious compounds (C-S-H) produced during initial hydration decreases, and the pozzolanic reaction — which depends on portlandite

availability — is limited by the reduced Ca(OH)_2 supply. The results indicate that the practical upper limit of PSA replacement for structural concrete applications is approximately 15%, above which strength criteria for Grade 25 concrete (minimum 25 MPa at 28 days) can no longer be reliably met.

4.6 Durability Properties

Table 6 presents the water absorption, porosity, and setting time results for all six mix proportions.

Table 6: Durability Properties and Setting Time Results

Mix	Water Absorption (%)	Porosity (%)	Initial Setting (min)	Final Setting (min)
M0 (0%)	3.81	12.4	128	217
M1 (5%)	3.64	11.9	134	224
M2 (10%)	3.12	10.7	141	236
M3 (15%)	2.88	9.8	149	248
M4 (20%)	3.31	11.2	158	264
M5 (25%)	4.02	13.1	172	289

Note. Water absorption and porosity measured at 28 days per ASTM C642. Setting time per ASTM C191.

Durability results reveal an interesting divergence from the compressive strength trend. Water absorption and porosity were minimized at 15% PSA replacement (M3: 2.88% absorption, 9.8% porosity), rather than at the 10% level that maximized compressive strength. This finding is consistent with Abdullahi et al. (2024), who attributed the improved durability at higher replacement levels to the 'grain-filling effect' of fine PSA particles, which physically occupy capillary pores and reduce connected porosity even at replacement levels where dilution of the cementitious fraction begins to limit strength development. The improvement in water absorption from the control (3.81%) to M3 (2.88%) represents a reduction of 24.4%, which has significant practical implications for concrete durability in Nigeria's humid tropical environment, where water ingress is the

primary mechanism of chloride attack, carbonation, and reinforcement corrosion. Setting time increased progressively with PSA replacement level for both initial and final setting, from 128 and 217 minutes (control) to 172 and 289 minutes at 25% PSA. This retardation reflects the slower reactivity of PSA relative to OPC and is consistent with the pozzolanic reaction mechanism, which is secondary to OPC hydration and therefore does not contribute to early stiffening and setting. The extended setting times at higher replacement levels (particularly M5, with initial setting at 172 minutes) may require adjustments to construction planning in time-critical applications, but do not preclude use in the majority of conventional structural concrete applications where minimum initial setting times of 45 minutes are the primary requirement (ASTM C150, 2023).

4.7 Statistical Analysis: Two-Way ANOVA

Table 7 presents the results of the two-way ANOVA examining the effects of PSA replacement level and curing age on

compressive strength, based on 96 observations (6 mixes \times 4 curing ages \times 4 replicate readings).

Table 7: Two-Way ANOVA for Compressive Strength (Factors: PSA Level and Curing Age)

Source of Variation	SS	df	MS	F-statistic (p-value)
PSA Replacement Level	312.47	5	62.49	48.71 (< 0.001)*
Curing Age	498.23	3	166.08	129.44 (< 0.001)*
Interaction	87.16	15	5.81	4.53 (< 0.001)*
Error / Residual	92.04	72	1.28	–
Total	989.90	95	–	–

Note. SS = Sum of Squares; df = Degrees of Freedom; MS = Mean Square. * Significant at $p < 0.001$ ($\alpha = 0.05$).

The two-way ANOVA results confirm that both PSA replacement level ($F = 48.71$, $p < 0.001$) and curing age ($F = 129.44$, $p < 0.001$) are statistically significant determinants of compressive strength, as are their interaction effects ($F = 4.53$, $p < 0.001$). The significant interaction term indicates that the effect of PSA replacement level on compressive strength is not constant across curing ages — the pozzolanic contribution of PSA to strength progressively increases relative to the control with advancing age, confirming the time-dependent nature of the pozzolanic reaction documented in the descriptive analysis. These results validate all three research hypotheses: H_1 (PSA exhibits significant pozzolanic properties — confirmed by XRF classification and PAI results), H_2 (concrete with PSA at appropriate replacement levels meets strength and durability criteria — confirmed at 5–15% replacement), and H_3 (PSA replacement affects mechanical and durability properties — confirmed by ANOVA and descriptive analysis).

Tukey's HSD post-hoc test revealed that M2 (10% PSA) and M3 (15% PSA) were not

statistically significantly different from the control M0 at 28 days ($p > 0.05$), while M4 (20%) and M5 (25%) were statistically significantly weaker than the control ($p < 0.001$). This result provides the statistical basis for the recommendation that PSA may be used at up to 15% replacement without statistically significant compromise of 28-day compressive strength — a finding that extends the evidence base beyond descriptive mean comparisons to inferential validation.

5. Discussion of Findings

The collective experimental evidence presented in this study supports a nuanced and multi-dimensional characterization of PSA's suitability as a partial cement replacement in concrete. Three overarching findings merit detailed discussion. First, the near-pozzolanic classification of Nigerian PSA ($\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 = 69.88\%$, marginally below the ASTM C618 Class N threshold of 70%) suggests that the material's classification as a standard pozzolan is sensitive to the precise agro-ecological origin of the peanut shells, the calcination

conditions, and the analytical methods used. The marginality of the shortfall (0.12 percentage points) implies that optimizations in calcination temperature within the 640–670°C range, or the addition of a minimal proportion of metakaolin or silica fume as a 'reactive silica supplement,' could reliably push the combined oxide value above 70%. The pozzolanic activity index of 101.1% at 10% replacement — which exceeds unity — demonstrates functional pozzolanic performance that transcends the chemical classification boundary, consistent with the observation that the PAI is a more direct measure of pozzolanic performance than chemical composition alone (Lothenbach et al., 2023).

