
PHYSICO-MECHANICAL PROPERTIES OF SUSTAINABLE TERNARY BLENDED CONCRETE INCORPORATING CORN COB ASH AND RICE HUSK ASH AS PARTIAL CEMENT REPLACEMENTS

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ABSTRACT

This study evaluated the physico-mechanical properties of sustainable ternary blended concrete incorporating corn cob ash (CCA) and rice husk ash (RHA) as partial cement replacements. The work assessed the suitability of these agricultural by-products as supplementary cementitious materials (SCMs) for sustainable concrete production. Laboratory investigations were carried out on CCA and RHA in accordance with British Standards (BS EN) and ASTM procedures to ensure reliable and accurate results. Physical characterization demonstrated compliance with standard requirements, including a cement soundness of 1.0mm. The cement exhibited a fineness of 97.7%. Aggregate tests, including specific gravity and particle-size grading, also met relevant standards for quality concrete production. Following the procedures and requirements of ASTM C618-2023, RHA was classified as a Class N pozzolan, with a combined SiO₂, Al₂O₃, and Fe₂O₃ of 81.33%, while CCA had 64.85%, which fell short of the Class N oxide composition threshold but contributed actively to the pore refinement and particle packing density of the cement matrix and secondary reactivity in the ternary blend. X-ray fluorescence (XRF) and X-ray diffraction (XRD) identified amorphous silica and other reactive phases in both ashes, confirming their pozzolanic reactivity and ability to participate in cement hydration, thereby enhancing concrete strength and durability. The reference Grade 25 concrete (Control) has the following strength margins of 22.1N/mm², 25.3N/mm², 28.0N/mm² and 32.1N/mm² for 7, 28, 56, and 90 days, respectively. In ternary-blended concrete, cement was replaced with 5% CCA and 10% RHA, yielding an optimum mix with compressive strengths of 25.5N/mm², 37.0N/mm², 39.5N/mm², and 41.5N/mm² at 7, 28, 56, and 90 days, respectively. These results showed increases of 15.4%, 46.3%, 41.1%, and 29.3% in the sustainable ternary blended concrete over the referenced concrete at the 7, 28, 56, and 90-day curing periods. The findings demonstrate that CCA and RHA are viable SCMs that reduce cement consumption, lower carbon emissions, promote effective waste management, and support environmentally sustainable concrete production without compromising material quality in practical construction applications and long-term infrastructure development.

Keywords: Rice husk ash; Corn cob ash; Ternary blended concrete; Pozzolanic reactivity; Sustainable construction; Compressive strength; Supplementary cementitious materials

1. INTRODUCTION

Concrete remains the most extensively utilized engineered material globally, with annual production exceeding 10 billion tons (Ge et al., 2022). This staggering volume underscores concrete's indispensable role in modern infrastructure development, spanning residential, commercial, and civil engineering applications worldwide. It is one of the oldest and most common construction materials in the world, mainly because of its low cost, availability, long-term durability, and ability to withstand extreme weather conditions. Amartey et al., (2024) asserted that concrete strength, durability, and other physical properties are affected by curing and applying the various types as they relate to the prevailing weather conditions in a particular locality.

Portland Limestone Cement (PLC), the primary binder in concrete production, is, however, associated with substantial environmental degradation. Cement production is an energy-intensive process that accounts for a substantial share of global anthropogenic carbon dioxide emissions. The calcination of limestone and the combustion of fossil fuels, needed for clinkering temperatures over

1400°C, largely drive these emissions. As the construction sector expands to meet the demands of rapid urbanization, particularly in developing regions, the search for sustainable alternatives that can reduce clinker demand while maintaining or enhancing the engineering performance of concrete has become a central research priority.

Supplementary cementitious materials (SCMs) derived from agricultural residues and industrial by-products have emerged as a promising avenue for achieving this objective. Agro-waste ashes such as corn cob ash (CCA), rice husk ash (RHA), sugarcane bagasse ash (SBA), and palm oil fuel ash (POFA) are rich in reactive silica and other pozzolanic oxides. Indumathi et al., (2024) inferred that rice husk ash has a positive impact on the strength and durability of concrete, while also contributing to a reduction in carbon emissions and construction expenses, and encouraging environmentally conscious building methods through the reuse of agricultural waste. The partial replacement of cement with supplementary cementitious materials (SCMs) offers both environmental and practical benefits. It reduces the amount of clinker required in concrete production, thereby lowering carbon emissions, while also providing a productive use for agricultural residues that might otherwise be disposed of through open burning or left to decompose, both of which contribute to environmental pollution. Researchers have extensively documented rice husk's pozzolanic potential in the literature. When burnt under controlled temperatures, this rice husk, a rice milling by-product, produces ash rich in amorphous silica. Corn cob, similarly abundant in maize-producing regions such as Nigeria, has more recently attracted research attention as a complementary agro-pozzolan, although its silica content and reactivity are generally lower than that of RHA and more sensitive to calcination conditions.

