

Physico-Chemical Characterization of the Constituent Materials for Sustainable Concrete: Incorporating Rice Husk Ash and Corn Cob Ash as Partial Cement Replacements

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ABSTRACT

This study evaluated the physico-chemical properties of constituent materials for sustainable ternary blended concrete incorporating rice husk ash (RHA) and corn cob ash (CCA) as partial cement replacements. The objective was to assess the suitability of these agricultural by-products as supplementary cementitious materials (SCMs) for sustainable concrete production. Experimental investigations were conducted on the constituent materials, RHA, and CCA following British Standards (BS EN) and ASTM procedures to ensure reliable and accurate results. X-ray fluorescence (XRF) analysis showed that the combined SiO_2 , Al_2O_3 , and Fe_2O_3 contents were 79.55% for RHA and 63.45% for CCA. Based on ASTM C618:2019, RHA was classified as a Class F pozzolan, while CCA was classified as a Class C pozzolan, confirming their suitability as SCMs. Physical characterization demonstrated compliance with standard requirements, including a cement consistency of 31%. The cement paste exhibited an initial setting time of 2 h 5 min and a final setting time of 3 h 39 min. Aggregate tests, including specific gravity and particle size grading, also satisfied relevant standards for quality concrete production. X-ray diffraction (XRD) and scanning electron microscopy (SEM) identified amorphous silica and other reactive phases in both ashes, confirming their pozzolanic potential and ability to participate in cement hydration, thereby enhancing concrete strength and durability. Overall, the findings demonstrate that RHA and CCA are viable supplementary cementitious materials capable of reducing cement consumption, lowering carbon emissions, and promoting environmentally sustainable concrete production without compromising material quality in practical construction applications and long-term infrastructure development across settings.

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INTRODUCTION

Concrete remains the most widely utilized construction material globally, with over ten billion tons produced annually, and its aggregates make up 70 to 80% of its quantity (Muhammad *et al.*, 2024)

Younis (2025) noted that concrete has exhibited remarkable compressive strength, enabling it to support substantial loads and withstand significant pressure, thereby making it suitable for a wide range of structural applications. The widespread use of concrete is largely due to its high compressive strength, durability, and superior mechanical properties compared to other construction materials (Zeyad *et al.*, 2020; Hosen *et al.*, 2024). Concrete's versatility cannot be matched as it can be shaped into a multitude of forms, fostering creativity in architectural design (Vaggar *et al.*, 2023). Regardless of its application, whether in residential homes, skyscrapers, or bridges, concrete effectively fulfills a diverse array of aesthetic and functional requirements, establishing itself as a vital material for ambitious infrastructure projects (Sun *et al.*, 2026; Xin *et al.*, 2026).

Effective curing is essential for maintaining the strength and integrity of concrete over time, which is crucial for the longevity and reliability of buildings and infrastructure (Amartey *et al.*, 2024)

However, Liao *et al.*, (2022); Etim *et al.*, (2021) affirmed that the production of Portland cement, a primary binder, contributes significantly to greenhouse gas emissions,

particularly carbon dioxide (CO_2), with its undeniable effects on both humans, the ecosystem, and the environment. The cement manufacturing process, as noted by Sanuja *et al.*, (2023), entails the extraction and processing of raw materials such as limestone, clay, and shale. These materials are then subjected to high temperatures in a kiln to create clinker. The clinker is subsequently finely ground with gypsum and other additives to produce cement. The United Nations Global Nitrous Oxide Assessment emphasized that N_2O is one of the most important substances contributing to ozone-layer depletion, while its long-lasting presence in the atmosphere also makes it a powerful greenhouse gas that plays a significant role in global warming (UNEP & FAO, 2024; Zhu *et al.*, 2025)

Cement serves as a vital building material that is produced worldwide, playing a key role in the success of every construction project. Its significance cannot be overstated, as it forms the backbone of countless structures and infrastructures (Dereje *et al.*, 2025). They further affirmed that this concern has necessitated the exploration of sustainable alternatives, especially supplementary cementitious materials (SCMs). These alternative materials, mostly agro-industrial wastes, are emerging as potential cement replacements due to high carbon dioxide emissions associated with cement manufacturing and the rising cost of cement.

