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Analysis, Assessment and Application of Cassava Peel and Groundnut Shell Biochar for Concrete Production

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Abstract

The increasing environmental costs of cement manufacturing, paired with mounting agricultural refuse have intensified the search for sustainable construction materials. This study evaluated the suitability of biochar produced from cassava peels and groundnut shells to partially substituting cement. Biochar was added at 1%, 1,5% and 2 % by cement weight in a 50:50 blend, while conventional concrete served as the control. Laboratory investigations included the physical and mechanical properties. Results indicated that the biochar possessed high porosity and low density, promoting internal curing and improved hydration within the concrete matrix. The inclusion of biochar influenced fresh concrete properties and enhanced mechanical performance at optimum replacement levels. Microstructural and chemical analyses further confirmed characteristics favourable for concrete improvement. The findings demonstrate that cassava peel and groundnut shell biochar can be advantageously employed as an environmentally responsible pozzolanic addition, providing a practical approach to agricultural waste valorization while supporting the development of more environmentally responsible concrete for construction applications.

Keywords: Cassava Peel, Groundnut Shell, Biochar, Concrete Production

Introduction

Manufacturing ordinary Portland cement stands to be one of the primary contributors of global atmospheric carbon in the world, making up between 8–10% of all carbon dioxide resulting from human activity. (IEA, 2023; Andrew, 2019). Due to an annual output exceeding 4.2 billion metric tons, there is a substantial demand on the cement business to develop greener alternatives particularly in fast-growing developing and industrialized countries experiencing substantial infrastructure growth. Nigeria currently boasts the largest cement production capacity in sub-Saharan Africa, with an installed capacity exceeding 60 million tonnes annually and a

consistent demand growth rate of 7–10% per year (NBS, 2024). The growth intensifies the release of climate-warming gases and heightens and the environmental weight of managing farm refuse.

Kwara State, at the Middle Belt region of Nigeria, is a major producer of cassava and groundnuts. The state generates an estimated 850,000–1,200,000 tonnes of cassava peels and over 450,000 tonnes of groundnut shells annually from processing activities concentrated in areas such as Omu-Aran, Ilorin, and Offa (Kwara State Ministry of Agriculture, 2023; FAO, 2022). As it stands, most of these by-products of more than 80% undergo open-air burning or unregulated dumping leading to air pollutants such as particulate matter, methane, and black carbon, while simultaneously leading to ecological contamination. (Adeleke et al., 2021). Addressing these challenges of both cement decarbonization and agro-waste utilization, provides a strategic opening for the region to gain significantly from long-term sustainable growth and development.

The performance of OPC concrete in tropical climates exhibits poor durability in hot and humid conditions and often compromised by issues such as early-age microcracking and cyclic wetting-drying degradation (Obla et al., 2022). Such shortcomings result in higher repair bills and an increased financial burden costs for physical structures and transport network both within the state and nationally.

Biochar, a solid carbon-rich product of biomass pyrolysis, emerged worldwide as a multifunctional cementitious additive capable of sequestering carbon permanently, providing internal curing through its porous structure, enhancing hydration kinetics, and improving mechanical and durability properties at replacement levels of 1–5% (Gupta et al., 2023; Mali & Nanthagopalan, 2024; Praneeth et al., 2024). Studies on wood, rice husk, and peanut/groundnut shell biochar have demonstrated reductions in setting time, increased early-age strength, and enhanced resistance to both carbonation and chloride ingress (Qin et al., 2022; Dixit et al., 2023). However, systematic investigations into the combined use of locally abundant Nigerian wastes particularly cassava peels and groundnut shells are virtually non-existent. Furthermore, the influence of pyrolysis temperature and blending ratio of these two feedstocks on setting behaviour, hydration heat evolution, early-age compressive strength, autogenous shrinkage, and long-term performance under simulated tropical exposure conditions remains unexplored in the literature.

This knowledge gap is significant because cassava peel biochar is highly porous and rich in oxygen-containing functional groups, while groundnut shell biochar is silica-rich and it is pozzolanic reactive in nature. Their synergistic combination has the potential to produce an optimized, low-cost, carbon-negative admixture tailored to Nigeria’s climate and resource base. This is in line with the Nationally Determined Contribution (NDC) of Nigeria under the Paris Agreement and the circular economy policy of the Federal Government and Landmark University 's mandate of agrarian revolution and sustainable development. Hence, the effect of the pyrolysis temperature and blending ratio of groundnut shell and cassava peel biochar on setting time, hydration kinetics, initial strength development and durability long-term of the cementitious materials, which will eventually cause the development of a scalable, sustainable and locally-sourced concrete admixture for applications structurally in Nigeria's tropical environment is investigated.

MATERIALS AND METHODS

Cement sourced locally from Kwara State, Nigeria, the Portland Limestone Cement grade 42.5R utilized for structural building works met the specifications of ASTM C150. The Mangal Industries Limited was placed in a low-humidity prior to and following application prevent premature hydration. The selection of locally available cement was to make sure that the study reflects typical construction

practices. Also provided a realistic basis for evaluating the influence of biochar on early-age hydration and strength development (Zhao et al., 2024; Sinha et al., 2023; Gupta & Kashani, 2021).



Plate 3.1: Mangal Cement.

Biochar Feedstocks and Production

Groundnut Shells

Local farms and markets within Kwara state were the main source of getting groundnut shell which was then washed lightly removing dirt and impurities, sun-dried followed by oven drying at 70°C to achieve uniform moisture content. (Egbosiuba et al., 2022; Gupta and Kashani, 2021). It is advantageous to dry the groundnut shells in an oven as this method will result in uniform dryness, prevent problem during pyrolysis and high throughput of shells with high purity



Plate 3.2: Groundnut shell.

Cassava Peels

From local garri processing sites within Kwara state, cassava peels were obtained. Which was then washed lightly removing dirt and impurities, sun-dried followed by oven drying at 70°C to achieve uniform moisture content. (Khater et al., 2024; Zhao et al., 2024; Dayoub et al., 2024).



Plate 3.3: Cassava peel.

Reason for Separate Treatment

Because of their distinct physicochemical characteristics, which control their thermal decomposition behavior, the effectiveness of the biochar produced, and their compatibility with cementitious binders, groundnut shells and cassava peels will be treated differently. Separate characterization allows for:

i. Understanding the individual contribution of each biochar type to early hydration, water absorption, and setting behaviour.
ii. Optimizing pyrolysis parameters for each feedstock to maximize carbon retention, porosity, and functional groups.

Aggregates

Fine Aggregate

River sand, which suit best for construction purposes in accordance to ASTM C136 specifications. Supply of fine aggregate was locally sourced. It is kept in a dry place to avoid contamination with water or other materials. (Zhao et al., 2024, Sinha et al,.2024).



Plate 3.4: Natural Fine Aggregate.

Coarse Aggregate

Crushed granite with a nominal maximum size of 20 mm selected to comply with ASTM C33 (2021) requirements and sourced from a single local quarry was adopted as the coarse aggregate for all concrete mixes in this study. (Mosaberpanah et al., 2024; Zhao et al., 2024).



Plate 3.5: Natural Coarse Aggregate

Water

Sourced locally from Kwara State, the drinking water used for this study conformed to the requirements of ASTM C1602.



Plate 3.6: Potable Water.

Methods Biochar Production and Characterization

Feedstock Preparation

To eliminate dirt, dust, and other contaminants, feedstocks underwent light washing. They were then dried in the sun and, subsequently, final oven heating at 70 °C for uniform moisture content. Drying process was carried out to reduce the loss of volatiles during pyrolysis, prevent uneven carbonization, and promote uniformity and porosity of the particles (Gupta & Kashani, 2021; Amusan et al., 2023). The dried feedstocks were milled to improve the heating during pyrolysis by creating smaller sizes. This stage ensured that the biochar is properly formed and has the right physical characteristics.





Plate 3.7: Drying.

Pyrolysis Process

Pyrolysis was carried out using a muffle furnace under controlled conditions. The feedstocks were heated in the absence of oxygen to produce biochar. (Egbosiuba et al., 2022; Tu et al., 2022).

Pyrolysis Parameters

Recent, practically-focused studies have improved the operating conditions under which the pyrolysis is carried out (Egbosiuba et al., 2022; Khater et al., 2024; Zhao et al., 2024).

Temperature

A biochar product with a high fixed carbon content, a stable pore structure, and enough functional groups to function as nucleation sites and interact with cement hydration was created at a temperature of 400–600 °C.

Heating Rate

In order to achieve consistent pyrolysis without cracking and repeatable particle morphology and pore structure, sample preparation entailed the use of a heating rate of 5°C/min.

Residence Time

The residence time needed for full carbonization and spent at that temperature were both set at 60 minutes. This is important for water absorption and early-age cement reactions. During pyrolysis, volatile gases were released and safely vented. The furnace temperature was also constantly checked to make sure it stays within the desired pyrolysis range.

Post-Pyrolysis Processing

After completing the pyrolysis process for the agricultural waste, the biochar was allowed to cool; thereafter, the physicocemical properties of the biochar were determined.



Plate 3.8: Post-Pyrolysis Processing

Reasons

The selected pyrolysis parameters optimized the reactivity and porosity of biochar while guaranteeing reproducibility. Separate processing of groundnut shells and cassava peels was used to evaluate the distinct contributions of each feedstock to early-age cement hydration, water absorption, and setting behavior (Egbosiuba et al., 2022; Gupta & Kashani, 2021).



Plate 3.9: Groundnut shell in Biochar form.



Plate 3.10: Cassava peel in Biochar form.

Characterization of Biochar

The biochar produced from the agro-waste underwent characterization both physically and chemically to clearly understand its impact on cement hydration, water absorption, and setting behavior. (Zhao et al., 2024; Sinha et al., 2023).

Physical Properties

Particle Size

Following the ASTM C136/C136M standard, the biochar from the agro-waste was sieved separately with particles passing through a 75 µm sieve to maintain a uniform fineness and to show a clear

comparison of the physical behaviour between the biochar type before concrete application. (Gupta & Kashani, 2021; Zhao et al., 2024). It is represented as;

$$FM = \Sigma \frac{(Cumulative\ \%\ Retained\ on\ Sieves)}{100} \quad \ldots\ldots(1)$$



Plate 3.11: Stack of Sieve.

Bulk Density

The bulk density of biochar produced from groundnut shells and cassava peels was determined separately after pyrolysis in accordance with ASTM C29/C29M by measuring the mass-to-volume ratio of loose biochar, to assess its packing behaviour, influence on mix yield, and potential impact on fresh density and early-age performance of concrete (Sinha et al., 2023; Mosaberpanah et al., 2024).

$$\rho\ bulk = \frac{M}{V} \quad \ldots\ldots(2)$$



Plate 3.12: Bulk Density

Moisture Content

Moisture content of groundnut shell and cassava peel biochar was determined separately by taking a small representative sample after pyrolysis by oven-drying, and reweighing to calculate moisture percentage, adapted from ASTM C128), since high absorption can reduce available mixing water and significantly affect setting time, workability, and early-age strength of concrete (Gupta & Kashani, 2021; Zhao et al., 2024). It is represented as;

$$\text{MC bc (\%)} = \frac{[(W\,initial - W\,dry)}{\text{W dry]}} \times 100 \quad \ldots\ldots(3)$$

MC bc (%) = Moisture content of biochar (%)

W initial = Initial mass of biochar sample before oven drying (g)

W dry = Mass of biochar after oven drying at 105 ± 5 °C (g)

Mix Design (Control and Biochar Blends) and Sample Preparation

A conventional concrete mix without biochar was used as a reference with the mix ratio 1:1:2, while biochar was then incorporated at 1%, 1.5% and 2%. While 0.40 water-binder ratio was used to balance workability and early strength development.