Recent studies continue to affirm the technical viability of RHA and CCA in blended cementitious systems. Kariyawasam and Semananda (2025) reviewed the challenges and opportunities associated with rice husk ash utilization in sustainable construction, noting that controlled combustion temperature and fineness are critical determinants of its pozzolanic efficiency. Sathiparan (2025a) similarly conducted a systematic review of corncob ash in construction, reporting that while CCA generally exhibits lower silica-alumina-iron content than RHA, appropriate calcination and particle size reduction can substantially improve its reactivity, and in a companion study applied machine learning approaches to predict the compressive strength of corn cob ash concrete from mix design variables (Sathiparan, 2025b). Okeke et al. (2026) demonstrated that corncob ash calcined within a 400 to 700°C furnace window consistently achieved combined pozzolanic oxide contents above the 70% threshold specified in ASTM C618, with amorphous silica content exceeding 80%, underscoring the importance of processing conditions in determining whether a given batch of CCA meets recognized pozzolan classification limits.

While the individual performance of RHA and CCA as binary cement replacements has received reasonable investigation, the synergistic use of these materials in ternary blended systems remains comparatively under-explored, especially for concrete produced and cured under ambient tropical conditions typical of sub-Saharan Africa. Ternary blending, in principle, allows the complementary strengths of two or more SCMs to be exploited simultaneously: the high pozzolanic reactivity of RHA can compensate for the comparatively lower reactivity of CCA, while the particle packing and micro-filler effects contributed by both materials can further refine the pore structure of the hardened cement matrix. Recent ternary blend studies involving other agro-industrial by-products support this synergy. Oyebisi and Alquraish (2025) reported that ternary blends incorporating shea nutshell ash and ground oyster seashell improved compressive, flexural, and split tensile strength at later curing ages relative to a control mix, alongside improved resistance to acidic and sulfate attack. Navaneetha et al. (2025) similarly developed durable ternary blended concrete using sugarcane bagasse ash and glass powder, while Ashok et al. (2025) demonstrated that ternary combinations of recycled fine aggregate, sugarcane bagasse ash, and ground granulated blast furnace slag markedly reduced rapid chloride penetration values relative to a control mix, confirming that combined SCM systems can enhance both strength and durability performance simultaneously.

Beyond ambient strength development, the behavior of RHA-blended concrete under elevated temperature exposure has also received recent attention because of its relevance to fire safety and structural resilience. Nazari and Toufigh (2024) investigated the effects of elevated temperatures and water re-curing on RHA concrete, reporting that RHA content influences residual strength retention after thermal exposure and that re-curing can partially recover strength lost to thermal damage, while a follow-up study developed predictive models for the ultrasonic pulse velocity and physicochemical

behavior of RHA concrete after fire exposure (Nazari & Toufigh, 2026). Singh and Tiwary (2026) reviewed the high-temperature resistance of silica-rich SCM-blended concretes, including RHA and silica fume systems, concluding that moderate RHA replacement levels generally improve residual mechanical performance up to a threshold temperature beyond which matrix degradation dominates. These findings collectively suggest that ternary RHA-CCA systems may offer both ambient-condition mechano-durability benefits and improved resilience under thermal stress, an area that has not been comprehensively addressed for the specific combination and replacement levels investigated in the present study.

This study, therefore, examines the physico-mechanical properties of Grade 25 ternary blended concrete produced by replacing 10% of cement with RHA and 5% with CCA, evaluated against a conventional Grade 25 control mix. The chemical suitability of both ashes as pozzolans is first assessed through oxide characterization referenced against ASTM C618 and NIS 444-1:2003 provisions, followed by a physical characterization of the cement, and finally the compressive strength development of both mixes is compared at 7, 28, 56 and 90 days. The specific objectives of the study are to: (i) characterize the physical properties (soundness and fineness) of the cement used; (ii) determine the oxide composition of RHA and CCA and assess their conformity to recognized pozzolan standards; (iii) evaluate the compressive strength development of ternary blended concrete relative to a conventional control mix over a 90-day curing regime; and (iv) quantify the percentage strength gain attributable to the ternary blend at each curing age, thereby providing an experimentally grounded basis for recommending RHA-CCA ternary blends for structural applications.

