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Performance Evaluation of Fonio Chaff, Eggshell Powder, and Charcoal Ash as Partial Cement Replacement in Compressed Stabilised Earth Bricks

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Abstract

Rapid urbanisation, natural resource depletion, and the high environmental impact of Portland cement production have intensified the search for sustainable, locally sourced construction materials. Compressed stabilised earth bricks (CSEBs) present a promising alternative due to their low energy demand and adaptability to local soils. This study investigated the strength performance of CSEBs incorporating agricultural by-products (Fonio chaff, Eggshell powder, and Charcoal ash) as partial cement replacements at 5% and 10% levels using a true experimental research design. The existing scientific evidence was reviewed to understand how these bio-derived additives influence the physical and chemical behaviour of stabilised earth matrices. The laboratory testing assessed physical properties. The compressive strength at different curing ages, water absorption, and workability. The materials exhibited specific gravity values of 1.4-2.7, bulk densities between 300-1700 g/cm^3, and moisture content of 16.20-21.21%. The compressive strength finding showed performance improvements at both 5% and 10% replacement levels. Eggshell powder and charcoal ash demonstrated the greatest strength gains, with 10% replacement producing the highest strength across curing periods. Fonio chaff showed moderate improvement, particularly at 5% replacement. Water absorption varied notably, with eggshell powder mixes recording the lowest strength, while fonio chaff mixes showed a higher absorption rate. The workability remained within acceptable ranges for all mixes. These findings supported the potential of agricultural waste as eco-friendly cement substitutes in CSEBs, by converting and utilising locally available agricultural by-products into value-added construction materials. This approach advances circular-economy principles and offers a pathway toward low-carbon, affordable, and resilient housing solutions, particularly in Nigeria.

Keywords: Agricultural wastes utilization; Compressed stabilised earth bricks; Fonio chaff; Eggshell powder; Charcoal ash; Pozzolanic materials; Sustainable construction; Circular economy

INTRODUCTION

Cement remains the cornerstone of modern construction, yet its production process produces approximately 8%-10% of global carbon dioxide (CO_2) emissions (Andrew, 2019; Mohamad *et al.,* 2019). One tonne of ordinary Portland cement releases nearly an equal amount of carbon dioxide owing to the calcination of limestone and the combustion of fossil fuels (Habert *et al*, 2020; Öztürk *et al*., 2025). As the world's urban population continues to expand, the demand for cement-based infrastructure places unsustainable pressure on natural resources and the environment. Consequently, researchers are exploring alternative materials that can deliver comparable structural performance with lower environmental impact (He *et al.,* 2020). Among the promising materials are compressed stabilised earth bricks (CSEBs) from engineered earthen units. Produced by mixing soil, sand, water, and a stabilising binder, like cement or lime, and compressing the mixture under controlled conditions (Abdullah, 2017). CSEBs combine the thermal comfort of traditional adobe with improved mechanical strength and durability, making them suitable for low-cost and sustainable housing. They require minimal energy for production. They can be manufactured locally, and reduce reliance on fired bricks whose kilns contribute to deforestation and greenhouse gas emissions (Bui *et al.*, 2023; Oghoghorie & Eboigbe, 2025). The versatility of CSEBs lies in their ability to incorporate diverse stabilising agents like agricultural and industrial by-products, thereby aligning with the principles of the circular economy.

On the global stage, research into sustainable materials and the utilisation of agricultural by-products as partial cement replacements represents a process of waste management and construction innovation (Vipul & Kumar, 2014). Agricultural by-products such as rice husk ash, palm kernel shell, bagasse ash, and eggshell powder have demonstrated pozzolanic properties that enhance strength and durability while mitigating environmental pollution (Pandey & Kumar, 2021; Tejas & Pasla, 2024; Olumodeji *et al*., 2023). These materials contain reactive oxides, silica, alumina, and calcium that can form additional calcium, silicate-hydrate (CSH) gel through secondary hydration reactions. This approach diverts organic waste from landfills, reduces cement demand and the associated energy consumption.

Nigeria, like many developing nations, faces an increase in housing deficit due to the high cost of conventional materials and rapid population growth. The construction sector's heavy dependence on imported materials has led to rapid price change, limited affordability, and the rise in substandard building practices (State House, 2023; Nwanya & Ononiwu, 2020). To bridge the housing gap in sustainability, attention has shifted towards locally sourced, low-energy materials such as CSEBs that integrate renewable additives. Nigeria's diverse agro-ecological zones produce abundant residues like fonio chaff (FC) from cereal milling, eggshells (ES) from poultry processing, and charcoal ash (CA)from biomass fuel. Each possesses chemical components comparable to those of cementitious binders. Harnessing these wastes can create local value chains to stimulate rural economies and reduce the environmental footprint of the building industry.

Globally, researchers are evaluating the mechanical and durability performance of such additives under varying conditions of mix proportion, curing age, and compaction energy. Eggshell powder (ESP), rich in calcium carbonate, has been shown to enhance compressive and flexural strength at moderate levels of 5%–15% cement replacement (Hardeep *et al.*, 2023). Charcoal ash (CA), containing silica and alumina, contributes to improved bonding and reduced permeability (William *et al.*, 2023). While fonio chaff (FC), composed of cellulose and lignin, acts as a fibrous reinforcement that mitigates micro-cracking and enhances thermal insulation (Babarinde *et al*., 2020; Bentur & Larianovsky, 2024).

Despite encouraging results, inconsistencies persist due to variations in raw-material composition, particle fineness, and curing age. Thus, the need for systematic reviews to consolidate current understanding. This study, therefore, presents a comprehensive exploration of literature on the partial replacement of cement with Fonio chaff, Eggshell powder, and Charcoal ash in CSEBs. It integrates theoretical foundations of cement hydration and microstructural development with empirical findings from recent studies, including experimental data from Nigeria. The study critically analyses their influence on key engineering properties like compressive strength, water absorption rate, and workability. Thus, situates these within broader sustainability objectives such as resource efficiency and emissions reduction. By bridging material science and environmental engineering perspectives, the study aims to provide a consolidated reference for researchers, practitioners, and policymakers pursuing sustainable construction strategies in both developed and developing countries.

