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Evaluating Sugarcane Bagasse Ash as Partial Cement Replacement in Compressed Earth Bricks for Sustainable Housing

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Abstract
This study investigates the use of Sugarcane Bagasse Ash (SCBA) as a partial replacement for Ordinary Portland Cement (OPC) in stabilizing lateritic soil for Compressed Earth Bricks (CEB) production. Materials used were locally sourced materials and they include OPC, laterite, and SCBA. SCBA was obtained by controlled combustion of sugarcane residue and was characterized through particle size analysis and X-ray fluorescence to confirm its pozzolanic properties. The laterite was tested for suitability using sedimentation, specific gravity, Atterberg limits, bulk density, and sieve analysis. Bricks were produced with 2%, 6%, and 8% stabilization levels using cement-only and cement + SCBA blends. Standard tests, including compressive strength and water absorption, were conducted at 7, 14, and 28 days of curing. Results show that compressive strength increased with both curing time and stabilizer content. At 28 days, bricks stabilized with 8% cement + SCBA achieved 4.11 N/mm² compared to 4.64 N/mm² for cement-only bricks, indicating that SCBA contributed significantly to strength development over time. SCBA enhanced bricks consistently demonstrated lower water absorption values, enhancing durability and suitability for entire building use. This study confirms that SCBA is a viable pozzolanic material for partial cement replacement in CEBs. The optimal replacement level was identified as 6%, balancing performance and cost. The research contributes to sustainable construction by promoting the reuse of agricultural waste, reducing dependence on OPC, and providing a cost-effective housing solution. It underscores the value of integrating waste valorization into construction practices, especially in developing contexts where material affordability and environmental impact are critical considerations.

Keywords: Compressed Earth Bricks, Sugarcane Bagasse Ash, Stabilization, Sustainable Housing, Pozzolanic Materials.

Introduction
Compressed earth bricks (CEBs) have gained increasing attention as a sustainable and economically viable alternative to conventional masonry units, particularly in low-income and rural settings. Their relevance is largely attributed to their low embodied energy, excellent thermal performance, and the feasibility of local production, which collectively help reduce construction costs and environmental impact. Unlike fired bricks, CEBs do not require energy-intensive kilns, thereby conserving energy and minimizing greenhouse gas emissions. However, their relatively low compressive strength and high susceptibility to moisture limit their broader application, thus necessitating the use of stabilising agents to improve their performance characteristics (Houben and Guillaud, 1994).

Cement, particularly Ordinary Portland Cement (OPC), remains the most widely used stabiliser in construction due to its strength-enhancing properties. Oladimeji et al (2024) opined that the high cost of cement and other conventional building materials in Nigeria has made affordable housing increasingly inaccessible to the average. This economic constraint has prompted the exploration of partial or complete substitution of OPC with locally available pozzolanic materials, such as volcanic ash, rice husk ash, sawdust

ash, millet husk ash, pulverised fuel ash, and sugarcane bagasse ash (SCBA), in both concrete and earth brick production. These alternatives are not only more affordable but also environmentally sustainable.
Sugarcane is a major agricultural crop grown in over 110 countries, including Nigeria, and generates large quantities of fibrous residue known as bagasse after juice extraction (Ajala et al., 2021). Although bagasse is used in the production of biofuel, pulp, paper, and building materials (Rainey and Covey, 2016), a significant portion remains underutilised. Its improper disposal often through open dumping or uncontrolled incineration poses serious environmental and public health challenges, particularly in rural and semi-urban areas where waste management infrastructure is inadequate (Ajani et al., 2024). Using this waste to produce stabilisers supports sustainable management and circular economy goals.
SCBA, produced from the controlled combustion of sugarcane bagasse, is rich in amorphous silica and exhibits pozzolanic properties that can enhance the durability and strength of stabilised earth bricks. Several studies have demonstrated that partial replacement of OPC with SCBA can improve the mechanical properties, abrasion resistance, and water stability of earth bricks (Cordeiro et al., 2009; Chusilp et al., 2009). Incorporating SCBA into earth construction reduces reliance on OPC, which lowers the environmental footprint of construction, and promotes the reuse of agricultural waste (Bizzo et al., 2014).
Despite these advantages, empirical research on the optimal utilisation of SCBA in CEB production remains limited. Bravo et al. (2024) observed that while the pozzolanic potential of SCBA is acknowledged, its effects on key durability parameters such as water absorption, erosion, and long-term strength performance have not been sufficiently explored. Similarly, Adityaa (2024) noted that the global significance of earth-based housing has not been matched by innovation in stabilisation techniques using agricultural waste products.
This study, therefore, aims to investigate the optimal use of SCBA as a partial replacement for OPC in CEB production. It seeks to determine the ideal substitution ratio that enhances the performance of CEBs. The broader goal is to support sustainable housing delivery with locally sourced materials and waste valorisation strategies, especially in developing countries where a large proportion of the population depends on earthen construction (Marsh and Kulshreshtha, 2022). The findings are expected to contribute to both affordable housing solutions and improved waste management practices.

