



## Multiscale Structural and Microstructural Investigation of Ternary Blends of Sawdust Ash and Sponge Gourd Ash in Concrete

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### ABSTRACT

Concrete production contributes significantly to global CO<sub>2</sub> emissions due to the energy-intensive manufacture of ordinary Portland cement (OPC), necessitating the development of sustainable cementitious alternatives. This study evaluates the performance of a novel agro-waste-based ternary supplementary cementitious material (SCM) system comprising sawdust ash (SDA) and sponge gourd ash (SGA) as partial replacements for OPC in concrete. A total OPC replacement level of 15% was adopted, with SGA contents ranging from 2.5% to 12.5% and SDA constituting the balance, along with a control mix containing 100% OPC. Fresh, mechanical, and microstructural properties were investigated up to 180 days of curing. The results revealed continuous strength development in all mixes, confirming sustained pozzolanic activity. At 180 days, the control concrete attained a compressive strength of 35.70 MPa, while the blended concretes achieved strengths ranging from 29.54 to 33.10 MPa. Among the ternary blends, the 2.5% SGA mix recorded the highest compressive strength of 32.40 MPa, representing only a 9.2% reduction relative to the control despite a 15% reduction in OPC content. Corresponding 180-day splitting tensile and flexural strengths ranged from 2.81–3.07 MPa and 3.01–3.56 MPa, respectively. Strong predictive relationships were established between compressive strength and splitting tensile strength ( $R^2 = 0.8739-0.9133$ ), compressive strength and flexural strength ( $R^2 = 0.9792-0.9979$ ), and splitting tensile strength and flexural strength ( $R^2 = 0.8874-0.9770$ ). SEM analysis revealed progressive pore refinement and matrix densification as the curing age increased. At the same time, EDX results showed a decrease in Ca content from 35.54 wt. % in the control mix to 31.16 wt. % in the 12.5% SGA mix at 90 days, accompanied by an increase in the Si/Ca ratio from 0.225 to 0.520. These changes indicate enhanced pozzolanic reactions and additional formation of calcium silicate hydrate (C–S–H), which contributed to the observed long-term strength development. The findings demonstrate that SDA–SGA ternary-blended concrete can deliver structurally adequate performance while reducing OPC consumption by 15% through the beneficial use of agricultural wastes.

**Keywords:** Pozzolanic Activity; Sawdust Ash (SDA); Sponge Gourd Ash (SGA); Sustainable Concrete; Ternary Blended Concrete

### INTRODUCTION

Concrete is a heterogeneous composite material consisting of cement, water, and aggregates, widely used in the construction industry for its versatility, durability, and structural performance. As reported by Salemi (2019), global concrete production has increased significantly with rapid urbanization, reaching approximately 25 billion tonnes annually. Despite its widespread use, concrete production is environmentally burdensome, primarily due to the high demand for ordinary Portland cement (OPC), which contributes about 8% of global CO<sub>2</sub> emissions (Purton, 2024). This has intensified the search for sustainable alternatives that can reduce cement consumption while maintaining acceptable engineering performance. Supplementary cementitious materials (SCMs), particularly those derived from industrial and agricultural wastes, have gained considerable attention as partial replacements for OPC. Materials such as sawdust ash (SDA) and sponge gourd ash (SGA) exhibit pozzolanic characteristics that can enhance long-term strength development, durability, and microstructural refinement while promoting waste valorization and environmental sustainability (Hargis, 2018). The use of a single SCM results in a binary blend, whereas combining multiple SCMs yields ternary blends that have been reported to exhibit synergistic effects that can improve mechanical performance and

durability compared with single-blend systems. Although numerous studies have investigated individual and binary applications of agro-waste ashes in concrete, there is a clear lack of research on the combined use of SDA and SGA in ternary blended structural concrete. The synergistic interaction between these two materials and their influence on strength development, strength interrelationships, and microstructural evolution remains largely unexplored. This represents a key research gap addressed in this study. Sponge gourd ash (SGA) was selected as a co-pozzolan due to its anticipated silica-rich composition and potential pozzolanic reactivity. It is expected to complement sawdust ash (SDA) by contributing additional reactive silica for secondary hydration reactions, thereby enhancing calcium silicate hydrate (C–S–H) formation, improving matrix densification, and providing a sustainable utilization pathway for an underutilized agricultural waste material. Accordingly, this study aimed to evaluate the performance of a ternary blended cementitious system comprising OPC, SDA, and SGA at a total replacement level of 15% in structural concrete. The study investigates fresh and hardened properties up to 180 days of curing, develops empirical relationships among compressive, splitting tensile, and flexural strengths, and examines the underlying microstructural mechanisms using scanning electron microscopy (SEM) and energy dispersive

X-ray spectroscopy (EDX) to assess hydration products and matrix evolution.



Figure 1: Sponge Gourd in Many States

## MATERIALS AND METHODS

### Ordinary Portland Cement (OPC)

Ordinary Portland limestone cement (Superset-brand, Type 42.5R, rapid hardening) manufactured by Elephant Cement was used as the binder for all concrete and mortar mixtures. It conforms to the requirements of BS EN 197-1:2011, Cement, Composition, specifications and conformity criteria for common cements, which defines composition, strength classes, and performance for structural applications (*standard: BS EN 197-1:2011*).