Overview of Sustainable Cement Substitutes

The demand for sustainable construction materials has driven extensive research into natural and waste-derived binders capable of partially substituting Portland cement without compromising performance. The concept of green cementitious materials is anchored in reducing the embodied energy and carbon footprint associated with traditional cement production, which emits approximately 8-10 tonnes of CO_2 per tonne of cement produced (Habert *et al*., 2020). Supplementary cementitious materials (SCMs) such as fly ash, rice husk ash, ground granulated blast-furnace slag, and silica fume have long been used for this purpose. However, access to these industrial by-products is often limited in developing regions, where agricultural residues are more abundant (Mosaberpanah & Umar, 2020; Rawat & Pasla, 2025). Agricultural by-products provide a renewable source of silica, alumina, and calcium compounds necessary for cementitious reactions, and mitigate waste disposal problems. When processed into fine powders or ashes, these residues exhibit pozzolanic activity. They react with calcium hydroxide to form additional calcium silicate hydrate (CSH) gel as the main strength-giving compound in cement (Chidiac *et al.*, 2015; Seun *et al.,* 2024). These materials improve particle packing and microstructural densification, leading to reduced porosity and improved durability. Among the many agricultural wastes studied, Fonio chaff (FC), Eggshell powder (ESP), and Charcoal ash (CA) stand out for their regional availability, compositional diversity, and synergistic properties when used together in stabilised earth bricks. Each of these materials contributes uniquely to the performance of CSEBs, combining mechanical reinforcement, chemical enhancement, and environmental benefits. Utilising agricultural by-products addresses waste-management challenges in urban and rural Nigeria. Where poultry production generates thousands of tonnes of discarded shells annually, the materials are easily processed, requiring minimal energy compared to conventional cement production. Incorporating agricultural by-products into CSEBs contributes to both emission reduction and resource efficiency, aligning with the United Nations Sustainable Development Goals (SDGs) on responsible production and sustainable cities.

METHODOLOGY

Theoretical Background

This study adopted a hybrid methodological approach that combined experimental investigation. Using locally produced compressed stabilised earth bricks (CSEBs) incorporating agricultural by-products, and a structured narrative review of relevant literature. This dual

framework enabled a comprehensive evaluation of the mechanical, physical, and sustainability contributions of fonio chaff (FC), eggshell powder (ESP), and charcoal ash (CA) as partial cement replacements.

Materials and Characterisation

Fonio Chaff: The fonio chaff used for the study was sourced from fonio processing mill in Kagarko Local Government of Kaduna State, Nigeria. The chaff was sun-dried and sieved with a 20mm sieve into fine powder.

Eggshell: The eggshell was obtained from a poultry farm and local processing sources within the Gidan Kwano community in Niger State. The eggshells were washed, dried and ground into fine powder.

Charcoal: The charcoal was sourced from a local processing source within the Gidan Kwano community in Niger State. The charcoal was screened to remove unburnt residues and grounded to fine powder suitable for a stabiliser.

Clay: The clay used for the CSEBs production was sourced from Gidan Kwano River in Minna, Niger State, Nigeria. The clay was dried and ground into powder to ensure suitability for stabilized earth construction.

Fine Aggregate: Natural River sand was used as the fine aggregate. It was properly washed to remove silt or organic impurities. The sand was inspected to confirm variation in grain size and gradation.

Water: Clean potable water sourced from the Department of Building, Federal University of Technology, Minna, Niger State, was used for mixing and curing of the bricks. A consistent water ratio of 0.5 was used for charcoal and eggshell powder mixes, while a 0.6 ratio was used for fonio chaff mix because it absorbed more water.

Cement: The cement used for the study is Ordinary Portland Cement (OPC) 42.5R (CEM II A-L) grade, which served as the principal binding material and stabiliser obtained from Gidan Kwano community in Minna, Niger State, Nigeria. All additives were processed to achieve particle sizes capable of enhancing filler action and potential pozzolanic behaviour. The experiment was conducted at the School of Environmental Technology, Laboratory of the Department of Building, Federal University of Technology, Minna, Niger State.

Mould: The CSEBs samples were cast using 200mm x 100mm x 100 mm metal moulds fabricated by a welder.
Equipment: The various equipment and tools used for the experimental procedures includes: (a) slump cone for workability, (b) compressive testing machine (UTM) for compressive strength test, (c) weighing balance for weighing of materials and samples for crushing, (d) 200mm x 100mm x 100mm moulds for casting bricks samples with rammer for compacting the mix and (e) shovel with head pan for mixing and transporting materials and concrete.

Preliminary investigations

Preliminary tests were conducted on the materials in the Building Laboratory of Federal University of Technology, Minna, to evaluate the physical and mechanical properties of the clay, fonio chaff, eggshell powder and charcoal.

Moisture content: The moisture content was determined by oven drying the samples A, B, and C, according to BS 812: Part 109: 1990. The samples were oven-dried at a constant temperature for 24 hours to achieve a constant weight. The test ensured that the water content in the materials did not interfere with the designed water-cement ratio. The moisture content of the samples ranges between 16.67% and 21.21% with a mean of 18.80% and SD = 2.28, which indicates that the moisture levels were relatively consistent across the three samples. Thus, suggesting limited variability in moisture distribution.

Sieve Analysis: The grain distribution (GSD) analysis was conducted using a 500g clay soil sample and the percentage passing for each sieve size was scaled and estimated. The coefficient of curvature (Cc) was 0.16, which indicates that the soil is a coarse soil (sand range) with some fines and a relatively narrow particle size range according to the Unified Soil Classification System (USCS).

Bulk Density: The bulk density was assessed in accordance with BS 812: Part 2: 1995. The bulk density of the clay was determined using the formula:

$$\text{Bulk Density (g/cm}^3\text{)} = \frac{\text{weight of clay (g)}}{Volume\ of\ mould\ (cm3)}$$

$$\text{Loose bulk density} = \frac{9200}{8763} = 1.05\text{g/cm}^3$$

$$\text{Compacted bulk density} = \frac{9759}{8763} = 1.11\text{g/cm}^3$$

i. Loose bulk density =1.05g/cm^3. It represents the density of clay when poured without compaction.
ii. Compacted bulk density =1.11g/cm^3. It represents the density of clay after compaction.
iii. The compacted density is slightly higher, as expected, since compaction reduces voids between soil particles.

iv. Clay soil bulk density usually ranges between 1.0 and 1.6g/cm^3

Mixing Design and Specimen Preparation: The mortar mix used in this study was the normal mix ratio of 1:1:2, respectively. For a standard compressive strength, the water ratio of 0.5 was used for eggshell powder and charcoal, while 0.6 for fonio chaff throughout the experiment. The cement was partially replaced with fonio chaff, eggshell powder, and charcoal at 5% and 10% replacement.

Preliminary Information: The mix design adopted for the study was 1:1:2, with a water ratio of 0.5 for eggshell powder and charcoal, while 0.6 was used for fonio chaff mix. The curing of samples was carried out for 7, 14, 21, and 28 days, respectively, with fonio chaff, eggshell powder, and charcoal ash incorporated at 5% and 10% replacement. A total of 105 CSEBs were produced at 0%, 5% and 10% partial cement replacement levels with 36 bricks, (12 bricks for 5% Fonio chaff, 12 bricks for Eggshell powder &12 bricks for Charcoal ash replacement), at 7, 14, 21 and 28-days curing age, 36 bricks for 10% replacement levels (12 bricks for Fonio chaff, 12 bricks for Eggshell powder & 12 bricks for Charcoal ash). With 12 bricks for 0% control samples respectively and 21 bricks for (O%, 5% & 10%) water absorption rate test.