1.1 Environmental Rationale for Agro-Waste Cement Replacement

The environmental case for reducing PLC content in concrete extends beyond carbon dioxide emissions alone. Cement production is also a significant consumer of virgin raw materials, principally limestone and clay, whose extraction contributes to land degradation, biodiversity loss, and dust and particulate emissions in quarrying regions. Concurrently, the disposal of agricultural residues such as rice husk and corn cob presents its own environmental challenge in many rice- and maize-producing economies, where uncontrolled open-field burning of these residues is a common disposal practice, generating particulate matter, black carbon and greenhouse gas emissions that degrade regional air quality. The conversion of these residues into value-added SCMs therefore addresses two environmental problems simultaneously: it reduces the clinker factor of concrete, thereby lowering the embodied carbon of the resulting structure, and it provides an economically incentivized outlet for agricultural residues that would otherwise be burned or landfilled. This circular-economy rationale has been a recurring theme in recent SCM literature, with several studies explicitly framing agro-waste ash valorization within sustainable development goal targets relating to responsible consumption and production, industry innovation, and climate action (Okeke et al., 2026).

From a materials science perspective, its oxide chemistry, its degree of amorphous (non-crystalline) silica content, and its particle fineness govern the suitability of any candidate ash for use as Reactive amorphous silica is essential because it is this phase, rather than crystalline silica, that participates readily in the pozzolanic reaction with calcium hydroxide liberated during PLC hydration. The combustion temperature at which agricultural residues are converted to ash is therefore a critical process variable: excessively high combustion temperatures promote the crystallization of silica into less reactive polymorphs such as cristobalite or tridymite, while insufficient combustion leaves residual unburnt carbon that increases loss on ignition and can adversely affect water demand and durability. This sensitivity to processing conditions has been demonstrated for both RHA and CCA in recent calcination optimization studies, which report that ashes produced within an optimal thermal window consistently outperform both under-burnt and over-burnt ashes in terms of both chemical reactivity and resulting concrete strength (Okeke et al., 2026).

1.2 Rice Husk Ash as a Supplementary Cementitious Material

Rice husk ash has, over the past two decades, become one of the most extensively studied agro-based SCMs, owing to the exceptionally high silica content of rice husk (typically in excess of 90% SiO₂ on an ash basis when combustion is properly conducted) and the sheer volume of rice husk generated annually as a by-product of rice milling in major rice-producing countries. When burnt under

controlled conditions, typically in the range of 500 to 700°C, rice husk yields an ash dominated by amorphous silica with a highly porous, cellular microstructure that, once ground to a fine particle size, exhibits substantial pozzolanic reactivity. Numerous studies have confirmed that RHA-blended concretes exhibit improved compressive, flexural and split tensile strength at later curing ages relative to plain PLC concrete, alongside reduced permeability, improved resistance to chloride ion penetration, and mitigation of expansive reactions such as alkali-silica reaction. Kariyawasam and Semananda (2025) provide a comprehensive synthesis of this body of work, highlighting that the principal barriers to widespread RHA adoption are not technical but relate to inconsistent ash quality arising from uncontrolled combustion practices at the point of generation, underscoring the importance of standardized processing protocols of the kind adopted in the present study.

1.3 Corn Cob Ash as a Complementary Pozzolan

Corn cob ash has attracted comparatively less research attention than RHA, but interest has grown markedly in the past two to three years as researchers have sought to diversify the portfolio of viable agro-waste SCMs beyond rice-based residues, particularly in maize-dominant agricultural economies. Corn cob ash typically exhibits a lower combined $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ content than RHA, and a comparatively higher content of potassium oxide, which does not contribute to pozzolanic reactivity and can, in excessive quantities, present concerns relating to alkali content and potential efflorescence. Nonetheless, recent characterization work demonstrates that, when calcined within an appropriate thermal window, CCA can achieve amorphous silica contents and combined pozzolanic oxide values that meaningfully exceed those obtained under uncontrolled open-burning conditions, narrowing the reactivity gap between CCA and RHA (Okeke et al., 2026; Sathiparan, 2025a). Sathiparan (2025b) further demonstrated, using machine learning models trained on a compiled dataset of CCA concrete mixes, that compressive strength outcomes for CCA-blended concrete are strongly influenced by replacement level, water-cement ratio and ash fineness, providing a data-driven confirmation of trends previously established through conventional experimental testing. These findings support the treatment of CCA, in the present study, not as a primary reactive binder component but as a complementary secondary pozzolan whose principal contribution within a ternary system lies in particle packing refinement and supplementary reactivity rather than as the dominant reactive phase.

