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ORIGINAL ARTICLE

Pozzolanic Potential of Ash from Updraft Co-Gasified Cow Horns and Bamboo in Concrete

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Abstract

The construction industry's reliance on traditional cement-based concrete has raised concerns about escalating production costs and substantial carbon emissions. To mitigate these challenges and promote sustainable construction, it is essential to find alternative Supplementary Cementitious Materials (SCMs) that can be utilised in concrete to partially replace cement. This study investigates the potential of ashes derived from cow horns and bamboo, gasified in an updraft reactor, and evaluates their impact on the mechanical properties of concrete. Cement conforming to NIS 444–1:2003 and EN 197–1:2011 was mixed with both coarse and fine aggregates at a mix ratio of 1:2:4 and a water-binder ratio of 0.6. Ash samples were sieved through a 90 µm mesh and characterised using SEM and FTIR, before being used as a partial replacement for cement. The concrete strength was evaluated using compressive and split-tensile strength tests at 7-, 28-, and 56-days following BS EN 12390 standards. SEM and FTIR analyses revealed diverse microstructural features, including spongy, porous, flaky, and granular textures, which enhance the binding properties and reactivity of the ashes. The optimal ratio of 1:0.67 cow horn to bamboo ash demonstrated superior pozzolanic properties. Concrete containing up to 15% of this pozzolan as a partial cement replacement exhibited significant strength development over time. By the 56th day, the concrete achieved compressive and split-tensile strengths of 43.07 MPa and 6.07 MPa, respectively, at 56 days, demonstrating suitability for reinforced concrete applications. These findings suggest that cow horn and bamboo ash could serve as a viable SCM for sustainable construction, reducing cement consumption while maintaining concrete performance.

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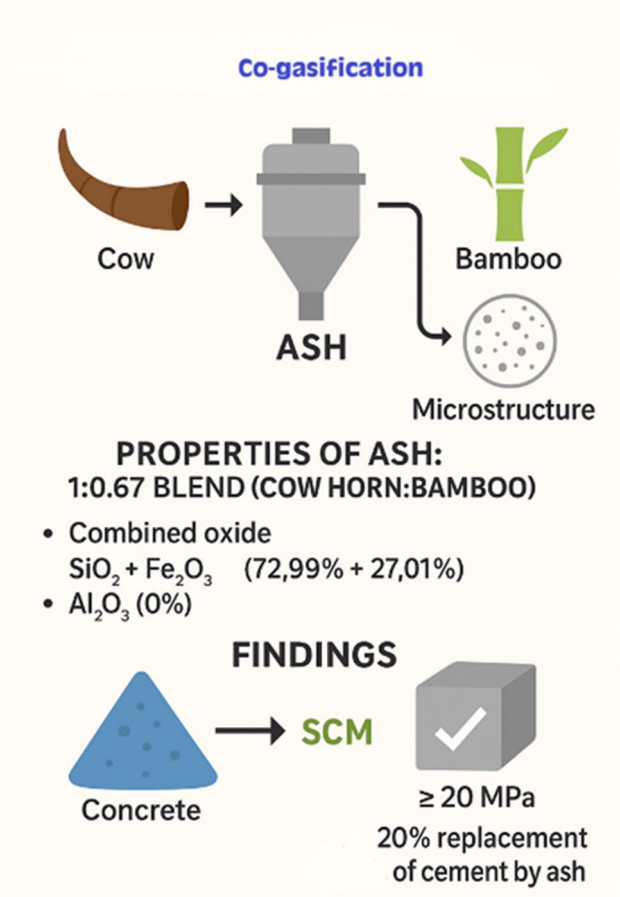
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Graphical Abstract



Keywords Bamboo · Cement · Concrete · Horn · Gasification

1 Introduction

Concrete is one of the most widely used materials in construction due to its high compressive strength and structural reliability [1]. However, the rising cost of cement, particularly in developing countries, has led to an increase in construction expenses, creating challenges in the affordability of public and private infrastructure projects. For instance, in Nigeria, the price of a 50 kg bag of cement rose by over 70% between 2020 and 2024, driven by inflation, increased energy costs, and disruptions in supply chains [2]. This price volatility directly affects large-scale infrastructure development, where cement can account for up to 40% of total construction costs. Consequently, Nigeria's estimated $1.5 trillion infrastructure investment requirement over the next decade is further strained by these escalating material costs [3]. Moreover, the environmental impact of cement production is becoming an increasingly urgent concern. The energy-intensive cement manufacturing process is responsible for roughly 5–6% of the world's CO_2 emissions, which have been reported to range from 0.657 to 0.76 tons per ton of cement produced [4–6]. As a result, the search for sustainable alternatives to traditional cement is critical [7, 8].

A key area of interest in sustainable construction is the development of supplementary cementitious materials (SCMs) that can partially replace cement in concrete mixtures. SCMs help reduce cement consumption, thereby lowering costs and decreasing the carbon footprint associated with cement production [9]. Research has shown that materials derived from industrial and agricultural waste can be effective SCMs, contributing to both environmental sustainability and improved concrete performance [10, 11]. Though SCMs derived from agricultural wastes offer environmental and economic benefits in concrete production, their adoption faces challenges [12]. The variability in chemical composition of agricultural ashes, influenced by feedstock source and processing methods, affects their

pozzolanic reactivity and concrete performance consistency [13]. They often exhibit slower early strength development compared to Portland cement, potentially limiting their use in rapid-strength applications [14]. Additional processing requirements may introduce extra costs or energy demands [13]. Furthermore, changes in setting time, water demand, and admixture compatibility must be addressed through proper mix design [14]. Despite these challenges, SCMs from agricultural wastes show promise in enhancing concrete properties and reducing carbon emissions, particularly as alternatives to conventional SCMs like fly ash, which face supply uncertainties [13].

This study explores the potential of pozzolanic ash obtained from co-gasifying cow horns and bamboo in an updraft gasifier as an SCM, aiming to address both economic and environmental challenges in the construction industry [15].

Gasification is a thermochemical process that transforms carbon-based materials into syngas, a mixture of gases that can be used as fuel [16]. This process involves subjecting materials to high temperatures in a low-oxygen environment, preventing complete combustion. However, unlike conventional cement production, which emits up to 0.76 tons of CO_2 per ton of cement, the gasification process operates at a lower temperature and primarily utilises waste biomass, resulting in significantly lower direct carbon emissions. The syngas produced primarily consists of nitrogen (N_2), carbon monoxide (CO), hydrogen (H_2), and carbon dioxide (CO_2), and can be used for energy generation [17]. Gasification is noted for its efficiency, as it extracts more energy from feedstock than traditional combustion methods [18]. In addition to energy generation, gasification also produces a solid by-product, ash, that retains residual inorganic minerals from the feedstock. Unlike conventional calcination or incineration, which operate at higher temperatures (typically above 500 °C) and may alter the mineral phases of biomass, gasification, particularly at moderate temperatures, can preserve amorphous silica and other reactive compounds beneficial for pozzolanic activity. This makes gasification a promising alternative for producing SCMs from organic and agricultural waste. One by-product of gasification is ash, which may contain pozzolanic properties, making it suitable for use as an SCM [19].