Control Mix

The control concrete mix served as the standard used for comparing all biochar-modified mixes. It is designed to achieve a target workability and early-age strength suitable for conventional structural concrete, following widely accepted codes such as ASTM C33 for aggregates and ASTM C150 for Ordinary Portland Cement (OPC). A water–binder ratio of 0.40–0.50 was selected to balance workability and early strength development, as recommended in contemporary concrete materials research (Scrivener et al., 2021; Mindess et al., 2021).

Biochar-Modified Mixes

Keeping aggregate proportions and water-binder ratios contant relative to the control, modified concrete was produced by substituting a portion of the cement weight with biochar made from cassava peels and groundnut shells. This method was widely adopted from recent studies to ensure that observed changes in setting time, workability, and early-age strength will be attributable to biochar addition rather than mix proportion variability (Gupta & Kashani, 2021; Zhao et al., 2024; Amoakwah et al., 2024). All biochar-modified mixes maintained the same mix ratio for cement, sand and water as the control mix to ensure consistency and allow meaningful comparison.

Batching and Mixing Procedure

Materials were measured out accurately per the mix ratios for uniform dispersion. To achieve homogeneous and workable concrete, water was added gradually while mixing. (Gupta & Kashani, 2021; Sinha et al., 2023).

Casting and Compaction

After mixing, in line with ASTM C31 the fresh concrete was placed into standard mould 100mm cubic moulds cubes and 100 x 100 x 500mm beam moulds in three uniform lifts.



Plate 3.13: Casting and Compaction

Curing Regime

After casting, specimens were covered at room temperature for 24 hours. Next, the specimens came out of their molds and cured underater (23 ± 2 °C). It observed a curing period of 7, 14, 21, and 28 days to check how the control and biochar mixes hardened over time.



Plate 3.14: Curing

Purpose of the Mix Design Approach

This mix design and sample preparation approach provides a controlled framework for comparing the performance of biochar-modified concrete with a standard reference mix. By maintaining constant proportions and curing conditions, the methodology ensures that observed changes in setting behaviour, water absorption, and early strength development are directly related to biochar type and dosage, consistent with recent findings in biochar cement composite research (Zhao et al., 2024; Dayoub et al., 2024).

Testing Procedures

The prepared biochar-cementitious mixes underwent multiple tests to measure early-age hydration, water absorption, setting characteristics, and strength at Landmark university Laboratories. Testing was conducted in accordance with ASTM standard, ensuring reproducible and reliable results.

Standard Consistency Test

In accordance to ASTM C187, the standard Vicat device was used to run a normal consistency test, measuring the precise water volume needed to create a uniform hydraulic cement mix. It is represented as:

Vicat penetration = 10 ± 1 mm from base

$$P\ (\%) = \frac{M\ water}{M\ cement} \times 100 \qquad \text{(Water-cement ratio for paste)} \quad \ldots\ldots(4)$$

P (%) = Water content as a percentage of cement mass for normal consistency

M water = Mass of water used (g)

M cement = Mass of cement used (g)

Setting Time

Using Landmark university laboratory, the initial and final setting times of the mixes were conducted on a cement-biochar paste using the Vicat needle apparatus in accordance with ASTM C191. (Zhao et al., 2024; Sinha et al., 2023).



Plate 3.16: Vicat Apparatus.

Workability (Slump Test)

At Landmark university in accordance with ASTM C143, the flow properties of freshly mixed concrete at all replacements level was evaluated via the slump cone method. The mold was filled in three identical tiers, with each layer receiving 25 standard rod strikes, and gauged right after mold extraction to evaluate biochar's impact on flow and placement It is represented as;

$$S = H_{cone} - H_{concrete} \quad \text{.....(5)}$$

S = Slump value (mm)

H cone = Height of the standard slump cone = 300 mm (fixed)

H concrete = Height of the highest point of the slumped concrete specimen (mm)



Plate 3.15: Slump Cone.

Density of Fresh Concrete

Fresh concrete density was determined following ASTM C138 taking the measurement of mass per unit volume (Density= Mass/ Volume) of concrete. This test helped in evaluating the effect of biochar inclusion on mixture compactness and air content. It is represented as;

$$\rho c = \frac{Mf - Mc}{Vm} \quad \text{....(6)}$$

ρ c = Fresh concrete density (kg/m³)

M f = Mass of measure filled with concrete (kg)

M c = Mass of empty measure (container) (kg)

V m = Volume of the measure (m³)

Water Absorption of Hardened Concrete

Cube specimen after a 24-hour curing period were subjected to ASTM C642 standard water absorption test to evaluate changes in pore structure caused by biochar addition.

$$WA\ (\%) = \frac{(B - A)}{A} \times 100 \quad \text{.....(7)}$$

WA (%) = Water absorption after immersion (%)

A = Mass of oven-dry specimen (g)

B = Mass of surface-dry specimen after immersion in water for 24 h (g)

Compressive Strength

Following the ASTM C109/C109M standard procedure, the control and biochar-modified concrete cube mould at 7, 14, 21, and 28 days, respectively, strength development was tested using the Universal Testing Machine (UTM) at Landmark university, Kwara state. (Li et al., 2022; Egbosiuba et al., 2022). It is represented in MPa as:

$$f c = \frac{P}{A} \quad \text{.....(8)}$$

f c = Compressive strength (N/mm² = MPa)
P = Maximum load applied at failure (N)
A = Cross-sectional area of the cube face = 100 × 100 = 10,000 mm²

Flexural Strength Test (Concrete Beam)

Following the ASTM C78 procedure standard, the flexural strength test took place on a Universal Testing Machine (UTM) at Landmark university, Kwara state via third-point loading arrangement. It is represented in MPa as:

$$f_r = \frac{3Pa}{(bd^2)} \quad \text{.....(9)}$$

f r = Modulus of rupture / flexural strength (MPa)
P = Maximum applied load at failure (N)
L = Span length between supports = 450 mm (for 500 mm beam) (mm)
b = Average width of specimen at the section of failure (mm)
d = Average depth of specimen at the section of failure (mm)
a = Average distance between line of fracture and nearest support (mm)



Plate 3.17: Compressive Strength Machine.

Microstructural and Chemical Analysis of Biochar-Modified Concrete

Elemental Composition (XRF)

Biochar-modified concrete from groundnut shells and cassava peels was sent to a laboratory in Ekiti State for separate XRF analysis to determine elemental composition (C, Si, Ca, Mg, K, oxides), which will indicate potential pozzolanic reactivity and compatibility with cement (Dayoub et al., 2024; Khater et al., 2024).

Scanning Electron Microscopy (SEM):

High-resolution scanning electron microscope analysis revealed the surface texture and structural features of the synthesized biochar. SEM analysis helped to understand how the porous structure of biochar affects water absorption and bonding within the cementitious matrix. The biochar-modified concrete from groundnut shells and cassava peels was sent to a laboratory in Ekiti State

Data Processing and Analysis

Observed behaviour obtained from hardened concrete tests were interpreted and related to the biochar characterization, recorded and analyzed using representation through graphs and ANOVA to validate the uniformity and accuracy of the findings.

$$F = \frac{\text{MS between}}{\text{MS within}} \text{ (One-Way ANOVA)} \quad \text{.....(10)}$$

F = F-statistic (Fisher's ratio)
MS between = Mean square between groups (treatment variance)
MS within = Mean square within groups (error/residual variance)

RESULTS AND DISCUSSION

The experimental data and findings are given in this context. A performance of concrete when 50:50 groundnut shell and cassava peel biochar was used in the replacement ratios of 0% (control), 1%, 1.5 and 2% of cement was evaluated. Tests were carried out on unhardened traits (flowability and setting time), and mechanical properties after 7, 14, 21 and 28 days on the cubes and after 14 and 28 days on the beams.

Particle Size Distribution (Sieve Analysis)

Sieve analysis was executed to see the granulometry of the produced biochar.

The test was carried out using a set of sieves with aperture sizes of 0.3 mm, 0.2 mm, 0.15 mm, 0.075 mm, 0.063 mm, and the pan. This analysis was performed on particles that were smaller than 0.075 mm. This process aided in determining the fineness of the groundnut shell biochar and its applicability with uniform dispersion in the cement matrix.

Table 4.1: Particle Size Distribution of Groundnut shell and Cassava peel Biochar

Sieve Size (µm)	Groundnut Shell Biochar (% Passing)	Cassava Peel Biochar (% Passing)
300	81.25	58.33
200	64.17	37.5
150	47.5	20.83
75	32.08	8.33
63	16.25	4.17
Pan	0.0	0.0

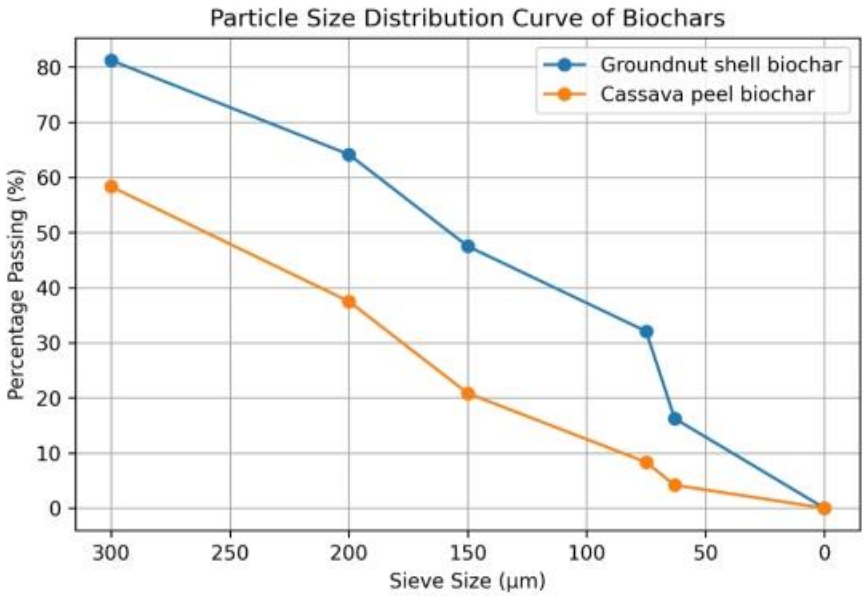


Figure 4.1: Particle Size Distribution Curve

The granulometric curves in Figure 4.1 showed that groundnut shell biochar (GSB) gave a higher cumulative percentage passing through all the sieve sizes than cassava peel biochar (CPB). GSB had 81.25% passing at 300 μm sieve as compared to CPB's 58.33%, showing presence higher percentage of fine-grained material in GSB. The gradient of the GSB curve is steeper than that of the CPB curve, indicating a more uniform gradation of fine particles; the steeper gradient of the CPB curve reflects a coarser gradation with a larger size retained above the top sieves. Greater fraction passing on the finest sieve (63 μm) for GSB (16.25%) than for CPB (4.17%) further illustrates that groundnut shell biochar is a finer particle biochar. The fineness differences can affect the pozzolanic activity and reactivity of each type of biochar as a cement replacement, and will likely have a higher pozzolanic reactivity the finer the material.

Bulk Density of Biochar

Bulk density is a key physical trait that measures biochar mass per unit volume, including pore spaces. It illustrates how the substances behaves, its movement characteristics and the internal void of the material when it is used in a concrete mix. A lower bulk density is usually associated with higher porosity and this is desirable for water absorption and for internal curing. Bulk density was measured by filling a known volume container with loose biochar (without compaction) and finding the mass/volume ratio.