Mix Design Calculations: Each CSEB sample had a volume of 0.002m^3 (2,000,000mm^3) with a total of 210 litres for 105 bricks. Calculating from the dimensions 200mm x 100mm x100mm (0.2m x 0.1m x0.1m), assuming the density of 2400 kg/m^3, the mass of a brick is 4.8 kg. Therefore, the total mass required for 105 bricks is 504 kg.

Table 1: Presents three brick mix designs with control, 0%, 5%, and 10% cement replacement using an equal combination of Fonio Chaff (FC), Eggshell Powder (ESP), and Charcoal Ash (CA)**.** The control mix (0%) contains only cement as the binder (50.40 kg), while the replacement mixes progressively reduce cement content to 47.88 kg (5%) and 45.36 kg (10%)**.** At each replacement level, FC, ESP, and CA are added in equal amounts. For the 5% mix, 2.52 kg of each material is included, while the 10% mix contains 5.04 kg of each. Meanwhile, the quantities of sand (100.8 kg) and water (50.4 kg) remain constant across all mixes, ensuring that any differences in brick performance can be attributed mainly to the binder modification rather than changes in aggregate or water content. The number of bricks produced also differs**:** 12 bricks for the control mix and 36 bricks each for the 5% and 10% replacement mixes, suggesting that more specimens were prepared for testing the modified mixes. This shows a structured approach to evaluating the effect of partially replacing cement with sustainable waste-derived materials while maintaining consistent aggregate and water proportions.

Table 1: **Mix Proportions for CSEBs with Partial Cement Replacement**

Cement Replacement (%)	Fonio Chaff (kg)	Eggshell Powder (kg)	Charcoal Ash (kg)	Cement (kg)	Sand (kg)	Water (kg)	No. of Bricks Produced
0 Control	0.00	0.00	0.00	50.40	100.8	50.4	12
5	2.52	2.52	2.52	47.88	100.8	50.4	36
10	5.04	5.04	5.04	45.36	100.8	50.4	36

RESULTS AND DISCUSSIONS

Chemical Analysis

The materials used in this study comprised cement, clay, FC, ESP, CA and sand. Their chemical compositions, summarised in Table 2, indicated the presence of compounds that can influence hydration, pozzolanic activity, and overall material performance. Ordinary Portland cement is primarily composed of calcium oxide (CaO) and silicon dioxide (SiO_2), which combine during hydration to form calcium silicate hydrates responsible for strength development. Minor constituents such as aluminium oxide (Al_2O_3), iron oxide (Fe_2O_3), magnesium oxide (MgO), and sulphur trioxide (SO_3) influence setting time, durability, and volume stability. Clay consists mainly of silica (SiO_2) and alumina (Al_2O_3), along with bound water and small amounts of iron and alkaline oxides. These oxides contribute to its plasticity and potential reactivity when thermally or chemically activated. FC is largely organic, containing cellulose, hemicellulose, and lignin. However, its ash contains reactive silica and minor mineral oxides, suggesting possible pozzolanic behavior when combusted under controlled conditions. Eggshell powder is rich in calcium carbonate ($CaCO_3$), making it a potential calcium-based filler or cementitious modifier after calcination. Charcoal is predominantly carbon with small mineral ash content, which may affect porosity and lightweight properties. Sand, composed mainly of silica, serves as an inert fine aggregate providing bulk and dimensional stability. Together, these materials present complementary chemical characteristics suitable for developing blended or sustainable construction composites

Table 2: **Chemical Composition of Selected Construction and Agricultural Materials**

Major Chemical Components	Material	Approximate Composition (% by Weight)	Notes
CaO	OPC	60–67	Primary compound responsible for strength development
SiO_2	OPC	17–25	Forms calcium silicates
Al_2O_3	OPC	3–8	Influences setting time
Fe_2O_3	OPC	0.5–6	Contributes to colour and compound formation
MgO	OPC	0.1–4	Excess may cause expansion
SO_3	OPC	1–3	From gypsum; controls setting time
SiO_2	Clay	45–60	Derived from quartz and silicates
Al_2O_3	Clay	15–30	From clay minerals such as kaolinite
H_2O	Clay	5–15	Structural water in clay minerals
Fe_2O_3	Clay	2–10	Influences clay colour
CaO, MgO, K_2O	Clay	1–5	Minor fluxing agents
Cellulose	Fonio chaff	35–45	Organic structural fiber
Hemicellulose	Fonio chaff	20–30	Biopolymer component
Lignin	Fonio chaff	15–25	Provides rigidity
SiO_2, in ash	Fonio chaff	5–15	Contributes to pozzolanic potential after burning
K_2O, CaO, MgO	Fonio chaff	3–10	Varies with soil conditions
$CaCO_3$)	Eggshell powder	94–97	Main mineral component
$MgCO_3$	Eggshell powder	~1	Minor component
$Ca_3(PO_4)_2$	Eggshell powder	~1	Trace mineral
Organic matter	Eggshell powder	<2	Membrane residues if not fully removed
Carbon (C)	Charcoal	70–90	Depends on carbonization temperature
Volatile matter	Charcoal	5–20	Residual hydrocarbons
Ash (SiO_2, CaO, K_2O, MgO)	Charcoal	2–10	Mineral residue after burning
Moisture	Charcoal	2–8	Absorbed water
SiO_2	Sand	85–98	Mainly quartz
Al_2O_3	Sand	1–5	From feldspar or clay impurities
Fe_2O_3	Sand	0.1–2	May give reddish coloration
$CaCO_3$	Sand	0–3	Present in some sand sources
Trace minerals	Sand	<1	Includes mica and heavy minerals

The values are approximate ranges. Composition varies depending on source, processing method, and environmental conditions.

Specific Gravity: The specific gravity of fonio chaff, eggshell powder, charcoal ash, clay and sand was found to be 2.1-2.4, 2.6-2.9, 1.4-1.8, 2.5-2.7 and 2.6-2.7, respectively. These values fall within the range specified by BS812: 1995. This states that most natural materials possess specific gravity values between 2.60 and 2.70. The materials with values below are classified as lightweight.

Moisture Content: The moisture contents recorded for fonio chaff and clay were between 16-20% and 16.67-21.21%. The proper control of moisture content is critical in mortar mix design as it directly influences the water-to- mortar (w/m) ratio, the workability and strength of the mortar. According to Abram's law, compressive strength is inversely related to the w/m ratio. Therefore, excess moisture can negatively affect mortar quality.

