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Influence of Ash from updraft co-gasified goat bones and wooden scaffold wastes on concrete performance

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Abstract
Nigeria, with an annual consumption of 360,000 tonnes of goat meat, faces significant environmental challenges due to improper disposal of abattoir waste including goat bones, leading to water pollution and foul odours. Additionally, wood waste from construction contributes to global waste management issues. This study investigates the potential use of ashes derived from goat bones and wooden scaffold waste as partial replacements for cement in concrete. The ashes were characterized for their morphology, chemical composition, and functional groups using SEM, EDS, and FTIR analyses. The hardened concrete samples were tested for compressive and split-tensile strengths at 7, 28, and 56 days to assess their mechanical performance. Results indicate that a 1:0.67 ratio of goat bone to wooden scaffold waste ash exhibited optimal pozzolanic properties. Concrete with 5–20% ash replacement showed strength gains over time with compressive strengths ranging from 38.8 to 51. 2 N/mm^2 and split-tensile strength ranging from 3.9 to 5.8 N/mm^2 aligning with the delayed strength development typical of pozzolanic materials, making it suitable for reinforced concrete applications. This study provides a sustainable solution to waste management and eco-friendly concrete production.

Keywords Cement · Concrete · Construction · Gasification · Pozzolans

1 Introduction

Concrete is a widely used building material, comprising aggregates, water, cement, and additives. Its mechanical performance, fire resistance, and cost-effectiveness have contributed to its global popularity. Cement, the bonding agent in concrete, is produced through a chemical combination of limestone, silica, alumina, and iron oxides, among other ingredients [1]. However, the growing concern over construction waste, particularly wood waste, poses significant environmental challenges. Globally, construction activities produce substantial waste, with Finland and Hong Kong generating approximately 40% of the world's construction waste [2, 3]. In the U.S., wood waste accounts for 16% of non-residential and 42% of residential building waste, often linked to temporary construction needs [4]. Similarly, Brazil's reliance on wood for formwork in concrete moulds produces considerable wood residue [5]. Addressing these challenges necessitates sustainable practices and circular economy strategies to mitigate the environmental impact of wood waste.

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In Nigeria, an estimated 360,000 tonnes of goat meat are consumed annually, representing half of West Africa's total consumption [6]. From these, 942.2 tonnes of bones are generated annually [7]. Abattoirs across the country often dump bones from slaughtered animals and waste slurry into ponds and streams, leading to environmental pollution and foul odours. This unsustainable practice poses significant health risks due to inadequate wastewater treatment facilities [8, 9]. Waste from slaughterhouses and households contributes to the broader issue of pollution, particularly in rural areas, while the demand for proper disposal sites adds stress to urban environments. Bones, a calcium-rich byproduct of animal slaughter, have potential as a substitute for cement in construction materials [10]. However, improper disposal of bones can result in pollution and the release of harmful gases, while also incurring substantial waste management costs [7, 11]. These issues underscore the need for effective waste management solutions to address both environmental and public health concerns.

Cementitious materials are produced when pozzolans, which are siliceous or alumino-siliceous materials with little to no cementitious value on their own, chemically react with alkalis and alkaline earth hydroxides at room temperature [12–14]. Previous research has demonstrated the potential of pozzolans to partially replace cement in concrete. Commonly explored pozzolanic materials include Ground Granulated Blast Furnace Slag (GGBS), ceramic wastes, fly ash, steel slag, and rice husk ash [15–17]. Waste materials such as foundry sand and recycled asphalt pavement are also integrated into construction processes.

The rising cost of cement production has intensified the search for alternative binding agents. Beyond cost concerns, this shift is also driven by the significant environmental issues associated with cement production. Cement manufacturing is a major contributor to global carbon emissions, accounting for approximately 7–8% of total CO_2 emissions worldwide. This is due to the energy-intensive calcination process and the depletion of natural limestone reserves. Additionally, the sustainability challenges posed by the continuous extraction of raw materials highlight the need for greener alternatives. The viability of substituting animal waste for cement has been studied by researchers. For instance, Adeboje et al. [18] reported that adding pulverized cow bone (PCB) to lateritic soil in increments of 2.5% up to 12.5% significantly improved the soil's California bearing ratio and unconfined compressive strength, particularly in road construction applications. Similarly, Falade et al. [19] found a substantial increase in the flexural strength of reinforced concrete when up to 20% of cement was replaced with pulverized bone (PB), with minimal impact on stiffness and deflection. Further, Ayininuola & Denloye [20] observed a significant improvement in the California Bearing Ratio (CBR) when 7% cattle bone ash (CBA) was added to soil layers in Ibadan, Nigeria. Akinyele et al. [11] demonstrated that animal bone ash outperformed wood ash as a cement substitute in concrete, yielding favorable results at a 10% replacement level.