Table 4.2: Bulk Density of Produced Biochar

Biochar Type	Average Bulk Density (kg/m^3)
Groundnut Shell Biochar	6.8158
Cassava Peel Biochar	6.6785

Groundnut shell biochar had bulk density of 6.8159 kg/m^3 and the cassava peel biochar had slightly lower bulk density of 6.6785 kg/m^3. The low bulk density values for both the biochar suggest high porosity and weightlessness. The bulk density of the cassava peel biochar was slightly lower which indicates that the biochar has higher internal porosity than groundnut shell biochar. Significant internal curing can be realized by this very low bulk density, as the cement hydration continues with the release of mixing water from the highly porous biochar. Too low a bulk density, however, may cause uneven mixing or more fluid demand in wet concrete. This study did not measure the bulk density of the 50:50 blend, but it is assumed that it will have intermediate properties. Both biochar show physical characteristics favorable for use in cement replacement and have a high potential to enhance early-age hydration by internal curing mechanisms, as these results confirm.

Moisture Content

Following ASTM D2216 guidelines, an oven-drying method at 105 ± 5°C was used to measure moisture levels of representative biochar samples. The moisture content was calculated as the percentage loss in mass relative to the initial wet mass of the sample.

Table 4.3: Moisture Content of Produced Biochar

Biochar Type	Average Moisture Content (%)
Cassava Peel	20.37
Groundnut Shell	25.00

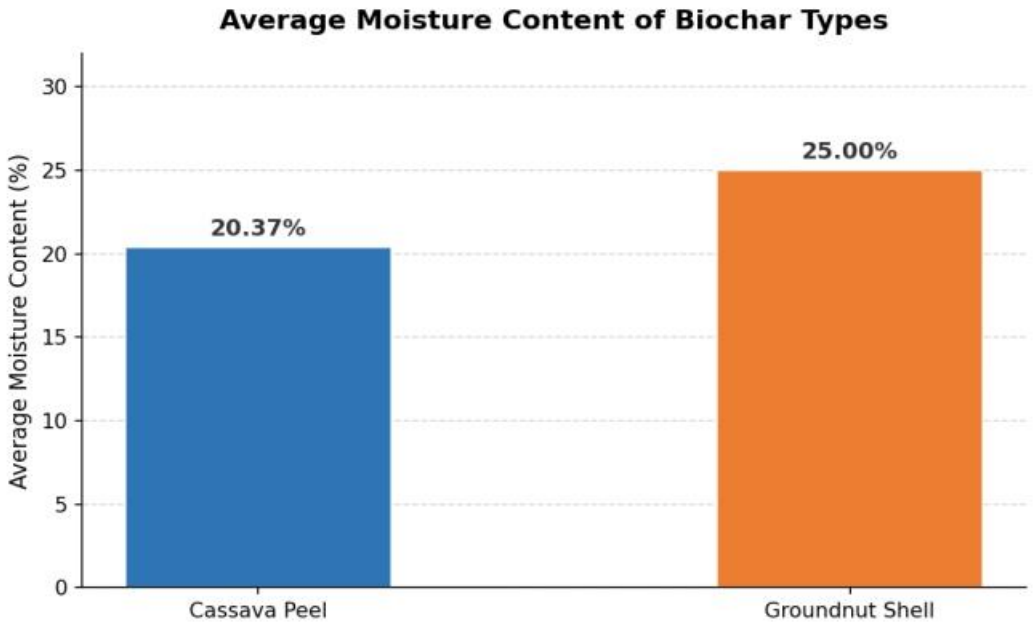


Figure 4.2: Average Moisture Content of Biochar Types

Table 4.3 reports the cassava peel and groundnut shell biochar moisture content, each determined from three independent samples. Cassava peel biochar exhibited a comparatively wider range of moisture content, spanning 11.11% to 25.00% with a mean of 20.37%, reflecting a degree of variability in its drying behavior. In contrast, groundnut shell biochar recorded a uniform moisture content of 25.00% across all three samples, indicating consistent and predictable moisture retention characteristics.

The disparity between the two materials is noteworthy. The fluctuation observed in cassava peel biochar may be attributable to its heterogeneous cellular structure, which can result in uneven moisture distribution and differential drying rates during processing. Groundnut shell biochar, on the other hand, appears to possess a more homogeneous internal structure, facilitating uniform moisture loss under identical drying conditions.

Workability (Slump Test)

The ASTM C143 slump test was used to evaluate the fresh concrete's workability. The goal was to observe how the biochar mixture made of equal parts groundnut shell and cassava peel affects the mix's behavior. The specific slump values for each sample appear below

Table 4.4: Slump Test Results of Concrete Mixes

Mix ID	Biochar Replacement (%)	Slump (mm)	Workability
C0	% (Control)	10	Very low
B1	1% (50:50 Blend)	15	Very low
B1.5	1.5% (50:50 Blend)	20	Low
B2	2% (50:50 Blend)	50	Medium

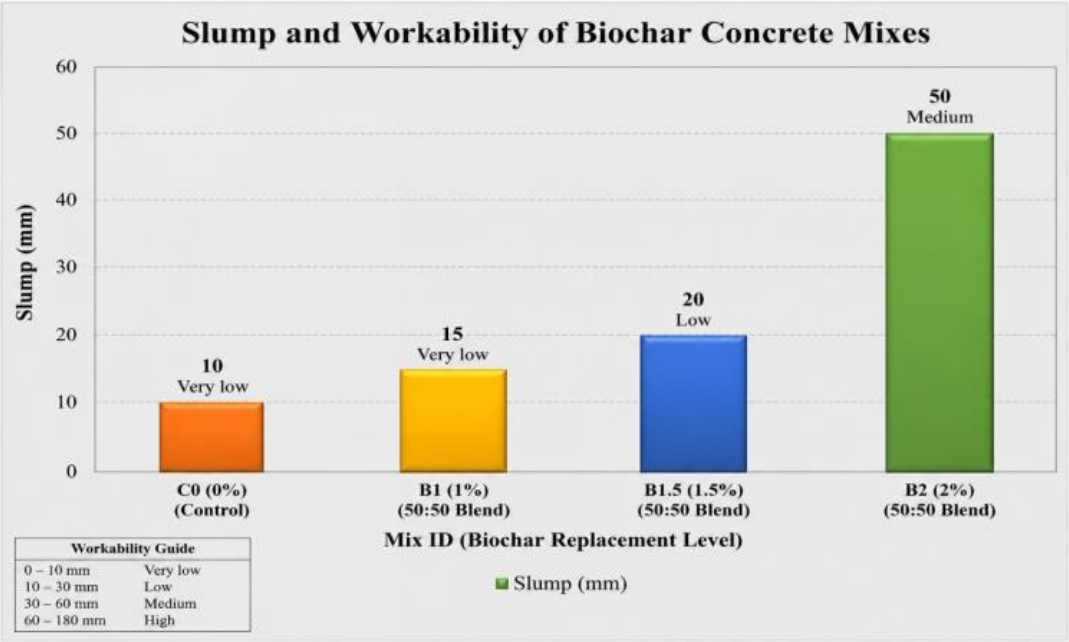


Figure 4.3: Slump and Workability of Biochar Concrete Mixes

Data presentation 4.3 shows that the control mix C0 had the lowest slump at 10mm, which means the workability was very low. For replacements level 1% and 1.5%, slump increased marginally to 15 mm and 20 mm respectively. Further increase in biochar content to 2% significantly improved slump value to 50 mm, translating to medium workability. It could be correlated to the effect of biochar particles on rheology of fresh concrete causing better dispersion of particles and reducing internal friction in the mix. On moving from 0% to 2% of biochar replacement level, slump increased by 400%. Consequently, it is seen that higher biochar amount improved mix workability.

Density of Fresh Concrete

Unit weight measurements of the plastic concrete followed standard ASTM C138 guidelines. This property gives information on the compactness of the mix, the effect of adding biochar on compaction behavior and unit weight. Tests were conducted in a container of internal dimensions 100 mm x 60 mm x 70 mm (V = 0.00042 m^3). For each mix, two replicate measurements were made. The table is shown below.

Table 4.5: Density of Fresh Concrete

Mix ID	Biochar Replacement (%)	Average mass (kg)	Average Density (kg/m^3)
C0	0% (Control)	2.24	3333
B1	1% (50:50 Blend)	2.195	3226
B1.5	1.5% (50:50 Blend)	2.455	3653
B2	2% (50:50 Blend)	1.855	2760

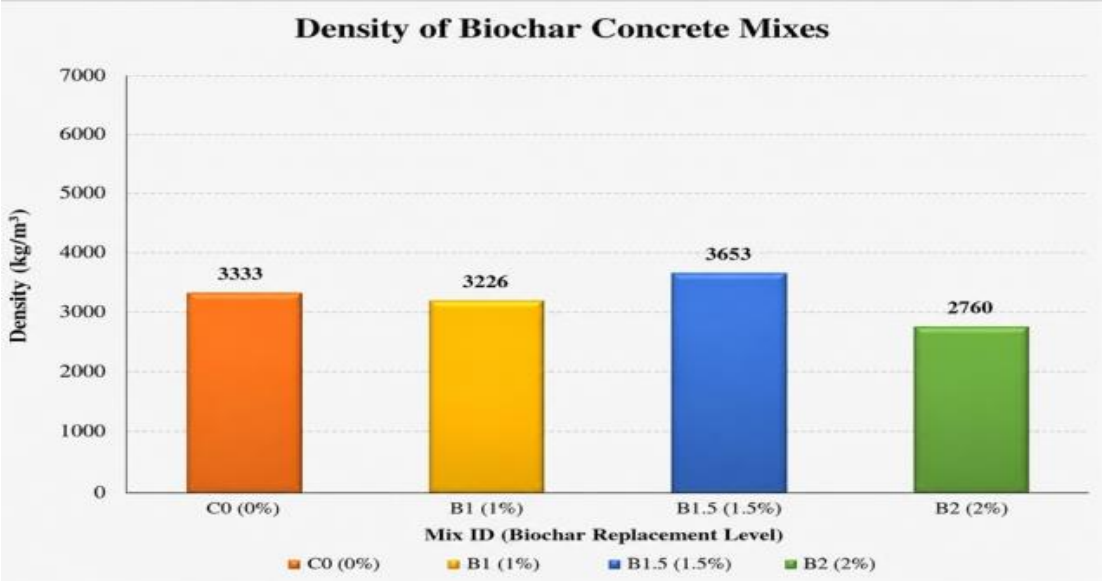


Figure 4.4: Density of Biochar Concrete Mixes

Figure 4.4 depicts the variation in concrete density as a percentage replacement with 50: 50 groundnut shell–cassava peel blended biochar produced from pyrolysis. At zero per cent biochar replacement blend (C0), the density obtained was found to be 3333 kg/m³. However, at 1% replacement of groundnut shell–cassava peel blended biochar (B1), a minor reduction in density was observed, reaching 3226 kg/m³. Then at the optimum percentage replacement level of 1.5% (B1.5), a density of 3653 kg/m³ was obtained. Also, the data demonstrates at higher replacement levels of 2%, there was a significant decrease in density (2760 kg/m³). Higher amounts of biochar lead to a drop in strength because the particle are light and full of tiny holes, which makes more empty spaces inside the concrete matrix. From the density results above, it can be concluded that up to certain levels of incorporation, biochar blends have no significant effect on density; however, beyond the optimum level, there is a sharp decrease in density as cement substitution becomes excessive. From outcome of density considered, 1.5% had the best density performance.

Setting Time

Adhering to ASTM C191 guidelines, the Vicat device was utilized to measure the start and end hardening periods of the cement mixtures. Prior to setting time test, the standard consistency of the control was established using the 10 mm diameter plunger to achieve a penetration of 4mm. The paste prepared at standard consistency was then used for determination of the beginning and end of the cement setting process.