1.4 Ternary Blending and Research Gap

The rationale for combining two or more SCMs within a single ternary or quaternary cementitious system rests on the principle of complementary particle packing and staggered reactivity. Concrete performance remains unaffected when RHA replaces 10% to 20% of cement, owing to RHA's strong pozzolanic qualities (Endale et al., 2022). They stated that using RHA as a partial cement substitute in concrete offers further environmental advantages, including conserving resources and managing agricultural waste, thereby promoting a circular economy within construction. Where a highly reactive, ultra-fine pozzolan such as silica fume or a well-processed RHA is combined with a comparatively coarser or moderately reactive material, the resulting particle size distribution of the combined binder can more effectively fill the voids between cement grains than either material used alone, producing a denser and less permeable matrix. This principle has been demonstrated across a range of ternary systems in the recent literature, including combinations of metakaolin and palm oil fuel ash with coal bottom ash fine aggregate, which achieved measurable reductions in water absorption and chloride resistance relative to binary and control mixes, and combinations of recycled fine aggregate, sugarcane bagasse ash and ground granulated blast furnace slag, which achieved substantial reductions in rapid chloride penetration values alongside improved compressive strength (Ashok et al., 2025). Despite this growing body of evidence supporting ternary SCM systems generally, and despite RHA and CCA each being individually well characterized, published experimental work specifically evaluating RHA-CCA ternary blends at defined replacement ratios, produced and cured under ambient tropical conditions and evaluated across a full 90-day strength development profile, remains limited. This represents the specific research gap addressed by the present study, which provides laboratory-derived compressive strength data for a 10% RHA plus 5% CCA ternary blend benchmarked directly against a Grade 25 control mix.

2. MATERIALS AND METHODS

2.1 Materials

Portland limestone cement (CEM II/B-L 42.5N), conforming to relevant national and international standards, served as the primary binder. Fine aggregate consisted of clean, well-graded natural river sand, and coarse aggregate comprised crushed granite with a maximum nominal size of 20 mm. Both aggregates were sourced locally and tested using standard sieve analysis and specific gravity procedures before batching. Potable water free of deleterious substances was used for mixing and curing throughout the experimental program.

Rice husk was sourced from a local rice milling facility and subjected to controlled open-air combustion followed by further heating to ensure complete carbon burn-off, after which the resulting ash was air-cooled, ground/ball milled, and sieved through a 75-micron sieve to obtain RHA of pozzolanic fineness as shown in Plates I(a), I(b) and VI. Corn cob was similarly sun-dried, combusted under controlled conditions, and the resultant ash ground and sieved to a comparable particle fineness to obtain CCA as shown in Plates II(a) and II(b)

Both ashes were stored in sealed, moisture-proof containers prior to use to prevent premature hydration or carbonation of reactive constituents.



(a)



(b)

Plate I(a): Rice husk

Plate I(b): Rice husk ash



(a)



(b)

Plate II(a): Corn Cob

Plate II(b): Corn Cob Ash

2.2 Characterization of Materials

The physical properties of the cement were determined in accordance with standard test methods, including the Le Chatelier soundness test, setting time and, the sieve method for fineness using the 75 μ m single sieve as shown in Plates III and IV. Specific gravity of the cement, fine aggregate, coarse aggregate, CCA and RHA was determined using the pycnometer and specific gravity bottle methods, respectively, while particle size distribution and silt/clay content of the aggregates were established through standard sieve analysis and silt/clay content test to confirm conformity with grading envelope requirements and minimum silt/clay content for normal-weight concrete as shown in Plates V(a) and V(b). The ball milling of the CCA and RHA are shown in Plates VI(a) and VI(b) while the calcination of the CCA and RHA is shown in Plate VII. The chemical composition of CCA and RHA was determined using X-ray fluorescence (XRF) spectroscopy to quantify the principal oxide constituents, including SiO₂, Al₂O₃, Fe₂O₃, CaO, MgO, K₂O, Na₂O and loss on ignition (LOI). The combined SiO₂ + Al₂O₃ + Fe₂O₃ content of each ash was compared against the minimum 70% threshold specified by ASTM C618 for Class N natural pozzolans and the equivalent provisions of NIS 444-1:2003, the Nigerian Industrial Standard governing the composition, specification and conformity criteria for cement and pozzolanic materials used in concrete production.