Wood debris has been investigated in a number of studies as a potential partial substitute for cement and aggregates. Awolusi et al. [21] reported that Sawdust ash (SDA) was found to be preferable for flooring applications due to its lower water absorption and higher compressive strength, making it a suitable partial cement replacement in non-pavement concrete applications. In their 2018 study, Morales-Conde et al. [22] reported a decrease in mortar density when using wood waste from home demolition in place of some of the sand in lightweight mortar mixes. Islam et al. [23] evaluated the compressive strength of concrete with fly ash partially replacing cement and wood powder substituting fine aggregate, finding that strength decreased when wood powder replacement exceeded 5%. Similarly, Fadiel et al. [24] tested wood shavings as a partial replacement for fine aggregate in woodcrete, with a 50% substitution resulting in compressive strength below 10 MPa. Baltazar [25] and Abed & Khaleel [26] further demonstrated the potential for wood waste as a fine aggregate replacement, with Abed & Khaleel identifying a 20% replacement as optimal.

Gasification, a process that converts materials like biomass or coal into syngas, produces ash rich in reactive silica and alumina—key components of pozzolans [27, 28]. The process offers multiple benefits, including waste utilization, energy efficiency, reduced environmental impact, and consistent quality control. Ash produced through gasification exhibits high pozzolanic activity, reacting with calcium hydroxide to form cementitious compounds, thereby reducing reliance on natural pozzolan sources and lowering greenhouse gas emissions [29].

Despite the extensive research on various waste materials as partial replacements for cement and aggregates in concrete, limited studies have focused on the combined use of animal bone and wooden scaffold waste ash produced through gasification. While individual waste products such as pulverized bone and wood ash have shown potential in improving concrete properties, the synergistic effects of these materials when gasified and used together remain underexplored. This research aims to bridge this gap by investigating the effect of ashes recovered from goat bones and wooden scaffold waste on the properties of concrete. This study will contribute to the development of sustainable construction materials while addressing environmental concerns related to waste management.

Table 1 Composition of samples

Samples	Goat bones (g)	Wooden scaffold waste (g)	Peak Temperature (°C)
A1	0	1500	206
A2	300	1200	200
A3	600	900	255
A4	900	600	305
A5	1200	300	209
A6	1500	0	254

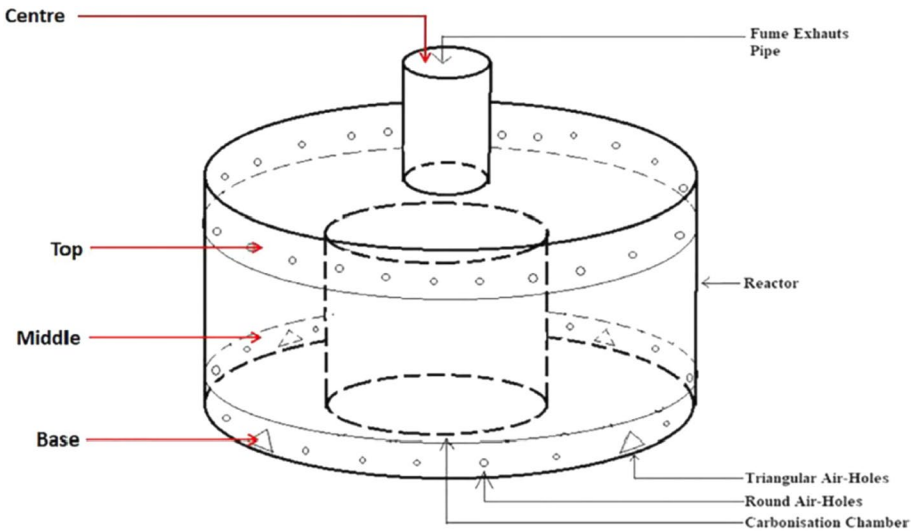


Fig. 1 Diagram of the gasification reactor [36]

2 Materials and method

The materials utilized in this study include BUA brand of Portland Limestone Cement conforming to Nigerian standards NIS 444–1: 2003 [30] and BS EN 197–1:2011 [31]. Fine aggregates were sourced from Asa River, Ilorin, passing through a 4.75 mm sieve and meeting ACI Committee 363 [32] standards. Coarse aggregates (granite), 12 mm in size, were bought from Ramsat Marble and Granites, Ilorin, and were angular and dust-free. Potable water used in the mixes conformed to BS EN 12620 [33]. The goat bones used in this study were obtained from Kwara Central Abattoir in Ilorin and were sun-dried before the gasification process.

The goat bones and wooden scaffold waste were combined in varying fractions as shown in Table 1 to determine the yield and the composition that would produce the best pozzolanic properties. Both biomasses (goat bones and wooden scaffold waste) were gasified using a reactor whose 2-D image is shown in Fig. 1 at the Laboratory of the Department of Chemical Engineering, University of Ilorin, Nigeria. The temperatures of the reactor were taken at the centre, top, middle and base to determine its average temperature (see Table 1) at which the gasification took place. The peak temperature of 305 ^{0}C is lower than the temperature used for calcination of most pozzolans found in literature which ranges from 450 to 800 ^{0}C [12, 34, 35]. After gasification, the ash was cooled in ambient air for 4 h until it reached approximately room temperature (25–30 °C). The cooled ash was then milled using a ball mill at 200 rpm with a 10:1 ball-to-powder ratio, ensuring the particles were finely ground. Following milling, the ash was sieved using a 90-micron sieve to remove larger particles and ensure uniformity. The processed ash was subsequently stored in airtight containers in a cool, dry environment to preserve its pozzolanic properties and prevent contamination as shown in Fig. 2 before determining their moisture content, chemical composition, microstructure and functional groups.