Table 4.6: Initial and Final Setting Times of the Mixes

Mix ID	Biochar Replacement (%)	Initial Setting Time (min)	Final Setting Time (min)
C0	0% (Control)	120	323
B1	1% (50:50 Blend)	100	236
B1.5	1.5% (50:50 Blend)	63	120
B2	2% (50:50 Blend)	73	150

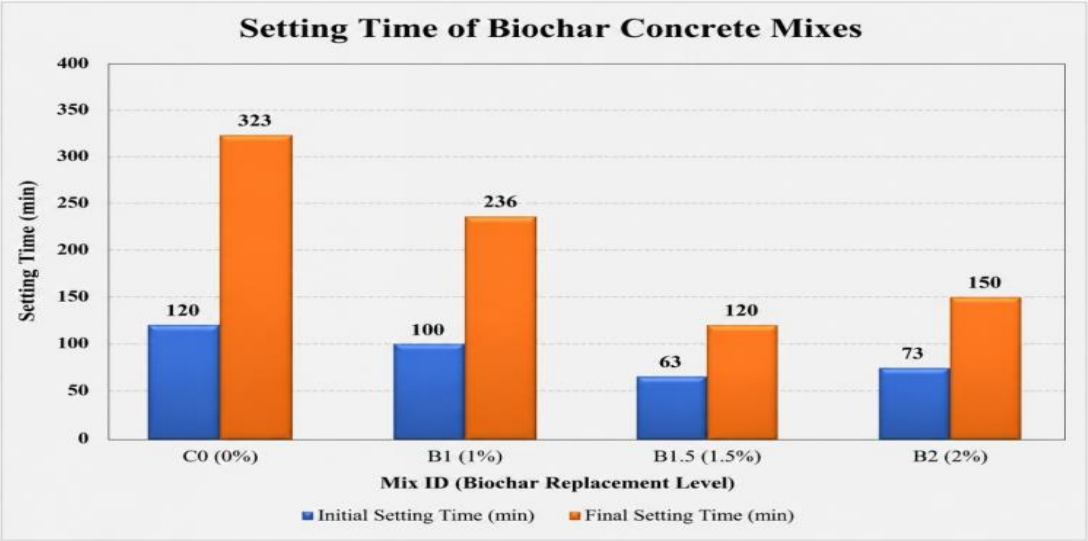


Figure 4.5: Setting Time of Concrete Mixes

Figure 4.5 above shows the addition of the 50:50 blended groundnut shell and cassava peel biochar resulted in a general reduction in both faster stiffening and hardening compared to the control mix. The control paste recorded the longest setting times (initial = 120 min, final = 323 min). Setting time was reduced at the increase of 0% - 1.5% replacement level. A great acceleration occurred at a replacement level of 1.5% (initial setting time = 63 min). There was a minor upward shift in the setting duration at a 2% substitution rate, though values were still below control mix values.

This speedup mostly comes from tiny biochar bits causing fast growth. Because biochar has a huge surface area, it creates an extra spot for new crystal formation like C-S-H gel and ettringite to form, which makes early reactions go faster. Although the biochar increased the water demand for standard consistency due to its porous nature, the overall influence on setting time was a net acceleration rather than retardation at the tested replacement levels.

These findings suggest that the blended biochar does not cause undesirable delay in setting time within the 1–2% replacement range and may even provide a moderate acceleration beneficial for construction scheduling in hot tropical climates.

Water Absorption of Hardened Concrete

The 28-day water absorption test measures the fluid intake of hardened concrete at room temperature. Expressed as a percentage of specimen's dry weight, this value served as a key indicator of concrete durability.

Table 4.7: Water Absorption of Hardened Concrete

Biochar Replacement Level (%)	Average Water Absorption (%)
0%	0.36
1%	0.39
1.5%	0.43
2%	0.40

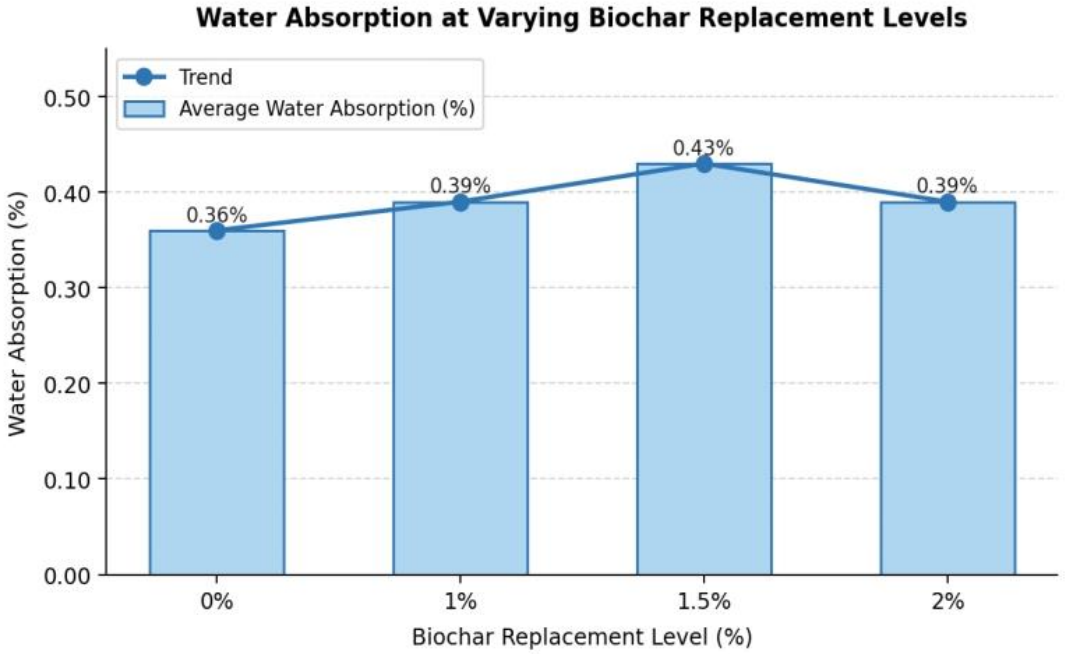


Figure 4.6: Average water absorption (%) at 0%, 1%, 1.5%, and 2% biochar replacement levels.

Figure 4.6 shows that of all the mixes tested, 1.5% replacement level had the highest average value of water absorption which was 0.43%, while the 0% mix exhibited the lowest average at 0.36%. Increasing the replacement level of 2% dropped slightly to an average of 0.40%. Raising the biochar content up to 1.5% leads to higher water uptake, which then decreases marginally at a 2% ratio. The introduction of extra gaps in the concrete structure stems from the highly porous quality of biochar granules. Nevertheless, the net growth remained negligible. All values fall well below the maximum limit of 5–6% typically recommended for good quality structural concrete in tropical environments, indicating acceptable porosity and potential durability.

Compressive Strength Test

The data in Table 4.8 illustrate how cassava peel and groundnut shell biochar affect compressive strength over 7,14, 21 & 28 curing days.

Table 4.8: Compressive Strength Results

Curing Age	0% Biochar (MPa)	1% Biochar (MPa)	1.5% Biochar (MPa)	2% Biochar (MPa)
7 Days	18.60	15.33	13.77	13.47
14 Days	12.40	17.87	14.80	18.63
21 Days	14.50	17.30	26.00	14.93
28 Days	19.73	17.03	16.17	13.77

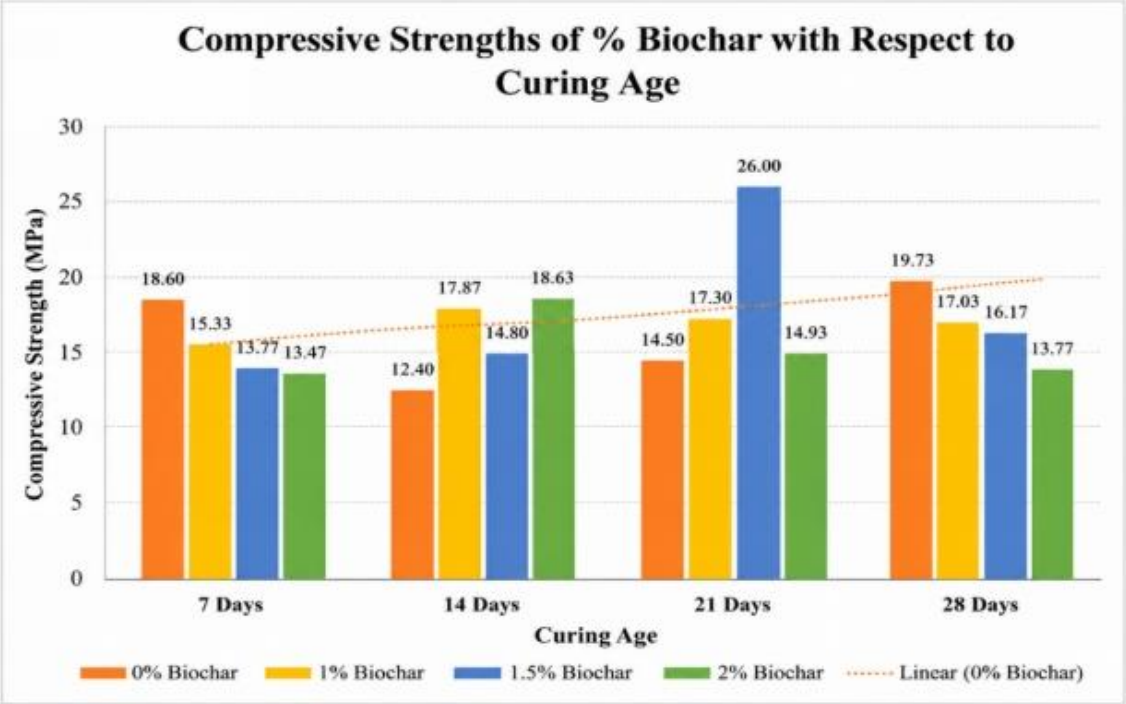


Figure 4.7: Compressive Strengths of % Biochar with Respect to Curing Age

The data Figure 4.7 indicate that compressive strength changes up and down across different curing ages, with some mixes showing increases and decreases in strength at different curing periods. It implied that biochar's effect on strength development was dependent not only on curing age but also on the replacement level. At the 7-day mark, the standard concrete mix reached a peak compressive strength of 18.60 MPa. In contrast, early strength dropped in all biochar-blended mixes, with 2% replacement dropping to the lowest compressive strength of 13.47 MPa. The reduced early compressive strength likely stems from biochar's substantial water absorption in the blended mixes, which limited the water available for initial hydration. However, at 14 days of curing, all biochar-containing blends exceeded the control mix's compressive strength. The 2% replacement sample reached a top strength of 18.63Mpa on day 14, whereas the 1.5% mix peaked at 26.00MPa on day 21. By day 28, the standard batch led with 19.73 MPa, with 1% and 1.5% mixes trailing at 17.03 MPa and 16.17 MPa. At later ages, mixes with 2% replacement depicted the lowest strength values. It can be concluded from the above results that 1% and 1.5% replacement of 50:50 groundnut shell–cassava peel blended biochar produced significant strength enhancement at intermediate curing ages, particularly between 14 and 21 curing days. This stems from the internal curing from porous biochar particles as they slowly released absorbed water content for continued hydration process and the nucleation effect of the fine particles filling in spaces thereby speeding up C-S-H gel formation. The comparatively lower strength values recorded at 2% replacement at later ages can be linked to the higher porosity introduced by the increased biochar dosage, thereby restricting strength development. The optimal blend mix for this study based on peak compressive strength performance is 1.5% replacement. Data also showed that the load capacities did not rise consistently in terms of curing age, as some mixes showed slight increases and decreases at different curing periods.

Flexural Strength Test

By testing concrete beams at 14 and 28days through the third-point loading method under ASTM C78, results of this test give insight into the tensile characteristics of the concrete specimens.

