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Pozzolanic Potential of *Anacardium Occidentale* Nutshell Ash (Aonsa) and Its Impact on the Mechanical Properties of Concrete

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ABSTRACT

This study investigates the pozzolanic potential of Anacardium occidentale nutshell ash (AONSA), an agricultural waste, and its influence on the mechanical properties of concrete. Discarded cashew nutshells, commonly dumped without control, pose environmental risks; however, their ash, when properly processed, can serve as a sustainable cement substitute. In this research, AONSA was produced through open-air combustion and calcined under two conditions: 800°C for 5 hours (Sample A) and 500°C for 7 hours (Sample B). The samples were characterized using X-Ray Diffraction (XRD), X-Ray Fluorescence (XRF), and Scanning Electron Microscopy (SEM). XRD revealed mineral phases including quartz, muscovite, glauconite, and illite. XRF showed substantial contents of SiO_2, CaO, and MgO, indicating pozzolanic suitability. SEM analysis revealed microstructural transformation at higher temperatures, with Sample A exhibiting increased porosity and lower potassium content, characteristics favourable for reactivity. Concrete samples incorporating 0–10% AONSA were tested for compressive strength at 7, 14, 28, and 56 days. Results showed that 2% AONSA replacement (Mix M2) yielded the highest compressive strength across most curing periods, surpassing the control at 7 days (10.64 vs. 6.31 N/mm²) and maintaining comparable strength at 28 days (17.78 vs. 18.13 N/mm²). However, strength declined beyond 4% replacement. The combination of chemical, microstructural, and mechanical evaluations confirms that AONSA, particularly at lower replacement levels, has strong potential as a pozzolanic material for sustainable concrete applications.

INTRODUCTION

Concrete stands as the backbone of the modern construction industry due to its versatility, strength, and durability. However, the production of traditional concrete is a resource-intensive process associated with significant environmental consequences. According to Adeyemi (2020), the primary source of the concrete's significant carbon dioxide emissions is the production of Portland cement, which serves as the primary binder, and the material transportation process. This poses a pressing challenge in the context of sustainability and climate change mitigation (Adriana *et al.* 2022). Pozzolanic materials have emerged as a promising solution to mitigate the environmental impact of concrete. While various pozzolanic materials have been investigated, the utilization of agricultural residue as pozzolans offer a twofold benefit: it reduces waste disposal issues and enhances the sustainability of concrete. Pozzolans are materials that, when mixed with cement, react with calcium hydroxide to form additional calcium silicate hydrate (C-S-H), the compound responsible for concrete's mechanical and durability properties (Seyedsaleh *et al.* 2023). By increasing the C-S-H content, pozzolans effectively enhance the mechanical properties of concrete, including compressive strength, tensile strength, and resistance to chemical attack (Mehta, 2014).

Admixtures are those ingredients in concrete other than Portland cement, water, and aggregates that are added to the mixtures immediately before or during mixing. When used in the right proportion, they can significantly enhance the durability, mechanical properties, and internal structure of concrete (Xiaoyan *et al.* 2022). By partially substituting Portland cement with pozzolans, the carbon footprint associated with concrete production can be considerably diminished (Valber *et al.* 2023). *Anacardium occidentale* nutshell ash (AONSA), derived from the incineration of *anacardium occidentale* nutshell, is rich in amorphous silica. It exhibits oxides of silica and alumina, and little cementitious value, making it a potential candidate for enhancing concrete performance (Oyebisi *et al.* 2019). According to Jugal *et al. (*2021), the amount of lime (CaO) in AONSA is roughly one-third that of Ordinary Portland Cement, as compared to alternative cement substitutes like fly ash.