The moisture content of the ashes were determined following the procedure outlined in BS 812–109 [37].



Fig. 2 Ashes recovered from the gasification process

Energy Dispersive X-ray Spectroscopy (EDS) and Scanning Electron Microscopy (SEM) studies were performed on the ashes to determine their chemical composition and micros-structure following the guide outlined in ASTM E1508 [38] at the Integrated Research Laboratories, Ibadan, Oyo State. The test procedure involved fixing the samples to SEM stubs using conductive tape, handled with tweezers to avoid contamination, and coated with a thin conductive layer, such as gold or carbon, using a sputter coater to prevent charging effects during imaging. The coated samples were loaded into the SEM chamber under a high vacuum, and imaging parameters such as accelerating voltage, working distance, and aperture size were optimized. The SEM was used to capture high-resolution images of the samples' surface morphology at various magnifications, while Energy Dispersive X-ray Spectroscopy (EDS) was performed for elemental analysis. Observations were documented ensuring safety protocols were strictly adhered to.

The Fourier Transform Infrared (FTIR) spectroscopy test was used to determine the functional groups of the ashes. The ashes were subjected to microwave digestion with aqua regia to dissolve the metals in them. The digested solutions were diluted and analyzed using a PerkinElmer Optima 8000 ICP-OES instrument, which measured the light emitted by excited elements to quantify their concentrations. Calibration with standard solutions ensured accuracy. This test was conducted at the Integrated Research Laboratories, Ibadan, Oyo State.

The cement used for the study met the specifications in Nigerian standards NIS 444–1: 2003 [30] and BS EN 196–3 [39]. It had a specific gravity of 2.8, an initial setting time of 48 min, a final setting time of 510 min, a fineness of 6.5%, and a standard consistency of 31%.

The fine aggregate had a fineness modulus of 3.3, a specific gravity of 2.58, a water absorption rate of 2.5%, and a bulk density of 1.50 g/cm3. The coarse aggregate had a fineness modulus of 6.7, a specific gravity of 2.61, and a water absorption rate of 1.4%. All these properties met the requirements specified in BS EN 12620 [33] of fineness modulus, specific gravity, water absorption and bulk density for fine aggregates ranging from 2.2 – 3.3, 2.39 – 2.80, less than 3% and 1.45 – 1.7 g/cm^3 respectively and fineness modulus, specific gravity and water absorption for coarse aggregates ranging from 6.5 and 8.0, 2.5—3.0 and 1–2% respectively.

A mix ratio of 1:2:4 and a water-binder ratio of 0.6 (which gave a workable consistency) were adopted for the concrete samples. The fresh concrete was tested for its slump before casting into cube moulds measuring 100 mm × 100 mm × 100 mm and cylindrical moulds measuring 100 mm × 200 at the Civil Engineering Department Laboratory of the University of Ilorin. Cement was partially replaced with the ashes with the highest pozzolanic properties at 5%, 10%, 15%, and 20%. A total of 45 cubes and and 45 cylinders were cast for the investigation.

The samples were cured for a maximum of 56 days and tested for their compressive and split-tensile strengths in accordance with BS EN 12390–3 [40] and BS EN 12390–6 [41] respectively using a Haida Universal Testing Machine (UTM) of 1560 kN capacity.

3 Result and discussions

3.1 Elemental and oxide composition, yield and moisture content of samples

Figure 3 shows the EDX images for the elemental composition of samples A1 to A6. The EDX analysis of these samples highlights variations in elemental composition, which play a crucial role in their reactivity and suitability as pozzolanic materials. Sample A1 contains moderate levels of Si and Fe. A2, A3, A5 and A6 however, do not contain silicon, which is a basic component of pozzolan. The high concentration of Si and Fe in A4 aligns with its superior performance in promoting pozzolanic reactions, as they contribute to the formation of cementitious compounds in concrete. The dominance of silica in A4, coupled with balanced proportions of iron, confirms its superior reactivity and suitability for partial cement replacement.