Materials and Methods

The materials for this study included OPC, locally sourced laterite, and SCBA, with the OPC meeting relevant standards and the laterite obtained from Rayfield, Jos. Bagasse, a byproduct of sugarcane juice extraction, was incinerated in a controlled kiln at 650–700°C for three hours and cooled for 24 hours to produce SCBA, which was then finely ground to improve its pozzolanic reactivity. This process allowed the use of agricultural waste as a partial cement replacement, supporting sustainability in the production of compressed earth bricks.

Testing of Materials

Sedimentation Test

Sedimentation analysis was conducted to assess the particle size distribution of the lateritic soil used. A transparent cylindrical measuring jar made of plastic, with a height of 30 cm and an internal diameter of approximately 6 cm, was used for the test. The soil sample was first sieved to remove particles larger than 5 mm, and the remaining soil was placed in the cylinder and mixed with water to three-quarters of its volume. The cylinder was sealed, shaken vigorously, and allowed to stand undisturbed on a flat surface. After 24 hours, distinct sedimentation layers were visually identified, and their depths were measured using a graduated ruler placed against the side of the transparent cylinder. These layers correspond to varying particle sizes, and the results provided insight into the soil’s textural composition, a key factor affecting brick strength, compaction, and workability.

Specific Gravity Test

Specific gravity of a material is the ratio of the weight of a given volume of the material to the weight of an equal volume of water displacement at a stated temperature (Neville, 1981). The specific gravity test was done in accordance with the provision of BS 812 (1975) and was carried out on the laterite soil to ascertain the density and quality of the soil (Eberemu et al., 2013).

Consistency Limit Test

The consistency limits test (or index test) was carried out on fine-grained soil, passing through 425µm sieve. The limits were based on the concept that a fine-grained soil can exist on any state (solid, semi-solid, plastic and liquid states) depending on its water content. The test was carried out to determine the percentage of clay content in the laterite and assess the plastic behaviour of the lateritic soil.

Bulk Density of Laterite

The bulk density test on laterite soil was carried out following BS 812-2:1975 to evaluate its suitability for compressed earth brick production. A soil sample collected from Rayfield, Jos, was air-dried and oven-dried at 105–110°C for 24 hours, then sieved through a 10 mm mesh to remove coarse particles. For the uncompacted (loose) test, a metal container of known volume was filled loosely with the soil, levelled, and weighed. For the compacted test, the same container was filled in three layers, each compacted with 25 blows using a tamping rod before levelling and weighing. Bulk density was calculated as the mass-to-volume ratio, with results recorded in g/cm^3. Higher compacted bulk density indicates better particle packing and lower voids, which are essential for achieving stronger and more durable bricks. The test results provided insight into the laterite's compaction behavior, confirming its potential use in producing quality stabilized earth bricks.

Physical and Chemical Analysis of SCBA

Particle Size Distribution of SCBA Sample

To determine the particle size distribution of the SCBA sample, 500g of SCBA sample was weighed and placed into the nest of the sieve in the order of sieve No. 70 (212 µm), No. 100 (150µm), No. 200 (75µm), using a bottom tray receiver and a lid on top, the nest of sieve was vibrated on the mechanical sieve shaker for 3-5 minutes until no more particles passed any of the sieves. The content of each sieve was weighed and recorded. The test was carried out in accordance with BS 410:1986.

Chemical Analysis of SCBA

The chemical composition of the SCBA used for the research was carried out at the National Metallurgical Development Centre (NMDC) Zaria Road, Jos Plateau State. The analysis was conducted using X-ray fluorescence (XRF) spectrometry, a non-destructive analysis technique to identify and quantify the element composition of SCBA. It was selected because of its ability to detect key elements such as SiO_2, Al_2O_3, CaO and Fe_2O_3, which are major indicators of pozzolanas.