### Sawdust Ash (SDA)

Sawdust ash (SDA) was produced from sawdust obtained from local sawmills in Ado-Ekiti, Nigeria; the raw sawdust was sun-dried for 72 hours to reduce its moisture content to  $\leq 3\%$  in line with procedures referenced for pozzolanic materials (*ASTM C618-22*), then calcined at  $600^\circ\text{C}$  for 2 hours to enhance pozzolanic reactivity and reduce loss on ignition. The calcined ash was ground and passed through a  $600\ \mu\text{m}$  mesh before storage.

### Sponge Gourd Ash (SGA)

Sponge gourds collected from natural vegetation in Ekiti and Ondo States, Nigeria, were washed, dried, crushed, and calcined at  $600^\circ\text{C}$  for 2 hours to produce sponge gourd ash (SGA). The ash was sieved to achieve fine particles suitable for partial cement replacement.

### Aggregates and Water

Natural fine aggregate (river sand) was obtained from the Ureje River in Ado-Ekiti, Nigeria, and prepared in accordance with ASTM C136 to ensure proper grading and cleanliness. Crushed granite used as coarse aggregate was sourced from the Kopek Construction Yard in Ikere-Ekiti, Nigeria, and satisfied standard specifications for particle size distribution and material quality. Potable water used for mixing and curing was collected from a borehole at the Ministry of Works laboratory in Ado-Ekiti, Nigeria, and conformed to ASTM C1602 requirements for mixing water.

### Mix Proportion and Concreting

Concrete with a characteristic compressive strength of  $25\ \text{N/mm}^2$  at 28 days was adopted for this study. Preliminary trial mixes were conducted to establish the optimum proportions of the constituent materials needed to achieve this target strength. The trials showed that a cement: fine aggregate: coarse aggregate mix ratio of 1:1.5:3, with a water–cement ratio of 0.50, was suitable for producing Grade 25 concrete. For the ternary blended mixes incorporating sawdust ash (SDA) and sponge gourd ash (SGA), the SDA content was maintained at 15% by mass of cement. The mix identification system used for the experimental program is presented in Tables 1 and 2.

Table 1: Mix Nomenclature for Concrete

Mix ID	Mix Name	Composition Description
Control	Control	Control (100% OPC)
T <sub>0</sub>	B <sub>0</sub> SGA	(85% OPC + 15% SDA + 0% SGA)
T <sub>1</sub>	T <sub>2.5</sub> SGA	(85% OPC + 12.5% SDA + 2.5% SGA)
T <sub>2</sub>	T <sub>5.0</sub> SGA	(85% OPC + 10% SDA + 5.0% SGA)
T <sub>3</sub>	T <sub>7.5</sub> SGA	(85% OPC + 7.5% SDA + 7.5% SGA)
T <sub>4</sub>	T <sub>10</sub> SGA	(85% OPC + 5% SDA + 10% SGA)
T <sub>5</sub>	T <sub>12.5</sub> SGA	(85% OPC + 2.5% SDA + 12.5% SGA)

The SDA content was progressively substituted with SGA at 2.5% intervals. The resulting mix proportions required to achieve the target concrete strength of  $25\ \text{N/mm}^2$  are presented in Table 2

Table 2: Mix Proportions for  $25\ \text{N/mm}^2$  Concrete

Mix ID	Mix Name	Cement	SDA	SGA	Sand	Granite	Water
Control	Control	4.6	0.0	0.0	6.8	13.6	2.3
T <sub>0</sub>	T <sub>0</sub> SGA	16.7	3.0	0.0	29.5	58.9	8.4
T <sub>1</sub>	T <sub>2.5</sub> SGA	16.7	2.5	0.5	29.5	58.9	8.4
T <sub>2</sub>	T <sub>5.0</sub> SGA	16.7	2.0	1.0	29.5	58.9	8.4
T <sub>3</sub>	T <sub>7.5</sub> SGA	16.7	1.5	1.5	29.5	58.9	8.4
T <sub>4</sub>	T <sub>10</sub> SGA	16.7	1.0	2.0	29.5	58.9	8.4
T <sub>5</sub>	T <sub>12.5</sub> SGA	16.7	0.5	2.5	29.5	58.9	8.4

Concrete was prepared according to the mix proportions in Table 2, and specimens were cast to evaluate the mechanical properties required to establish strength relationships. The test specimens included  $150 \times 150 \times 150$  mm cubes for density and compressive strength,  $150 \times 300$  mm cylinders for splitting tensile strength, and  $150 \times 150 \times 500$  mm unreinforced beams for modulus of rupture. All samples were cured by water immersion and tested at 7, 14, 21, 28, 60, and 90 days, with the resulting mean values used to develop empirical relationships among compressive strength, splitting tensile strength, and flexural strength. Microstructural analysis using SEM–EDX was performed on gold-coated samples under high-vacuum conditions (Figure 3.25), revealing densely interwoven C–S–H gel, needle-like ettringite formations, and residual portlandite crystals, indicative of a refined and compact matrix. EDX mapping confirmed the presence of Ca, Si, Al, and Fe, demonstrating enhanced pozzolanic activity and matrix densification in the SDA–SGA blended concrete, consistent with findings reported by Simeidru et al. (2023).