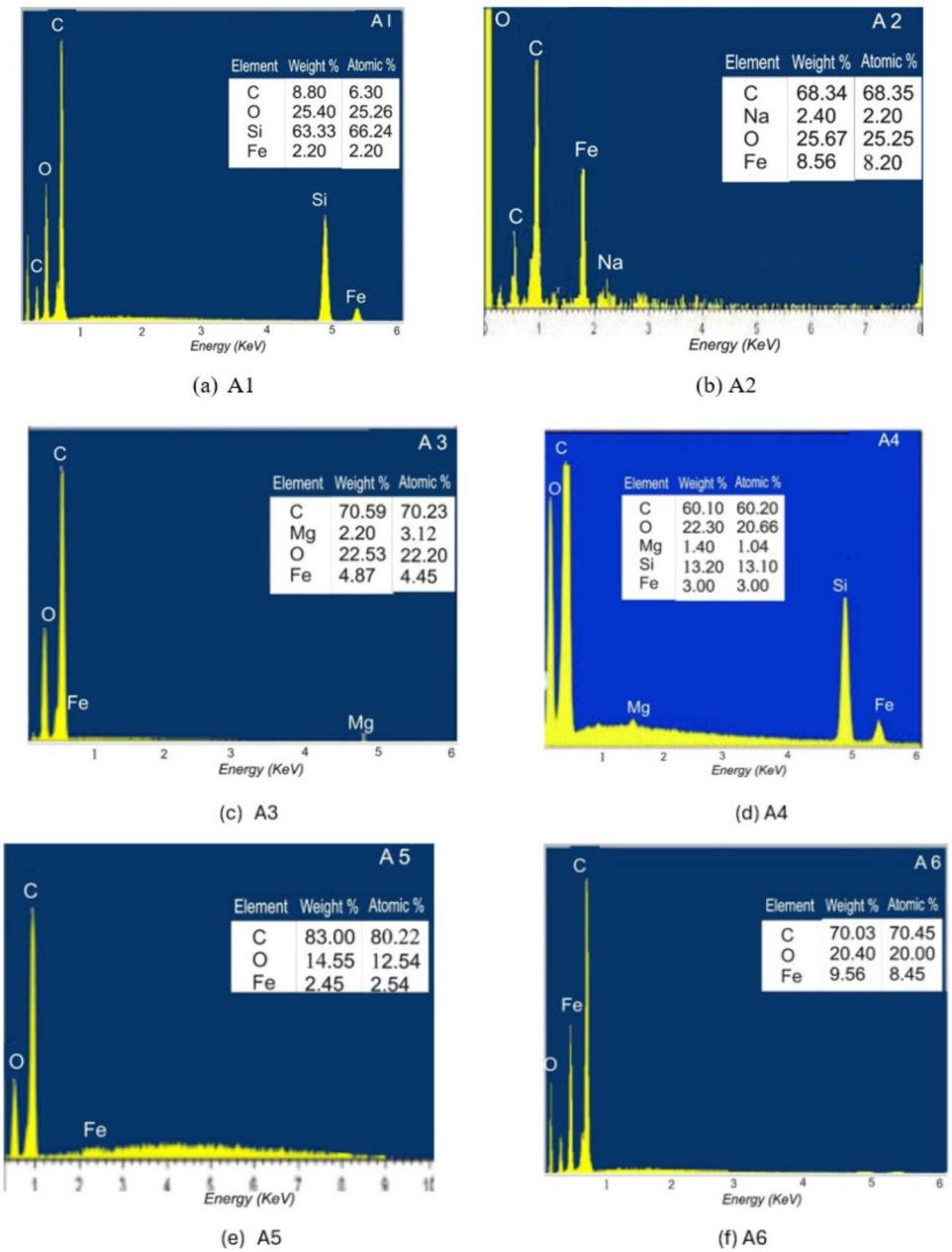


Fig. 3 EDX images of ashes **a** A1, **b** A2, **c** A3, **d** A4, **e** A5, **f** A6

Table 2 shows the yield, oxide composition and moisture content of samples A1 to A6. It was discovered that the yield increased as the bone content in the mix increased. Based on the specification in ASTM C618 [42], Sample A4 has the highest percentage combination of silicon dioxide (SiO_2), Aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3) and the lowest moisture content and can be classified as a Class N pozzolan. This shows that the ratio of goat bone to wooden scaffold waste used in A4 likely provided an ideal mix of calcium-rich and silicate-rich materials. Also, the reduced proportion of wooden scaffold waste—known to be more organic and porous—minimizes the retention of moisture. This balance effectively decreases the overall hygroscopic nature of the ash, contributing to A4's significantly lower moisture content. Consequently, Sample A4 was selected as the ash combination to substitute cement in the concrete samples utilized in this research.

3.2 Sample morphology

SEM micrographs of the ashes are presented in Figs. 4(a)–(f). The particle sizes and morphologies are clearly observed in these images. The particle sizes are described in terms of their working distance (WD) in millimeters (mm), which represents the distance between the sample surface and the electron gun (or the objective lens) of the SEM instrument. Smaller WDs are typically used to image smaller particles, while larger WDs are employed for bigger particles [43]. At a magnification of 9000 × and an accelerating voltage of 15 kV, A1, A2, A4, and A6 exhibit smaller particle sizes with a WD of 15 mm, whereas A3 and A5 display larger particles with a WD of 18 mm.

Regarding morphology, A1 shows relatively coarse particles with a smooth surface and low porosity, limiting its reactive potential by providing fewer active sites for pozzolanic reactions. A2, with a rougher and more irregular surface texture, offers increased surface area and more nucleation sites for hydration reactions, promoting the formation of calcium silicate hydrate (C-S–H). However, its lower $SiO_2 + Al_2O_3 + Fe_2O_3$ content (79.1%) and higher moisture content (5.75%) reduce its reactivity, making it less optimal. A3 has larger particles (18 mm) than A1, A2, A4 and A6, with a $SiO_2 + Al_2O_3 + Fe_2O_3$ content of 65.62% and a higher moisture content of 4.1%, further limiting its pozzolanic potential. In contrast, A4 exhibits finely textured, angular, and highly porous particles with the summation of SiO_2, Al_2O_3 and Fe_2O_3 content exceeding 70% (93.34%) and a very low moisture content (0.5%), making it the most suitable ash for concrete applications due to its superior surface morphology and chemical composition.