Plate III: Soundness test of cement



Plate IV: Final setting time test of cement



Plate V(a): Fine aggregate grading



Plate V(b): Silt and clay content of sand



Plate VI(a): Ball milling of CCA & RHA



Plate VI(b): Ball milling of CCA & RHA



Plate VII: Calcination of CCA & RHA

2.3 Mix Design and Specimen Preparation

Two concrete mixes were designed and batched by weight to achieve a target characteristic strength of 25 N/mm² (Grade 25) at 28 days, in accordance with standard absolute volume mix design procedures. The control mix (designated CM) contained 100% PLC as the sole binder, while the ternary blended mix (designated TM) incorporated a combined 15% cement replacement, comprising 10%

RHA and 5% CCA by mass of total binder, with the balance of the mix proportions (water-cement ratio, fine aggregate, and coarse aggregate content) held constant between the two mixes to isolate the effect of the binder substitution on strength development as shown in Table 1. Batching by weight was applied.

Table 1: Mix proportion for CM and TM

I.D	RHA (kg)	CCA (kg)	Cement (kg)	Sand (kg)	Grave (kg)	Water (kg)	W/C
CM	0	0	22.1	49.3	72.6	12.6	0.57
TM	2.2	1.1	18.8	49.3	72.6	12.6	0.57

Concrete cubes of 100 mm × 100 mm × 100 mm were cast for each mix, compacted in accordance with standard practice to minimize entrapped air voids, and demoulded after 24 hours before being transferred to a curing tank maintained at ambient laboratory temperature until the respective testing ages of 7, 28, 56, and 90 days.

2.4 Compressive Strength Testing

Compressive strength testing was performed on triplicate cube specimens for each mix at each curing age using a calibrated universal compression testing machine at a uniform loading rate, in accordance with standard cube-crushing procedures. The average of the three specimens at each age was recorded as the representative compressive strength for that mix and curing age. The percentage strength variation of the ternary blend relative to the control at each age was subsequently computed.

2.5 Experimental Rigour and Quality Control

Several quality control measures were adopted to ensure the reliability and reproducibility of the results obtained. All batching was carried out by weight rather than by volume to minimize proportioning error, and a single source of cement, aggregate, and water was maintained throughout the experimental programme to eliminate material-source variability as a confounding factor between the control and ternary mixes. Slump testing was conducted on both fresh mixes to confirm that workability remained within an acceptable range for the compaction method employed, since excessive loss of workability arising from the high-water demand and fine particle size of agro-waste ashes is a commonly reported side effect of SCM incorporation that can, if unmanaged, itself depress hardened concrete strength independently of any pozzolanic effect. Curing water temperature was monitored throughout the 90-day curing period to confirm that specimens were maintained under consistent ambient curing conditions, and cube specimens exhibiting visible casting defects, edge damage, or non-planar bearing surfaces at the time of testing were excluded from the reported average strength values in line with standard practice for compression testing of concrete.

$$\text{Percentage strength gain (\%)} = [(f_c, \text{TM} - f_c, \text{CM}) / f_c, \text{CM}] \times 100$$

where f_c, TM is the compressive strength of the ternary blended concrete and f_c, CM is the compressive strength of the control concrete at the corresponding curing age.

3. RESULTS AND DISCUSSION

3.1 Physical Properties of Cement

The soundness and fineness of the PLC used in this study were determined before concrete production to confirm suitability for structural use. The cement recorded a soundness value of 1.0 mm, well below the 10 mm maximum expansion limit typically specified by BS EN 196-3:2016, indicating a negligible risk of delayed expansion arising from free lime or magnesia content. The fineness of the cement was determined as 97.7%, indicating that a high proportion of cement particles passed the specified sieve, consistent with adequate hydration reactivity and early strength development potential. Both results confirm that the cement used conformed to standard requirements and provided a reliable baseline binder for evaluating the effect of RHA and CCA substitution.

Table 2: Physical properties of the cement used

Parameters	Result	Typical Limit
Soundness (Le Chatelier)	1.0 mm	≤ 10 mm
Fineness	97.7%	90%

3.2 Chemical Composition and Pozzolanic Conformity of CCA and RHA

XRF analysis of the two agro-waste ashes revealed a combined $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ content of 64.85% for CCA and 81.33% for RHA, as presented in Table 2. Figures 1 and 2 show the amorphous and crystalline phases of the two ashes. When referenced against the 70% minimum threshold stipulated by ASTM C618 for Class N natural pozzolans and the corresponding conformity criteria of NIS 444-1:2003, RHA satisfies the pozzolanic classification requirement with a comfortable margin, confirming its suitability as a reactive cement replacement material. CCA, at 64.85%, falls marginally short of the 70% threshold when considered in isolation, a finding consistent with recent characterization studies which report that unmodified or moderately calcined corncob ash frequently records combined pozzolanic oxide values in the 60 to 70% range, with only carefully controlled calcination regimes achieving values consistently above the threshold (Okeke et al., 2026; Sathiparan, 2025a). This is attributable to the relatively higher content of potassium oxide (K_2O) and other non-pozzolanic alkaline constituents typically present in corn-derived ashes, which dilute the proportion of reactive silica-alumina-iron oxides relative to rice-derived ashes.