Bulk Density: The bulk density of fonio chaff, eggshell powder, charcoal, clay and sand were 600-900 kg/m^3, 900-1200 kg/m^3, 300-500 kg/m^3, loose bulk density1050 kg/m^3, compacted bulk density 1110 kg/m^3 and 1500-1700 $kg/m^{3,}$ respectively. Sand having the bulk density of 1500-1700kg/m^3 contains fewer voids, ideal for a good mix.

Table 3: **Physical Properties of Selected Materials (FC, ESP, CA, C & S)**

Property	Fonio Chaff Ash	Eggshell Powder	Charcoal Powder	Clay Soil	Sand
Specific gravity	2.1–2.4	2.6–2.9	1.4–1.8	2.5–2.7	2.6–2.7
Bulk density (g/cm³)	600-900	900-1200	300-500	Loose: 1050 Compacted: 1110	1500–1700
Moisture content (%)	16–20	—	—	16.67–21.21	—
Porosity	Moderate	Low	Very high	High	Low
Plasticity	Non-plastic	Non-plastic	Non-plastic	High plasticity	Non-plastic

Table 3: presents the physical properties of materials used in CSEB production. Fonio chaff ash has a moderate porosity, low bulk density (600–900 g/cm³), and is non-plastic with a specific gravity of 2.1–2.4. Eggshell powder is denser (900–1200 g/cm³), non-plastic, low porosity, and has a higher specific gravity (2.6–2.9). Charcoal powder is very light (300–500 g/cm³), highly porous, non-plastic, and has a low specific gravity (1.4–1.8). Clay soil exhibits high plasticity, high porosity, moderate density (1050–1110 g/cm³), and specific gravity of 2.5–2.7. Sand is dense (1500–1700 g/cm³), non-plastic, low porosity, and high specific gravity (2.6–2.7). These properties influence water absorption, workability, and strength of bricks.

Experimental Procedures

A total of 105 CSEBs were produced at 0%, 5% and 10% partial cement replacement levels. The mix composition consisted of clay, sand, stabiliser (cement + additive), and water. The mixtures were thoroughly homogenised and compacted manually to ensure uniform density across samples. The production distribution was 36 bricks for 5% replacement level (12 for Fonio chaff, 12 for Eggshell powder &12 for Charcoal ash), at 7, 14, 21 and 28-day curing age. The 10% replacement level had 36 bricks (12 for Fonio chaff, 12 for Eggshell powder & 12 for Charcoal ash, respectively). While 12 bricks were for 0% control samples and 21 bricks for (O%, 5% & 10%) water absorption rate test. All the specimens are 200mm x 100mm x 100mm, with 3 replicates for each curing age, cured using the open air method under atmospheric temperature and crushed for 7-28-days. The mix ratio used was a 1:1:2 mix (Cement: Additives: Sand) with 1-part cement, 1-part additives and 2-parts of sand, while the compaction ratio was 0.9 Mpa. Mechanical and physical tests were conducted according to relevant standards (Nigerian Industrial Standard (NIS 87), American Society for Testing and Materials (ASTM), and Building Code BS codes). The tests include: (a) Compressive strength test carried out at curing ages of 7, 14, 21, and 28-days to assess load-bearing capacity. (b) Water absorption rate test was performed by oven-drying and soaking specimens in water with sacks to determine permeability and porosity effects. (c) Workability test: Workability of fresh mixes was determined using slump cone consistency observations before moulding. The experimental data provided the empirical basis for evaluating the effect of Fonio chaff, Eggshell powder, and Charcoal ash on the engineering performance of CSEBs

Testing Standards

Compressive Strength: The compressive strength was determined for the CSEBs with fonio chaff, eggshell powder and charcoal ash as partial replacement at 7, 14, 21 and 28-day curing ages. Results are shown in Tables 4, 5, 6 and also Figures 1, 2 and 3.

Table 4: Mean and Standard Deviation for Compressive Strength (N/mm²) of CSEBs with 0%, 5% and 10% Fonio Chaff Replacement Levels Across Curing Ages

Curing Age (Days)	Replacement Level (%)	*M* (N/mm²)	*SD*	*N*
7	0 (Control)	0.06	0.01	3
	5	0.32	0.02	3
	10	0.33	0.02	3
	Total (5–10%)	**0.33**	**0.02**	**9**
14	0 (Control)	0.13	0.03	3
	5	0.23	0.06	3
	10	0.25	0.04	3
	Total (5–10%)	**0.24**	**0.05**	**9**
21	0 (Control)	0.23	0.06	3
	5	0.40	0.07	3
	10	0.21	0.04	3
	Total (5–10%)	**0.31**	**0.12**	**9**
28	0 (Control)	0.24	0.05	3
	5	0.36	0.06	3
	10	0.21	0.01	3
	Total (5–10%)	**0.29**	**0.10**	**9**

Note. *M = mean compressive strength; SD = standard deviation; N = number of specimens tested. Total values represent results for 5% and 10% replacement levels at each curing age.*

The findings indicated that the compressive strength for FC varied across 7, 14, 21, and 28 days, which falls below the NIS 87: 2007 minimum standard. Repeated measures ANOVA showed that curing age and fonio chaff replacement significantly affected CSEBs compressive strength. Strength varied across 7–28 days, with a large treatment effect ($\eta^2p = .494$).

A significant age × replacement interaction ($\eta^2p = .684$) indicated different strength development patterns between 5% and 10% replacement levels. Linear contrasts confirmed a strong divergent trend, while between-subjects analysis revealed a substantial replacement effect ($\eta^2p = .838$), with 5% replacement consistently producing higher strength than 10%. Bonferroni comparisons supported this difference (Mdiff = .077, p = .010). Overall, results reject H_{01} and show that higher fonio content may reduce long-term compressive strength.

Table 5: Mean and Standard Deviation for Compressive Strength (N/mm²) of CSEBs with 0%, 5% and 10% Eggshell Powder Replacement Levels Across Curing Ages

Curing Age (Days)	Replacement Level (%)	*M* (N/mm²)	*SD*	*N*
7	0	0.93	0.32	3
	5	1.08	0.01	3
	10	2.18	0.39	3
	Total (5–10)	**1.63**	**0.65**	**9**
14	0	0.94	0.36	3
	5	1.30	0.27	3
	10	3.17	0.64	3
	Total (5–10)	**2.24**	**1.12**	**9**
21	0	0.95	0.38	3
	5	1.30	0.15	3
	10	3.73	0.56	3
	Total (5–10)	**2.51**	**1.38**	**9**
28	0	1.11	0.18	3
	5	2.35	0.64	3
	10	4.17	0.28	3
	Total (5–10)	**3.26**	**1.09**	**9**

Note. *M* = mean compressive strength; *SD* = standard deviation; *N* = number of specimens tested per group. "Total (5–10%)" represents the combined statistics for the 5% and 10% replacement groups at each curing age

The findings indicated a significant effect on curing age, which is highly statistically significant, less than 0.005. The results showed that 10% replacement optimizes strength development, making it preferable for structural applications, both 5% at 28-days and 10% falls within the NIS 87: 2007 minimum specified standard for bricks. Repeated measures ANOVA revealed that curing age and eggshell powder replacement significantly influenced CSEB compressive strength. Strength increased with curing time, showing a very large age effect ($\eta^2p = .812$).