Recent studies have demonstrated that agricultural waste ashes (AWA) can serve as effective pozzolanic materials for partial cement replacement in concrete. Rice husk ash (RHA), coconut husk ash (CHA), and other AWAs contain reactive silica and alumina, which contribute to concrete strength and durability [20, 21]. The pozzolanic activity of these ashes depends on calcination temperature, duration, and fineness [22]. Optimal calcination temperatures range from 300 °C to 800 °C, with 600 °C showing favourable results for various ashes [22]. RHA can potentially replace 10–20% of cement without compromising concrete performance [23]. Incorporating AWAs in concrete can improve workability, mechanical properties, and durability while reducing environmental impact [21, 23]. However, proper processing, including controlled combustion and grinding, is crucial to achieve optimal pozzolanic properties and concrete performance [23].

Pozzolans are materials that, while not cementitious on their own, react with calcium hydroxide in the presence of water to form compounds with cement-like properties [24]. Bamboo, a fast-growing and renewable resource, has been widely studied for its potential in sustainable construction. It reaches maturity in just four to five years and can be harvested continuously, offering long-term viability as a construction material [25, 26]. Similarly, cow horns, composed of keratin and bone, are an abundant waste product in many agricultural regions [27]. Research has begun to explore the potential of agricultural waste products like bamboo and animal by-products as pozzolans in concrete mixtures [28, 29].

Recent studies have demonstrated the potential of Bamboo Leaf Ash (BLA) as a supplementary cementitious material in high-performance concrete. BLA, rich in amorphous silica, exhibits high pozzolanic reactivity when calcined at temperatures around 500–700 °C [30–32]. Partial replacement of cement with BLA (up to 15%) can improve compressive strength, durability, and microstructural properties of concrete [31, 33]. Notably, concrete with 5% BLA replacement showed optimal strength at 56 days of curing and enhanced grain interlocking [30]. BLA-blended cement concrete also demonstrates increased resistance to sulphate attack, with strength improvements observed in various sulphate environments [11].

Similarly, studies have shown that cow bone ash (CBA) can be successfully deployed as a partial cement replacement in concrete, improving its properties. CBA contains high levels of calcium oxide, making it suitable as a supplementary cementitious material [34, 35]. Concrete with 10% CBA replacement demonstrated increased compressive strength, enhanced durability, and improved microstructure compared to control specimens [36]. The addition of CBA resulted in denser concrete with lower porosity, particularly at the transition zone, leading to better resistance against water ingress and alkali-silica reaction [37]. However, CBA content above 10% generally led to decreased compressive strength [35, 36]. CBA-blended concrete also showed improved resistance to aggressive environments, particularly hydrochloric acid [34].

These findings suggest that BLA and CBA can be effective, eco-friendly alternatives in concrete production, potentially reducing environmental impacts associated with cement manufacturing while maintaining or improving concrete performance. However, the synergistic effect

of blending BLA and CBA with cement is yet to be fully explored, particularly in terms of how their combined silica- and calcium-rich compositions might influence pozzolanic reactions and strength development over time.

Also, despite the growing body of research on waste-based SCMs, the potential of ash derived from co-gasified cow horns and bamboo has not been studied in terms of its pozzolanic reactivity, microstructure, or mechanical performance in concrete applications. For example, Chen et al. [38], Nicoara et. al [39] and Ahmed et al. [13] provided a broad review of sustainable materials derived from waste but focused primarily on well-established SCMs such as fly ash, rice husk ash, and biomass combustion residues, with little to no reference to animal-based waste or hybrid biomass gasification. This study addresses this gap by investigating the pozzolanic properties of ash recovered from an updraft gasifier using cow horns and bamboo as feedstock. The research assessed the mechanical performance of concrete containing this ash as a partial cement replacement, focusing on its compressive and split-tensile strengths as an SCM.

It is hypothesised that incorporating ash from updraft co-gasified cow horns and bamboo will influence the mechanical properties of concrete. The strength is expected to improve with curing age due to pozzolanic reactivity, and an optimal cow horn to bamboo ratio exists that can yield structural-grade concrete even at up to 20% replacement.

By exploring this novel material, the study aims to contribute to the reduction of cement usage, lowering construction costs, and minimising the environmental footprint of concrete production [40].

2 Materials and Methods

2.1 Materials

BUA Portland Limestone Cement was used as the binder in this study. It conformed to the Nigerian Industrial Standard NIS 444–1:2003 [41] and EN 197–1:2011 [42]. Fine aggregates were sourced from the Asa River in Ilorin, passed through a 4.75 mm sieve, and met the specifications of BS EN 12620 [43]. Coarse aggregates comprised 12 mm granite obtained from Kam Quarry and Mines Ventures, Ilorin, also conforming to BS EN 12620 [43]. Potable water used in all mixes complied with BS EN 1008:2002 [44]. Cow horns, obtained from Kwara central abattoirs, were cleaned, dried, ground, and used for this study. Bamboo wastes were collected from local wood merchants in Kwara State, Nigeria, sorted, chipped, dried, and stored for the gasification process.

2.2 Methods

Cow horn and bamboo were blended in different proportions, as shown in Table 1, to evaluate the yield and identify the most effective composition for pozzolanic performance. The combined biomass samples were gasified in a reactor (2-D image shown in Fig. 1) at the Department of Chemical Engineering Laboratory, University of Ilorin, Nigeria.