Despite CCA falling marginally below the individual ASTM C618 threshold, its inclusion at a modest 5% replacement level within a ternary system incorporating a highly reactive RHA component is expected to contribute beneficially through both a secondary pozzolanic reaction, in which residual reactive silica and alumina combine with calcium hydroxide liberated during PLC hydration to form additional calcium silicate hydrate (C-S-H) and calcium aluminate silicate hydrate (C-A-S-H) gel, and a physical filler effect, whereby the fine ash particles occupy pore spaces within the cement matrix, refining pore structure and improving particle packing density. This synergistic mechanism, whereby a highly reactive pozzolan compensates for a moderately reactive one within a ternary blend, has been similarly reported for other combined agro-waste systems, including shea nutshell ash and oyster seashell blends (Oyebisi & Alquraish, 2025) and sugarcane bagasse ash and glass powder blends (Navaneetha et al., 2025), both of which demonstrated improved strength and durability performance relative to single-SCM or plain control mixes.

Table 3: Combined pozzolanic oxide content of RHA and CCA

Parameter	CCA (%)	RHA (%)	ASTM C618/NIS 444-1 Limits
$\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$	64.85	81.33	≥ 70 (min.)
Conformity status	Marginal / Sub-threshold	Conforms	—

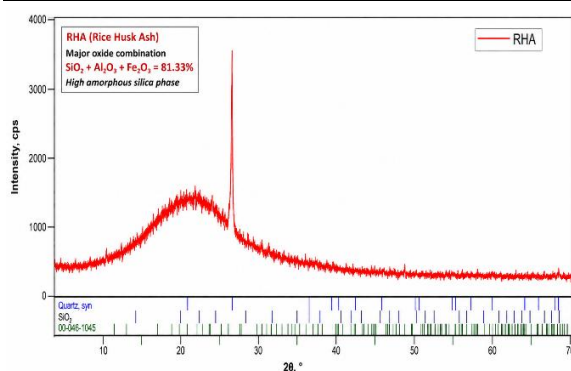


Figure 1: Diffractometer of RHA

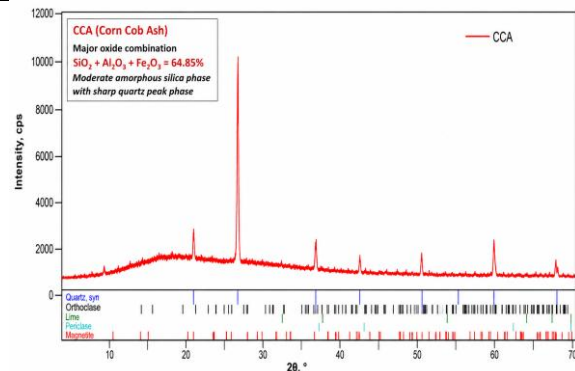


Figure 2: Diffractometer of CCA

3.3 Compressive Strength Development

Table 3 presents the compressive strength results of the control (CM) and ternary-blended (TM) concretes at 7, 28, 56, and 90 days, along with the corresponding percentage strength gain of the ternary blend over the control at each age. The control concrete developed compressive strengths of 22.1, 25.3,

28.0 and 32.1 N/mm² at 7, 28, 56 and 90 days, respectively, consistent with expected strength development trends for Grade 25 concrete. The ternary blended concrete recorded correspondingly higher strengths of 25.5, 37.0, 39.5 and 41.5 N/mm² at the same respective ages, exceeding the control at every stage of curing.

Table 4: Compressive strength and percent strength gain of TM over CM concrete

Curing Age (Days)	Control Concrete, CM (N/mm ²)	Standard Deviation (N/mm ²)	Coefficient of Variation (%)	Ternary Blend, TM (N/mm ²)	Standard Deviation (N/mm ²)	Coefficient of Variation (%)	Strength Gain of TM over CM (%)
7	22.1	2.59	11.70	25.5	0.5	1.96	15.4
28	25.3	1.47	5.80	37.0	0.5	1.35	46.3
56	28.0	0.50	1.80	39.5	0.5	1.27	41.1
90	32.1	0.53	1.65	41.5	0.5	1.20	29.3

At 7 days, the ternary blend exceeded the control by 15.4%, an outcome attributable primarily to the physical filler effect of the finely ground RHA and CCA particles, which improved particle packing and reduced early-age capillary porosity, rather than a substantial pozzolanic contribution, since the pozzolanic reaction between reactive silica and calcium hydroxide is generally slower to activate than primary PLC hydration at early ages. By 28 days, the strength gain rose sharply to 46.3%, the highest recorded improvement across all curing ages, reflecting the onset of significant secondary pozzolanic reactivity as calcium hydroxide liberated from PLC hydration became available for combination with the reactive silica-alumina-iron oxides contributed by both ashes, generating additional C-S-H and C-A-S-H gel that densified the microstructure and enhanced load-bearing capacity beyond what filler action alone could achieve.