Bricks Production

The production of the compressed laterite bricks is divided into six stages. These are: preparation of the soil, proportioning, stabilization, mixing, and compression of the mix and curing of the bricks. The choice of 2%, 6% and 8% SCBA replacement levels was based on the findings from Ali et al (2020) and Khan et al (2022) which suggests that optimum SCBA replacement levels are between 5-10% replacement.

Preparation of the Soil (Laterite)

The laterite soil was first pulverized (or broken down) into smaller fragments. A 10mm wire mesh was inclined at an angle of 45^{o} to the horizontal and used to sieve the soil by throwing shovel full of laterite against its surface, so that the soil rolls down along the slope of the mesh. The wire mesh was inclined to take advantage of gravity and momentum as the shovel loads of laterite were thrown against the mesh.

Larger particles were retained while the particles smaller than 10mm passed through the sieved laterite was then used for the mixing.

Figure 1: Sieve analysis of laterite (Source; Rimtip, 2014)

Proportioning

The proportioning of materials, also known as batching, is a critical step in the preparation of construction materials. There are two main methods of batching: by weight and by volume. While batching by weight is generally more accurate and is preferred for high-precision concrete works, this research adopted batching by volume (as shown in Table 1 and 2) due to its practicality, accessibility, and alignment with local construction practices in resource-constrained environments. The bricks produced in this study were solid (non-hollow) and had standard dimensions of 290 mm × 140 mm × 100 mm, which are commonly used in compressed earth brick construction in Nigeria. These dimensions were maintained throughout the production process to ensure uniformity in physical and mechanical testing.

Table 1: Proportion materials for 18 bricks for cement stabilization (control)

Batch no.	Stabilization (%)	Cement (m^3)	Laterite (m^3)
1	2	0.0036	0.108
2	6	0.00738	0.108
3	8	0.00878	0.108

Source: Rimtip (2014)

Table 2: Proportion materials for 18 bricks for SCBA

Batch no.	Stabilization (%)	Cement (m^3)	30% SCBA (m^3)	Laterite (m^3)
1	2	0.00252	0.00108	0.108
2	6	0.0052	0.00223	0.108
3	8	0.00615	0.00263	0.108

Source: Rimtip (2014)

Mixing

There are two stages involved in the mixing of the materials: dry mixing and wet mixing. In the dry mixing stage, only the laterite and the stabilizer (cement or cement-SCBA blend) were thoroughly mixed until a homogeneous mixture with uniform colour was achieved. Water was not added during this stage, as the natural moisture content in the laterite was initially considered adequate for preliminary blending. In the wet mixing stage, a controlled amount of water was gradually added to the dry mix to achieve the desired workability and binding consistency. This process ensured proper hydration of the stabilizing agent and enhanced the cohesion of the mix. The wet mixing continued manually until a consistent, workable mixture was obtained, suitable for moulding into compressed earth bricks. This stage is crucial for activating the chemical reactions necessary for strength development and ensuring uniform compaction during brick pressing

Compression of the Mix

A mix of laterite, OPC (control) or OPC+SCBA, and water was placed in the mould of a hand-operated CIVA press in a single layer at once as seen in Figure 2. The mixture was closed and smoothed, then the handle was raised and released. The handle was pulled down to a horizontal position, then returned to its rest position. The cover was swung back, and the handle was pulled in the opposite direction to eject the brick. Discarded engine oil was used to moisten the mould sides for easy ejection.

Figure 2: Compression of mix

Curing

Curing was performed following the procedure described by CRATerre (1991). Wet curing of the CEB involved covering freshly made bricks with polythene and maintaining moisture for 7 days, followed by air drying for 21 days. This process minimises early cracking and supports adequate strength development by preserving the moisture required for the stabiliser's chemical reactions. Wet curing also increases durability and mechanical performance.

Tests on Stabilized Earth Bricks

Bricks were designated for testing at 7 days, 14 days and 28 days of curing to monitor the performance characteristics of the stabilized earth bricks.