Agro-industrial wastes such as rice husk ash (RHA) and corn cob ash (CCA) have emerged as promising SCMs due to their high silica content and pozzolanic reactivity (Olafusi *et al.*, (2018). While previous studies have explored their use in binary blends, limited research exists on their combined performance in ternary systems. This study aims to evaluate the physico-chemical properties of concrete constituents incorporating RHA and CCA to determine their suitability for sustainable construction applications.

MATERIALS AND METHODS

Materials

The materials used include Portland limestone cement (CEM II/B-L 42.5N), fine aggregate (river sand), coarse aggregate (crushed stone), potable water, rice husk (RH), rice husk ash (RHA), corn cob (CC), and corn cob ash (CCA). RH and RHA are shown in Plates I (a) and (b), while CC and CCA, in Plates II (a) and (b)



Plate I(a): Rice husk



Plate II(a): Corn Cob



Plate I(b): Rice husk ash



Plate II(b): Corn Cob Ash

Methods

Material characterization was conducted in accordance with BS EN and ASTM standards. Tests performed include:

Design of Concrete

The American Concrete Institute (ACI) method was used in the design of grade 25N/mm² concrete.

Consistency of Cement Test

The consistency test using the Vicat apparatus was carried out following the procedures outlined in BS EN 196- 3:2016, as shown in Plate III. The depth of penetration in each trial was measured and noted. The equation for the determination of cement consistency is presented in Equation 1.

$$\text{Standard Consistency (\%)} = \frac{\text{Weight of Water Added}}{\text{Weight of Dry Cement}} \times 100 \quad (1)$$



(a)



(b)

Plate III (a): Paste mixing for consistency test. (b) Consistency test

Setting Time of Cement Test

The test was conducted following the provisions of BS EN 196-3: 2016. The initial and final setting times were determined.

Soundness of Cement Test

The soundness test followed the procedures outlined in BS EN 196-3:2016 using the Le-chatelier mould. The distances between the pointers before and after heating were noted as in Equation 2.

$$\text{Volume expansion (mm)} = L2 - L1 \quad (2)$$

Where;

L1 = Initial indicator reading after 24 hours in water (27±2°C)
L2 = final reading after bringing to boil the same sample, measuring the change in distance between the indicator points to detect excessive lime/magnesia.

Compressive Strength of Cement Test

The procedures of BS EN 196-1: 2016 were employed to determine the compressive strength of the cement for this research. It is calculated using Equation 3

$$\text{Compressive strength} = \frac{P}{A} \quad (3)$$

Where;

P = Failure load (kN)

A = Cross-sectional area of the cube (mm²)

Silt and Clay Content of Sand Test

This test was carried out by the procedures outlined in BS EN 196-3:2016. The different levels of silt/clay and sand were measured. The silt/clay content is calculated from Equation 4

$$\text{Silt and Clay content of sand (\%)} = \frac{\text{Height of clay/silt}}{\text{Height of sand}} \times 100 \quad (4)$$

Specific Gravity of Aggregates

River sand and Crushed stones were used, and the BS EN 1097 -3 (1998) procedure was followed. The specific gravities of the aggregates were determined to know their level of conformity with standards. Specific gravities of fine and coarse aggregates were determined as shown in Plates IV (a and b) and (c and d), respectively. The formula is shown in Equation 5

$$\text{Specific gravity (Gs)} = \frac{B}{(P+B-Ps)} \quad (5)$$

Where;

B = Mass of sample

P = Mass of Pycnometer bottle + water

Ps = Mass of Pycnometer bottle + water + sample



(a)

Plates IV(a) and (b): Specific gravity of fine aggregate test



(b)



(c)

Plates IV(c) and (d): Specific gravity of coarse aggregate test



(d)

Particle Size Distribution

The sieve analysis was done in line with BS EN 933: 1 (2012). This property of aggregates determines the distribution of the different sizes in the sand and crushed stones and enables their placement in the appropriate zones.