### Experimental Investigations

#### Determination of Setting Times

The effect of ternary blends of SDA and SGA on mortar setting times was evaluated using the Vicat needle test in accordance with BS EN 196-3:2016 — Methods of testing cement — Determination of setting times and soundness. Initial and final setting times were recorded as the times at which specified needle penetration limits were reached, providing insight into hydration kinetics in blended binder systems (*standard: BS EN 196-3:2016*).

#### Determination of Workability

Workability of fresh concrete containing SDA and SGA was determined using the slump test in accordance with BS EN 12350-2:2019. The Abrams cone was filled in three layers, each compacted with 25 strokes of a standard tamping rod, after which the cone was lifted vertically and the slump measured in millimetres. All results are reported strictly as slump values (mm) without qualitative classification, in line with standard practice. Occasional loss of symmetry observed in some mixes is noted as instability of the fresh concrete rather than a workability class, indicating reduced cohesion at higher SGA contents and possible need for mix adjustment or admixture use.

#### Density and Compressive Strength

Concrete density was determined from  $150 \times 150 \times 150$  mm cube specimens by measuring mass and volume after curing and surface drying, in accordance with BS EN 12350-6:2019. Compressive strength was determined on the same cube specimens at 7, 14, 21, 28, 60, 90, and 180 days using a calibrated Universal Testing Machine at a loading rate of  $0.6 \pm 0.2$  MPa/s, in accordance with BS EN 12390-3:2019. For each mix and curing age, three (3) specimens were tested, and the reported strength values represent the mean of replicate results. Variability was assessed using the standard deviation

( $\pm$ SD) and the coefficient of variation (COV). At the same time, statistical significance between the control and ternary mixes was evaluated using one-way ANOVA at the 95% confidence level ( $p \leq 0.05$ ).

#### Splitting Tensile Strength

Splitting tensile strength was measured on  $150 \times 300$  mm cylindrical specimens in accordance with BS EN 12390-6:2019. Specimens were loaded diametrically, and tensile strength was calculated as  $f_t = (2P)/(\pi DL)$ , where P is the maximum load, D is the cylinder diameter, and L is the length. Each reported value represents the average of three specimens, with variability and statistical significance assessed using standard deviation and one-way ANOVA ( $p \leq 0.05$ ).

#### Modulus of Rupture (Flexural Strength)

The modulus of rupture was determined on  $100 \times 100 \times 500$  mm beam specimens in accordance with BS EN 12390-5:2019 under third-point loading. Flexural strength was calculated using  $f_r = (PL)/(bd^2)$ , where P is the failure load, L is span, and b and d are the beam width and depth, respectively. As with other strength tests, three specimens were tested per mix and curing age, and results are reported as mean values with accompanying standard deviation and ANOVA-based significance evaluation at 95% confidence level ( $p \leq 0.05$ ).

#### Microstructural Analysis (SEM–EDX)

Hardened concrete specimens were examined at 28 and 90 days using scanning electron microscopy (SEM), with representative mixes (CT, T2, and T5) selected to capture the behaviour at the control, intermediate, and high replacement levels. Samples were oven-dried, sectioned, and gold-coated prior to imaging to eliminate charging effects. All micrographs were clearly referenced to their corresponding mix ID and curing age to ensure proper traceability. Energy dispersive X-ray spectroscopy (EDX) was conducted to determine elemental composition (Ca, Si, Al, Fe) at selected points within the matrix and to assess variations in the Si/Ca ratio as an indicator of pozzolanic activity and calcium silicate hydrate (C–S–H) formation. Due to the heterogeneous nature of concrete, EDX results are interpreted as localized microstructural evidence rather than bulk chemical composition. The observed trends provide qualitative support for progressive matrix densification, although limited 28-day control data partly constrain the interpretation of the Si/Ca evolution. SEM–EDX observations were used to qualitatively support trends in strength development and hydration mechanisms. However, it is acknowledged that SEM–EDX does not fully quantify pore structure refinement; therefore, complementary techniques such as X-ray diffraction (XRD), thermogravimetric/differential thermal analysis (TG/DTG), backscattered electron (BSE) imaging, or mercury intrusion porosimetry (MIP) are recommended for more comprehensive characterization.



Figure 2: Hitachi SU-3500 Field Emission Scanning Electron Microscope, Tokyo, Japan

### Experimental Investigation on Paste and Mortar of SDA–SGA Ternary Blends

This section outlines the procedures used to assess the paste and mortar properties of ternary blends of Sawdust Ash (SDA) and Sponge Gourd Ash (SGA) as partial replacements for Ordinary Portland Cement (OPC), focusing on fineness, soundness, consistency, and setting times as indicators of binder reactivity, stability, workability, and early hydration. All blends contained a total of 15% SDA–SGA replacement, while the control mix was 100% OPC. All tests were conducted using standard laboratory methods under controlled conditions.