A5, with a particle size of 18 mm, shows a mix of coarse and fine particles with irregular surface features, but its $SiO_2 + Al_2O_3 + Fe_2O_3$ content is extremely low (3.5%), indicating limited chemical reactivity. Its high moisture content (5.68%) further decreases its suitability as a pozzolan. Similarly, A6 presents a heterogeneous surface morphology with smooth and porous particles. However, its low $SiO_2 + Al_2O_3 + Fe_2O_3$ content (13.67%) and high moisture content (5.87%) limit its reactivity and bonding potential in concrete. Overall, A5 and A6 are less suitable for cement replacement due to their poor chemical composition and surface characteristics.

3.3 Ashes functional groups

Figure 5(a–f) shows the FTIR spectra for samples A1 to A6 respectively, highlighting various functional groups and their corresponding peak values while Table 3 shows the Infrared Spectral Assignment.

The FTIR spectrum of A1 shows a broad and weak peak at 1080–1100 cm^{-1}, corresponding to Si–O stretching vibrations, indicating a trace appearance of silicates. However, this silicon-oxygen bond was not detected by the EDX spectrum where it shows a 0% weight abundance. This shows that the trace silica content is insufficient for the

Table 2 Yield, oxide composition and moisture content of ashes (%)

Sample	Yield	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	MgO	% of $SiO_2 + Al_2O_3 + Fe_2O_3$	Moisture Content
A1	13.53	97.7	0	2.3	0	0	100	5.25
A2	14.67	0	0	79.1	20.9	0	79.1	5.75
A3	28.7	0	0	65.62	0	34.38	65.62	4.1
A4	55.53	81.03	0	12.31	0	6.66	93.34	0.5
A5	56.87	0	0	3.5	0	0	3.5	5.68
A6	91.73	0	0	13.67	0	0	13.67	5.87

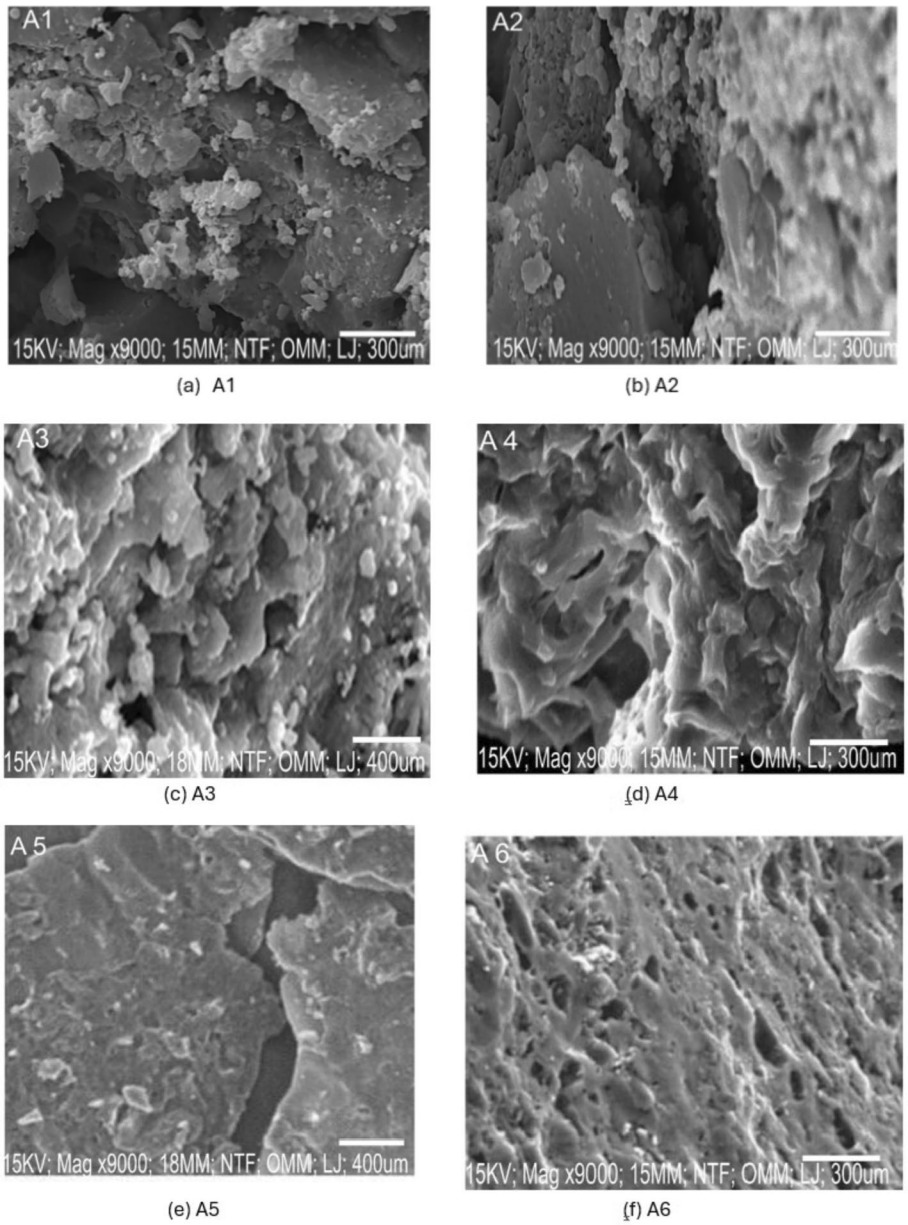


Fig. 4 SEM images of ashes **a** A1, **b** A2, **c** A3, **d** A4, **e** A5, **f** A6

pozzolanic effect required by the material. This also aligns with its coarse particle morphology and higher moisture content, limiting its efficiency in concrete.