The degree of pozzolanic activity of AONSA can vary based on factors such as its fineness, chemical composition, and the curing conditions of the concrete mixture. Research has shown that finely ground AONSA particles with a high amorphous silica content tend to exhibit superior pozzolanic reactivity (Nagrockiene *et al.* 2019). According to Farqad *et al.* (2023). This amorphous silica content enables AONSA to react with calcium hydroxide ($Ca(OH)_2$) when mixed with water, forming additional calcium silicate hydrate (C-S-H) gel—a crucial component for enhancing the strength and durability of concrete.

Anacardium occidentale nutshell is a readily available agricultural residue in many regions. However, there is a notable dearth of comprehensive studies exploring the pozzolanic potential and the impact of *anacardium occidentale* nutshell ash (AONSA) on the mechanical properties of concrete; therefore, the problem at hand is the need to assess the feasibility and effectiveness of *anacardium occidentale* nutshell ash as a pozzolanic material in concrete to advance sustainable construction practices and reduce the environmental impact of the industry (Mohamed *et al.* 2023). The study will assess the pozzolanic activity of *anacardium occidentale* nutshell ash (AONSA*)* through laboratory tests and evaluate its influence on the mechanical properties of concrete. Data collected from laboratory tests will undergo thorough analysis and statistical techniques to draw meaningful conclusions regarding the pozzolanic potential and mechanical properties of *anacardium occidentale* nutshell ash.

MATERIALS AND METHODS

Materials

Ordinary Portland Cement (OPC) and standard aggregates, including coarse and fine aggregates, were sourced according to concrete specifications. These aggregates were selected based on their compatibility with AONSA and OPC, and their ability to provide the necessary structural integrity to the concrete. *Anacardium Occidentale* Nutshells used in this study were sourced from local *Anacardium Occidentale* processing unit located in Ogbomoso, Oyo State, Nigeria (approximately 8.119°N, 4.271°E); renowned for their extensive production. *Anacardium Occidentale* nutshells were subjected to air-drying and an open combustion process to obtain ash. The burning of shells was carried out at the LAUTECH Bakery.

Sample Preparation

For the case of this study, Ordinary Portland Cement was used as the primary binder, and partial replacements were made with AONSA at 2%, 4%, 6%, 8%, and 10%, while 0% served as the control. The selected replacement levels are consistent with previous studies on agro-waste pozzolans (e.g., cashew nutshell ash, rice husk ash), which typically explore 0–10% substitution to determine the optimum dosage that balances strength development and pozzolanic reactivity without compromising concrete integrity (Jugal & Rama Mohan, 2021). The mix ratio that was used is 1:3:6, and the water/cement ratio used is 0.5.

Table 1: Proportioning of Concrete

Samples	Cement (kg)	AONSA (kg)	Sand (kg)	Granite (kg)	Water (ltrs)
Control	2.3200	0.0000	6.96	14.0	1.2
Control + 2% (AONSA)	2.2736	0.0464	6.96	14.0	1.2
Control + 4% (AONSA)	2.2272	0.0928	6.96	14.0	1.2
Control + 6% (AONSA)	2.1808	0.1392	6.96	14.0	1.2
Control + 8% (AONSA)	2.1344	0.1856	6.96	14.0	1.2
Control + 10% (AONSA)	2.0880	0.232	6.96	14.0	1.2

In casting the concrete cubes, six mix variations were prepared with AONSA added at different proportions. These mixes are designated as M1, M2, M3, M4, M5, and M6, corresponding to 0%, 2%, 4%, 6%, 8%, and 10% AONSA content by weight of cement, respectively. The samples were cured in a curing tank for 7, 14, 28, and 56 days.

Figure 1. A curing tank

The compressive strength of the concrete samples was evaluated to assess their load-bearing capacity. Cube specimens from different concrete mixtures were subjected to axial compression using a hydraulic testing machine. Testing was performed in accordance with ASTM standards. The test was carried out at ages of 7, 14, 28 and 56 days to examine the strength development over time.

Experimental setup

The experimental setup encompasses these components: Scanning Electron Microscopy (SEM) analysis, X-Ray Diffraction (XRD) analysis and XRF (X-Ray Fluorescence) analysis, each playing a pivotal role in understanding the microstructure and mineral phases of the concrete.