Aggregate Crushing Value

The toughness of the sample and its performance in terms of strength when used in concrete production were determined according to the provisions of BS 812:110 (1995) as in Equation 6. This is shown in Plate 4(b)

$$\text{Aggregate Crushing Value (\%)} = \frac{\text{Mass of fines (M2)}}{\text{Mass of aggregate (M1)}} \times 100 \quad (6)$$

Aggregate Impact Value

This gives a relative measure of the resistance of the material to sudden impact or shock. The test was executed according

to BS 812:112 (1990) and is shown in Plate V (a). Equation 7 is applied for aggregate impact value determination.

$$\text{Aggregate Impact Value (\%)} = \frac{\text{Mass of fines (M2)}}{\text{Mass of aggregate (M1)}} \times 100 \quad (7)$$



(a)



(b)

Plates V (a) and (b): Aggregate Impact Value and Aggregate Crushing Value Tests

Bulk Density

The bulk density of aggregate was determined in line with BS 812:2 (1995). It is the measure of the mass of an aggregate

sample in a container of unit volume filled or compacted under specified conditions as shown in Plates VI (a) and (b). This is determined using Equation 8

$$\text{Bulk density} = \frac{\text{Mass of aggregate required to fill the container}}{\text{Volume of the container}} \quad (\text{Kg/m}^3) \quad (8)$$



(a)



(b)

Plates VI (a) and (b): Bulk densities of fine and coarse aggregates Tests

Oxide and Mineral Content of RHA and CCA

The chemical properties of the materials were determined to assess their viability and conformity to standard codes of practice.

X-ray Fluorescence (XRF) of RHA and CCA

The oxide contents of the RHA and CCA were determined through XRF tests in the Chemical Engineering Department laboratory, A. B. U., main campus, Zaria. This is to assess their pozzolanic reactivity and the class of pozzolan

X-ray Diffraction (XRD) of RHA and CCA

The mineralogical composition of the RHA and CCA was assessed through an XRD test in the Chemical Engineering Department laboratory, A. B. U., main campus, Zaria.

Scanning Electron Microscopy (SEM)

The microstructure of the composite was determined in the Chemical Engineering Department laboratory, A. B. U., main campus, Zaria.

Development of the Mix Matrix

The Design Expert software was used for the Design of Experiments (DOE) and the development of concrete mix proportions through the application of the Response Surface Methodology (RSM). Rice Husk Ash, Corn Cob Ash, and Curing Age were the independent variables (factors) used for the development of the mix matrix. Table 1 shows the summary of the independent variables considered with their respective dosages (levels). The mix proportions for 1m³ of concrete are presented in Table 2,

Table 1: Design Factors and Dosages (Levels)

Categoric Factors	Name	Units	Type	Levels	L[1]	L[2]	L[3]	L[4]	L[5]
A [Categoric]	Rice Husk Ash (RHA)	%	Nominal	3	0	10	15		
B [Categoric]	Corn Cob Ash (CCA)	%	Nominal	3	0	5	10		
C [Categoric]	Curing Age (CA)	Days	Nominal	5	0	7	28	56	90

Table 2: Details of Mix Proportions (kg/m³)

Concrete Mix	Cement	Fine Aggregate	Coarse Aggregate	RHA	CCA	W/C	Water
0MR(Control)	333	741	1091	-	-	0.57	190
10RHA.0CCA	299.7	741	1091	33.3	-	0.57	190
15RHA.0CCA	283.05	741	1091	49.95	-	0.57	190
0RHA.5CCA	316.35	741	1091	-	16.65	0.57	190
0RHA.10CCA	299.7	741	1091	-	33.3	0.57	190
10RHA.5CCA	283.05	741	1091	33.3	16.65	0.57	190
10RHA.10CCA	266.4	741	1091	33.3	33.3	0.57	190
15RHA.5CCA	266.4	741	1091	49.95	16.65	0.57	190
15RHA.10CCA	249.75	741	1091	49.95	33.3	0.57	190