#### Fineness Test

The fineness of the control and blended cementitious materials was determined using the Blaine air permeability method in accordance with standard procedures. Results were expressed in specific surface area ( $\text{m}^2/\text{kg}$ ) to ensure uniformity and comparability across all samples. The test was used to evaluate particle size distribution and surface area, which directly influence hydration rate and early strength development. All values for the control cement and SDA–SGA-blended mixes were reported on the same measurement basis to ensure consistency in comparison.

#### Soundness Test

The soundness of the control and blended cement pastes was determined using the **Le Chatelier method** in accordance with relevant standards. Results were expressed in **millimetres (mm)** as the measured expansion of the soundness mould after boiling. The test assessed the volumetric stability of the binders and their resistance to delayed expansion caused by free lime and magnesia. All mixes were evaluated under identical curing and testing conditions to ensure comparability between the control and SDA–SGA-blended samples.

**Table 3: Effect of Ternary Blends of SDA and SGA on Workability**

Mix ID	Mix Composition	Slump (mm)	Type of Slump	Workability Classification
CT	100% OPC	24	True slump	Very Low
T0	85% OPC + 15% SDA + 0% SGA	28	True slump	Low
T1	85% OPC + 12.5% SDA + 2.5% SGA	33	True slump	Low–Medium
T2	85% OPC + 10% SDA + 5.0% SGA	38	True slump	Medium
T3	85% OPC + 7.5% SDA + 7.5% SGA	42	Shear slump	Medium
T4	85% OPC + 5% SDA + 10.0% SGA	46	Shear slump	Medium–High
T5	85% OPC + 2.5% SDA + 12.5% SGA	51	Shear slump	High

#### Density of Hardened Concrete

From Table 4, the density decreased slightly as SGA content increased, consistent with the lower specific gravity of

#### Consistency Test

The standard consistency of the control and blended cement pastes was determined using the **Vicat apparatus** in accordance with standard testing procedures. Results were expressed as **percentage water content (%)**, representing the amount of water required to produce a paste of standard consistency. The test was used to evaluate the influence of incorporating SDA–SGA on the water demand and workability of the cementitious blends. Consistency values were determined under identical mixing and testing conditions for all samples to ensure reliable comparison.

#### Setting Time Test

The initial and final setting times of the control and blended cement pastes were determined using the Vicat needle apparatus in accordance with standard methods. Results were expressed in minutes (min) from the time of water addition. The test was used to evaluate the rate of hydration and stiffening behaviour of the blended binders containing SDA–SGA, compared with the control cement. All samples were tested under the same environmental and procedural conditions to ensure consistency and validity of results.

## RESULTS AND DISCUSSION

### Workability of Fresh Concrete

From Table 3, the results indicate that increasing SGA content improved workability, transitioning the slump from very low for the control too high for T5. The observed increase is likely due to the spherical shape and lower water demand of SGA particles, which reduces internal friction in the mix. Similar trends have been reported by Imageonyechere (2022) for sawdust ash–concrete blends and by Mirzaei et al. (2025) for agricultural biomass ashes, both of which enhanced workability at moderate replacement levels.

biomass ashes relative to OPC. Densities increased over time for all mixes due to ongoing hydration and pozzolanic reactions, as supported by Mirzaei et al. (2025). The control

concrete remained the densest, reflecting the higher cement content and absence of porous biomass.

**Table 4: Density of Concrete Specimens (kg/m<sup>3</sup>)**

Mix ID	Mix Composition	7 d	14 d	21 d	28 d	60 d	90 d	180 d
CT	100% OPC	2576	2582	2580	2587	2589	2590	2594
T0	85% OPC + 15% SDA	2570	2576	2574	2580	2583	2586	2590
T1	85% OPC + 12.5% SDA + 2.5% SGA	2565	2572	2570	2576	2579	2582	2586
T2	85% OPC + 10% SDA + 5.0% SGA	2561	2568	2566	2571	2575	2578	2582
T3	85% OPC + 7.5% SDA + 7.5% SGA	2558	2563	2561	2566	2571	2574	2578
T4	85% OPC + 5% SDA + 10.0% SGA	2555	2560	2558	2563	2568	2571	2574
T5	85% OPC + 2.5% SDA + 12.5% SGA	2547	2554	2556	2558	2563	2568	2569

**Compressive Strength**

Compressive strength decreased slightly, as shown in Table 5, with higher SGA substitution beyond 5–7.5%, suggesting that excessive replacement reduced the cementitious content, thereby lowering matrix cohesion. Early-age strength was

more affected, but long-term strength improved due to pozzolanic reactions, consistent with Imageonyechere (2022) and supported by Mirzaei *et al.* (2025). The trend indicates that 5–7.5% SGA is optimal for enhancing strength without compromising workability.