A significant age × replacement interaction ($\eta^2p = .633$) indicated that strength development differed between 5% and 10% replacement levels. Linear and quadratic trends across ages were also significant, confirming progressive strength gain. Between-subjects analysis showed a strong replacement effect ($\eta^2p = .935$), with 10% replacement outperforming 5%. Bonferroni comparisons confirmed this difference (Mdiff = 1.805, p = .002).

Overall, H_{02} was rejected, demonstrating that higher eggshell content substantially improves long-term compressive strength.

Table 6: Mean and Standard Deviation for Compressive Strength (N/mm²) of CSEBs with 0%, 5% and 10% Charcoal Ash Replacement Levels Across Curing Ages

Curing Age (Days)	Replacement Level (%)	*M* (N/mm²)	*SD*	*N*
7	0	1.12	0.17	3
	5	1.78	0.55	3
	10	2.25	0.03	3
	Total (5–10%)	**2.02**	**0.43**	**9**
14	0	1.14	0.17	3
	5	1.46	0.25	3
	10	2.41	0.61	3
	Total (5–10%)	**1.94**	**0.67**	**9**
21	0	1.15	0.16	3
	5	1.14	0.01	3
	10	4.23	0.45	3
	Total (5–10%)	**2.68**	**1.72**	**9**
28	0	1.17	0.12	3
	5	0.87	0.10	3
	10	4.69	0.28	3
	Total (5–10%)	**2.78**	**2.10**	**9**

Note. *M* = mean compressive strength; *SD* = standard deviation; *N* = number of specimens tested. Totals represent combined statistics for 5% and 10% replacement levels at each curing age.