The gasification process began by preparing the biomass feedstock, cow horns and bamboo, which were cleaned, dried, and weighed in predetermined proportions. These materials were then fed into an updraft fixed-bed gasification reactor. In this configuration, the biomass was loaded from the top of the reactor chamber, while controlled air inflow was introduced from the bottom to facilitate partial combustion. Unlike complete combustion, which requires a high oxygen supply, gasification was conducted under sub-stoichiometric conditions to limit oxygen availability and promote thermochemical conversion rather than full oxidation. As the biomass was heated, a drying zone formed at the top of the reactor, followed by a pyrolysis zone where volatile matter was released, and a reduction zone at the base where char and residual mineral content accumulated. The reactor's temperature was monitored at four vertical points — top, middle, centre, and base—with the average peak temperature recorded at 207 °C (see Table 1). This temperature was lower than the temperatures typically used for calcining most pozzolans reported in the literature [45–47]. This moderate thermal environment facilitated partial decomposition of organic matter while preserving mineral oxides, including amorphous silica and calcium compounds. The primary gaseous by-product (syngas) escaped through the top vent, while the solid residue — ash containing both carbon-rich char and inorganic minerals — was collected from the base after the reactor cooled. The ash was then sieved through a 90-micron mesh, as depicted in Fig. 2, to ensure uniform fineness before undergoing microstructural, chemical, and mechanical property analyses. The yield of ash was calculated as a percentage of the input biomass mass [48–50], enabling assessment of process efficiency for each cow horn–bamboo combination.

Table 1 Proportions of Biomass Blends

Samples	Cow horns (g)	Bamboo wastes (g)	Peak Temperature (^{0}C)
B1	0	1500	121
B2	300	1200	145
B3	600	900	184
B4	900	600	207
B5	1200	300	178
B6	1500	0	165

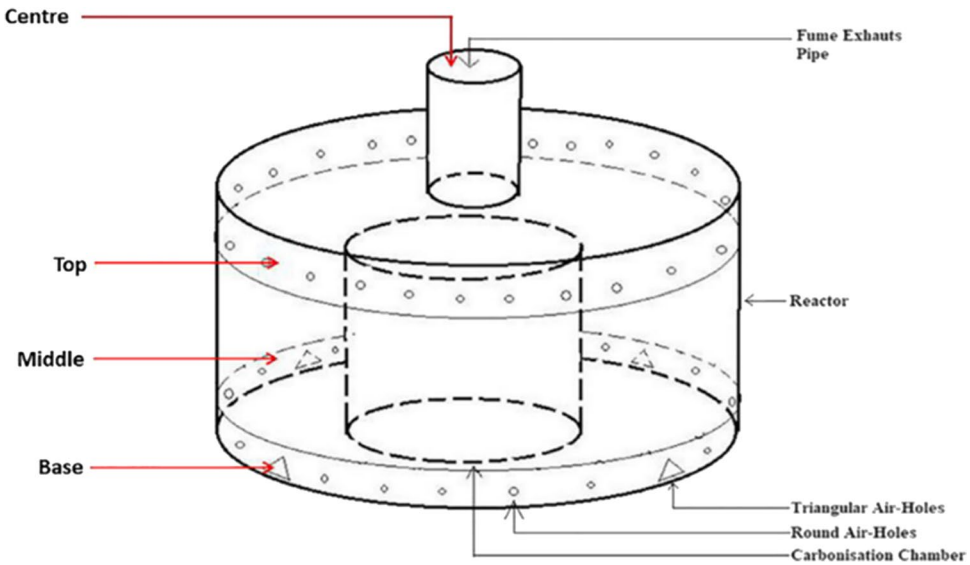


Fig. 1 Model of the reactor used for gasification [51]



Fig. 2 Image of ash samples recovered from the gasification process

The samples were first dried in an oven at 105 °C until a consistent weight was reached to determine the moisture content of the ashes. The initial weight of the sample was recorded before drying, and after drying, the final weight was taken. The difference between the initial and final weights, represented as a percentage of the initial weight, was then used to compute the moisture content. This method aligns with BS 812–109 [52] for determining the moisture content in soil and aggregates.

The ash samples were dried, cleaned, and ground into a fine powder in preparation for the Scanning Electron Microscopy (SEM) investigation. Following the steps outlined in ASTM E1508 [53], the samples were positioned on SEM holders and covered with a small coating of conductive material to stop surface charge during electron bombardment. The surface morphology of the ash particles was investigated using the SEM, which produced fine-grained images that aided in the analysis of the ash materials'texture, particle size, and structural properties. This test was conducted at the Integrated Research Laboratories, Ibadan, Oyo State.

The ash samples were subjected to Fourier Transform Infrared (FTIR) spectroscopy to determine their functional groups and bonds. The ash was ground into a fine powder, and an FTIR spectrum was obtained by passing infrared radiation through the sample. The resulting absorption peaks provided insight into the chemical structure of the gasified ash. The ash samples were digested using microwave-assisted aqua regia treatment (a 3:1 mixture of HCl and HNO_3) to extract their metallic constituents. The resulting solutions were diluted and analyzed with a PerkinElmer Optima 8000 ICP-OES, which quantified elemental concentrations based on emitted light spectra. Calibration was performed using certified standard solutions to ensure analytical accuracy. This analysis was also conducted at the Integrated Research Laboratories in Ibadan, Oyo State.

The cement used in this study complied with the requirements of BS EN 196–3 [54], exhibiting 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, sourced locally, had a fineness modulus of 3.3, specific gravity of 2.58, water absorption of 2.5%, and a bulk density of 1.50 g/cm^3. The coarse aggregate showed a fineness modulus of 6.7, specific gravity of 2.61, and a water absorption capacity of 1.4%. All aggregate properties were within the limits specified in BS EN 12620 [55].