**Table 5: Compressive Strength of Concrete (N/mm<sup>2</sup>)**

Mix ID	7 d	14 d	21 d	28 d	60 d	90 d	180 d
CT	17.10	20.30	21.60	25.34	26.60	28.50	35.70
T0	15.87	18.09	19.98	23.98	24.78	26.64	33.10
T1	15.52	17.75	19.62	23.60	24.43	26.29	32.40
T2	15.20	17.37	19.29	23.26	24.12	25.92	31.75
T3	14.86	17.05	18.92	22.88	23.77	25.56	31.00
T4	14.51	16.71	18.57	22.52	23.43	25.22	30.29
T5	14.15	16.34	18.26	22.21	23.13	24.88	29.54

**Splitting Tensile Strength**

Tensile strength trends mirrored compressive strength patterns, as shown in Table 6, with minor reductions as SGA content increased beyond 5%, due to a lower cohesive bond

between the cement paste and aggregates at higher ash replacements. Strength gains at 180 days demonstrate ongoing pozzolanic activity. These observations are supported by Imageonyechere (2022).

**Table 6: Splitting Tensile Strength (N/mm<sup>2</sup>)**

Mix ID	7 d	14 d	21 d	28 d	60 d	90 d	180 d
T0	1.04	1.16	1.26	1.39	1.54	1.78	3.10
T1	1.02	1.14	1.23	1.37	1.52	1.75	3.07
T2	0.97	1.12	1.21	1.35	1.49	1.73	3.02
T3	0.92	1.10	1.18	1.33	1.47	1.71	2.95
T4	0.84	1.08	1.15	1.31	1.44	1.79	2.88
T5	0.75	1.06	1.11	1.28	1.41	1.77	2.81

**Flexural Strength (Modulus of Rupture)**

Flexural strength as shown in Table 7, decreased with higher SGA content beyond 5–7.5%, confirming that excessive substitution compromises tensile behaviour, although long-

term curing improves matrix densification. The relationship between flexural and compressive strength aligns with ACI 318 (2019) correlations for blended cementitious systems.

**Table 7: Flexural Strength (N/mm<sup>2</sup>)**

Mix ID	7 d	14 d	21 d	28 d	60 d	90 d	180 d
T0	2.08	2.27	2.39	2.69	2.78	2.86	3.61
T1	2.02	2.24	2.37	2.66	2.72	2.83	3.56
T2	1.99	2.18	2.34	2.63	2.69	2.80	3.48
T3	1.96	2.13	2.29	2.59	2.65	2.77	3.40
T4	1.91	2.09	2.27	2.57	2.63	2.75	3.32
T5	1.88	2.04	2.23	2.54	2.61	2.72	3.01

**Microstructural Analysis (SEM–EDX)**

SEM–EDX analysis of concrete containing ternary SDA–SGA blends revealed that the control and T0 mixes exhibited dense, crack-free microstructures with well-formed C–S–H, CH, and ettringite phases and small, uniform pores at both 28 and 90 days, as shown in Table 8 and Figure 3, indicating

efficient hydration and high strength. With increasing SGA content (T1–T5), microcracks, larger and irregular pores, scattered hydration products, and unhydrated ash particles became more pronounced, reflecting heterogeneous microstructures, delayed hydration, and reduced early- and long-term strength. These observations confirm that higher

SGA proportions in ternary blends negatively affect matrix densification and microstructural integrity, consistent with findings by Wasiu et al. (2025), Sun et al. (2023), Mirzaei et al. (2025), and Liang et al. (2024).

**Table 8: SEM Microstructure Summary**

Mix ID	28-Day SEM	90-Day SEM
CT	Absence of cracks; very small uniform pores; abundant C–S–H, CH, ettringite	Absence of cracks; refined pores; densified C–S–H; few unhydrated grains
T0	Small, uniform pores; moderately compact C–S–H	Minor microcracks; denser C–S–H
T1	Small microcracks; irregular pores; scattered C–S–H	Slightly increased cracks; moderately densified C–S–H
T2	Small cracks; moderately large pores; less dense C–S–H	Slightly widened cracks; increased hydration products but loose arrangement
T3	Minor cracks; large irregular pores; scattered C–S–H	Slightly larger cracks; scattered hydration products
T4	Small–moderate cracks; large non-uniform pores; scattered C–S–H	Pronounced cracks; limited densification
T5	Small–moderate cracks; large irregular pores; scattered C–S–H	Clearly pronounced cracks; poorly refined pores; scattered hydration products