S/No	Equipment	Manufacturer (Country)	Model No
1	Weighing balance (AVERY)	England	BN 64499
2	Aggregate Crushing Value	England	T.I.B/MC/EL42-4300
3	Aggregate Impact Value	England	EL42-4000
4	Vicat Apparatus	England	EL38-2700
5	XRF Equipment	Israel	Xenometrix Genius IF EDX/XRF
6	XRD Equipment	Japan	Rigaku Miniflex benchtop diffractometer
7	SEM Equipment	Netherlands	Oxford PhenomProx system

RESULTS AND DISCUSSION

Cement Hydration and Baseline Performance

The measured consistency (31%) aligns with the standards set in BS EN 196-3 (2016) and setting times (2 hrs. 5 mins initial; 3 hrs. 39 mins final) indicate a well-balanced clinker–gypsum system with adequate sulfate availability, avoiding both flash set and excessive retardation. This result conformed to the provisions of BS EN 196-3 (2016) and are consistent with the findings of Ejeh (2017). The 7-day strength (about 28 MPa) is in tandem with the provisions of BS EN 196-1 (2016), which stipulates a minimum compressive strength of 23.1N/mm² at 7days, suggests efficient early formation of C-S-H and the presence of limited deleterious phases. This baseline is critical because the introduction of SCMs (RHA, CCA) will modify both dissolution kinetics and subsequent hydrate precipitation through dilution and pozzolanic effects.

Aggregate Skeleton and Interfacial Transition Zone (ITZ)

The fine aggregate is within the acceptable gradation according to BS 882-2: 1992 as presented in Figure 1. The

fineness modulus (3.096) falls in Zone 1 which implies a relatively coarse material, will typically reduce water demand but may increase void content if not balanced by paste volume. The coarse aggregate's crushing value (20%) and impact value (21%) indicate high mechanical integrity, supporting load transfer. These results are supported by BS 812-2 (1995), which stipulates a maximum crushing and impact values of 30% for wearing surfaces. This result also conformed to Amartei (2013), who obtained an average crushing value of 27% in their research findings. From a microstructural standpoint, a stable aggregate skeleton limits microcrack initiation, while the ITZ becomes the critical region where SCM-induced refinements can enhance performance. The relatively clean sand (1.62% silt/clay) minimizes weak boundary layers, enabling clearer attribution of performance changes to RHA/CCA reactivity rather than contamination effects.

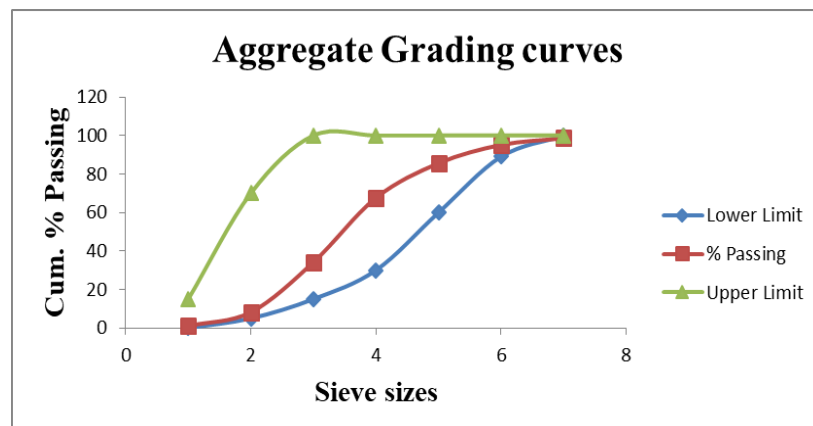


Figure 1: Particle Size Distribution Curves for Fine Aggregate, (Zone 1)

Chemical Reactivity: Pozzolanic and Latent Hydraulic Contributions

XRF results show that RHA ($\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 = 79.55\%$) behaves as a Class F pozzolan, while CCA (63.45%) approaches Class C behavior. This distinction is

mechanistically important and supported by the provisions of ASTM C618-23.