Table 4.9: Flexural Test Result

Curing Age	0% Biochar (MPa)	1% Biochar (MPa)	1.5% Biochar (MPa)	2% Biochar (MPa)
14 Days	8.10	11.50	13.45	12.35
28 Days	18.35	16.40	18.15	12.85

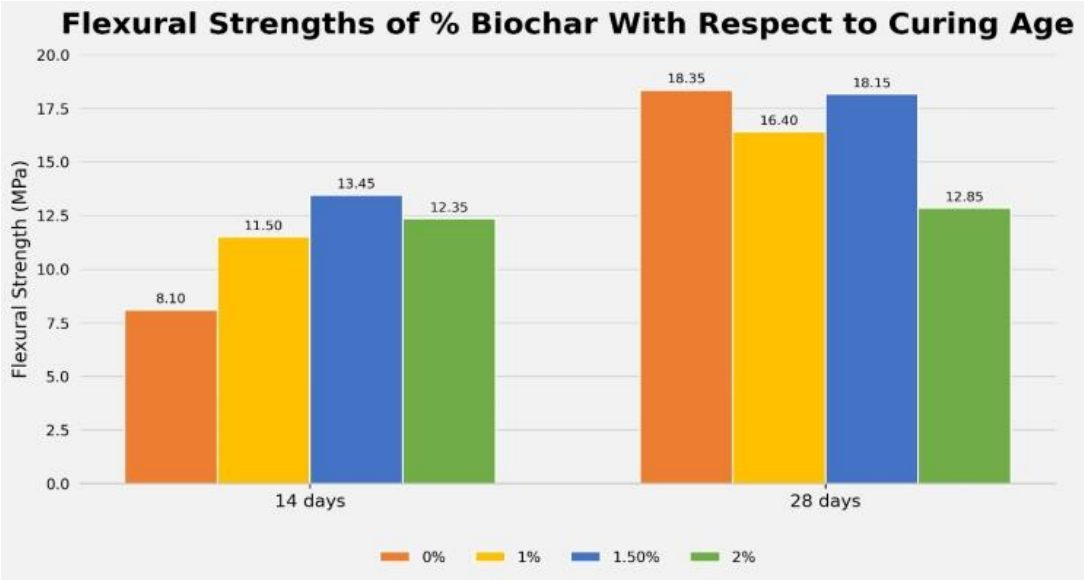


Figure 4.8: Flexural Strength of % Biochar with Respect to Curing Age

Data in Table 4.9 present the flexural strength results for different mixes at 14 and 28 days of curing. By day 14, every biochar mixture exceeded the control sample in strength, with the 1.5% substitution achieving a peak value of 13.45 MPa. Followed by the 2.0% and 1.0% replacement levels which had flexural strengths of 12.35 MPa and 11.50 MPa respectively. Compared to the control mix at 8.10 MPa, these strengths are higher.

The control mix reached its peak flexural strength of 18.35MPa after curing for 28 days. The flexural strengths recorded from the biochar mixes were all less than that of the control mix however they still maintained good strength capacity. The 1.5% replacement level had a flexural strength value of 18.15 MPa. The 1.0% replacement level had a flexural strength of 16.40 MPa. The highest loss of strength capacity was from the 2.0% replacement level having flexural strength of 12.85 MPa.

In summary, replacement at 1.0% and 1.5% of the 50: 50 groundnut shell–cassava peel blended biochar showed improvements or retained the flexural strength of concrete especially at 14 days. This decrease at 2.0% replacement level relates to greater pore space, resulting in lower density of the mixes. Weak zones created by void within the concrete matrix that facilitated the movement of cracks under flexural loads. 1.5% showed the best overall performance, implying that it could be the optimum dosage needed to improve flexural strength without sacrificing long-term strength capacity.

Elemental Composition Test (XRF)

X-ray fluorescence (XRF) data in Table 4.10 shows the oxide makeup of the biochar concrete mixture, while Figure 4.9 illustrates these mixing levels in comparative bar chart

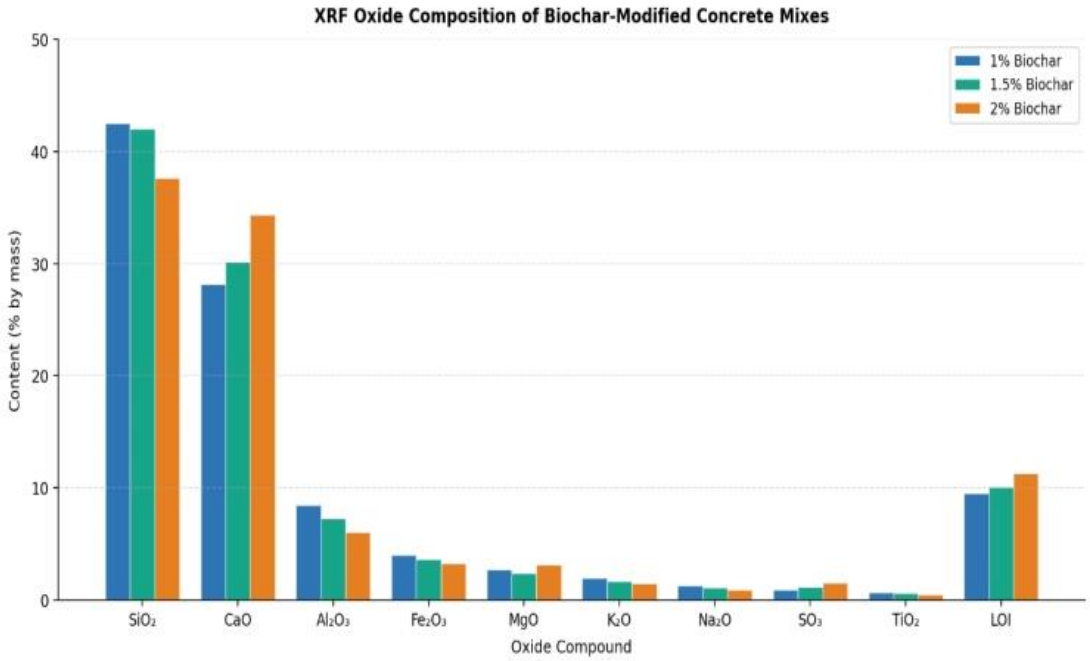


Figure 4.9: Grouped Bar Chart of Oxide Composition (% By Mass) At 1%, 1.5%, and 2% Biochar Replacement Levels.

Table 4.10: XRF Oxide Composition (% by mass) at Varying Biochar Replacement Levels

Oxide	Formula	1%	1.5%	2%
Silicon Dioxide	SiO_2	42.52	42.05	37.62
Calcium Oxide	CaO	28.16	30.18	34.39
Aluminum Oxide	Al_2O_3	8.42	7.26	6.02
Iron (III) Oxide	Fe_2O_3	3.99	3.62	3.27
Magnesium Oxide	MgO	2.72	2.39	3.15
Potassium Oxide	K_2O	1.94	1.64	1.43
Sodium Oxide	Na_2O	1.28	1.06	0.92
Sulfur Trioxide	SO_3	0.87	1.14	1.49
Titanium Oxide	TiO_2	0.63	0.59	0.45
Loss on Ignition	LOI	9.47	10.07	11.26

The XRF analysis was carried out for the biochar–cementitious materials. Table 4.10 Oxides composition from XRF analysis of the biochar modified cementitious materials is presented. The findings show that silicon dioxide (SiO_2) was the major oxide at all replacement levels, but in decreasing amounts from 42.52% in 1% replacement to 37.62% in 2% replacement, respectively. However, the highest amount of calcium oxide (CaO) had been observed at the highest biochar percentage, going from 28.16% to 34.39%.

The dominant presence of SiO_2 implies that the presence of chemically reactive constituents which may be able to undergo secondary cementitious reactions within the concrete matrix. These reactions can also help to fix the tiny holes and make the main material stronger. These beneficial reactions may however become less when you use a higher amount because there is less silica.

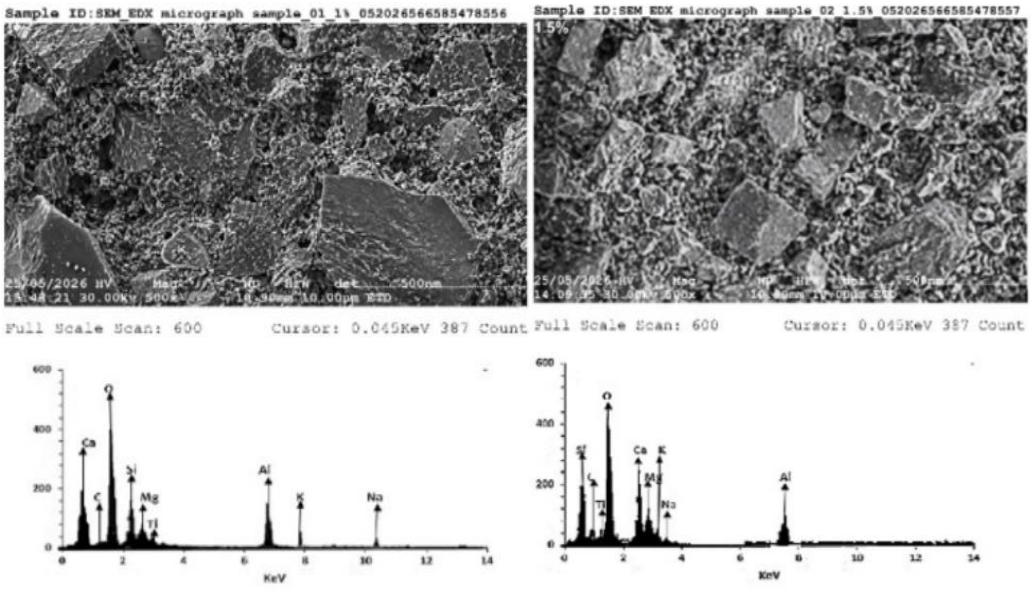
Higher the percentage of CaO in the biochar, the more calcium compounds are available, potentially affecting moisture interaction dynamics and the rate of early-stage structural hardening. The increase in Loss on Ignition (LOI) percentage was also observed, from 9.47% to 11.26%, which indicates that the amount of carbonaceous materials in the system is gradually increasing. Carbon content of moderate levels can enhance moisture holding capacity, while over high levels can disrupt binder continuity and diminish the effectiveness of binder bonding. These changes in composition give clues to the mechanical behaviour that is observed in the biochar-modified concrete mixtures.

Scanning Electron Microscopy (SEM)

The scan demonstrated the material shape in which the particles are irregular in shape, rough in surface texture and had a network of interconnected pores. These properties indicate a very porous material, with a potential to affect the microstructure.

Notably, the rough surface morphology can be important as it can also influence the physical interaction between the biochar particles and surrounding cement paste. Better surface contact can lead to better bonding between the interface and transfer of stresses to the hardened matrix. Moreover, the extensive amount of pores indicates that biochar can have a temporary water holding capacity for water, which can be slowly released with the hydration process of the cement and can help internal curing.

Although all these benefits may be achieved, if the percentage of replacement is too large, too much water may be absorbed and may lead to more voids in the concrete which helps explain the drop in structural performance observed for higher biochar contents, which can be explained by such effects. The microstructural analysis confirmed the strength trends exhibited during compressive and flexural testing which have also been explained from the microstructural point of view through the SEM observations.