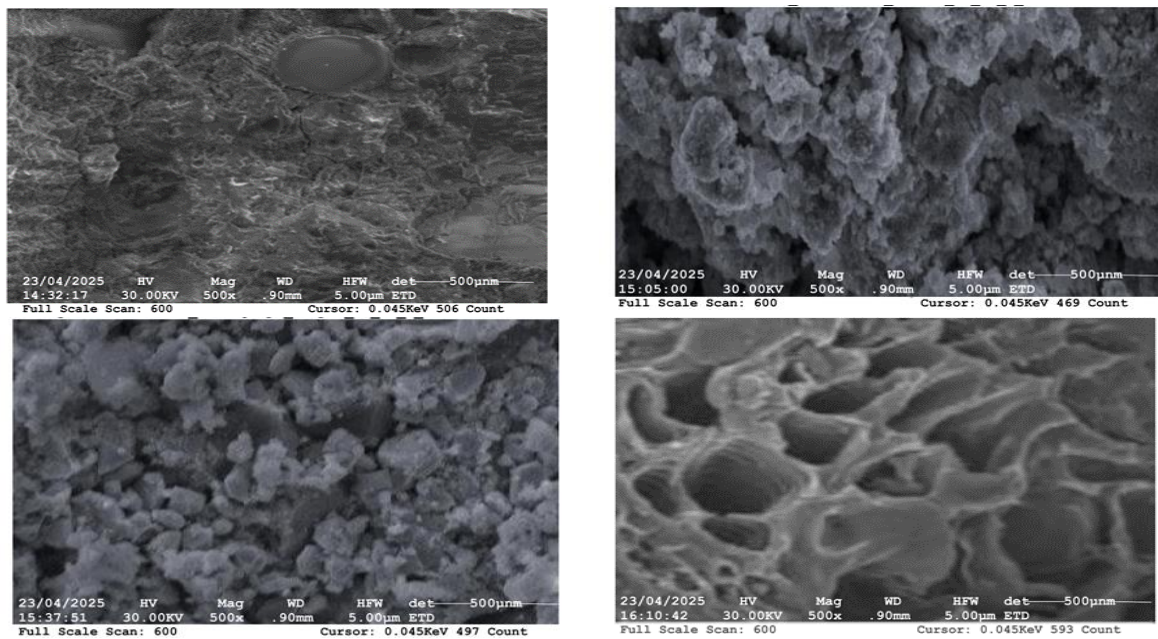


Figure 3: SEM Images

**Microstructural Analysis (SEM–EDX)**

The EDX results presented in Table 9 and Figure 4 show that the elemental composition of concrete changes with increasing SGA content. Specifically, calcium (Ca) decreases from 35.78 wt% in the control (CT) to 31.52 wt% in the 12.5% SGA mix (T5), while silicon (Si) increases from negligible in CT to 12.67 wt% in T5. This trend continues at 90 days, with Ca declining and Si rising, increasing the Si/Ca ratio from 0.225 (CT) to 0.520 (T5). The rising Si/Ca ratio reflects enhanced pozzolanic activity at later ages, as the additional silica from SGA participates in secondary C–S–H

formation. Consequently, early-age compressive strength is reduced due to cement dilution in higher SGA mixes. However, long-term strength improves as the pozzolanic reaction progresses, confirming the latent strength-gaining potential of SGA in ternary-blended concrete. These observations are consistent with the findings of Fapohunda et al. (2020), which highlight that SGA substitution systematically decreases Ca, increases Si, and elevates the Si/Ca ratio, which correlates directly with strength development.

**Table 9: EDX Elemental Composition and Si/Ca Ratio**

Mix	28 d Ca (wt %)	28 d Si (wt %)	28 d Si/Ca	90 d Ca (wt %)	90 d Si (wt %)	90 d Si/Ca
CT	35.78	—	—	35.54	8.00	0.225
T0	34.37	—	—	34.65	12.41	0.358
T1	34.68	3.55	0.102	32.82	14.07	0.429
T2	33.78	5.76	0.171	33.85	15.38	0.454
T3	32.33	9.46	0.293	32.65	15.98	0.490
T4	32.00	10.30	0.322	32.10	16.70	0.520
T5	31.52	12.67	0.402	31.16	16.20	0.520