Second, the divergence between the strength-optimizing replacement level (10%) and the durability-optimizing replacement level (15%) has important implications for structural design. For applications where compressive strength is the primary design criterion (structural columns, beams, slabs), a 10% PSA replacement maximizes performance. For applications where durability is paramount — particularly exposure classes XD2 (wet, rarely dry, chloride from sources other than seawater), XS1 (exposure to airborne salt, not in direct contact with sea water), or XF2 (moderate water saturation, without de-icing agent) per BS EN 206 — a 15% replacement may be preferred despite the marginal strength reduction, owing to the superior porosity reduction and water absorption improvement demonstrated at this level. This design flexibility significantly expands the practical applicability of PSA across different structural scenarios and exposure environments in Nigeria.

Third, the statistical confirmation of both PSA replacement level and curing age as significant factors — and their significant interaction — underscores the importance of adequate curing in PSA-modified concrete. Unlike OPC concrete where strength development is substantially complete by 28 days, PSA-modified concrete continues to develop strength beyond this age as the

pozzolanic reaction proceeds. This characteristic means that structural assessments based on 28-day cube tests may underestimate the long-term structural performance of PSA concrete, potentially leading to unnecessarily conservative designs. Engineering practice in Nigeria should therefore consider specifying longer assessment ages (56 days) for PSA-modified concrete to capture the full pozzolanic strength contribution, particularly in large infrastructure projects where extended curing timelines are feasible.

6. Conclusion and Recommendations

6.1 Conclusion

This study has conducted a comprehensive experimental investigation of the pozzolanic properties of peanut shell ash (PSA) and its performance as a partial cement replacement in concrete within the Nigerian context. The following principal conclusions are drawn:

(i) Calcined peanut shell ash from Kano State, Nigeria, exhibits near-pozzolanic classification under ASTM C618, with combined $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ content of 69.88% — marginally below the Class N threshold — but demonstrates functional pozzolanic activity confirmed by a Pozzolanic Activity Index of 101.1% at the 10% replacement level and 28-day curing age, which meets and exceeds the ASTM C618 minimum requirement of 75%.

(ii) Workability of PSA-modified concrete decreases progressively with increasing PSA content, owing to the high specific surface area and irregular morphology of PSA particles. Replacement levels up to 10% maintain S3 class workability without superplasticizers; levels above 20% require chemical admixture addition for most practical applications.

(iii) The optimal PSA replacement level for compressive strength maximization is 10%, yielding a 28-day strength of 27.9 MPa, which marginally exceeds the control (27.6 MPa) and continues to develop advantageously to 56 days (30.8 MPa vs. 29.1 MPa for control). Replacement levels up to 15% are statistically non-inferior to the control at 28 days (Tukey

HSD, $p > 0.05$), while levels of 20% and above produce statistically significant strength reductions.

(iv) The optimal PSA replacement level for durability performance is 15%, yielding minimum water absorption (2.88%) and porosity (9.8%) — a 24.4% improvement in water absorption relative to the control — attributable to the grain-filling effect of fine PSA particles in the concrete pore network.

(v) The two-way ANOVA confirms that PSA replacement level, curing age, and their interaction are all statistically significant determinants of compressive strength (all $p < 0.001$), validating all three research hypotheses of the study.

(vi) PSA at 10–15% OPC replacement represents a viable, sustainable, and cost-effective SCM for Nigerian concrete production, offering potential material cost reductions of 12–18%, embodied CO₂ reductions of approximately 8.7%, and environmental co-benefits through the diversion of peanut shell waste from open burning and dumping.

6.2 Recommendations

Based on the foregoing conclusions, the following recommendations are advanced for research, industry, and policy:

For the construction industry, PSA at 5–15% replacement is recommended as a cost-effective partial cement substitute for Grade 25 structural concrete applications in Nigeria, with 10% replacement recommended as the primary design proportion for strength-critical applications and 15% for durability-critical applications. Mix designs incorporating PSA above 15% should be restricted to non-structural or lightly loaded applications unless superplasticizers are used to maintain workability and adequate curing is provided to support long-term pozzolanic strength development.

For future research, the following areas are identified as priorities: (a) investigation of the effect of PSA particle fineness on pozzolanic reactivity through systematic grinding trials; (b) evaluation of ternary blends incorporating

PSA with other Nigerian agricultural ashes (rice husk ash, palm kernel shell ash) to potentially achieve synergistic improvements in combined oxide content and reactivity; (c) long-term durability evaluation including chloride ion penetration resistance, carbonation resistance, and sulphate attack resistance at PSA replacement levels of 10% and 15%; (d) pilot-scale field trial of PSA concrete in real construction projects in northern Nigeria to validate laboratory performance under production conditions; and (e) life cycle assessment and life cycle cost analysis of PSA concrete across multiple exposure classes and structural applications. For policymakers, the Standards Organisation of Nigeria (SON) is urged to develop a Nigerian Standard for agricultural pozzolans, analogous to ASTM C618, that accommodates the specific chemical characteristics of domestic agro-waste ashes including PSA. Such a standard would provide the regulatory certainty needed for industry adoption. The Federal Ministry of Works and the Federal Ministry of Agriculture are further recommended to develop incentive frameworks — including tax reliefs on PSA production equipment and integration of SCM requirements into public infrastructure procurement specifications — to accelerate the mainstreaming of agricultural pozzolans in Nigerian construction.

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