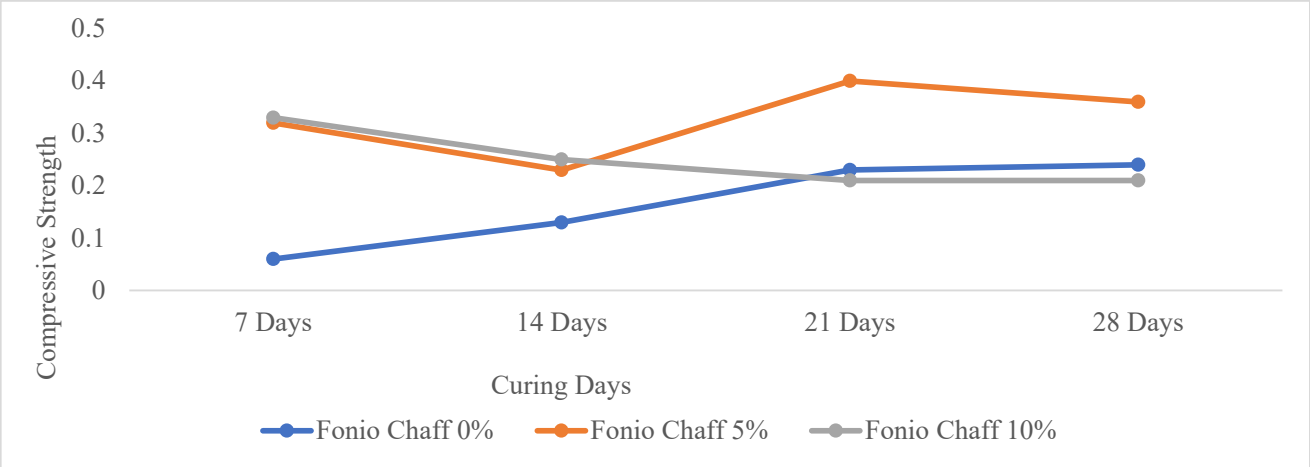


Figure 1: Compressive Strength for 0%, 5% and 10% Fonio Chaff Replacement

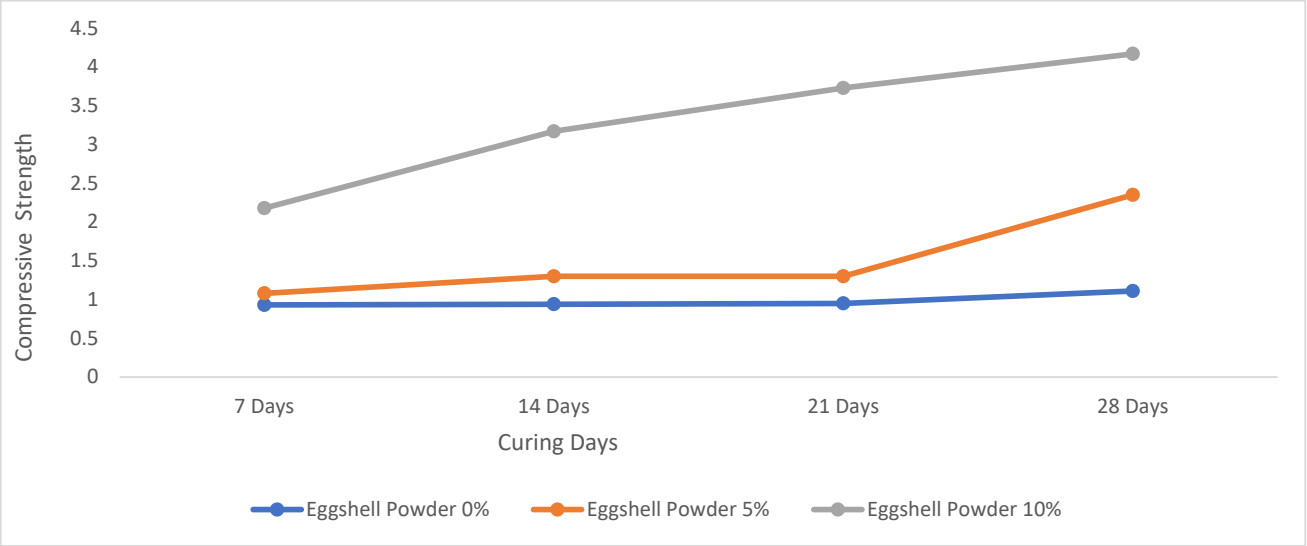


Figure 2: Compressive Strength for 0%, 5% and 10% Eggshell Powder Replacement

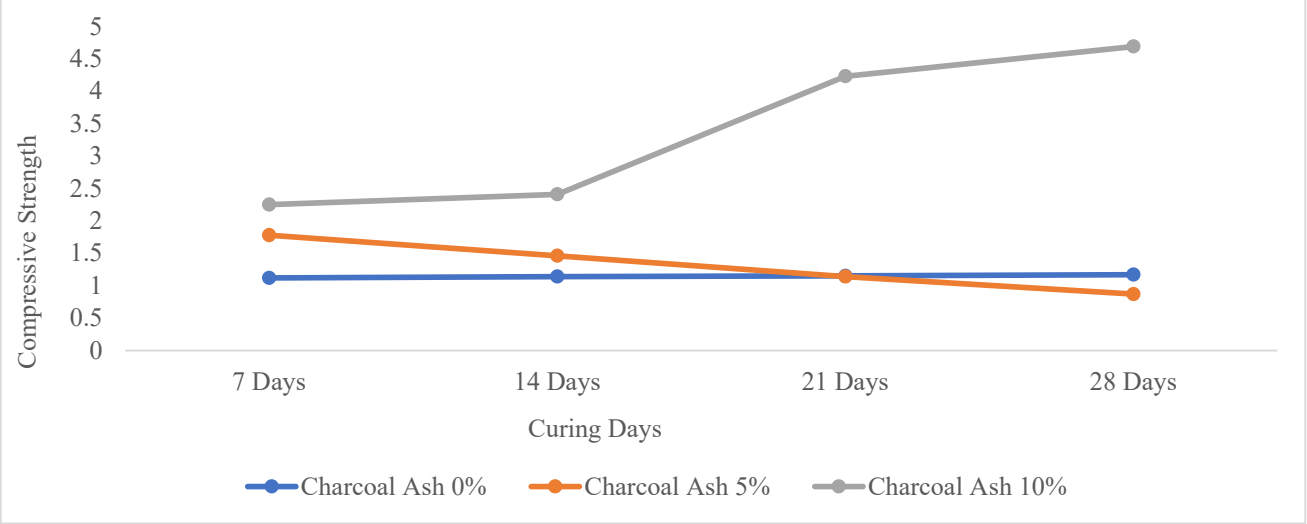


Figure 3: Compressive Strength for 0%, 5% and 10% Charcoal Replacement Levels

The findings of the study indicated that there is a statistically significant difference between the compressive strength of CSEBs with 5% and 10% partial replacement of cement using charcoal ash. The 10% replacement at 7-14-days falls within the NIS 87: 2007 standard, while at 21-28-days were above the minimum standard but still within the range. Repeated measures ANOVA showed that curing age and charcoal ash replacement significantly influenced CSEB compressive strength. Strength changed across ages with a large age effect ($\eta^2p = .705$). A very strong age × replacement interaction ($\eta^2p = .890$) indicated different strength development patterns between 5% and 10% replacement. Trend analysis revealed significant linear and cubic age effects, along with strong interaction trends, confirming differing growth patterns. Between-subjects analysis showed an extremely large replacement effect ($\eta^2p = .978$). Bonferroni comparisons confirmed that 10% replacement produced significantly higher strength than 5% (Mdiff = 2.168, $p < .001$). Thus, H_{03} was rejected, showing 10% charcoal ash greatly improves strength

Water Absorption Rate Test

The water absorption rate was assessed by soaking in water the brick samples for fonio chaff, eggshell powder and charcoal ash at 5% and 10% replacement with fiber sack for 24 hours. The results are shown in Tables 7, 8 and 9. This finding indicated that the water absorption rate for 0% and 10% falls within the Industrial Standard IS 1077, with the minimum allowable water absorption of bricks conforming to a class of 33%. but relatively high for 5% with the need for optimizing replacement ratios. A dependent samples t-test showed that bricks with 5% fonio replacement had higher water absorption (M = 39.25, SD = 7.67) than 10% replacement (M = 33.00, SD = 3.45). However, the difference was not statistically significant, $t(4) = 1.29$, $p = .27$, 95% CI [–7.23, 19.73], though the effect size was large ($d = 1.05$). Therefore, H_{04} was retained.

Table 7: Water Absorption Rate of CSEBs with Fonio Chaff at 0%, 5% and 10% Replacement Levels

Replacement Level (%)	Replicate (Sample)	Dry Weight, W_1 (g)	Wet Weight, W_2 (g)	Water Absorption (%)	SD
0	1	2715	2715	0.00	0.06
	2	2668	2671	0.11	
	3	2601	2601	0.00	
	Total Replicates (n)	3	3	3	
	Average Absorption (%)			0.04	0.06
5	1	1905	2803	47.14	7.62
	2	1867	2591	38.77	
	3	1976	2605	31.83	
	Total Replicates (n)	3	3	3	
	Average Absorption (%)			39.25	7.62
10	4	1987	2593	30.49	3.46
	5	1986	2613	31.57	
	6	1876	2569	36.94	
	Total Replicates (n)	3	3	3	
	Average Absorption (%)			33.00	3.46

Note. *Water absorption Rate was calculated based on the difference between wet weight (W_2) and dry weight (W_1) divided by dry weight, expressed as a percentage. Each replacement level consisted of three test replicates.*

The absorption rate for 0%, 5% and10% eggshell powder replacement was within the conformity range for Nigeria Industrial Standard NIS87: 2007 minimum absorption rate of 12% allowable water absorption of bricks conforming to class. Thus, the produced bricks met the standard durability requirements, making them suitable for structural applications in humid environments. A dependent samples t-test revealed that 5% eggshell replacement had lower water absorption (M = 5.66, SD = 1.65) than 10% replacement (M = 9.96, SD = 2.04). The difference was significant, $t(4) = –2.83$, $p = .047$, 95% CI [–8.51, –0.09], with a large effect ($d = –2.31$). Thus, H_{05} was rejected.