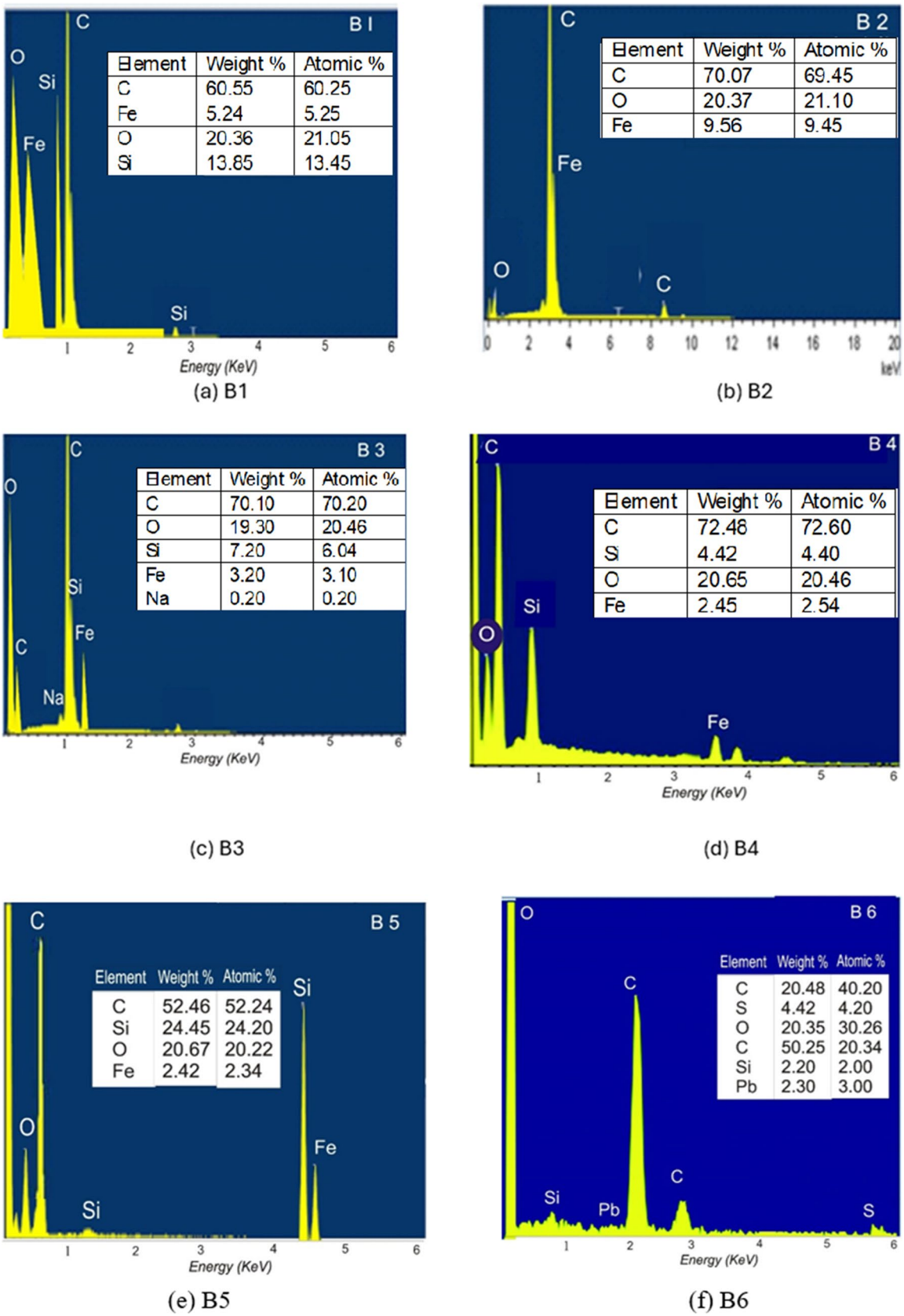


Fig. 3 Elemental composition of the gasified materials (**a**) B1 (**b**) B2 (**c**) B3 (**d**) B4 (**e**) B5 (**f**) B6

The fresh concrete was prepared using a mix ratio of 1:2:4 and a water–binder ratio of 0.6. Workability was assessed using the slump test in accordance with BS EN 12350–2:2019 [56], and the target slump range (75–100 mm) was achieved for all mixes. Cement was partially replaced with the gasified cow horn and bamboo ash, which has the highest pozzolanic properties at replacement levels of 5%, 10%, 15%, and 20%. The concrete was cast into cube moulds measuring 100 mm × 100 mm × 100 mm and allowed to cure for 7, 28, and 56 days, following BS EN 12390–3 [57]. All specimens were cured by immersion in water at ambient laboratory conditions. A single curing tank was used for all samples to ensure uniform curing and consistent temperature and moisture exposure throughout the test period. After curing, the compressive strength of the cubes was tested using a universal testing machine (UTM) to determine the maximum load they could withstand before failure. This test was conducted in the concrete laboratory of the University of Ilorin, Nigeria.

Following BS EN 12390–6 [58], split-tensile strength tests were performed on cylindrical specimens (100 mm in diameter and 200 mm in height) at 7, 28, and 56 days of curing. The test was performed by applying a compressive load along the cylinder's vertical axis until failure, with the maximum load at failure used to calculate the tensile strength. This test was also conducted in the concrete laboratory of the University of Ilorin, Nigeria.

For each cement replacement level and curing age, three specimens were prepared and tested. The average values of these replicates were recorded and reported as representative strength values. Standard deviations were used to construct error bars in the strength plots to reflect variability across replicates.

3 Results and Discussions

The elemental composition of the samples, obtained from the electron diffraction spectrum (Fig. 3), identified carbon (C), oxygen (O), and silicon (Si) as the predominant elements across all samples. These elements are essential indicators of pozzolanic potential, with silicon in particular playing a central role in forming calcium silicate hydrates (C-S–H) when reacting with calcium hydroxide in cement paste. Higher silica content enhances the long-term strength of concrete due to this secondary hydration reaction. Iron (Fe), which was present in appreciable quantities in samples B1 through B5 (with B1 having the highest at 5.24%), is known to contribute to the early strength of cementitious systems through the formation of tetracalcium aluminoferrite (C_4AF), especially when interacting with alumina and calcium oxides. The decreasing trend of iron content from B2 to B5 may partly explain the gradual reduction in early strength observed in the corresponding concrete specimens, although its role is typically secondary to that of silica and alumina in pozzolanic reactivity. Lead (Pb), a heavy metal not typically involved in pozzolanic reactions, was only detected in B6 at 2.30% and was absent in other samples. Its presence could be attributed to contamination from either the feedstock or the reactor wall corrosion. While lead does not contribute to cementitious reactions, its presence, though in trace amounts, raises environmental and durability concerns, as it may interfere with hydration processes or pose leaching risks over time.

Table 2 shows the oxide composition, moisture content, and yield for samples B1 to B6. According to ASTM C 618 [59], Sample B4 has the highest summation of silicon dioxide (SiO_2), Aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3) in the combination of cow horns and bamboo wastes (containing ash from cow horn and bamboo in a 1:0.67 ratio) and the lowest moisture content. Therefore, Sample B4 was considered for the partial replacement of cement in this study.

The surface morphologies of the pure bamboo ash (B1), cow horn ash (B6), and their various blend compositions (B2–B5) were analysed using Scanning Electron Microscopy (SEM) at a magnification of 9000x. The resulting micrographs, presented in Fig. 4, reveal clear distinctions in the structural characteristics of the ashes, which directly influence their pozzolanic behaviour and potential performance in cementitious systems.