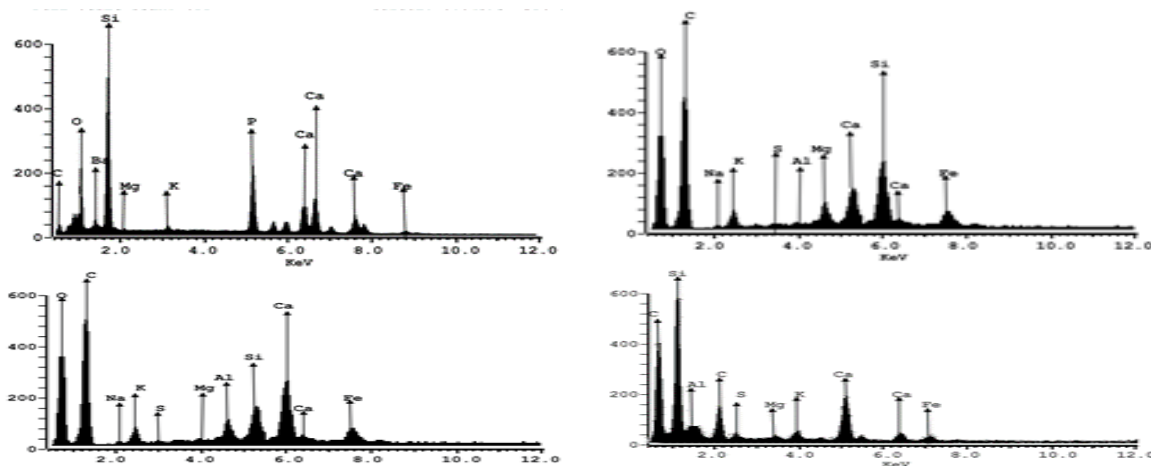


Figure 4: EDX Images

### Fineness

**Table 10: Effects of Ternary Blends of SDA and SGA on Fineness**

Mix Composition	Fineness
Control (Pure OPC)	9.06
15% SDA + 0% SGA + OPC	262.56
12.5% SDA + 2.5% SGA + OPC	295.44
10% SDA + 5% SGA + OPC	328.31
7.5% SDA + 7.5% SGA + OPC	361.19
5% SDA + 10% SGA + OPC	394.06
2.5% SDA + 12.5% SGA + OPC	426.94

As shown in Table 10, the fineness of the ternary blended binders increased progressively from 262.56 to 426.94 as the proportion of SGA increased. This trend was observed during the experimental investigation and is mainly due to the finer particle size and higher surface area of SGA compared with those of SDA and OPC. The finer particles fill voids between cement grains, thereby improving packing density and reducing pore spaces within the paste matrix. This enhanced

packing promotes better contact between cement and water, leading to improved hydration and strength development. Similar behaviour was reported by Fapohunda et al. (2019), Olugbenga (2019), and Ettu et al. (2013), who noted that ternary blends with fine supplementary materials improve binder performance.

### Soundness

**Table 11: Effects of Ternary Blends of SDA and SGA on Soundness**

Mix Composition	Soundness (mm)
Control (Pure OPC)	5.90
15% SDA + 0% SGA + OPC	5.50
12.5% SDA + 2.5% SGA + OPC	5.30
10% SDA + 5% SGA + OPC	5.10
7.5% SDA + 7.5% SGA + OPC	4.90
5% SDA + 10% SGA + OPC	4.70
2.5% SDA + 12.5% SGA + OPC	4.50

As investigated in Table 11, soundness values decreased steadily from 5.90 mm to 4.50 mm as the SGA content increased. This reduction indicates improved volumetric stability of the blended binders. The pozzolanic reaction of SDA and SGA consumes free calcium hydroxide, reducing the likelihood of delayed expansion. In addition, the refined

pore structure formed by fine ash particles helps restrain internal stresses in the paste. Comparable results were reported by Wang et al. (2024) and Raghav et al. (2021), confirming that supplementary cementitious materials improve dimensional stability.

### Consistency

**Table 12: Effects of Ternary Blends of SDA and SGA on Paste Consistency**

Mix Composition	Consistency (%)
Control (Pure OPC)	28.1
15% SDA + 0% SGA + OPC	27.5
12.5% SDA + 2.5% SGA + OPC	27.2

Mix Composition	Consistency (%)
10% SDA + 5% SGA + OPC	26.9
7.5% SDA + 7.5% SGA + OPC	26.6
5% SDA + 10% SGA + OPC	26.3
2.5% SDA + 12.5% SGA + OPC	26.0

As shown in Table 12, paste consistency decreased from 28.1% to 26.0% with increasing SGA content. This trend is attributed to the higher fineness and surface area of SGA, which increases water demand and reduces workability. The porous nature of the ash particles also contributes to higher

absorption. However, the improved packing density enhances hydration and reduces porosity, which supports better strength and durability. Similar observations were reported by Majeed (2024) and Fapohunda et al. (2019).

### Setting Times

**Table 13: Effects of Ternary Blends of SDA and SGA on Setting Times**

Mix Composition	Initial (min)	Final (min)
Control (Pure OPC)	98	216
15% SDA + 0% SGA + OPC	93	206
12.5% SDA + 2.5% SGA + OPC	90	203
10% SDA + 5% SGA + OPC	88	201
7.5% SDA + 7.5% SGA + OPC	85	198
5% SDA + 10% SGA + OPC	83	196
2.5% SDA + 12.5% SGA + OPC	80	194

As shown in Table 12, both the initial and final setting times decreased from 98/216 min to 80/194 min as the SGA content increased. This is attributed to the higher reactivity and finer particle size of SGA, which accelerates hydration and promotes the early formation of C–S–H gel. While shorter setting times support early strength gain, excessively rapid setting may reduce the workable time, necessitating proper proportioning. These trends are consistent with those reported by Ettu et al. (2013) and Fapohunda et al. (2019).