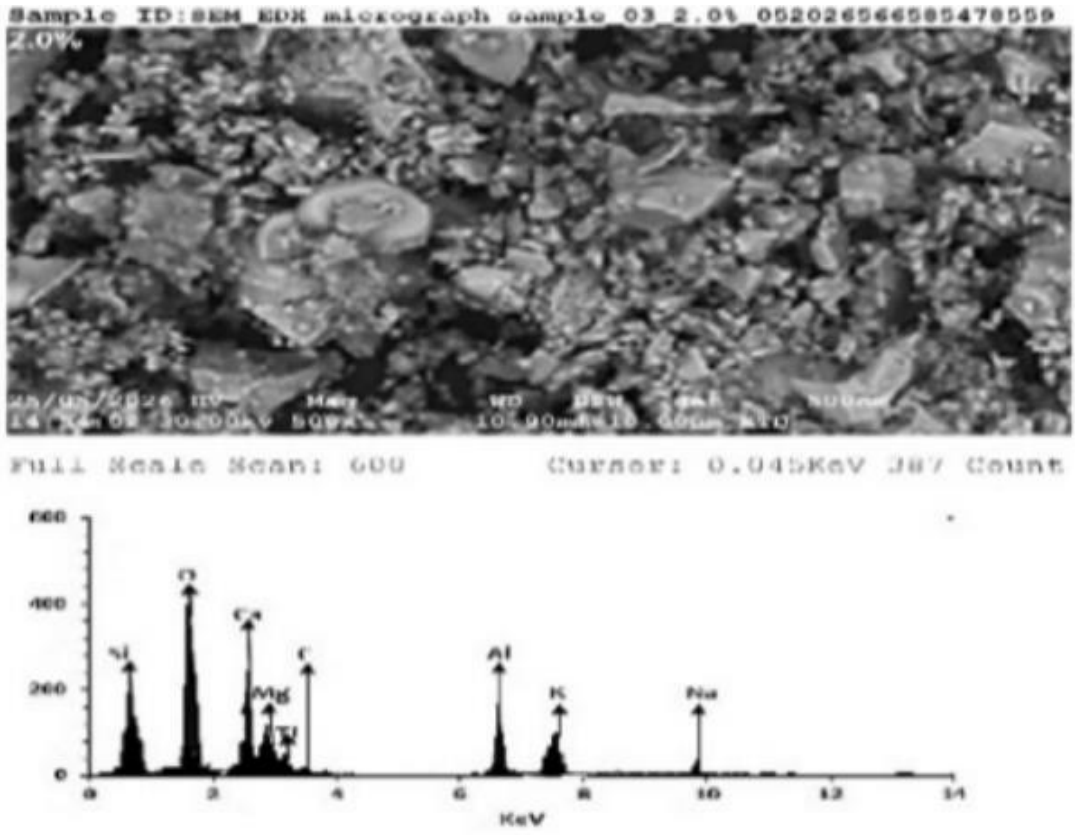


Figure 4.10: Scanning Electron Microscopy (SEM)

Statistical Analysis

Statistical analysis using (ANOVA) helped determine if the biochar caused real changes in concrete properties.

Table 4.11: One-Way ANOVA for Compressive Strength

Source of Variation	Sum of Squares	df	Mean Square	F	Sig. (p-value)
Between Groups	39.271	3	13.090	0.506	0.680
Within Groups	1138.582	44	25.877		
Total	1177.853	47			

Based on the one-way ANOVA in Table 4.11, the F-value obtained in the analysis was 0.506 and the significance value obtained was 0.680. Because the p value exceeds 0.05, the groups do not differ significantly, meaning we fail to reject the null hypothesis. The assumption of homogeneity of variance was accepted as the result of the Levene's test was significant at 0.104. Therefore, the results of ANOVA could be considered valid and reliable. This data revealed that with replacement level of up to 2%, addition of biochar to concrete did not significantly impact its compressive strength. Biochar addition up to a two percent substation rate likely will not notably affect the concrete's weigth-bearing strength.

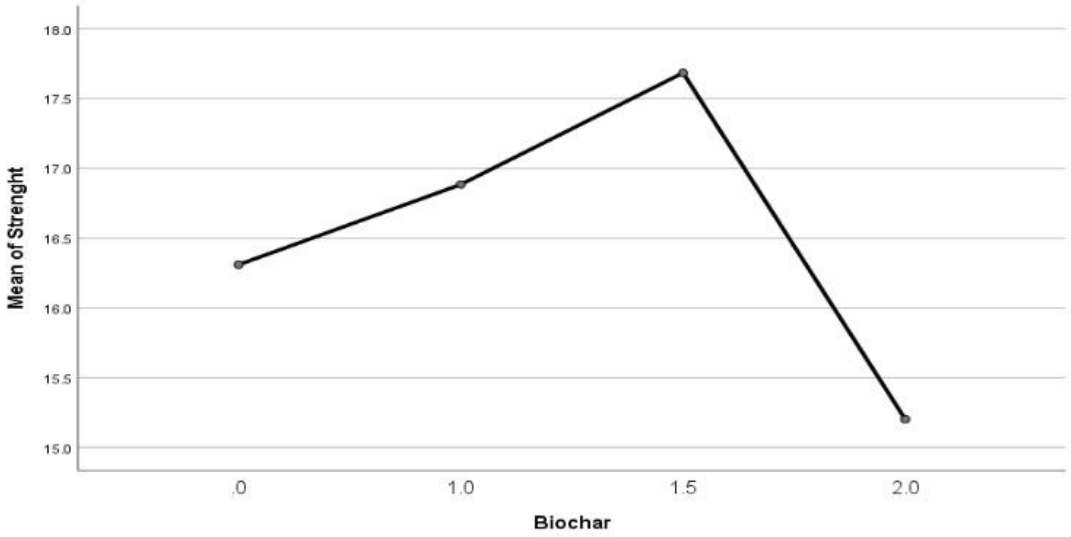


Figure 4.11: Descriptive Statistics for Compressive Strength of Concrete Cubes

Figure 4.11 explains that while 1.5% replacement ratio achieved the highest mean compressive strength, statistical analysis revealed no real differences among the replacement percentages

Table 4.12: One-Way ANOVA for Flexural Strength

Source of Variation	Sum of Squares	df	Mean Square	F	Sig. (p-value)
Between Groups	34.548	3	11.516	0.579	0.635
Within Groups	397.534	20	19.877		
Total	432.082	23			

The ANOVA results from Table 4.12 (F=0.579, p=0.635) show no significant difference among the replacement levels, leading us to accept the null hypothesis since the p-value exceeds 0.05. Levene's test yielded a p-value of 0.035, pointing to unequal variances across the group. Because the ANOVA test did not show a significant difference, no further follow-up tests were required.

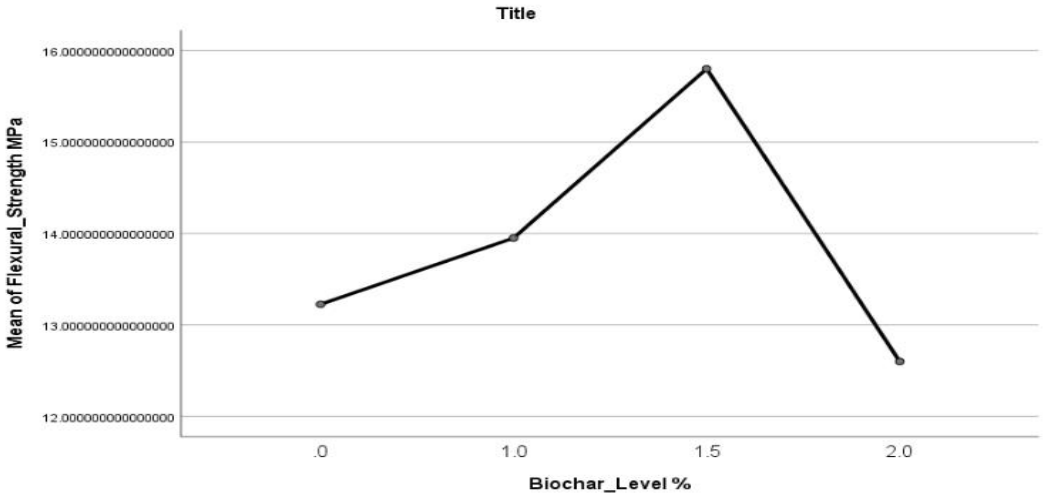


Figure 4.12: Descriptive Statistics for Flexural Strength of Concrete Beams

It is observed in Figure 4.12 that the biochar mix (1.5%) was able to reach the highest flexural strength average, but it is not statistically proven that this is as a direct effect of biochar. These observed differences could be due to natural experimental differences in the samples tested.

RECOMMENDATION AND CONCLUSION

The following are what the study revealed:

Groundnut shell biochar showed higher percentage passing values in all sieve sizes which shows a high proportion of fine particles. This smaller particle size distribution may indicate better packing properties and higher surface area, potentially leading to better interaction with cement hydration products.

The bulk density for the biochar showed that both had very low bulk density value, with the value of cassava peel biochar being slightly lower than groundnut shell biochar. This suggests a very porous material that holds water and can help to achieve internal curing in the concrete matrix. At higher replacement percentages, however, too much porosity can be introduced and have an adverse impact on strength gaining.

While the moisture content analysis revealed that the moisture holding capacity of groundnut shell biochar was more stable compared to cassava peel biochar where the differences can be attributed to the variation in internal structure and moisture distribution of biochar.

The properties of fresh concrete were performed after the addition of biochar noting that the biochar modified mixes gave better workability of concrete mixes. Starting at 10mm for the control mix, the values for slump enhanced steadily as more biochar was added, achieving 50 mm at 2% replacement level.

There were differences in the fresh concrete density according to the replacement percentage. Replacement level 1.5% of the fresh density had the highest fresh density, whereas the lighter and porous properties of the biochar particles led to a noticeable decrease in fresh density at the higher level of 2% replacement.

The setting time results also pointed out that biochar addition enhanced the time of setting compared to control mix. The replacement level of 1.5% gave the shortest setting time, suggesting that the small biochar particles may have created more nucleation points for the hydration product reactions to take place.

Water absorption results indicated an increase slightly at 1% to the highest level at 1.5% replacement rate. This behaviour is thought to result from the porosity of biochar particles. Absorption rates however, were still within acceptable limits and indicated that the concrete produced still possessed acceptable durability properties.

The compressive strength results indicated that the biochar influenced the strength development, depending on age of curing and replacement level. Concrete with biochar had better performance at mid curing ages, while the early curing age, the control concrete, had high strength at early curing ages.

The best compressive strength was obtained at 1.5% replacement level for 21 days cured, which showed that there was a balance between the internal curing, particle filling effect and hydration enhancement. Increased replacement levels (2% and more) led to lower strength as a result of higher porosity and lower cement content.

The flexural strength results indicated that the biochar was found as an effective constituent in improving the early flexural strength, particularly the 1.5% replacement level had the highest flexural strength at 14 days. The 28-day flexural strength of the control mix was the highest, but the 1.5% biochar mix had similar flexural results.

The chemical and microstructural characteristics were also analyzed. Showing that;

XRF analysis indicated the major oxide in the biochar modified cementitious materials silicon dioxide (SiO_2). Silica presence indicates possible secondary cementitious reactions, that may have involved strength development and pore refinement.

The increase in calcium oxide (CaO) content at increasing replacement levels also suggests that it may have some influence on the hydration behaviour. The increase in loss on ignition however indicates an increase in carbon content which may present bond issues if present in excess.

The morphology, surface texture and pore structure of the biochar particles were characterized by SEM, which showed that the particles had a non-spherical shape and irregular surfaces with interconnected pores. These properties are beneficial for the ability of biochar to hold water and for internal curing. The biochar also has a rough surface area, which has beneficial effects on mechanical interaction between the biochar particles and cement paste. Too much biochar content may increase void formation and decrease strength though.

The ANOVA analysis revealed that the difference between the levels of replacement with respect to compressive strength and flexural strength were not statistically significant at 95% confidence level.

The compressive strength analysis gave a significance value more than 0.05, showing that biochar replacement of up to 2% did not have a significant difference on the behaviour of the concrete compressive strength.