Sample B1 (pure bamboo ash) exhibited irregular, aggregated particles with a caked structure, suggesting poor

Table 2 Properties of ash samples

Samples	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	MgO	PbO	% of $SiO_2 + Al_2O_3 + Fe_2O_3$	Moisture Content (%)	Yields (%)
B1	79.82	0	20.18	0	0	0	100%	6.16	6.4
B2	0	0	100	0	0	0	100%	5.18	15.53
B3	80.33	0	18.26	1.41	0	0	98.59%	8.73	48.53
B4	72.99	0	27.01	0	0	0	100%	4.1	50.4
B5	93.79	0	6.2	0	0	0	99.99%	5.68	47.13
B6	65.51	0	0	0	0	34.49	65.51%	5.87	94.93

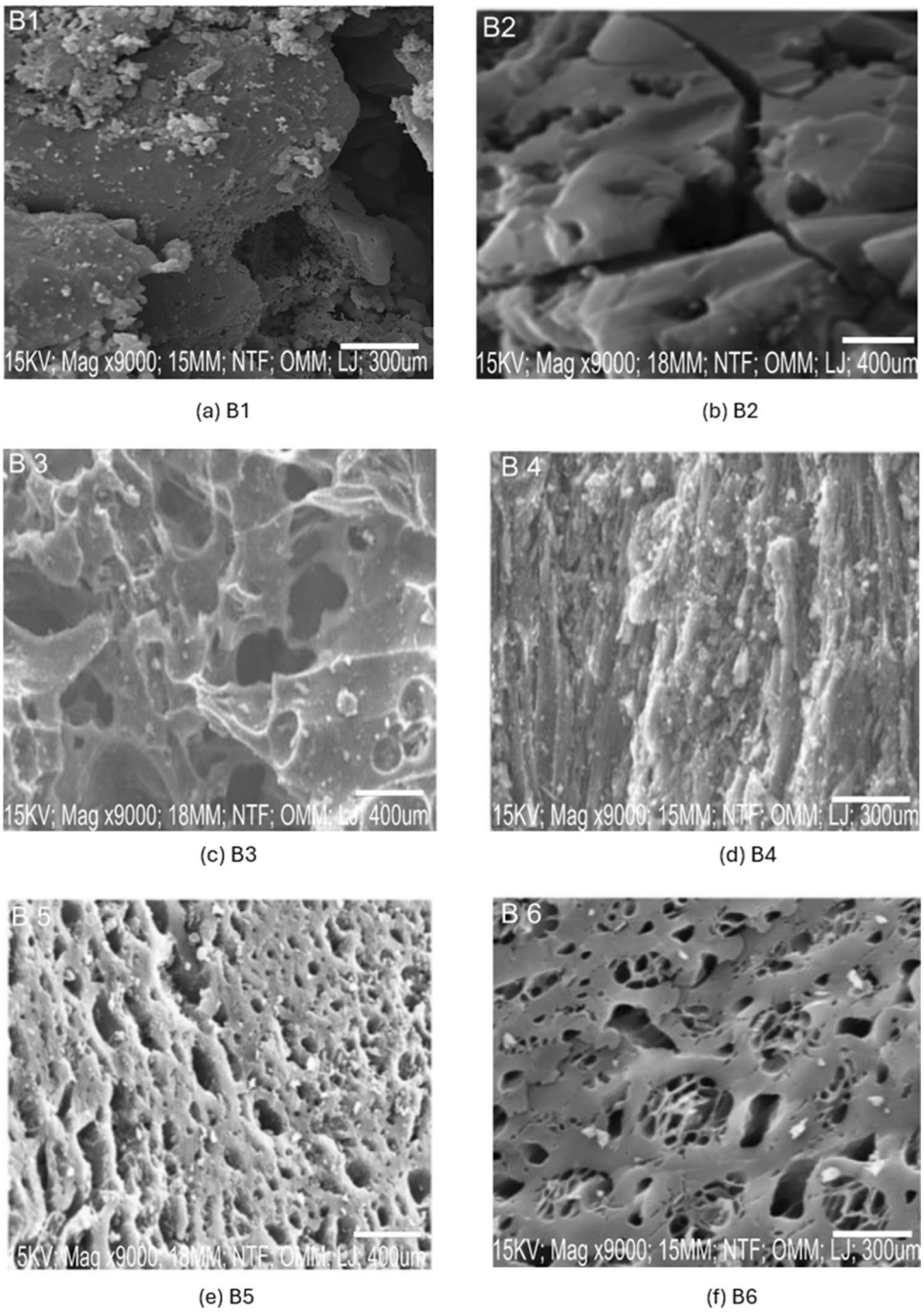


Fig. 4 SEM images of the gasified materials (**a**) B1 (**b**) B2 (**c**) B3 (**d**) B4 (**e**) B5 (**f**) B6

dispersion and limited fineness. Such morphology can hinder uniform blending in cement paste, reduce reactive surface area, and lead to weak interfacial transition zones (ITZ) in the concrete matrix. The densely packed clusters suggest a dominance of closed or occluded porosity, where internal voids are inaccessible to water or calcium hydroxide during hydration. This observation is consistent with Rajamma et al. [60] who found that poorly calcined biomass ashes often form agglomerates with low reactivity due to incomplete breakdown of fibrous cellulose structures.

In contrast, Sample B6 (pure cow horn ash) displayed large, relatively smooth particle surfaces overlaying a substrate with finer, highly porous particles. The outer smooth surfaces may limit pozzolanic reactivity due to reduced surface roughness, while the presence of fine, spongy underlying textures hints at surface-connected porosity. These features are indicative of low processing efficiency or incomplete decomposition of bamboo constituents, leading to heterogeneous ash quality. This dual morphology resembles the microstructure of dual-layered keratin/hydroxyapatite

scaffolds, mimicking alveolar bone structures described by Feroz et al. [61], where dense outer shells and porous inner layers were observed to influence hydration kinetics. They noted that while porous cores enhance reactivity, outer smooth layers can reduce early-age bonding with cementitious matrices.

Samples B2 to B5, representing various blend ratios of cow horn and bamboo, demonstrated intermediate features reflecting the influence of both precursors. B2 showed evidence of surface cracking, likely due to thermal shrinkage or brittle fracture during gasification. While such cracking may suggest structural weakness, it could also enhance the specific surface area, promoting reactivity with cement hydration products. Cracking observed in biomass ashes has also been reported by Reinmoller et al. [62], who linked surface fracture patterns in fly ash to increased water absorption and improved nucleation of hydration products. B3 exhibited more loosely dispersed particles with increased roughness, indicative of open surface porosity and better fineness compared to B2. This configuration facilitates water ingress and ion diffusion, essential for effective pozzolanic reactions. This aligns with the findings of Nnochiri et al. [63], who observed that loosely packed, rough-surfaced particles from rice husk ash and bamboo leaf ash yielded greater pozzolanic performance due to enhanced internal hydration.