Table 8: Water Absorption Rate of CSEBs with Eggshell Powder at 0%, 5%, and 10% Replacement Levels

Replacement Level (%)	Replicate (Sample)	Dry Weight, W_1 (g)	Wet Weight, W_2 (g)	Water Absorption (%)	SD
0	1	3146	3152	0.19	0.02
	2	3252	3257	0.15	
	3	3859	3865	0.16	
	Total Replicates (n)	**3**	**3**	**3**	
	Average Absorption (%)			**0.17**	0.02
5	1	3986	4155	4.23	1.66
	2	3198	3367	5.28	
	3	4015	4315	7.47	
	Total Replicates (n)	**3**	**3**	**3**	
	Average Absorption (%)			**5.66**	1.66
10	4	3868	4168	7.75	2.04
	5	3875	4276	10.34	
	6	3817	4267	11.78	
	Total Replicates (n)	**3**	**3**	**3**	
	Average Absorption (%)			**9.96**	2.04

Note. *Water absorption was calculated as the percentage increase in weight after immersion relative to dry weight (W_1). Each replacement level consisted of three replicate specimens.*

Table 9: Water Absorption Rate of CSEBs with Charcoal Ash at 0%, 5%, and 10% Replacement Levels

Replacement Level (%)	Replicate (Sample)	Dry Weight, W_1 (g)	Wet Weight, W_2 (g)	Water Absorption (%)	SD
0	1	3013	3103	2.99	1.99
	2	3402	3521	3.50	
	3	3005	3205	6.66	
	Total Replicates (n)	**3**	**3**	**3**	
	Average Absorption (%)			**4.38**	1.99
5	1	2705	3103	14.71	1.90
	2	3170	3521	11.07	
	3	2815	3205	13.85	
	Total Replicates (n)	**3**	**3**	**3**	
	Average Absorption (%)			**13.21**	1.90
10	4	2815	3204	13.81	0.82
	5	3118	3498	12.18	
	6	3051	3451	13.11	
	Total Replicates (n)	**3**	**3**	**3**	
	Average Absorption (%)			**13.03**	0.82

Note. Water absorption was calculated as the percentage increase in weight after immersion relative to dry weight (W_1). SD represents the sample standard deviation of replicate measurements.

The findings on absorption rate for both 0%, 5% and 10% charcoal replacement conformed with Nigeria Industrial Standard NIS87, minimum absorption rate of 12% allowable water absorption of bricks conforming to class. Thus, falls within the acceptable standard range with no statistically significant difference and the bricks achieved a favourable compromise between durability and moisture compatibility, making the bricks suitable for practical construction use.

A dependent samples t-test showed similar water absorption for 5% (M = 13.21, SD = 1.90) and 10% (M = 13.03, SD = 0.82) charcoal ash replacement. The difference was not significant, t(4) = 0.15, p = .89, 95%

CI [–3.14, 3.50], with a negligible effect size (d = 0.12). Therefore, H_{06} was retained.

Workability Test

The workability was assessed through the slump test for fonio chaff, eggshell powder and charcoal ash as replacement at 55 and 10%. The results are shown in Tables 10, 11 and 12 and also in Figure 4.

Table 10: Slump Value for 5% and 10% Fonio Chaff Replacement

Proportion (%)	0%	5%	10%
Slump (mm)	3.20	5.00	6.00

The workability of fonio chaff mixes at 5% and 10% replacement as indicated by the slump test are high, which falls within the conformity with BS EN 771-1 European Standard Specification. The finding shows not statistically significant and suggests that increasing fonio chaff from 5% to 10% slightly improved workability with greater variability, while 5% provides stable workability, higher replacement 10% may increase fluidity. A dependent samples t-test found no significant difference in workability between 5% (M = 5.00, SD = 1.00) and 10% (M = 6.00, SD = 2.00) replacement, t(4) = –0.78, p = .482. The mean difference was –1.00 (d = –0.63), 95% CI [–4.58, 2.58]. Thus, H_{07} was retained.

Table 11: Slump Value for 5% and 10% Eggshell Powder Replacement

Proportion (%)	0%	5%	10%
Slump (mm)	4.01	5.00	6.00

The workability of eggshell powder mixes at 5% and 10% replacement as indicated by the slump test falls within the conformity with BS EN 772 British Standard. Thus, not statistically significant and increasing eggshell powder from 5% to 10% led to a modest improvement in workability while maintaining the same level of variability across mixes. A dependent-samples t-test showed lower workability at 5% (M = 5.00, SD = 1.00) than 10% eggshell replacement (M = 6.00, SD = 1.00), but the difference was not significant, t(4) = –1.23, p = .288. Mean difference = –1.00, 95% CI [–3.27, 1.27], with a large effect (d = –1.00). H_{08} was retained.

Table 12: Slump Value for 5% and 10% Charcoal Ash Replacement

Proportion (%)	0%	5%	10%
Slump (mm)	3.50	4.00	5.67

The workability of the charcoal mix for 5% replacement slump test was low and moderate for 10% replacement, which conforms with BS EN 771-1 European Standard Specification. This shows a noticeable increase in slump with higher charcoal ash replacement thus, not statistically significant. A dependent-samples t-test showed lower workability at 5% (M = 4.00, SD = 1.00) than 10% charcoal ash replacement (M = 5.67, SD = 1.53), but the difference was not significant, t(4) = –1.58, p = .189. Mean difference = –1.67, 95% CI [–4.59, 1.26], with a large effect (d = –1.29). H_{09} was retained.

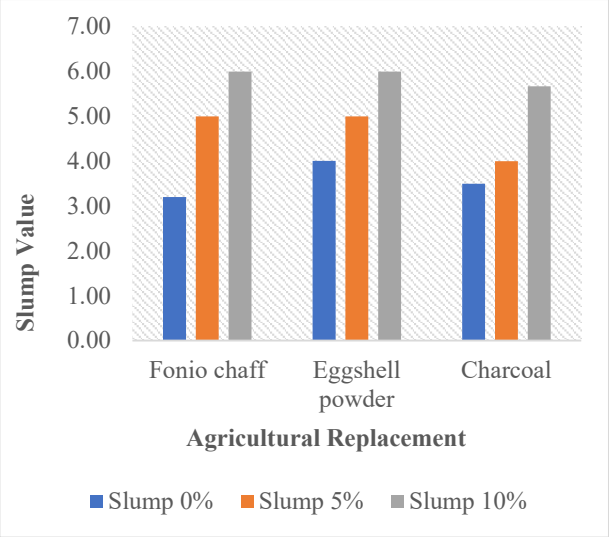


Figure 4: Variation in Workability of Agricultural Materials

Discussion of Findings

The empirical results presented across various studies and experimental data reveal the promising performance of agricultural by-products as partial cement replacements in CSEBs. The discussion explored these findings in relation to material chemistry, structural performance, sustainability benefits, and practical applicability. The primary mechanisms through which FC, ESP, and CA improve CSEB properties can be grouped into chemical, physical, and microstructural effects.

1. Chemical Reactions and Pozzolanic Activity: Eggshell Powder and Charcoal Ash are rich in oxides, CaO, SiO_2, and Al_2O_3, which react with calcium hydroxide during cement hydration to form additional CSH and calcium aluminate hydrates (CAH). These secondary hydration products densify the matrix, refine pore structures, and increase compressive strength. The reaction also consumes calcium hydroxide, reducing the susceptibility of bricks to efflorescence and chemical attack. The higher long-term strength observed in Charcoal Ash

CSEBs supports this delayed pozzolanic reaction mechanism.