The same was observed in the flexural strength test. This is an indication that the structural performance of the concrete was retained within the investigated range when both biochar was incorporated.

Recommendations

Following these insights, the subsequent steps are advised:

1. Additional testing at 56 and 90 days is needed to understand the long-term strength of the biochar concrete.
2. Different carbonisation temperatures and production conditions should be studied to determine their influence on biochar quality and performance.
3. Future studies should investigate wider replacement ranges beyond 2% to determine the maximum practical replacement limit.
4. Additional durability tests such as sulphate resistance, chloride penetration, permeability, and shrinkage behaviour should be carried out to further establish the suitability of biochar concrete for construction applications.
5. The impact of different biochar particle sizes and grinding methods should be explored to understand their influence on strength and hydration behaviour.
6. Using of agricultural byproduct biochar as a supplementary material for construction should be encouraged due to its potential contribution to waste management, sustainability, and reduction of dependence on conventional cement materials.

Conclusion

The data and evidence from this study support these conclusions:

1. Wastes from groundnut shell and cassava peel can be effectively turned into biochar and serves as a partial substitute for the materials used for making of a cementitious composite.
2. The fine particle properties and porous structure produced by the biochar allow to improve their hydration behaviour and their ability to support the development of internal curing.
3. The mix of 50:50 groundnut shell and cassava peel blended biochar enhanced the fresh quality of the concrete by increasing workability and decreasing setting time of the concrete.

4. The amount of biochar and the curing time altered both the physical traits of the concrete mixtures. The replacement rate of 1.5% gave the best overall performance with the highest compressive strength on day 21 and highest flexural strength on day 14.
5. Adding more biochar than the optimum level had the effect of decreasing strength because it increased porosity, and it decreased the amount of cement binder.
6. The chemical and microstructural analyses verified biochar's addition of desirable properties that include surface roughness, internal water storage capacity, and silica content, which contributed to hydration and strength development.
7. The analysis of the results showed that the strength properties of compressive strength and flexural strength were not significantly affected up to 2% biochar blending.
8. Thus, 50:50 ratio of biochar (GS: CP) can be seen as an optimum replacement level for 1.5% replacement of cement in the scope of this study.

REFERENCES

Adeleke, A. A., Ogunjobi, J. K., & Adewumi, J. R. (2021). Environmental impacts of agricultural waste disposal practices in Nigeria. *Journal of Environmental Management, 285*, Article 112124. https://doi.org/10.1016/j.jenvman.2021.112124

Ahuja, A. (2023). *Concrete materials and sustainability practices.* Springer. https://doi.org/10.1007/978-3-031-21518-9

Aïtcin, P. (2019). The influence of the water/cement ratio on the sustainability of concrete. In *Lea's chemistry of cement and concrete.* https://doi.org/10.1016/b978-0-08-100773-0.00017-4

Akinwumiju, A. S., Ajayi, L. A., & Ojo, O. O. (2020). Assessment of aggregate sources and environmental degradation in southwestern Nigeria. *Construction and Building Materials, 240*, Article 117938. https://doi.org/10.1016/j.conbuildmat.2019.117938

Alhassan, E., Olaoye, J., Olayanju, T., & Okonkwo, C. (2019). An investigation into some crop residues generation from farming activities and inherent energy potentials in Kwara State, Nigeria. *IOP Conference Series: Materials Science and Engineering, 640.* https://doi.org/10.1088/1757-899x/640/1/012093

Amoakwah, A. N., Afrifa, R. O., & Adjei, E. (2024). Performance of biochar-modified cementitious composites under early-age curing conditions. *Journal of Cleaner Production, 412*, Article 137496. https://doi.org/10.1016/j.jclepro.2023.137496

Amusan, L. M., Oyekanmi, A. O., & Bello, M. O. (2023). Pretreatment effects on lignocellulosic biomass for pyrolysis applications. *Renewable Energy, 201*, 1235–1246. https://doi.org/10.1016/j.renene.2022.11.071

Andrew, R. M. (2019). Global CO2 emissions from cement production. *Earth System Science Data, 11*(4), 1675–1710. https://doi.org/10.5194/essd-11-1675-2019

ASTM International. (2021a). *Standard specification for concrete aggregates* (ASTM C33/C33M-21). ASTM International.

ASTM International. (2021b). *Standard specification for mixing water used in the production of hydraulic cement concrete* (ASTM C1602/C1602M-21). ASTM International.

ASTM International. (2021c). *Standard specification for Portland cement* (ASTM C150/C150M-21). ASTM International.

ASTM International. (2021d). *Standard test method for compressive strength of cylindrical concrete specimens* (ASTM C39/C39M-21). ASTM International.

ASTM International. (2021e). *Standard test method for flexural strength of concrete (using simple beam with third-point loading)* (ASTM C78/C78M-21). ASTM International.

ASTM International. (2021f). *Standard test method for slump of hydraulic-cement concrete* (ASTM C143/C143M-21). ASTM International.

Barham, W. S., Mahdi, A. A., & Hassan, A. H. (2023). Mechanical performance of recycled aggregate concrete: A review. *Materials Today: Proceedings, 65*, 341–349. https://doi.org/10.1016/j.matpr.2022.08.220

Bartoli, M., Arrigo, R., Malucelli, G., Tagliaferro, A., & Duraccio, D. (2022). Recent advances in biochar polymer composites. *Polymers, 14.* https://doi.org/10.3390/polym14122506

Dayoub, M., Benazzouk, A., & Douzane, O. (2024). Characterization of biochar for cementitious applications using XRF and microstructural techniques. *Construction and Building Materials, 387*, Article 131645. https://doi.org/10.1016/j.conbuildmat.2023.131645

Dixit, A., Gupta, S., & Kashani, A. (2023). Carbon sequestration potential and durability enhancement of biochar-based concrete. *Cement and Concrete Composites, 141*, Article 105125. https://doi.org/10.1016/j.cemconcomp.2023.105125

Dunuweera, S. P., & Rajapakse, R. M. G. (2018). Cement types, composition, uses and advantages of nanocement, environmental impact on cement production, and possible solutions. *Advances in Materials Science and Engineering, 2018*, Article 4158682. https://doi.org/10.1155/2018/4158682

Egbosiuba, T. C., Abdulkareem, A. S., & Tijani, J. O. (2022). Pyrolysis of agricultural waste biomass: Process parameters and material properties. *Cleaner Engineering and Technology, 7*, Article 100447. https://doi.org/10.1016/j.clet.2022.100447

Food and Agriculture Organization of the United Nations. (2022). *FAOSTAT statistical database.* FAO. https://www.fao.org/faostat

Getahun, A., Mekonnen, A., & Tadesse, B. (2024). Production and characterization of cassava peel biochar for environmental applications. *Biomass and Bioenergy, 178*, Article 106858. https://doi.org/10.1016/j.biombioe.2023.106858

Grema, A. S., Ahmed, A. A., & Lawal, A. M. (2023). Biochar production from agricultural residues: Implications for construction materials. *Journal of Materials Research and Technology, 25*, 3567–3578. https://doi.org/10.1016/j.jmrt.2023.04.112

Gupta, S., & Kashani, A. (2021). Biochar as a carbon-negative additive in cementitious materials. *Cement and Concrete Composites, 119*, Article 104001. https://doi.org/10.1016/j.cemconcomp.2021.104001

Gupta, S., Dixit, A., & Kashani, A. (2023). Biochar-modified concrete: A review on performance and sustainability. *Journal of Cleaner Production, 387*, Article 135879. https://doi.org/10.1016/j.jclepro.2023.135879

International Energy Agency. (2023). *Cement technology roadmap: Towards net zero emissions.* IEA. https://www.iea.org/reports/cement

Jayaraju, R. M., Gaddam, K., Ravindiran, G., Palani, S., Paulraj, M., Achuthan, A., Saravanan, P., & Muniasamy, S. K. (2021). Biochar from waste biomass as a biocatalyst for biodiesel production: An overview. *Applied Nanoscience, 12*, 3665–3676. https://doi.org/10.1007/s13204-021-01924-2

Khater, H. M., El-Sayed, S. A., & Abdelrahman, M. A. (2024). Influence of biochar physicochemical properties on cement hydration and early-age strength. *Materials, 17*(2), Article 418. https://doi.org/10.3390/ma17020418

Kim, J. (2022). Influence of quality of recycled aggregates on the mechanical properties of recycled aggregate concretes: An overview. *Construction and Building Materials.* https://doi.org/10.1016/j.conbuildmat.2022.127071

Kirthika, S. K., Singh, S. K., & Chourasia, A. (2020). Alternative fine aggregates in production of sustainable concrete: A review. *Journal of Cleaner Production, 268*, Article 122089. https://doi.org/10.1016/j.jclepro.2020.122089

Li, Y., Zhang, J., & Wang, K. (2022). Effect of biochar fineness and dosage on cement hydration kinetics. *Construction and Building Materials, 323*, Article 126546. https://doi.org/10.1016/j.conbuildmat.2022.126546

Mindess, S., Young, J. F., & Darwin, D. (2021). *Concrete* (3rd ed.). Pearson Education.

Mosaberpanah, M. A., Eren, O., & Al-Shathr, B. S. (2024). Early-age behavior of sustainable concrete incorporating bio-based additives. *Materials Today Sustainability, 26*, Article 100465. https://doi.org/10.1016/j.mtsust.2023.100465

National Bureau of Statistics. (2024). *Cement production and consumption statistics in Nigeria.* NBS. https://www.nigerianstat.gov.ng

Obla, K. H., Lobo, C. L., & Kim, H. (2022). Concrete performance in hot and humid environments. *ACI Materials Journal, 119*(5), 45–58.

Olawale, O., Akinyemi, B., & Attabo, F. (2020). Optimization of the mixing ratio for particleboard production from groundnut shell and rice husk. *Acta Technologica Agriculturae, 23*, 168–175. https://doi.org/10.2478/ata-2020-0027

Rocco, C., & Elices, M. (2008). Effect of aggregate shape on the mechanical properties of a simple concrete. *Engineering Fracture Mechanics, 76*, 286–298. https://doi.org/10.1016/j.engfracmech.2008.10.010

Scrivener, K. L., Snellings, R., & Lothenbach, B. (2021). *A practical guide to microstructural analysis of cementitious materials* (2nd ed.). CRC Press.

Shanks, W., Dunant, C., Drewniok, M., Lupton, R., Serrenho, A., & Allwood, J. (2019). How much cement can we do without? Lessons from cement material flows in the UK. *Resources, Conservation and Recycling.* https://doi.org/10.1016/j.resconrec.2018.11.002

Sinha, A., Kumar, S., & Mishra, P. (2023). Biochar–cement interactions and implications for sustainable construction. *Journal of Materials in Civil Engineering, 35*(9), Article 04023217. https://doi.org/10.1061/(ASCE)MT.1943-5533.0004881

Tu, Y., Liu, H., & Chen, B. (2022). Influence of pyrolysis conditions on biochar properties for cement-based materials. *Fuel, 319*, Article 123784. https://doi.org/10.1016/j.fuel.2022.123784

Wang, Q., Li, J.-S., & Poon, C. (2022). An iron-biochar composite from co-pyrolysis of incinerated sewage sludge ash and peanut shell for arsenic removal: Role of silica. *Environmental Pollution,* Article 120115. https://doi.org/10.1016/j.envpol.2022.120115

Wijitkosum, S. (2023). Biomass-derived additives for cement hydration control. *Case Studies in Construction Materials, 18*, Article e01962. https://doi.org/10.1016/j.cscm.2023.e01962

Zhao, S., Wang, Y., & Li, X. (2024). Early-age hydration and mechanical performance of biochar-blended concrete. *Construction and Building Materials, 392*, Article 132002. https://doi.org/10.1016/j.conbuildmat.2023.132002

APPENDICES

APPENDIX A: MIX CALCULATION

A.1 Specimen Details and Volume Calculations

Cubes: 100 mm × 100 mm × 100 mm
Volume of one cube = 0.001 m³
Total for 12 cubes = 0.012 m³
Beams: 100 mm × 100 mm × 400 mm
Volume of one beam = 0.004 m³
Total for 6 beams = 0.024 m³
Total volume of concrete per batch = 0.036 m³

A.2 Mix Ratio and Assumptions

A concrete mix ratio of 1:1:2 (cement: fine aggregate: coarse aggregate) by weight was adopted for this study. The calculations were based on an M25 grade mix using a cement content of 1440 kg/m³ for the batch volume.