Sample B4 presented the most favourable morphology, with a well-distributed range of angular particles, moderate roughness, and minimal visible porosity. The absence of large agglomerates or excessive voids suggests better packing density and dispersion potential in concrete mixes. The rough, angular texture increases the contact area with cement and water, accelerating the formation of calcium silicate hydrates (C-S–H) and improving the mechanical interlocking within the hardened matrix. These microstructural traits, coupled with B4's optimal chemical composition (notably high silica and calcium content) and low moisture level, explain its superior performance in compressive and tensile strength tests. Similar morphologies have been described by Zhu et al. [64] for metakaolin and ground granulated blast furnace slag (GGBFS), where angularity and surface roughness significantly enhanced bond strength and pozzolanic activity.

In contrast, B5 displayed a highly porous structure, characterised by interconnected voids and loosely bound particles. This morphology suggests high surface-connected porosity, which can improve pozzolanic activity by increasing the reactive surface area. However, the same porous network can also act as capillary channels, increasing water absorption and permeability. In the absence of densification, this may compromise long-term durability and resistance to environmental degradation. This observation closely parallels Zhang et al. [65], who reported that high-porosity biomass ashes enhance early-age strength but can lead to shrinkage and microcracking if not balanced with densifying additives. Magalhães [66] also noted that open porosity promotes reactivity but compromises resistance to chemical attack unless matrix densification occurs.

Although quantitative porosity measurements were not obtained from the SEM images, the visual differences in particle dispersion, surface roughness, and pore continuity offer qualitative evidence to rank the samples in terms of microstructural suitability. The observed trends align with literature reports by Kumar et al. [67], who emphasised the role of surface morphology in enhancing ash–cement interaction, as well as Odeyemi et al. [68], who noted the benefits of roughness and angularity in SCMs.

Among all samples, B4 stands out with its well-defined, angular particles and rough surface texture, which are beneficial for pozzolanic activity. These characteristics suggest improved dispersion and mixing within the concrete matrix. Given that B4 also exhibited the optimal chemical composition and moisture content, its surface morphology further supports its potential as the most effective pozzolanic material among the tested samples.

The FTIR spectral of the ashes (B1 – B6) are shown in Fig. 5.

The spectral features of B1 (Bamboo) are observed at 1034 cm^{-1} and 490 cm^{-1}, corresponding to C–OH and Si–O stretching vibrations, respectively. These spectral assignments are absent in B6 (Cowhorn), which instead exhibits a stretching frequency at 1700 cm^{-1}, indicative of a carboxylic acid of the ester functional group (COOR). Likewise, the features of B6 are absent in B1, implying that the two samples are distinct. Other spectral assignments are defined in Table 3.

The B2 composite shares some similarities with B1 in the C–OH stretching frequency, which exhibits a hyperchromic shift to 1050 cm^{-1} upon the introduction of 300 g of B6. Additionally, the peak indicative of Si–O is absent.

B3 also shares spectral features with B1. However, a hypsochromic shift to a lower wavenumber at 1000 cm^{-1} and a hypochromic shift indicate the strong presence of B6 in the composition. Since no spectral features identify cow horn in the mixture, it can be inferred that its concentration of 600 w/w is not significant. Additionally, the peak indicative of Si–O is absent.

B4 shares spectral features with both B1, exhibiting hypochromic and bathochromic shifts at 1200 cm^{-1}, as well as a peak at 490 cm^{-1}, and with B6, at 1700 cm^{-1}. This suggests that B4 provides the most reliable representation of the composites, where the concentrations (w/w) of B1 and B6 become highly significant.

The B5 composite shares some similarities with B6 at the C–OOR stretching frequency of 1700 cm^{-1}, which exhibits a hyperchromic shift due to the presence of 300 g of B1. Additionally, the peak indicative of Si–O at 490 cm^{-1} is absent.

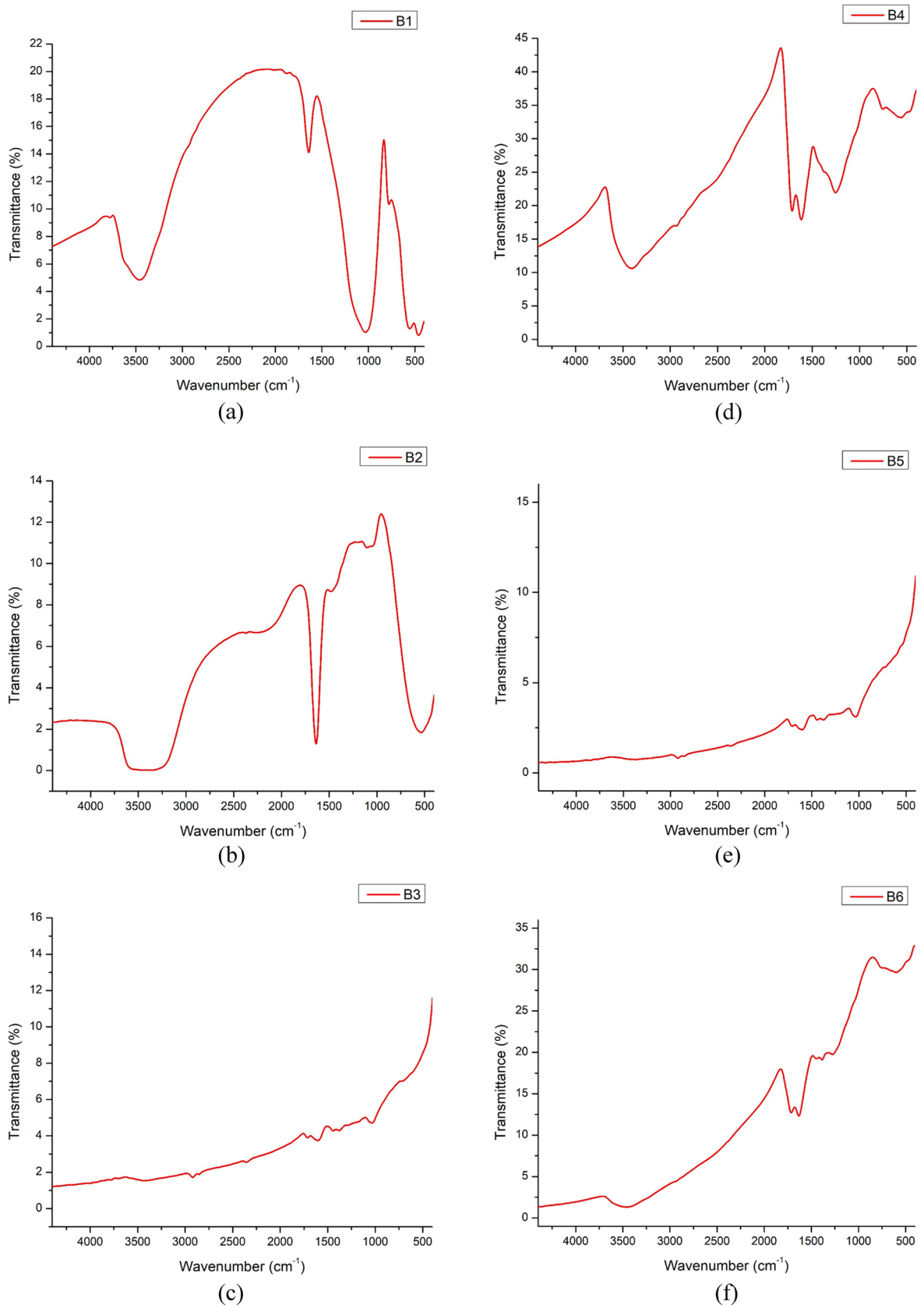


Fig. 5 FTIR images of the gasified materials (**a**) B1 (**b**) B2 (**c**) B3 (**d**) B4 (**e**) B5 (**f**) B6