Compressive Strength Test

The test was carried out in accordance with BS EN 12390-7:2019. Firstly, the bricks were weighed and recorded. For the compressive strength test, each brick was placed in the machine in the same orientation as it was cast, that is, horizontally with the bed face (the largest surface) in contact with the compression plates. The bricks were aligned so that their vertical axis coincided with the centre of thrust of the compression plates. The load was then gradually applied until failure occurred, and the maximum load at failure was recorded. This procedure was carried out for bricks cured for 7, 14, and 28 days to assess strength development over time. The compressive strength and density were then calculated using equation 1 and 2 respectively.

$$\text{Compressive strength} = \frac{\text{maximum load at failure (kg)}}{\text{Area of bed (cm2)}} \quad (1)$$

$$\text{Density} = \frac{\text{mass (g)}}{\text{volume (cm3)}} \quad (2)$$

Water Absorption Test

Water absorption is a critical performance indicator for walling materials such as laterite bricks, as it directly affects durability, moisture resistance, and long-term structural integrity. In this study, the capillary water absorption method was employed to evaluate the rate and extent of moisture ingress in stabilised laterite bricks. Each brick sample was placed vertically on a soft absorbent towel at the base of a water-tight container. Water was gradually introduced until it made contact with the base of the bricks, and the level was kept constant throughout the test. The use of a towel ensured consistent and uniform contact between the water and the brick base, minimizing uneven wetting. The capillary rise or wetting height was measured along the vertical face of the brick using a graduated ruler at intervals of 10 minutes, 30 minutes, 1 hour, and 24 hours.

Results and Discussion

Physical Properties of Laterite

Sedimentation

The sedimentation test showed a sand layer of 3.7 cm, within the acceptable 3.5–4.5 cm range, indicating a sand content of 61.7%, which aligns with the ideal 50–70% range for lateritic brick production (Walker & Standards Australia, 2002). According to ASTM D2487, the particle size classification confirms the predominance of sand, with minimal gravel (8.3%) and a moderate clay fraction (30.0%). This balance supports good compaction, cohesion, and workability while minimizing shrinkage and cracking. Overall, the soil's composition meets the required standards and is deemed suitable for compressed earth brick production.

Table 3: Result of Sedimentation Test

Material	Height (cm)	Percentage
Gravel	0.5	8.3
Sand	3.7	61.7
Clay	1.8	30.0

Source: Rimtip (2014)

Specific gravity of laterite

The result of the specific gravity test of laterite sample presented in Table 4 indicates a specific gravity of 2.66 which lies within the limit of 2.48 - 2.72 as reported by Ogunbode and Apeh (2012). Indicating that the soil has good compaction properties and can be used for CEBs.

Table 4: Result of Specific Gravity Test

Test	1	2
Weight of pycnometer (W_1) kg	0.60	0.60
Weight of pycnometer + laterite (W_2) kg	0.95	0.90
Weight of pycnometer + laterite + water (W_3) kg	1.80	1.80
Weight of water ($W_3 – W_2$) g = (W_4) g	0.85	0.90
Weight of water to the brim + bottle (W_5)	1.60	1.60
Apparent specific Gravity $= \frac{W2 - W1}{W5 - W4 - W1}$	2.33	3.00
Mean Apparent Specific Gravity		2.66

Source: Rimtip (2014)

Sieve analysis of laterite

The result of the sieve analysis shown in Figure 3 indicates that the soil grading meets the specifications outlined in Clause 6201 of the Federal Ministry of Works and Housing (FMWH, 1997). According to these specifications, for a soil to be suitable for use as subgrade/fill or base material, the percentage by weight passing through the 75 µm sieve (No. 200) must not exceed 35%. From the analysis, the percentage of material passing through the 80 µm sieve (which is close in size to the 75 µm sieve) is 31.16%, which is within the allowable limit. Therefore, the laterite sample is suitable for subgrade or base construction purposes, particularly when properly stabilised.