The chemical properties of RHA and CCA are presented in Table 3

Table 3: Chemical properties of RHA and CCA

Chemical Composition (%)									
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	MnO	$\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$
RHA	74.11	2.72	2.72	2.95	Not detected	6.21	Not detected	0.41	79.55
CCA	51.57	5.65	6.23	8.88	Not detected	17.95	-	0.40	63.45

The RHA (Class F): Predominantly siliceous, reacting slowly with $\text{Ca}(\text{OH})_2$ to form secondary C-S-H gel, leading to strength gain at later ages and improved durability via pore refinement.

While the CCA (Class C) contains a relatively higher Fe_2O_3 and Al_2O_3 , which indicates moderate pozzolanic activity but contributes to aluminosilicate hydrate formation and later age densification since it is a slower reacting pozzolan, thus contributing to later strength development, between 56 and 90 days. In ternary systems, these materials can act synergistically. The RHA accelerates early hydration from 28 to 56 days, while CCA sustains long-term hydration and densification by consuming portlandite and generating a low-Ca/Si-ratio C-S-H with superior packing.

Mineralogy and Amorphous Content (XRD)

XRD patterns indicate crystalline quartz peaks ($\sim 26.6^\circ 2\theta$) superimposed on a broad hump ($15\text{--}35^\circ 2\theta$), evidencing significant amorphous silica in both ashes. The amorphous fraction governs reactivity; higher disorder in RHA typically translates to higher pozzolanic activity. Identified phases in CCA (orthoclase, lime, periclase) suggest additional sources of CaO and alkalis that can modify pore-solution chemistry and accelerate reactions. Figures 2(a) and 2(b) present the Diffractogram and Mineral content of RHA, while Figures 2(c) and 2(d) present the Diffractogram and Mineral content of CCA. However, excessive free lime or periclase could pose expansion risks if not stabilized but such deleterious effects are absent, implying acceptable phase proportions.

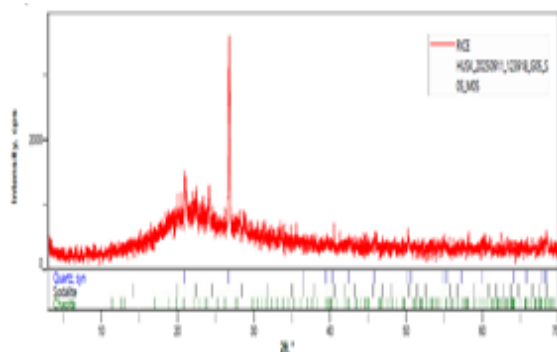


Figure 2(a): Diffractogram of RHA

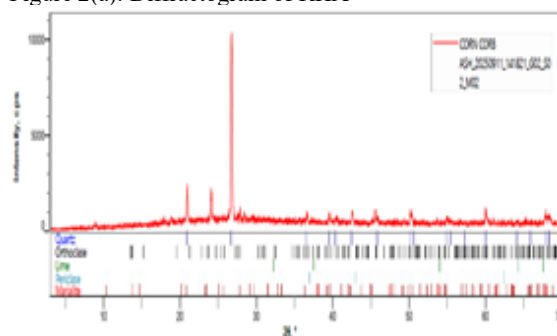


Figure 2(c): Diffractogram of CCA

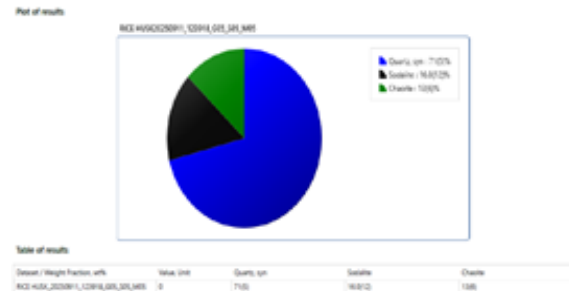


Figure 2(b): Mineral content of RHA



Figure 2(d): Mineral content of CCA

Microstructure (SEM) and Pore System Evolution

SEM observations show a porous, honeycomb morphology for RHA particles, providing a high specific surface area and abundant nucleation sites for C-S-H. CCA exhibits comparatively denser, angular particles. The expected microstructural evolution in blended systems includes Filler effect (early age) when fine RHA/CCA particles improve packing, reducing capillary porosity, Nucleation effect when surfaces of ash particles accelerate C-S-H