### Reconciliation of Strength Results with Literature and Code-Based Correlations

Although previous studies report that agro-based ashes such as rice husk ash (RHA) and sugarcane bagasse ash (SBA) can enhance workability and, under optimized conditions, achieve comparable or improved later-age strength, the present study recorded no strength gain over ordinary Portland cement (OPC) at any curing age. This discrepancy is mainly attributed to variations in ash quality, fineness, and amorphous silica content, which strongly govern pozzolanic reactivity. High-performing RHA and SBA are typically characterized by high specific surface area, controlled combustion, and predominantly amorphous silica phases that promote the formation of secondary calcium silicate hydrate (C–S–H). In contrast, the SDA–SGA used in this study likely contained higher crystalline content, residual carbon, or lower fineness, resulting in a predominantly filler or dilution effect rather than a strong pozzolanic contribution. This behaviour is consistent with the literature showing that agro-ash performance is highly dependent on processing conditions and that optimal replacement levels and particle refinement are essential to achieve strength parity with OPC. Therefore, the absence of strength improvement does not contradict previous studies but rather reflects limitations in material quality and processing. To further evaluate mechanical consistency, established predictive relationships such as the ACI tensile–compressive correlation ( $f_t \approx 0.1\sqrt{f_c}$ ) and Eurocode models should be applied to the experimental data. Regression analysis of tensile strength versus  $\sqrt{f_c}$ , including the best-fit equation and coefficient of determination ( $R^2$ ), is recommended to assess conformity with standard cementitious behaviour. Finally, comparison with well-processed RHA and SBA systems

(typically 5–20% replacement, fine particle size  $<45 \mu\text{m}$ , and high amorphous silica content) provides a benchmark for expected performance and highlights the importance of ash processing quality in achieving improved long-term strength. This study aligns with findings by Udoumoh et al. (2024), who applied Bayesian simulation modelling to interpret complex relationships between socio-economic variables and observed outcomes. Similarly, the present study integrates microstructural observations with mechanical performance data to explain strength development in SDA–SGA-blended concrete.

### CONCLUSION

Based on the experimental investigation of concrete containing ternary blends of sawdust ash (SDA) and sponge gourd ash (SGA) as partial replacements for ordinary Portland cement (OPC), the following conclusions are drawn:

- i. **Workability:**  
The incorporation of SGA significantly improved the workability of fresh concrete. Slump values increased progressively with increasing SGA content, ranging from very low for the control mix to high at 12.5% SGA. This improvement is attributed to the particle morphology of SGA, which reduces inter-particle friction and enhances flow.
- ii. **Density:**  
Concrete density slightly decreased with increasing SGA content due to the lower specific gravity of biomass ashes. However, density increased with curing age for all mixes, indicating ongoing hydration and matrix densification.
- iii. **Strength Development:**  
Compressive, splitting tensile, and flexural strengths generally decreased with increasing replacement levels, particularly beyond 7.5% SGA. However, mixes containing 5–7.5% SGA provided the most balanced mechanical performance, indicating a practical optimum range for partial cement replacement.

iv. **Key Contribution – Microstructure–Strength Relationship:**

A key outcome of this study is the establishment of a direct relationship between microstructural evolution and long-term strength development. SEM–EDX analysis revealed that mixes with moderate SDA–SGA content developed a denser matrix characterized by increased C–S–H formation and reduced porosity over time. In contrast, higher replacement levels led to increased voids and microcracking. This confirms that the long-term mechanical performance of SDA–SGA blended concrete is governed primarily by microstructural refinement and pozzolanic densification mechanisms.

v. **Pozzolanic Activity:**

EDX results showed increasing Si/Ca ratios with curing age, confirming ongoing pozzolanic reactions and the progressive formation of secondary hydration products that contribute to strength development in optimized mixes.

vi. **Paste Properties:**

SDA–SGA incorporation improved particle packing and reduced soundness, indicating improved volumetric stability. However, water demand increased slightly, affecting consistency. Setting times were moderately reduced, supporting improved early-age performance.

vii. **Engineering Application and Sustainability Implication:**

SDA–SGA blended concrete can be considered suitable for low- to moderate-load structural applications, such as non-critical structural elements, pavement works, and low-cost housing components. The use of these agricultural wastes reduces OPC demand and promotes sustainable construction practices through waste valorisation, although a quantitative life-cycle assessment was not conducted in this study.

viii. **Study Limitation:**

A major limitation of this study is the absence of durability performance evaluation. Long-term resistance to chloride penetration, carbonation, sulfate attack, shrinkage, and permeability was not assessed; therefore, full service-life performance under aggressive environments cannot be established.

Based on the findings of this study, the following targeted recommendations are made:

i. **Durability Performance Assessment (High Priority):**

Future research should evaluate chloride resistance, carbonation depth, sulfate attack resistance, and permeability to establish long-term service performance of SDA–SGA concrete.

ii. **Microstructure–Performance Modelling:**

Further studies should develop quantitative models that link SEM/EDX microstructural parameters (porosity, C–S–H density, Si/Ca ratio) to the development of mechanical strength.

iii. **Sustainability Quantification:**

Life-cycle assessment (LCA) and embodied carbon analysis should be conducted to quantify the environmental benefits of partial OPC replacement with SDA–SGA materials

iv. **Field Validation:**

Pilot-scale and real-world structural applications should be conducted to validate laboratory findings under actual environmental and loading conditions.

v. **Material Optimization:**

Improvements in ash processing (controlled combustion and finer grinding) are recommended to increase amorphous silica content and pozzolanic reactivity, thereby enhancing strength performance at higher replacement levels.

vi. **Extended Performance Studies:**

Future work should include shrinkage behaviour, creep performance, and long-term strength beyond 90 days to fully capture delayed pozzolanic effects.

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