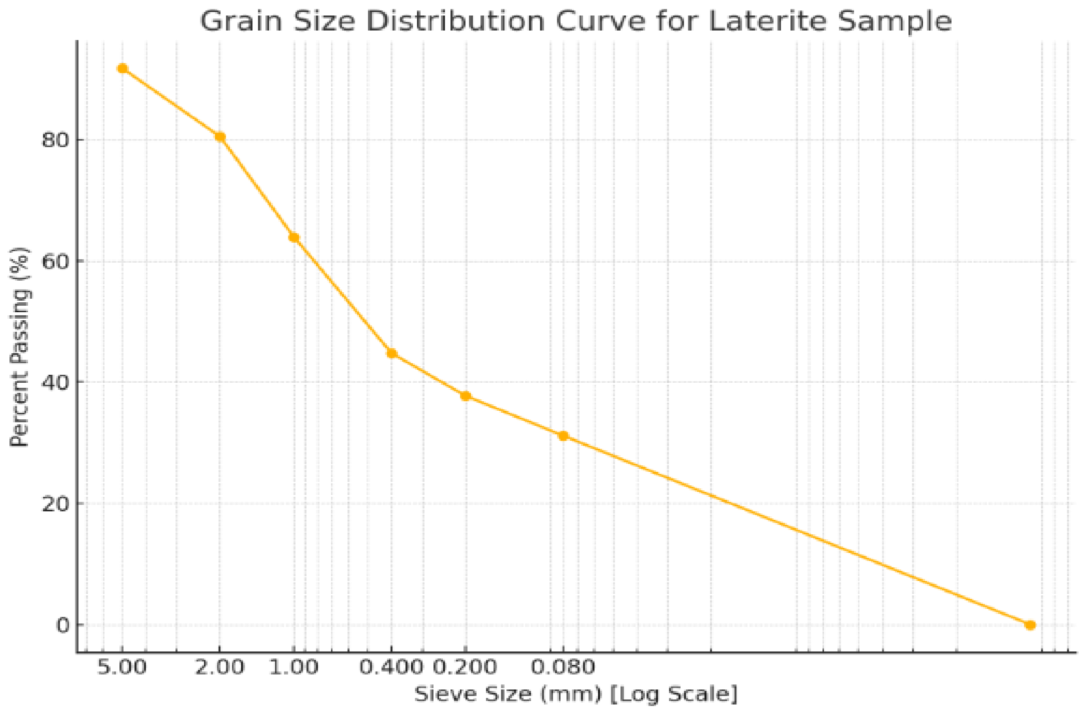

Fig 3: Sieve analysis of laterite (Source: Rimtip, 2014)

Consistency limit

The Atterberg limits test on the laterite soil yielded values of 37.70% (liquid limit), 27.10% (plastic limit), and 11.0% (plasticity index), essential for assessing its suitability for compressed earth brick stabilization. According to FMWH (1997) specifications and ASTM standards (Quadri et al., 2012), the plasticity index of 11% meets the requirement (≤12%), indicating good workability and cohesion. Although the liquid limit slightly exceeds the 35% limit, this deviation is attributed to sample disturbance. The plastic limit falls within the acceptable range of 21.10%–28.92% (Olayemi & Van, 2016), confirming the soil's adequacy for stabilized brick production.

Table 5: Consistency (Limit) Test

	Liquid Limit				**Plastic Limit**	
	WL1	**WL2**	**WL3**	**WL4**	**WP1**	**WP2**
Number of Bumps (N)	25	24	24	27	X	X
Number of Container	A	B	C	D	1	2
Total Weight – Humid	32.60	33.94	31.67	32.24	33.39	43.84
Total Weight – Dry	31.36	32.59	30.60	31.09	32.24	42.25
Weight of Container	28.19	29.17	27.65	27.92	28.12	37.15
Weight of Water	1.24	1.35	1.07	1.15	1.15	1.39
Weight of Dry Soil	3.21	3.42	2.94	3.17	4.12	5.30
Moisture Content % (W)	38.60	39.50	36.40	36.30	27.90	26.20

Liquidity Limit	LL=	37.70%
Plasticity Limit	LP=	27.10%
Plasticity Index	IP= LL – LP=	

Source: Rimtip (2014)

Bulk Density of Laterite

The result of the bulk density test conducted on the laterite sample, in accordance with BS 812: Part 2: 1975, is presented in Table 6. The uncompacted (loose) bulk density was found to be 1199 kg/m³, while the compacted bulk density was 1427 kg/m³. These values indicate the degree to which the laterite compacts under controlled conditions, providing insight into its suitability for use in compressed earth brick production. The ratio of uncompacted to compacted bulk density is 0.84, which is slightly lower than the recommended range of 0.87 to 0.96 typically observed for aggregates, as noted by Neville (1999). This slight deviation could be attributed to sample disturbance or the inherent variability of natural lateritic soils.