The characterization of Anacardium occidentale nutshell ash (AONSA) was conducted at Ahmadu Bello University (ABU), Zaria, which houses advanced instrumentation for material analysis. X-Ray Diffraction (XRD) analysis was performed using a Rigaku MiniFlex diffractometer equipped with Cu-Kα radiation (λ = 1.5418 Å), operated at 30 kV and 15 mA. Samples, pulverized to ≤150 µm, were scanned across a 2θ range of 2°–70° at a rate of 20°/min to identify crystalline phases and assess mineral composition.

X-Ray Fluorescence (XRF) analysis was conducted using an Energy Dispersive X-Ray Fluorescence (EDXRF) spectrometer to determine the oxide composition of the ash, including SiO_2, CaO, MgO, and Fe_2O_3. For microstructural analysis, Scanning Electron Microscopy (SEM) was carried out using a high-resolution SEM system operated at 15 kV in BSD mode. AONSA samples were gold-coated to enhance conductivity before imaging. SEM provided visual insights into the particle morphology, porosity, and thermal effects on the ash structure under different calcination conditions (800°C for 5 hours and 500°C for 7 hours). Together, these techniques provided complementary information on the physical, chemical, and structural characteristics of AONSA, essential for evaluating its pozzolanic potential.

Scanning Electron Microscopy (SEM) Analysis

The SEM analysis provided valuable insights into the microstructure of the concrete, enabling us to explore the effects of AONSA on the cementitious matrix. Before conducting SEM analysis, AONSA samples were placed differently inside the furnace at 800℃ for 5 hours and 500℃ for 7 hours for calcination. (Bahurudeen and Santhanam, 2015).

X-Ray Diffraction (XRD) Analysis:

XRD analysis is essential for identifying the mineral phases within the concrete and detecting any changes induced by the inclusion of AONSA. AONSA samples were also placed differently inside furnace at 800℃ for 5 hours and 500℃ for 7 hours for calcination and then loaded into the XRD instrument.

Figure 2. Furnace for calcination

X-Ray Fluorescence (XRF) Analysis:

XRF analysis is a technique used for determining the elemental composition of materials. AONSA samples were also placed differently inside the furnace at 800℃ for 5 hours and 500℃ for 7 hours for calcination, and then loaded into the XRF machine (Bahurudeen and Santhanam, 2015).

RESULTS AND DISCUSSION

Compressive strength analysis

The researchers conducted a series of compressive strength tests on concrete specimens with varying percentages of *Anacardium Occidentale* Nutshell Ash (AONSA). The results, presented in Table 4.1 and Plate 4.1, illustrate the impact of AONSA on the compressive strength of the concrete.

Figure 3. Compressive Strength Testing Machine

Table 2. Compressive Strength Data

Mix ID	AONSA Content (%)	Compressive Strength (N/mm^2)			
		7 Days	14 Days	28 Days	56 Days
M1	0	6.31	10.82	18.13	2.27
M2	2	10.64	9.45	17.78	10.71
M3	4	7.94	8.92	16.44	5.48
M4	6	7.22	4.08	15.11	4.57
M5	8	7.59	7.61	13.33	5.17
M6	10	4.45	7.73	12.00	8.14

XRD analysis results

Phase Identification

X-ray Diffraction (XRD) analysis was conducted to identify the crystalline phases present in AONSA specimens with varying temperature and time during calcination. The XRD results, as illustrated in charts, reveal the crystalline composition at different AONSA content levels.