A.3 Detailed Calculations for Each Replacement Level

1. Control Mix (0% Biochar)
Cement for cubes = (1/4) × 0.001 × 12 × 1440 = 4.32 kg
Cement for beams = (1/4) × 0.004 × 6 × 1440 = 8.64 kg
Total Cement = 4.32 + 8.64 = 12.96 kg
Fine Aggregate = (1/4) × 0.001 × 12 × 1600 = 4.80 kg
Coarse Aggregate = (2/4) × 0.004 × 6 × 1600 = 9.60 kg
Water = 0.45 × 12.96 = 5.83 kg
2. 1% Replacement
Total Binder = 12.96 kg
Biochar = 1% of 12.96 = 0.1296 kg
Cement = 12.96 – 0.1296 = 12.8304 kg
Fine Aggregate = 12.96 kg
Coarse Aggregate = 25.92 kg
Water = 0.45 × 12.96 = 5.83 kg
3. 1.5% Replacement
Total Binder = 12.96 kg
Biochar = 1.5% of 12.96 = 0.1944 kg
Cement = 12.96 – 0.1944 = 12.7656 kg
Fine Aggregate = 12.96 kg
Coarse Aggregate = 25.92 kg
Water = 0.45 × 12.96 = 5.83 kg
4. 2% Replacement
Total Binder = 12.96 kg
Biochar = 2% of 12.96 = 0.2592 kg
Cement = 12.96 – 0.2592 = 12.7008 kg
Fine Aggregate = 12.96 kg
Coarse Aggregate = 25.92 kg
Water = 0.45 × 12.96 = 5.83 kg

APPENDIX B: PARTICLE SIZE DISTRIBUTION

PARTICLE SIZE DISTRIBUTION OF GROUNDNUT SHELL

Sieve Size (µm)	Mass Retained (g)	% Retained	Cumulative % Retained	% Passing
300	450	18.75	18.75	81.25
200	410	17.08	35.83	64.17
150	400	16.67	52.50	47.50
75	370	15.42	67.92	32.08
63	380	15.83	83.75	16.25
Pan	390	16.25	100.00	0.00
Total	2400	100	-	-

PARTICLE SIZE DISTRIBUTION OF CASSAVA PEEL BIOCHAR

Sieve Size (µm)	Mass Retained (g)	% Retained	Cumulative % Retained	% Passing
300	1000	41.67	41.67	58.33
200	500	20.83	62.50	37.50
150	400	16.67	79.17	20.83
75	300	12.50	91.67	8.33
63	100	4.17	95.83	4.17
Pan	100	4.17	100.00	0.00
Total	2400	100.00	-	-

APPENDIX C: BULK DENSITY

BULK DENSITY OF BIOCHAR SAMPLES

Trial	Cassava Peel Mass (kg)	Cassava Bulk Density (kg/m³)	Groundnut Shell Mass (kg)	Groundnut Bulk Density (kg/m³)
1	0.04242	6.809	0.04112	6.600
2	0.04258	6.834	0.04325	6.942
3	0.03982	6.391	0.04302	6.905
Mean	—	6.678	—	6.815

APPENDIX D: MOISTURE CONTENT

MOISTURE CONTENT OF BIOCHAR SAMPLES

Biochar Type	Sample	Initial Weight (kg)	Final Dry Weight (kg)	Moisture Loss (kg)	Moisture Content (%)
Cassava Peel	A	0.010	0.008	0.002	25.00
Cassava Peel	B	0.010	0.009	0.001	11.11
Cassava Peel	C	0.010	0.008	0.002	25.00
Cassava Avg	—	—	—	—	20.37
Groundnut Shell	A	0.010	0.008	0.002	25.00
Groundnut Shell	B	0.010	0.008	0.002	25.00
Groundnut Shell	C	0.010	0.008	0.002	25.00
Groundnut Avg	—	—	—	—	25.00

APPENDIX E: STANDARD CONSISTENCY AND INITIAL AND FINAL SETTING TIME

STANDARD CONSISTENCY

Water Content (%)	Water Required (kg)	Vicat Penetration (mm)
25	0.075	10
32	0.096	8
38	0.114	6
40	0.120	4

INITIAL AND FINAL SETTING TIME

Biochar Content (%)	Cement (kg)	Biochar (kg)	Water (kg)	Initial Setting Time	Final Setting Time
0.0	0.3000	0.0000	0.102	2 h 00 min	5 h 23 min
1.0	0.2970	0.0030	0.102	1 h 40 min	3 h 56 min
1.5	0.2955	0.0045	0.102	1 h 03 min	2 h 00 min
2.0	0.2940	0.0060	0.102	1 h 13 min	2 h 30 min

APPENDIX F: FRESH CONCRETE DENSITY

FRESH CONCRETE DENSITY

Mix (%)	Trial 1 (kg/m³)	Trial 2 (kg/m³)	Average (kg/m³)
0%	3407.74	3258.93	3333.335
1%	3258.93	3273.81	3266.37
1.5%	3675.60	3630.95	3653.275
2%	2723.21	2797.62	2760.415

APPENDIX G: COMPRESSIVE STRENGTH

COMPRESSIVE STRENGTH FOR CONCRETE CUBE

Biochar (%)	Sample	Weight (kg)	Failure Load (kN)	Strength (MPa)
0%	1	1.55	160	16.0
0%	2	1.70	202	20.2
0%	3	1.65	146	14.6
			Average	**18.60**
1%	1	2.70	107	10.7
1%	2	2.62	176	17.6
1%	3	2.96	177	17.7
			Average	**17.33**
1.5%	1	2.45	108	10.8
1.5%	2	2.82	140	14.0
1.5%	3	2.82	165	16.5
			Average	**13.77**
2%	1	2.61	138	13.8
2%	2	2.73	125	12.5
2%	3	2.70	141	14.1
			Average	**13.47**

APPENDIX H: FLEXURAL STRENGTH

FLEXURAL STRENGTH FOR CONCRETE BEAM

Biochar Replacement	Sample	Failure Load (kN)	Flexural Strength (MPa)
0%	1	30	4.50
0%	2	37	5.55
0%	3	95	14.25
		Average	**8.10**
1%	1	56	8.40
1%	2	80	12.00
1%	3	94	14.10
		Average	**11.50**
1.5%	1	122	18.30
1.5%	2	77	11.55
1.5%	3	70	10.50

Biochar Replacement	Sample	Failure Load (kN)	Flexural Strength (MPa)
		Average	**13.45**
2%	1	91	13.65
2%	2	63	9.45
2%	3	93	13.95
		Average	**12.35**

APPENDIX I: WATER ABSORPTION

WATER ABSORPTION FOR CONCRETE CUBES

Biochar Level	Replacement	Sample	Dry Weight (kg)	Saturated Weight (kg)	Water Absorbed (kg)	Water Absorption (%)
0%		A	2.700	2.710	0.010	0.37
0%		B	2.900	2.910	0.010	0.34
0%		C	2.850	2.860	0.010	0.35
Average 0%		—	—	—	—	0.36
1%		A	2.710	2.720	0.010	0.37
1%		B	2.480	2.490	0.010	0.40
1%		C	2.500	2.510	0.010	0.40
Average 1%		—	—	—	—	0.39
1.5%		A	2.470	2.480	0.010	0.40
1.5%		B	2.200	2.210	0.010	0.45
1.5%		C	2.400	2.410	0.010	0.42
Average 1.5%		—	—	—	—	0.43
2%		A	2.300	2.310	0.010	0.43
2%		B	2.810	2.820	0.010	0.36
2%		C	2.600	2.610	0.010	0.38
Average 2%		—	—	—	—	0.39

APPENDIX J: WATER ABSORPTION

DATA ANALYSIS

Oneway

Notes		
Output Created		22-JUN-2026 01:04:23
Comments		
Input	Data	C:\Users\HP\Downloads\one way.sav
	Active Dataset	DataSet1
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	53
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics for each analysis are based on cases with no missing data for any variable in the analysis.
Syntax		ONEWAY Strenght BY Biochar /STATISTICS DESCRIPTIVES HOMOGENEITY /PLOT MEANS /MISSING ANALYSIS.
Resources	Processor Time	00:00:01.27
	Elapsed Time	00:00:00.95

[DataSet1] C:\Users\HP\Downloads\one way.sav

Descriptives

Strenght

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
.0	12	16.308	4.2839	1.2367	13.586	19.030	10.7	25.2
1.0	12	16.883	3.7728	1.0891	14.486	19.280	10.7	23.9
1.5	12	17.683	7.9715	2.3012	12.618	22.748	10.8	39.8
2.0	12	15.200	2.7159	.7840	13.474	16.926	12.5	22.4
Total	48	16.519	5.0061	.7226	15.065	17.972	10.7	39.8

Test of Homogeneity of Variances

		Levene Statistic	df1	df2	Sig.
Strenght	Based on Mean	2.180	3	44	.104
	Based on Median	1.463	3	44	.238
	Based on Median and with adjusted df	1.463	3	22.511	.251
	Based on trimmed mean	1.686	3	44	.184

Oneway

Notes		
Output Created		22-JUN-2026 01:18:17
Comments		
Input	Data	C:\Users\HP\Downloads\Flexural SPSS.sav

		Active Dataset	DataSet4
		Filter	<none>
		Weight	<none>
		Split File	<none>
		N of Rows in Working Data File	24
Missing Handling	**Value**	Definition of Missing	User-defined missing values are treated as missing.
		Cases Used	Statistics for each analysis are based on cases with no missing data for any variable in the analysis.
Syntax			ONEWAY Flexural_StrengthMPa BY Biochar_Level /STATISTICS DESCRIPTIVES HOMOGENEITY /PLOT MEANS /MISSING ANALYSIS.
Resources		Processor Time	00:00:00.56
		Elapsed Time	00:00:00.29

[DataSet4] C:\Users\HP\Downloads\Flexural SPSS.sav

Descriptives

Flexural_Strength MPa

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
.0	6	13.225000000000000	6.633607615769868	2.708158968746111	6.263455746983397	20.186544253016603	4.500000000000000	19.350000000000000
1.0	6	13.949999999999998	3.647190699702992	1.488959368149447	10.122508094266243	17.777491905733750	8.400000000000000	18.900000000000000
1.5	6	15.799999999999997	4.134851871591050	1.688046207898350	11.460739080297717	20.139260919702280	10.500000000000000	20.100000000000000
2.0	6	12.600000000000000	2.258982071642005	.92222556893 6364	10.229343704152473	14.970656295847526	9.450000000000000	14.850000000000000
Total	24	13.893749999999997	4.334299815576254	.88473524503 3421	12.063535702155766	15.723964297844232	4.500000000000000	20.100000000000000

Test of Homogeneity of Variances

		Levene Statistic	df1	df2	Sig.
Flexural_Strength MPa	Based on Mean	3.474	3	20	.035
	Based on Median	1.841	3	20	.172
	Based on Median and with adjusted df	1.841	3	11.929	.194
	Based on trimmed mean	3.255	3	20	.043