precipitation, and the Pozzolanic reaction (later age) when the consumption of $\text{Ca}(\text{OH})_2$ and formation of secondary C-S-H/C-A-S-H gels, refining pores from capillary ($>50\text{ nm}$) to gel pores ($<10\text{ nm}$) take place. The surface morphology, microstructure/particle arrangement of RHA and CCA are presented in Figure 3(a) and Figure 3(b). Collectively, these mechanisms densify the ITZ and bulk paste, reducing permeability and enhancing durability indicators (e.g., resistance to chloride ingress and sulfate attack).

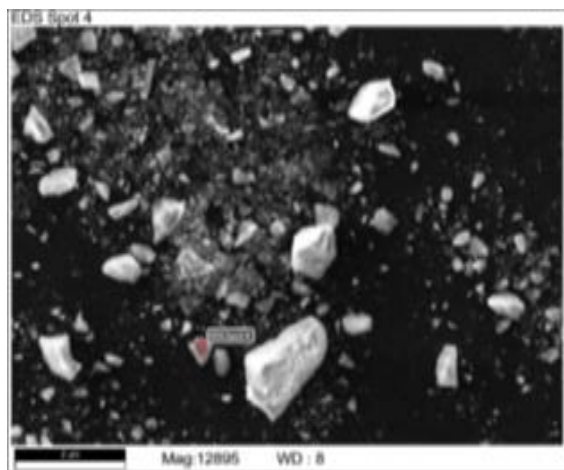


Figure 3(a): SEM for RHA

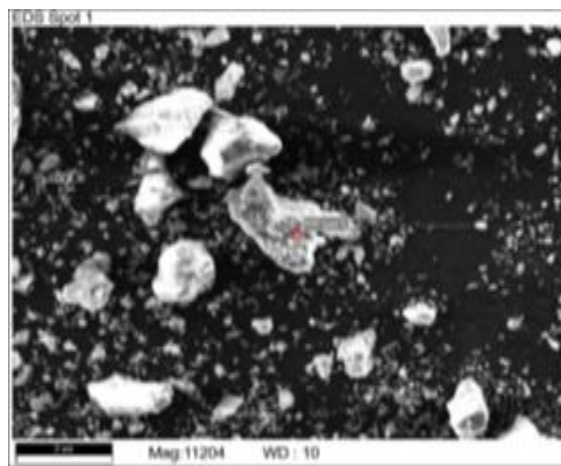


Figure 3(b): SEM for CCA

Response Surface Methodology (RSM) can be used to quantify interactions among RHA%, CCA%, and curing age. Typically, significant interaction terms (RHA and Age, CCA and Age) indicate time-dependent synergy, with optimum regions shifting toward higher RHA at later ages.

Durability and Sustainability Performance

The reduction of portlandite and refinement of pore structure imply lower sorptivity and diffusivity. From a sustainability perspective, partial cement replacement directly reduces embodied CO₂. The dual use of agro-wastes (RHA, CCA) also addresses disposal issues, aligning with circular economy principles. The ternary approach is advantageous over binary systems by enabling tailored early-late strength balance and improved lifecycle performance.

CONCLUSION

This study demonstrates that rice husk ash and corn cob ash possess significant physico-chemical properties suitable for use as supplementary cementitious materials. Both materials satisfy standard requirements and exhibit strong pozzolanic behavior. RHA shows higher reactivity due to its elevated silica content, while CCA contributes additional cementitious characteristics with later-age strength development. The findings support the development of sustainable ternary blended concrete systems with reduced environmental impact.

The laboratory investigation results show that the cement, sand, crushed stones, rice husk ash, and corn cob ash met the minimum engineering requirements for concreting and cement replacement. Therefore, these materials are recommended for the production of sustainable ternary blended concrete. Field-scale experimental investigation is necessary for further validation and practical implementation.

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