A2 displays a sharp and strongly intense peak at 1625 cm^{-1} characteristic of C-O stretching vibrations, suggesting the presence of carbonates. There is also a noticeable peak at 3600–3200 cm^{-1}, which might indicate the presence of water molecules in the sample, showing that it is not absolutely dry. However, since there is no characteristic peak for the presence of Si–O bond, A2 is observed to be less suitable as a pozzolan.

The FTIR spectrum for A3 shows a sharp and strong peak at 1100—800 cm^{-1} indicative of Si–O stretching. This aligns with the EDX spectra that the sample contains silica necessary for pozzolans. The presence of a broad and strong peak at 1400 also aligns with the results of EDX that the sample contains carbon while the presence of adsorbed water molecules was observed at 3400 cm^{-1}.

A4 exhibits similar FTIR spectra assignment as A3 with a sharp and strong peak at 900 cm^{-1} for Si–O stretching, a broad and strong peak at 1400 cm^{-1} for the presence of C-O bonding as well as a broad and weak band at 3300 cm^{-1} indicative of the presence of water molecules. However, a slight decrease in the intensity of the band at 3300 is observed as compared to that of A3 showing that A4 contains less adsorbed water molecules than A3. This

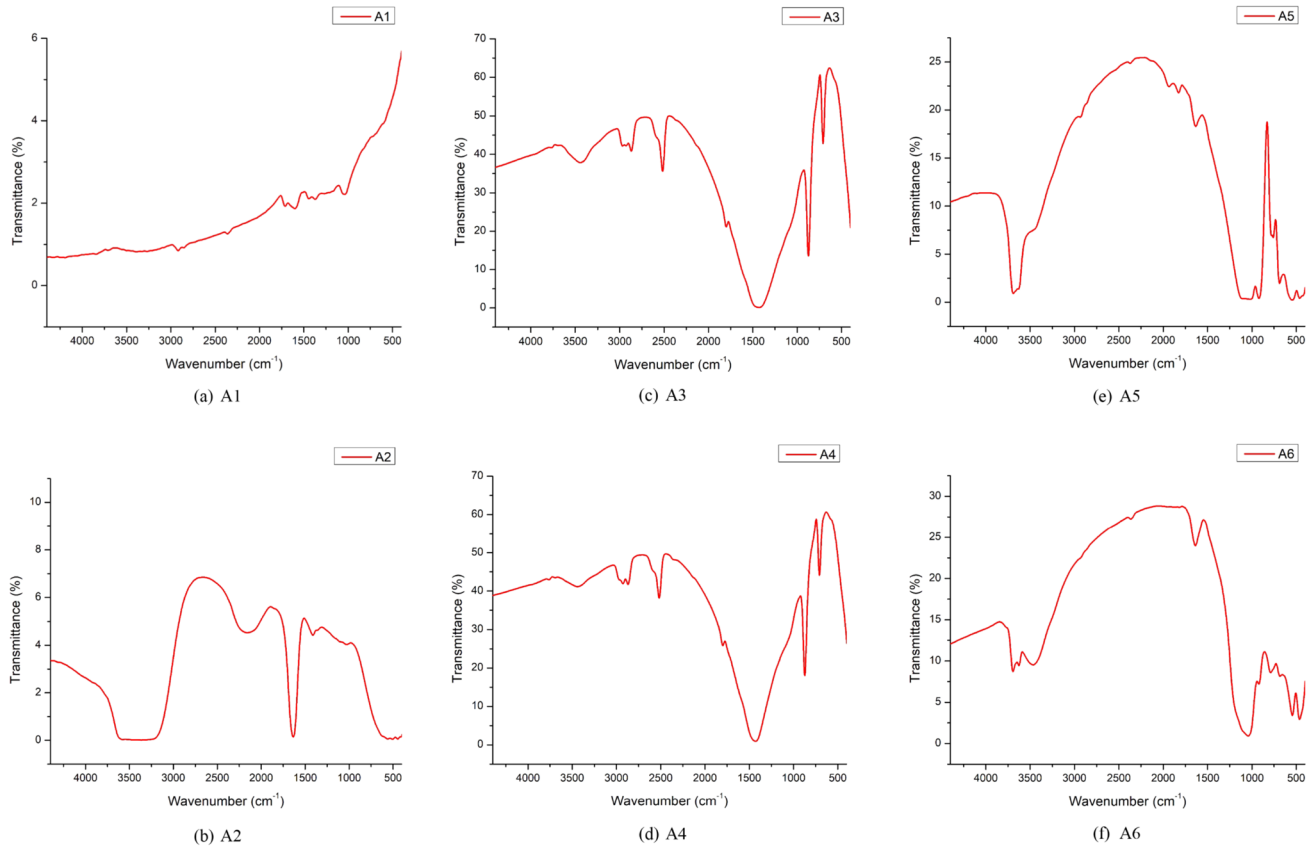


Fig. 5 FTIR Images **a** A1, **b** A2, **c** A3, **d** A4, **e** A5, **f** A6

Table 3 Infrared spectral assignment

Samples	Vibration bands		
	$\bar{\upsilon}$(O–H) str 3600–3200 cm^{-1}	$\bar{\upsilon}$(C-O) 1600–1400 cm^{-1}	$\bar{\upsilon}$(Si–O-Si) 1100–800 cm^{-1}
A1	–	1550 b, w	1020 b,w
A2	3600–3200 b, s	1625 sh, s	–
A3	3400 b, w	1400 b, s	875 sh, s
A4	3300 b, w	1400 b, s	900 sh, s
A5	3600 sh, s	1500 sh, w	900 sh, w
A6	3400 b, s	1550 sh, w	1020 b, s

Where *b* broad, *sh* sharp, *w* weak, *s* strong

is evidenced in the moisture content calculations and suggests that A4 is drier. A good property necessary for pozzolanic effect is dryness and this is observed with A4.

A5 shows a weak Si–O stretching peak at 900 cm^{-1} as compared to the same but sharp peak of A4. This suggests that the silica content of A5 is so minute that it cannot constitute its pozzolanic strength. The peak at 3600 shows the presence of moisture which dilutes its pozzolanic potential.

The FTIR spectrum of A6 shows a very broad and sharp peak for Si–O stretching at 1020 cm^{-1} indicating minimal reactive silica content. The spectrum also shows distinct peaks at 1550 cm^{-1} representing carbonate presence and peak at 3400 cm^{-1} representing presence of moisture, which further reduces its reactivity.

The FTIR results demonstrate that A4 has the strongest and most well-defined peaks for Si–O, confirming its high content of reactive silica and less water content.

3.4 Effect of sample A4 on workability