Table 6: Result of Bulk Density of Laterite

Procedure	Test 1	Test 2
Weight of empty cylinder (W_1) kg	4.60	4.60
Weight of cylinder + water (W_2) kg	11.40	11.40
Weight of uncompacted laterite + cylinder (W_3) kg	12.10	13.40
Weight of compacted laterite + cylinder (W_4) kg	14.00	14.60
Weight of uncompacted laterite A($W_3 – W_1$)	7.50	8.80
Weight of compacted laterite B($W_4 – W_1$)	9.40	10.00
Volume of water V = (W_2 - W_1) x 10^3	6.80	6.80
Density of uncompacted laterite A/V	1103	1294
Density of compacted laterite B/V	1382	1471
Mean value of loose bulk density = 1199kg/m^3		
Mean value of compacted bulk density =1427kg/m^3		

Source: Rimtip (2014)

Physical and Chemical Properties of Sugarcane Bagasse Ash

Sieve Analysis of SCBA

The result of the sieve analysis of the SCBA sample shown in Figure 4 revealed that the percentage passing through the 212µm sieve lies within the range of 75 – 100% for Pozzolanas as specified by ASTM C618-78 (1978).

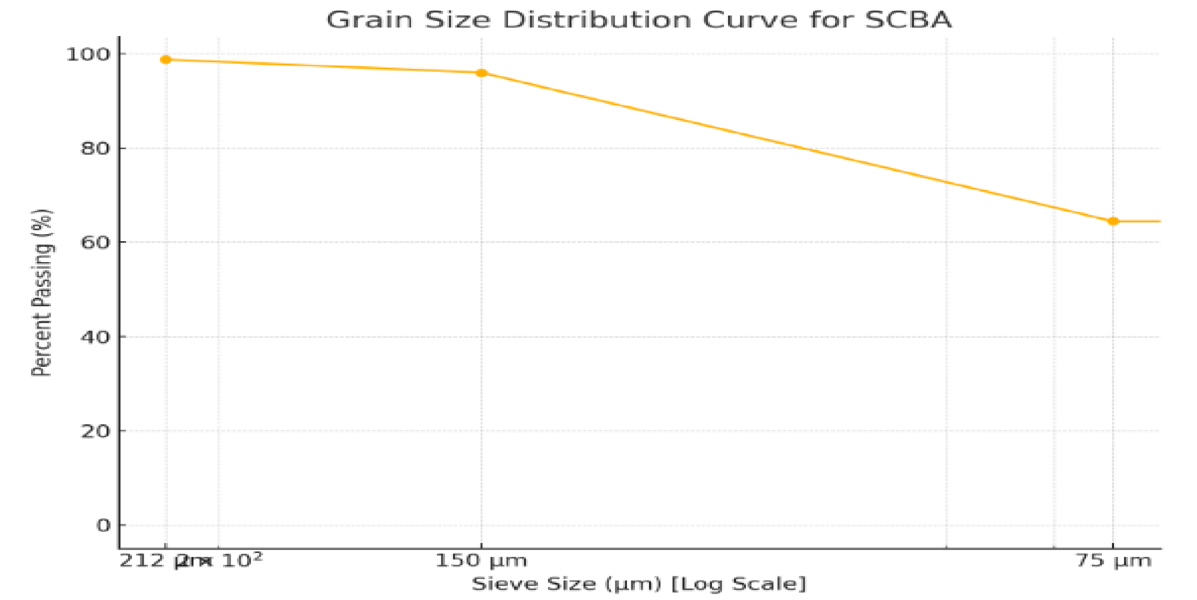

Figure 4: Sieve analysis of SCBA (Source: Rimtip, 2014)

Chemical Analysis of SCBA

The chemical composition of the sugarcane bagasse ash (SCBA) used in this study is presented in Table 7. The combined content of silicon dioxide (SiO_2 = 63.28%), aluminium oxide (Al_2O_3 = 6.59%), and iron oxide (Fe_2O_3 = 5.19%) is 75.06%. This total exceeds the minimum requirement of 70% for natural pozzolans as specified in ASTM C618-19, Section 5.1.1, which states that the sum of SiO_2, Al_2O_3, and Fe_2O_3 must be at least 70% by mass for a material to qualify as a Class N pozzolan. The Loss on Ignition (LOI) for the SCBA sample is 5.23%, which falls below the maximum allowable limit of 10% for Class N pozzolans as specified in ASTM C618-19, Section 5.1.4. While earlier versions of the standard allowed a maximum LOI of 12%, the more recent revision (ASTM C618-19) reduced this limit for natural pozzolans to enhance quality control. Based on the chemical composition, the SCBA used in this study meets the ASTM requirements for a Class N pozzolanic material and is suitable for partial replacement of cement in earth brick stabilisation.