The percentage strength gain moderated to 41.1% at 56 days and further to 29.3% at 90 days. This trend, while still representing substantial and consistent superiority of the ternary blend over the control, reflects the progressive strength gain of the control mix itself as PLC hydration continues over time, gradually narrowing the relative gap even as the absolute strength of the ternary blend continues to increase. A similar pattern, in which the percentage advantage of SCM-blended concrete over control concrete is most pronounced at intermediate curing ages before moderating at later ages as the control mix and ternary blended mix continue to gain strength through ongoing cement hydration, has been reported in comparable ternary blend studies (Ashok et al., 2025; Navaneetha et al., 2025), reinforcing the plausibility of the trend observed in the present study. Importantly, the ternary blend's compressive strength at 90 days (41.5 N/mm²) considerably exceeds both the 25 N/mm² target grade and the corresponding 90-day control strength (32.1 N/mm²), confirming that the 15% combined RHA-CCA replacement not only meets minimum structural strength requirements but also delivers substantial long-term strength enhancement.

These results are consistent with the chemical characterization findings discussed in Section 3.2, wherein the high pozzolanic oxide content of RHA (81.33%) due to appropriate calcination temperature as supported by (Ang'ang'o *et al.*, 2024; Su *et al.*, 2024) provided the principal reactive silica source driving secondary C-S-H formation, while CCA, despite its marginally sub-threshold oxide content, contributed complementary filler action and residual pozzolanic activity that collectively enhanced the mechanical performance of the ternary system relative to the single-binder control. This synergy between a highly reactive primary pozzolan and a moderately reactive secondary pozzolan within a ternary blend aligns with observations reported for other combined agro-industrial waste systems in the recent literature (Oyebisi & Alquraish, 2025; Ashok et al., 2025). The consistent strength superiority of the ternary blend across all curing ages also carries favourable implications for the durability performance of the concrete, since a denser, more refined pore structure arising from pozzolanic C-S-H and C-A-S-H formation is typically associated with reduced permeability, lower susceptibility to chloride ion ingress, and improved resistance to aggressive environmental exposure, as reported for comparable ternary SCM systems evaluated through rapid chloride penetration and sorptivity testing (Ashok et al., 2025).

The findings also have relevance to the thermal performance of the ternary blend, an aspect not directly investigated in the present study but of practical significance for structural fire safety. Prior

work on RHA-blended concrete indicates that moderate levels of RHA replacement can improve residual compressive strength retention following exposure to elevated temperatures up to a threshold in the region of 400°C, beyond which progressive dehydration of C-S-H gel and thermal incompatibility between aggregate and paste phases begin to dominate degradation behavior (Nazari & Toufigh, 2024; Singh & Tiwary, 2026). Given the denser microstructure indicated by the enhanced compressive strength of the ternary blend investigated here, it is plausible that the RHA-CCA ternary system would exhibit comparable or improved elevated-temperature resilience relative to plain PLC concrete, a hypothesis that warrants dedicated experimental investigation, as elaborated in the recommendations.

3.4 Strength Development Trend and Rate of Gain

Examining the rate of strength gain between successive curing ages provides further insight into the reaction kinetics of the two mixes. For the control concrete, strength increased from 22.1 to 25.3 N/mm² between 7 and 28 days (a gain of 14.5%), from 25.3 to 28.0 N/mm² between 28 and 56 days (a gain of 10.7%), and from 28.0 to 32.1 N/mm² between 56 and 90 days (a gain of 14.6%), reflecting the comparatively gradual and steady hydration behavior typical of plain PLC systems, in which the bulk of strength development occurs within the first 28 days with more modest subsequent gains as unhydrated cement grains continue to react slowly over time. The ternary blend, by contrast, exhibited a markedly steeper early rate of gain, increasing from 25.5 to 37.0 N/mm² between 7 and 28 days (a gain of 45.1%), before moderating to a gain of 6.8% between 28 and 56 days and a further 5.1% between 56 and 90 days. This pattern, of a sharp acceleration in strength gain concentrated in the 7 to 28-day window followed by a more gradual plateau at later ages, is characteristic of pozzolanic systems in which secondary C-S-H formation is strongly dependent on the availability of calcium hydroxide generated by primary PLC hydration; once a substantial proportion of the available calcium hydroxide has been consumed in the secondary pozzolanic reaction, the rate of further strength gain necessarily slows, even though the absolute strength of the blend remains consistently higher than that of the control at every subsequent age.