The slump heights for the various replacements of cement with A4 at 0, 5, 10, 15, and 20% are 40, 31, 23, 12, and 8 mm, respectively. The reduction in slump height from 40 mm (0% replacement) to 8 mm (20% replacement) reflects a significant decrease in workability as the percentage of A4 ash increases. This trend is attributed to the physical properties of the ash particles, such as their angularity and high surface area, which create higher internal friction within the concrete mix. The porous nature of A4 also increases water demand, as the particles absorb more water compared to cement, reducing the amount available for lubrication and flow. Consequently, mixes with higher A4 content become stiffer and harder to handle, particularly in applications requiring high flowability.

This reduction in workability aligns with observations from studies on pozzolanic materials like guinea corn husk ash and silica fume, which report similar trends due to increased water absorption and particle friction [44–47]. The low slump values at higher replacement levels highlight the need for adjustments in mix design, such as incorporating superplasticizers or water-reducing agents to enhance flowability without altering the water-cement ratio. Ensuring a balance between workability and strength is critical, particularly for practical applications like reinforced concrete, where sufficient flow is essential for proper placement and compaction.

3.5 Compressive strength

Figure 6 displays the compressive strength results for the concrete samples containing A4 as a partial replacement for cement from 0 to 20%. At 7 days, the control mix (with no ash) had the highest strength (16.8 N/mm^2), which gradually decreased as more ash was added, down to 8.5 N/mm^2 at 20%. Similar patterns were observed at 28 and 56 days, where compressive strength was highest for the control (23.1 N/mm^2 and 53.2 N/mm^2, respectively) and decreased as ash content increased. Remarkably, the 56-day results indicate that even at 20% replacement, the concrete achieves a reasonable strength of 38.79 N/mm^2, reflecting the long-term reactivity of A4 ash. This observation is in line with the research by Odeyemi et al. [48] which found that for all curing days taken into consideration, the compressive strength of concrete decreased as the percentage of combined maize straw and palm oil fuel ashes increased. The 56th-day strength of the concrete samples shows that all the levels of incorporation of the ash are suitable for constructing reinforced concrete structural members [49].

The observed decrease in compressive strength with the addition of ashes as partial replacements for cement can be attributed to factors including particle packing, pozzolanic activity, and microstructural changes. Ashes, particularly at higher replacement levels, may disrupt particle packing, leading to increased voids and reduced density in the concrete matrix. Poor compatibility of particle size and shape can further weaken inter-particle bonds. Additionally, replacing cement with ash reduces the immediate availability of cementitious materials, resulting in a slower formation of calcium silicate hydrate (C-S–H), the primary strength-giving compound. Pozzolanic reactions of ashes, while beneficial in the long term, are delayed compared to the rapid hydration of cement, thereby contributing to lower early-age compressive strength.