Table 3 Spectral Assignment

IR Frequencies (cm^{-1})	B1 (cm^{-1})	B2 (cm^{-1})	B3 (cm^{-1})	B4 (cm^{-1})	B5 (cm^{-1})	B6 (cm^{-1})
O–H str 3500–3200	3437	3779	-	3400	-	3400
N–H 1680–1630	1650	1650	1620	1650	1620	1620
COO- 1700–1650	-	-	-	1700	-	1700
C–OH 1200–1000	1034	1032	1000	1200	1000	-
C-H 590–700	590	590	-	590	-	590
Si–O 490	490	-	-	490	-	-

The graphs in Figs. 6 and 7 provide information on the compressive strength and split-tensile strength of concrete containing ash from cow horn and bamboo (in a 1:0.67 ratio, tagged as B4) as a partial replacement for cement.

The compressive strength values at 7 days decrease with increasing ash content. At 0% ash, the strength is 16.89 MPa, but it drops to 8.80 MPa at 20% ash replacement. This decline indicates that early strength development is hindered by the higher ash content, which is typical when using pozzolanic materials, as they react more slowly than cement.

The same trend is observed at 28 days, with strength values decreasing as the ash content increases. However, the overall strength increases compared to the 7-day values, with 22.3 MPa for 0% ash and 11.6 MPa for 20% ash. This demonstrates that pozzolanic reactions are progressing and contributing to strength gain over time.

At 56 days, the strength continues to increase for all samples, indicating the long-term strength development of pozzolanic materials. The strength ranges from 48.07 MPa at 0% ash to 29.73 MPa at 20% ash replacement. Even at higher replacement levels, the concrete achieved substantial strength at 56 days, suggesting that it can be used for reinforced concrete structures.

Though the compressive strength decreases with higher ash content, the 56-day values show significant strength development. The concrete containing up to 20% ash maintains a strength above 20 MPa at 56 days, indicating that all the levels of incorporation of the ash are suitable for

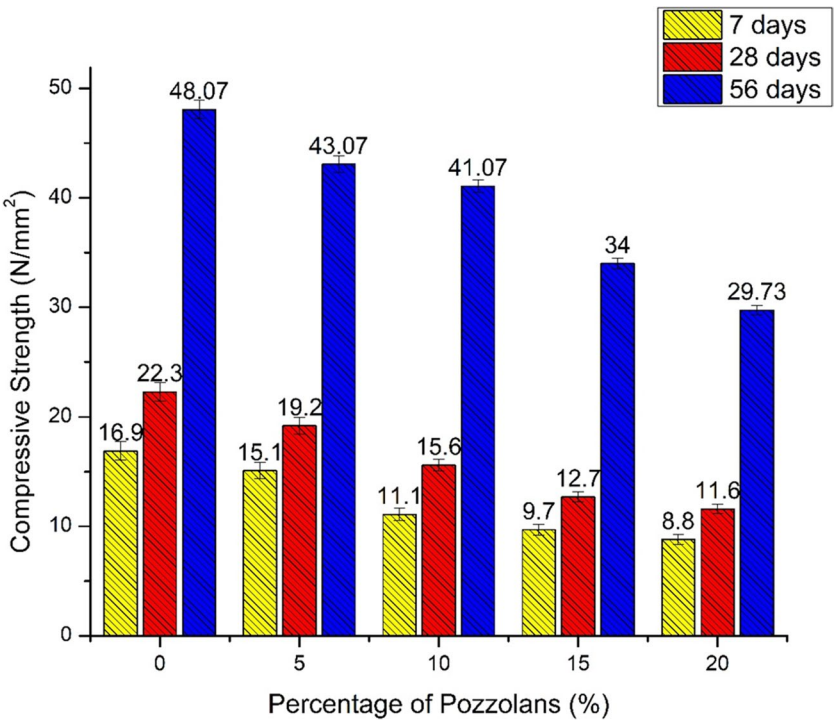


Fig. 6 Compressive strength

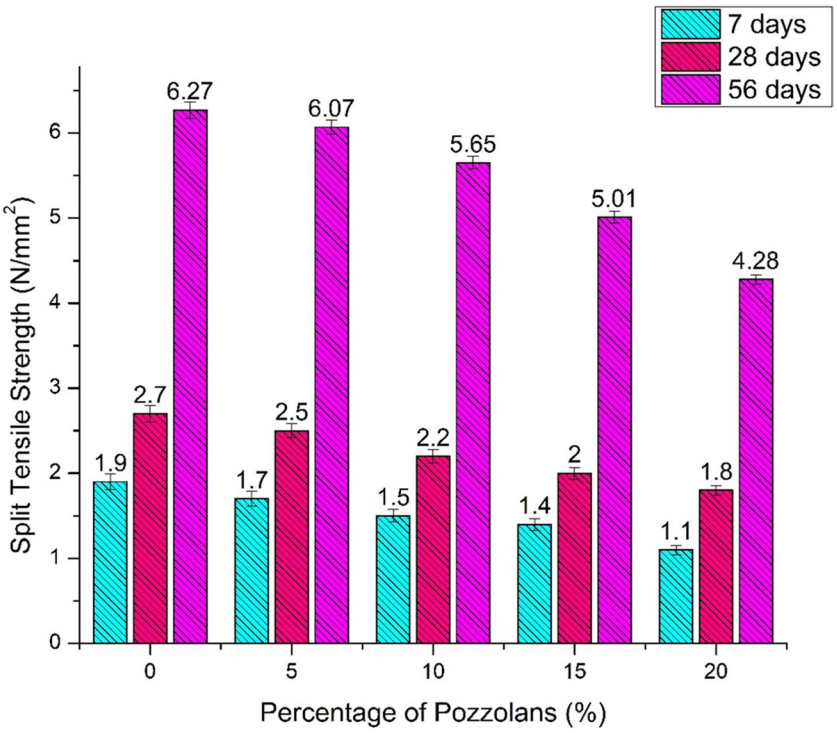


Fig. 7 Split tensile strength

constructing reinforced concrete structural members, especially where long-term strength is critical [69, 70].