Temperature and hours of calcination

SPECIMEN A- 800℃ for 5 hours

SPECIMEN B- 500℃ for 7 hours

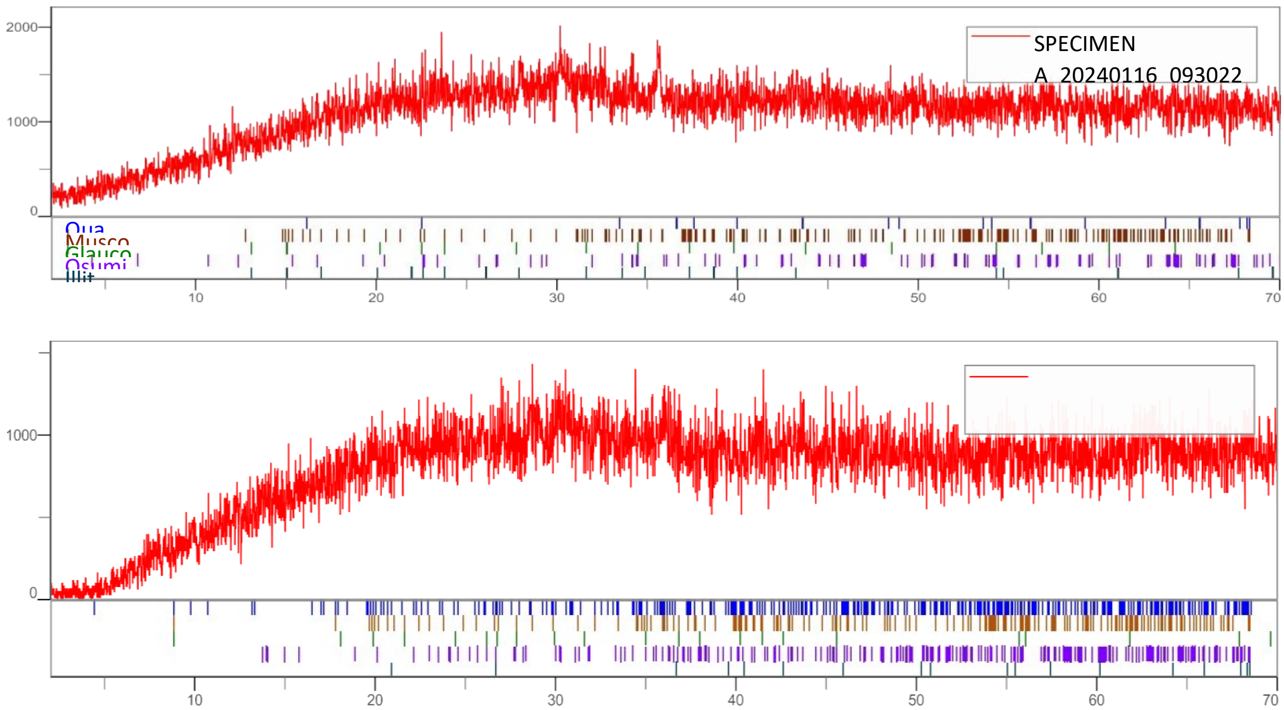

Figure 4. XRD Analysis results

Table 3 Comparisons of XRD results on both specimens

Mineral	Specimen A	Specimen B
Quartz	6.4 (2) %	24.3 (10) %
Muscovite	47.8 (9) %	21.3 (9) %
Glauconite	18.3 (6) %	29.9 (11) %
Osumilite	23.6 (7) %	0 %
Illite	3.9 (7) %	19.8 (9) %
Albite	0 %	4.7 (2) %

The XRD analysis confirms the presence of Quartz, Muscovite, Glauconite, Osumilite, Albite and Illite. This indicates the potential for the sample to serve as a pozzolan in sustainable concrete. These minerals offer opportunities for enhancing concrete properties, such as strength, durability, and sustainability, by reacting with calcium hydroxide to form additional binding phases.

XRD and XRF results

XRD analysis identified crystalline phases of cementitious materials, with potential alterations associated with AONSA. XRF results reveal changes in elemental composition, notably higher silica content in Specimen A which is more than Specimen B, corresponding to the addition of AONSA.