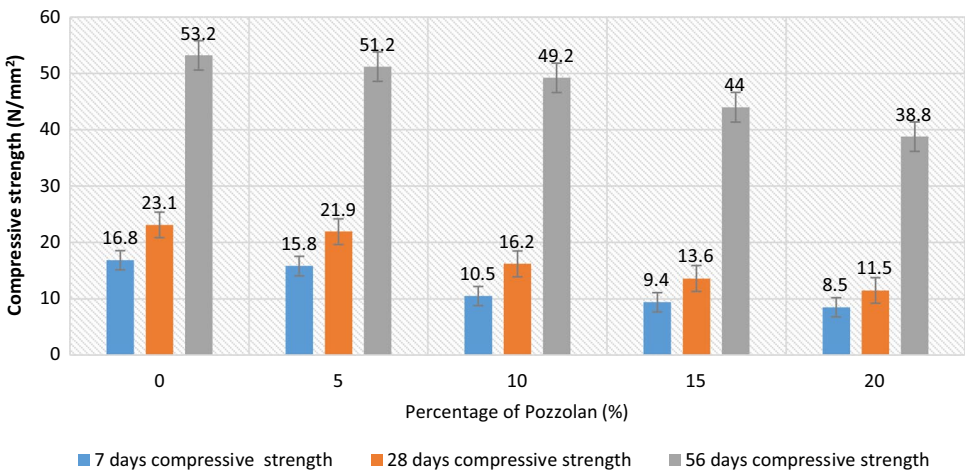


Fig. 6 Compressive strength results

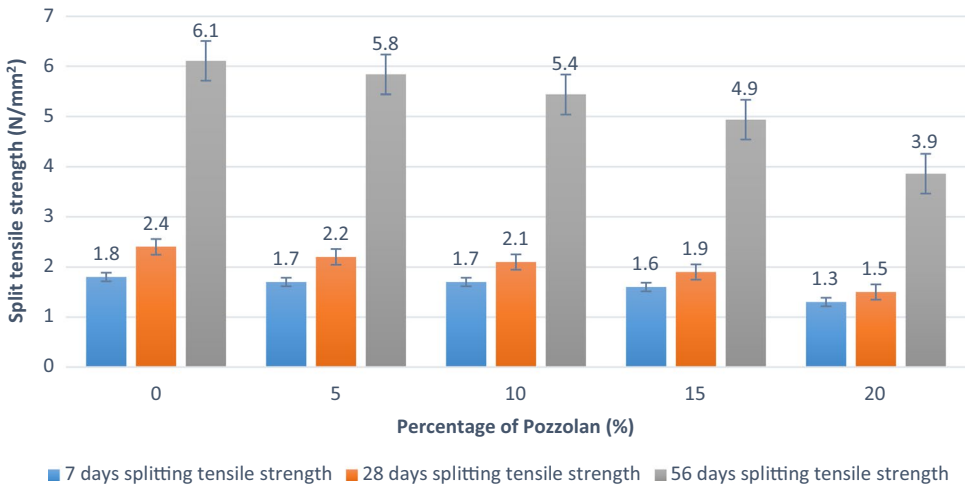


Fig. 7 Split tensile strength result

3.6 Split-tensile strength

The results for the split-tensile strength of the concrete samples containing A4 as a partial replacement for cement, shown in Fig. 7, reveal similar trends to those observed in the compressive strength results. At 7 days, the split-tensile strength starts at 1.8 N/mm^2 for the control (0% replacement) and gradually decreases with increasing ash content, reaching 1.3 N/mm^2 at 20% replacement. At 28 days, the control mix exhibits 2.4 N/mm^2, while 20% replacement shows 1.5 N/mm^2. By 56 days, the split-tensile strength peaks at 6.11 N/mm^2 for the control mix, with the 20% replacement achieving 3.86 N/mm^2. This trend highlights the long-term pozzolanic activity of A4, which contributes to the gradual development of strength over time. This outcome is also similar to the findings of Odeyemi et al. [50].

The results demonstrate that while the early-age strength is lower at higher replacement percentages, the concrete gains significant strength at later ages, as is typical for pozzolanic materials. This behavior aligns with established literature [48, 51–53], which highlights the delayed but substantial strength development in concrete containing pozzolans due to the prolonged pozzolanic reaction and the gradual formation of calcium silicate hydrate (C-S–H). Such long-term strength improvements make A4 suitable for reinforced concrete applications.

4 Conclusions

This study led to the following conclusions:

1. The recovered pozzolans from goat bones and wooden scaffold waste exhibit varying oxide content of silica, Alumina, Sodium and Magnesium. Physically, the samples show a range of textures and structures, from rough and irregular particles to honeycomb-like and porous structures.
2. Ashes containing a ratio of 1:0.67 goat bone to wooden scaffold waste offered the optimal pozzolanic properties.
3. Within the scope of this research, all replacement levels (5–20%) were shown to achieve satisfactory compressive and split-tensile strengths at advanced ages, making them suitable for reinforced concrete applications under similar experimental conditions.

5 Recommendation

1. Further investigations beyond 20% replacement are recommended to fully establish the limits of pozzolan incorporation and its suitability for diverse structural applications.

Authors contribution S.O. and A.G. developed the concept for the work while R.T. and O.T. did the laboratory work. S.O. wrote the manuscript and all the authors reviewed it.

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Data availability The data used in this study are presented in Tables 1 and 2 and Figs. 3, 4, 5, and 6. No other datasets were generated or analyzed in the study.

Declarations

Ethics approval and consent to participate This research was conducted in compliance with ethical standards. The protocol was approved by the Kwara State University Faculty of Engineering and Technology Ethical Committee in accordance with the Nigerian Code of Health Research Ethics (NCHRE).

Competing interest The authors declare no competing interests.

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