The error bars presented in Fig. 6 represent the standard deviations from triplicate compressive strength measurements at 7, 28, and 56 days. At 7 days, noticeable overlap is observed between the control and the 5% and 10% ash replacement levels, suggesting that early-age reductions in strength for these mixes may not be statistically significant. However, at 28 and 56 days, the error bars for mixes with 15% and 20% replacement are separated from those of the control, indicating statistically significant differences at a 95% confidence level. This separation implies that the observed strength variations at later ages are not due to experimental variability but reflect the progressive pozzolanic activity of the ash over time.

Similar to the compressive strength, the split-tensile strength decreases with increasing ash content. At 0% ash, the tensile strength is 1.9 MPa, reducing to 1.10 MPa at 20% ash replacement. Early tensile strength is lower, as expected, due to the slow pozzolanic reaction.

The 28-day split-tensile strength improves across all replacement levels, with values ranging from 2.7 MPa at 0% ash to 1.8 MPa at 20% ash. The improvement highlights the ongoing pozzolanic activity contributing to strength gain.

By 56 days, the tensile strength has significantly increased, with 6.27 MPa for 0% ash and 4.28 MPa for 20% ash. The strength improvement over time aligns with the slow reaction rate of pozzolanic materials, which contribute to long-term durability and crack resistance.

The split-tensile strength results demonstrate a similar trend as the compressive strength, with higher ash content reducing early tensile strength but showing substantial improvement over time. At 56 days, the concrete containing up to 20% ash still achieves satisfactory tensile strength, making it viable for structural applications, particularly in reinforced concrete, where tensile capacity is enhanced by steel reinforcement [69, 70].

Figure 7 shows the error bars for split-tensile strength at the same curing intervals. Similar to the compressive strength results, there is partial overlap at 7 days between the control and lower ash replacement levels, indicating that the reduction in tensile strength at early age may not be statistically significant. However, at 28 and 56 days, the error bars for 15% and 20% replacement levels show a clear divergence from the control mix. This indicates statistically meaningful differences, suggesting that the tensile strength gains at later ages are influenced by the gradual formation of secondary cementitious compounds resulting from the ash's pozzolanic reaction. The trend supports the conclusion that ash incorporation affects both compressive and tensile strength development over time.

The results suggest that the ash from cow horn and bamboo (B4) can be effectively used for partial cement replacement in concrete. While the strength decreases as ash content increases, the significant strength gain at 56 days indicates that this material is suitable for reinforced concrete structures where long-term strength is prioritised. These findings align with those of Odeyemi et al. [30] that cement can be effectively replaced with bamboo leaf ash in concrete. These results also align with

established literature [71–73]. Compared to other SCMs such as fly ash, rice husk ash, and metakaolin, B4 offers a balance of long-term strength development and makes it a viable alternative, particularly where delayed strength gain is acceptable.

The sustained strength gain observed in concrete incorporating B4 ash is closely linked to its favourable microstructural and chemical characteristics. SEM analysis showed that B4 consists of well-distributed angular particles with moderate surface roughness and minimal visible porosity. This morphology enhances particle packing, improves dispersion within the cement matrix, and increases the contact area with water and cement, promoting effective hydration and strong interfacial bonding. Complementing this, the FTIR spectrum of B4 revealed strong absorption bands around 980–1060 cm^{-1}, corresponding to Si–O–Si and Si–O–Al vibrations—functional groups that actively participate in pozzolanic reactions by consuming calcium hydroxide and forming secondary calcium silicate hydrate (C–S–H). Additionally, the presence of O–H stretching near 3400 cm^{-1} and H–O–H bending around 1640 cm^{-1} indicates surface hydroxylation, further enhancing reactivity. Together, these features confirm B4's capacity for continued pozzolanic activity, which underlies the progressive development of compressive and split-tensile strengths observed between 7 and 56 days.

The reduction in early-age strength observed with higher supplementary cementitious material (SCM) content is a well-documented phenomenon in concrete research. This effect is primarily due to the slower pozzolanic reaction of SCMs compared to the rapid hydration of cement [74]. While beneficial for long-term strength and durability such as foundations, retaining walls, and dams, this delay can be problematic in projects requiring early strength, such as precast elements and pavement repairs [75, 76].

4 Conclusion

The following conclusions were drawn from the study:

1. The ash derived from the co-gasification of cow horn and bamboo in a 1:0.67 ratio (B4) exhibited high pozzolanic potential, with oxide contents of 72.99% SiO_2, 0% Al_2O_3, and 27.01% Fe_2O_3, resulting in a combined total of 100% for the primary pozzolanic oxides. This meets and exceeds the minimum 70% threshold set by ASTM C618 for Class F pozzolanic materials, supporting its suitability as a supplementary cementitious material.
2. SEM analysis of B4 revealed a well-distributed range of angular particles with moderate surface roughness and minimal visible porosity, which enhance bonding with cement hydrates and promote effective microstructural integration within the concrete matrix.
3. Concrete specimens incorporating B4 ash at replacement levels of 5–20% consistently achieved 56-day compressive and split-tensile strengths exceeding 20 MPa and 2 MPa, respectively. The 20% replacement level yielded 29.73 MPa (compressive) and 4.28 MPa (split-tensile), indicating that all levels tested are structurally adequate for use in reinforced concrete construction.
4. Based on mechanical performance and pozzolanic characteristics, co-gasified cow horn and bamboo ash is recommended as a viable supplementary cementitious material for partial cement replacement in structural concrete at levels up to 20%, aligning with sustainability goals and material efficiency in construction.
5. A limitation of this study is that it did not evaluate durability under aggressive environments such as sulfate, chloride, or freeze–thaw exposure. It was also limited to a maximum of 20% ash replacement. Future research should assess higher replacement levels and the cost-effectiveness of using the ash in concrete.

Author Contributions S.O. and A.G. conceived and designed the study. J.A., O.T., K.O., and E.C. conducted the laboratory experiments. S.O. prepared the initial manuscript draft, and all authors contributed to its review and approved the final version.

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Data Availability All data utilized in this study are illustrated in Figs. 3 through 7. No additional datasets were generated or analysed beyond those presented.

Declarations

Ethical Approval Not applicable.

Informed Consent Not applicable.

Competing interests The authors declare no affiliation with any organization or institution that holds a financial or non-financial interest in the subject matter or materials discussed in this manuscript.

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