Table 7: Chemical Composition of SCBA

Constituent	Percentage Present (%)
SiO_2	63.28
Al_2O_3	6.59
Fe_2O_3	5.19
Na_2O	0.58
CaO	7.22
K_2O	4.97
MnO	0.85
L.O.I	5.23

$S_iO_2 + Al_2O_3 + Fe_2O_3 = 75.06$

Source: Rimtip (2014)

Compressed Earth Bricks

Compressive Strength (Destructive) Test

The compressive strength results (Table 8) show a clear relationship between curing age, stabilizer type, and stabilizer content. Compressive strength increased notably from 7 to 28 days across all samples, underscoring the importance of curing in achieving optimal performance. This trend is attributed to the continuous hydration of cement and the delayed pozzolanic reaction of Sugarcane Bagasse Ash (SCBA), which enhances long-term strength development. At 28 days, cement-only bricks exhibited slightly higher strength than SCBA-stabilized bricks at early ages; however, SCBA mixes approached similar values. For instance, at 8% stabilization, cement-only bricks reached 4.64 N/mm², while cement + SCBA bricks achieved 4.11 N/mm². These findings indicate that SCBA is effective as a partial cement replacement, particularly at 6–8% levels, which align with previous studies (Cordeiro et al., 2009; Ali et al., 2021). Overall, 8% stabilization was the most effective, validating SCBA's potential as a sustainable material for durable, low-cost earth brick construction.

Table 8: Compressive Strength of Bricks

Curing Age (Days)	Type of Stabilization	% Stabilization	Average Strength (N/mm²)
7	Cement + SCBA	2	0.05
7	Cement + SCBA	6	1.09
7	Cement + SCBA	8	1.19
7	Cement only	2	0.13
7	Cement only	6	1.33
7	Cement only	8	2.74
14	Cement + SCBA	2	1.28
14	Cement + SCBA	6	3.64
14	Cement + SCBA	8	3.35
14	Cement only	2	1.31
14	Cement only	6	3.02
14	Cement only	8	4.02
28	Cement + SCBA	2	2.03
28	Cement + SCBA	6	3.84
28	Cement + SCBA	8	4.11
28	Cement only	2	1.13
28	Cement only	6	3.78
28	Cement only	8	4.64

Source: Rimtip (2014)

Water Absorption Test

The result of the test is shown in Table 9. The result reveals that all bricks containing admixture SCBA absorbed less water than the control bricks (bricks with 100% cement stabilization). The result shows that the SCBA improved bricks by reducing water absorption. The water absorption of 2% stabilization of both cement and cement plus SCBA is between 10cm – 20cm indicating that the bricks cannot be used for the base (first three courses on top of the slab) in construction as seen in Ojerinde (2020). 6% and 8% stabilization of control bricks and OPC/SCBA shows the water absorption below 10cm indicating that it can be used for the entire building. From this result it can be concluded that bricks with OPC/SCBA absorb less fluid.

Table 9: Water Absorption of Bricks

% Stabilisation	Stabiliser	Average Height of absorption			
		10 Min	30 Min	1 Hr	24 Hrs
	Cement	4.87	6.43	7.50	18.33
2	Cement + SCBA	2.93	4.50	4.63	15.53
	Cement	3.97	5.63	6.00	10.33
6	Cement + SCBA	2.33	3.30	4.43	8.60
	Cement	4.70	5.83	6.60	8.70
8	Cement + SCBA	5.33	5.67	6.60	8.03

Source: Rimtip (2014)

Conclusion

This study demonstrates that Sugarcane Bagasse Ash (SCBA) is a viable and sustainable partial replacement for OPC in CEB production. SCBA at 6% and 8% replacement levels met and exceeded the minimum compressive strength requirement of 2.5 N/mm² for non-load-bearing walls, confirming its practical suitability. Beyond strength performance, SCBA contributes to environmental sustainability by reducing cement usage and promoting the beneficial reuse of agricultural waste in line with circular economic principles. Additionally, the geotechnical properties of the lateritic soil used were within acceptable limits, affirming its appropriateness for stabilized earth construction. To support the broader implementation of SCBA-stabilized bricks, construction policies and standards should be revised to include alternative pozzolanic materials. Collaborative efforts among government agencies, researchers, and manufacturers are essential for promoting production, standardizing quality, and training local artisans. Future studies should explore the long-term durability and adaptability of SCBA-enhanced bricks under diverse climatic conditions.

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