SEM analysis results

Scanning Electron Microscopy (SEM) was utilized to examine the microstructure of AONSA specimens. Figure 5 and Figure 6 present SEM images, providing visual insights into the impact of AONSA on the microstructure. The SEM micrographs reveal significant differences in surface morphology between samples A and B. Sample A, calcined at 800°C for 5 hours, exhibited more porous and fragmented structures with microcracks, suggesting a greater degree of thermal activation and improved reactivity. This morphology is beneficial for pozzolanic activity, as it facilitates higher surface area for reaction with calcium hydroxide. In contrast, Sample B, calcined at 500°C for 7 hours, showed relatively smoother and denser surfaces with fewer pores, indicating lower reactivity. The presence of these microstructural features supports the inference that higher calcination temperature enhances the pozzolanic potential of AONSA.

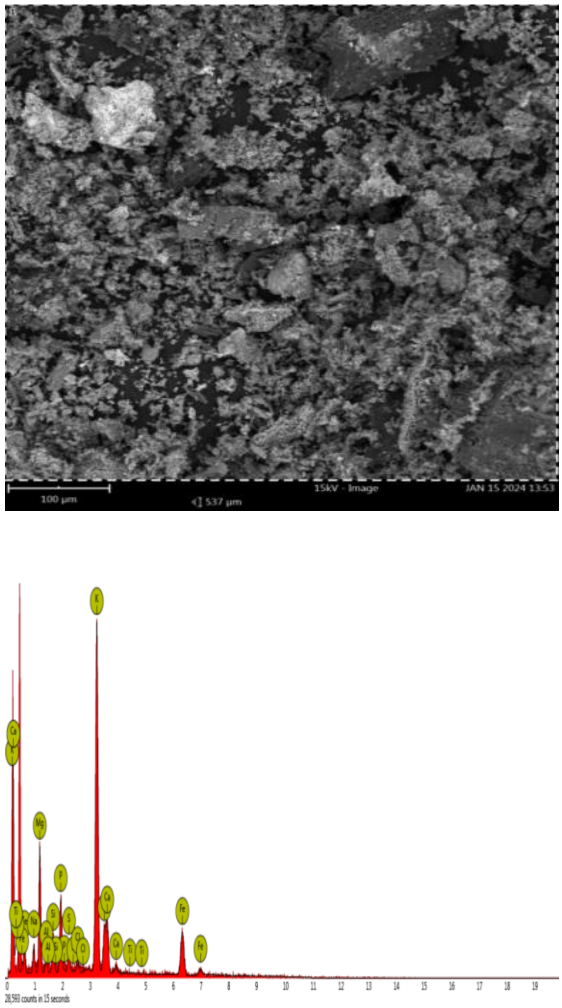

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Figure 5. SAMPLE A SEM analysis results

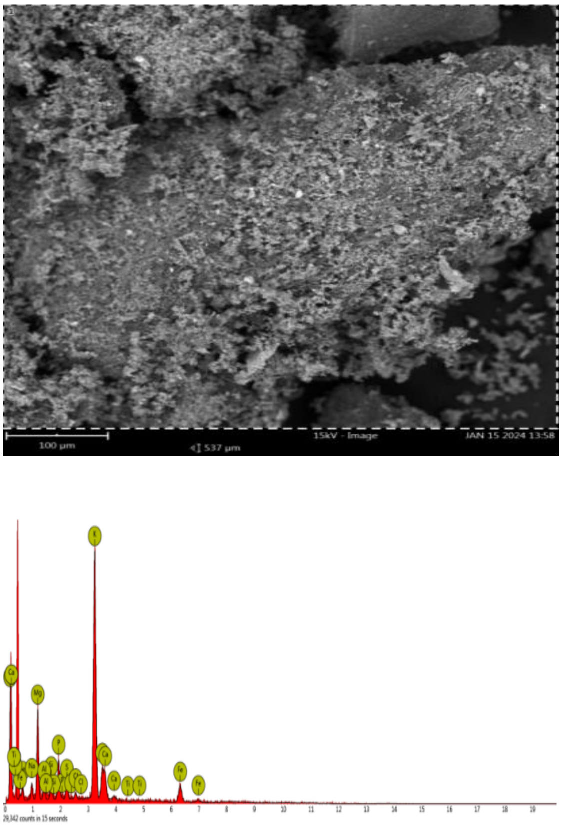

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Figure 6. SAMPLE B SEM analysis results