2. Physical Filler Effect: The fine particle size of Eggshell Powder and Charcoal Ash contributes to the filler effect, whereby smaller particles occupy voids between soil and sand grains, improving particle packing and reducing capillary porosity. This results in denser, stronger, and more water-resistant bricks. The improved water absorption rates (4–11%) observed in Eggshell Powder and Charcoal Ash samples confirm this effect.

3. Microstructural and Reinforcement Effects: Fonio chaff introduces a fibrous phase that acts as micro-reinforcement, bridging cracks and improving tensile toughness. It contributes little to chemical strength development. Its structure distributes stresses and delays crack propagation, leading to enhanced ductility and dimensional stability. The internal curing effect of Fonio Chaff fibres, which retain water and release it gradually, supports continuous hydration during curing.

These mechanisms explain the complementary performance trends across materials: ESP and CA enhance strength and durability through chemical and physical effects. While FC contributes resilience and thermal efficiency through microstructural modification. Comparing the results across the three additives shows a clear hierarchy of mechanical performance.

Eggshell Powder and Charcoal Ash emerge as superior stabilisers for structural CSEBs, achieving compressive strengths above 3.45N/mm² within the Nigerian and international standards for load-bearing masonry. While FC, offers lower compressive strength but greater toughness and thermal insulation. This suggests that ESP and CA are for structural components and FC for non-structural or hybrid composites.

The synergy of these materials offers a promising research direction. For instance, hybrid formulations incorporating small percentages of FC as reinforcement with ESP or CA as pozzolanic fillers could produce bricks combining high strength, ductility, and insulation. Such composite designs align with modern materials engineering principles, where multifunctional performance is prioritised over single-parameter optimisation. Curing plays a vital role in determining the final performance of CSEBs. And extended curing periods of 21–28 days consistently result in higher strength and lower water absorption across all additive types. This trend reflects continued hydration and pozzolanic reactions for CA mixtures where strength development extends beyond early ages.

Environmental factors such as temperature and humidity also affect performance. In arid regions, rapid moisture loss can arrest hydration, while in humid climates, poor curing management may lead to inconsistent strength gain. Fonio chaff's water-retention capacity offers a partial solution by maintaining internal moisture balance during curing, suggesting its utility in warm, dry environments of sub-Saharan Africa. From a sustainability perspective, the utilisation of agricultural by-products in CSEBs embodies the principles of the circular economy, resource recovery, waste reduction, and value creation from residues. Each additive offers unique contributions to sustainability goals.

By localising material sourcing, these additives also strengthen rural economies and reduce dependence on imported cement, a key driver of high housing costs in developing nations. Thus, the widespread adoption of FC, ESP, and CA CSEBs could contribute directly to UN Sustainable Development Goals (SDGs) 9 Industry, Innovation, and Infrastructure, 11 Sustainable Cities and Communities, and 12 Responsible Consumption and Production

STRATEGIC RECOMMENDATIONS FOR IMPLEMENTATION

For the scientific advancements discussed to translate into real-world impact, coordinated strategies across research, industry, and policy domains are required.

1. Policy Frameworks: Governments should incorporate agricultural waste-based CSEBs into national sustainable housing policies and encourage public-private partnerships to scale production.
2. Standardisation: Development of local standards specifying mix design, quality control, and testing methods for CSEBs with agricultural additives will ensure product reliability and user confidence.
3. Capacity Building: Training programs for local artisans and small-scale producers will improve production quality and create employment opportunities.
4. Awareness Campaigns: Demonstration projects showcasing successful CSEB housing prototypes can dispel misconceptions and build public trust.

5. Research Industry Collaboration**:** Partnerships between universities, building research institutes, and construction firms can accelerate technology transfer and innovation

The reviewed studies confirm that fonio chaff, eggshell powder, and charcoal ash represent viable, sustainable partial cement replacements in compressed stabilised earth bricks. Their integration enhances strength, durability, and sustainability while reducing the carbon and cost intensity of building production. However, achieving large-scale impact requires addressing material variability, establishing standards, and promoting enabling policies. Future research should prioritise hybrid mix optimisation, advanced characterisation, and life-cycle assessments to consolidate the scientific and practical foundations for adoption.

CONCLUSION

The transition to sustainable construction demands innovative materials with environmental efficiency and structural adequacy. This review examined the performance, theoretical foundations, and sustainability implications of fonio chaff (FC), eggshell powder (ESP), and charcoal ash (CA) as partial cement replacements in CSEBs. Drawing from global literature and experimental data, the analysis revealed that the substitution of cement with these agricultural by-products significantly enhances sustainability without compromising mechanical properties when applied within optimal ranges. The results show that ESP and CA provide substantial improvements in compressive strength and durability due to their pozzolanic reactivity and fine particle structure. Eggshell Powder contributes additional calcium ions that accelerate early hydration and densify the matrix. Charcoal Ash supports long-term strength through CSH formation and pore refinement. Fonio chaff introduces fibrous reinforcement and thermal insulation, reducing brittleness and improving the energy performance of buildings. These effects illustrate the potential of bio-derived additives to customize CSEB properties for diverse functional and environmental needs.

Empirical evidence confirms that optimal replacement levels between 5–10% yield compressive strengths exceeding 3.45N/mm² for ESP and CA bricks, surpassing Nigerian and international standards for load-bearing applications while maintaining acceptable water absorption rates of 4–11%. Fonio-based mixes achieve lower compressive strength but offer superior toughness and internal curing advantages relevant in arid climates. Beyond technical performance, the integration of FC, ESP, and CA addresses critical sustainability goals. Each material exemplifies circular-economy practice, converting agricultural residues into high-value construction resources and reducing dependence on energy-intensive cement production. Thus, lowering greenhouse-gas emissions, minimising landfill waste, and fostering local economic empowerment through value-added utilisation of regionally available wastes.

However, the widespread adoption of such materials remains constrained by challenges like composition variability, lack of standardised design codes, and limited policy support. Addressing these barriers requires a coordinated effort involving research institutions, policymakers, and industry stakeholders. Standardisation of testing protocols, development of hybrid formulations, and comprehensive life-cycle assessments will be essential to legitimise and scale this technology.

Finally, the study reaffirms that agricultural by-products such as fonio chaff, eggshell powder, and charcoal ash are essential tools in achieving sustainable, affordable, and climate-resilient construction. When systematically developed, these materials have the potential to redefine the landscape of green building technologies in Nigeria and globally, bridging the gap between ecological responsibility and engineering performance.

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