Table 4 presents the SEM analysis showing the atomic and weight concentrations of elements in Specimens A and B. From the results, it is evident that Potassium (K) exhibits the highest concentration in both specimens, with values increasing from 39.04% (atomic) and 42.51% (weight) in A to 45.34% and 50.63% in B, respectively. This suggests a higher retention or accumulation of potassium in Specimen B, which may influence the alkali content and potential reactivity of the matrix.

Iron (Fe) shows a notable decrease in atomic concentration from 12.24% in A to 7.28% in B, indicating possible migration or lesser incorporation in Specimen B. Similarly, Magnesium (Mg) remains relatively stable, while Calcium (Ca) slightly decreases, which might impact the hydration products and overall strength characteristics.

Silicon (Si), a key component in C-S-H gel formation, shows a modest reduction from 3.02% to 2.48% (atomic), which could suggest minor

Table 4. Microstructure changes in Specimens A & B

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.	Atomic Conc.	Weight Conc.
		SPECIMENS	**A**	**A**	**B**	**B**
19	K	Potassium	39.04	42.51	45.34	50.63
26	Fe	Iron	12.24	19.03	7.28	11.61
12	Mg	Magnesium	18.95	12.83	20.90	14.51
20	Ca	Calcium	6.81	7.60	5.93	6.78
15	P	Phosphorus	6.98	6.02	6.08	5.38
11	Na	Sodium	6.93	4.44	6.27	4.12
16	S	Sulfur	2.81	2.51	2.25	2.06
14	Si	Silicon	3.02	2.36	2.48	1.99
13	Al	Aluminium	2.04	1.54	2.46	1.90
17	Cl	Chlorine	1.18	1.17	1.01	1.03
22	Ti	Titanium	0.00	0.00	0.00	0.00

variations in the silica content influencing the microstructure densification. The low levels of Aluminium (Al) and Sulfur (S) across both specimens indicate minimal formation of ettringite or other sulfate-related phases.

According to Lima *et al*. (2009). The Anacardium occidentale nutshell ash (ARCN) exhibits low silicon content and significant potassium, magnesium, and calcium levels. Scanning electron microscopy (SEM) reveals particle size variability and lamellar structure, aiding in assessing its pozzolanic potential and interaction in cement matrices. Overall, the microstructural analysis implies that Specimen B has a slightly altered elemental distribution compared to Specimen A, potentially affecting its long-term durability and mechanical performance. The increase in potassium might enhance certain alkali-related reactions, while the reduction in iron and silica may modestly affect the matrix stability.

CONCLUSIONS

From the analysis of the obtained data it may be concluded that:

i. A small addition of AONSA (2 %) accelerates early strength gain and sustains longer-term strength
ii. Mixes M3–M6 (4–10 % AONSA) all developed lower strength at every age compared both to M2 and the control.
iii. XRD, XRF and SEM analyses revealed alterations in crystalline phases elemental composition, and microstructure, indicating potential interactions between AONSA and the cement matrix.
iv. The presence of silicate, lime, and aluminum oxides oxide in AONSA contributes to its suitability as a pozzolan.
v. The SEM analysis shows that with increase temperature at 5 hours, the atomic weight of Potassium got reduced compared to decrease in temperature at 7 hours.
vi. The partial substitution of cement with AONSA offers a sustainable alternative by reducing cement consumption, lowering CO_2 emissions, and promoting the utilization of agricultural waste.

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