This kinetic behaviour has direct practical implications for construction scheduling and formwork removal timelines. The substantial 28-day strength of the ternary blend (37.0 N/mm², corresponding to 148% of the 25 N/mm² design grade) indicates that structural elements incorporating this ternary blend would achieve standard design strength requirements well within conventional construction programme durations, while the continued, albeit more gradual, strength gain observed through to 90 days provides an additional long-term durability and safety margin relative to the control mix.

3.5 Workability and Practical Considerations

Consistent with widely reported behavior for fine, high-surface-area agro-waste ashes, the incorporation of RHA and CCA at the combined 15% replacement level used in this study was observed to increase the water demand of the ternary mix relative to the control at a constant water-cement ratio, necessitating close attention to compaction during specimen casting to avoid entrapped air voids that could otherwise depress hardened strength independently of any pozzolanic benefit. The control mix (CM) recorded a higher slump of 95 mm, which is in the slump class of S2–S3 (borderline, adjacent to S3), indicating relatively better workability, while the ternary mix (TM) recorded 78 mm, slump class S2, and showed medium workability. The lower slump of the TM may be attributed to the fine, porous RHA particles, which increased water demand and reduced the flowability of the concrete (Barbhuiya *et al.*, 2025). This water demand effect arises from the high specific surface area and internal porosity of both RHA and CCA particles, which absorb a proportion of the mixing water during the initial stages of mixing. Where field application of this ternary blend is contemplated at a larger scale, this observation supports the recommendation, discussed further in Section 5, that either a water-reducing admixture be incorporated or the water-cement ratio be modestly adjusted and validated through trial mixes to maintain the target workability without compromising the water-cement ratio upon which the strength results reported in this study were obtained.

3.6 Comparative Discussion with Recent Literature

The magnitude of strength enhancement observed in this study is broadly consistent with, and in some respects exceeds, values reported in comparable recent ternary blend studies. Oyeibisi and Alquraish (2025) reported strength increases in the order of 3% at 10% combined replacement of shea nutshell ash and ground oyster seashell relative to control concrete after 90 days of curing, a considerably more modest gain than the 29.3% recorded for the RHA-CCA ternary blend in the present study at the same age, suggesting that the specific combination of RHA and CCA investigated here provides a comparatively more effective pozzolanic and filler synergy than some alternative agro-industrial waste pairings. Similarly, studies combining rice husk ash with extracted microsilica in ternary high-strength concrete systems have reported 28-day compressive strength increases in the range of 6 to 12% relative to a control mix, again below the 46.3% recorded in the present study, although differences in target concrete grade, aggregate type, and baseline mix design between studies necessarily limit the extent to which direct numerical comparison can be drawn. The comparatively larger strength gains recorded here may be partly attributable to the relatively higher combined replacement level (15%) and the specific 10:5 RHA-to-CCA ratio employed, which appears, based on the oxide chemistry discussed in Section 3.2, to have provided a favourable balance between highly reactive silica supply from RHA and complementary filler and secondary reactivity from CCA.

The results also lend indirect support to the durability inferences drawn from ternary systems investigated elsewhere in the literature. Ashok et al. (2025) demonstrated that ternary blends incorporating recycled aggregate and agro-industrial by-products achieved substantial reductions in rapid chloride penetration values, a durability benefit generally attributed to the same pore-refining mechanism responsible for the compressive strength enhancement observed in the present study. While the present investigation was limited in scope to mechanical strength testing and did not directly evaluate permeability or chloride resistance, the consistency of the observed strength trend with mechanisms reported in these durability-focused studies provides reasonable grounds to anticipate that the RHA-CCA ternary blend investigated here would similarly exhibit enhanced durability performance, a hypothesis that should be confirmed through dedicated testing as outlined in the recommendations.

4. CONCLUSION

This study evaluated the physico-mechanical properties of Grade 25 sustainable ternary blended concrete incorporating rice husk ash (10%) and corn cob ash (5%) as partial cement replacements, relative to a conventional control mix. Based on the laboratory characterization and compressive strength results obtained, the following conclusions are drawn. The cement used in the study conformed to standard requirements, with a soundness of 1.0 mm and fineness of 97.7%, providing a reliable baseline for assessing the effect of SCM substitution. XRF characterization confirmed that RHA possessed a combined $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ content of 81.33%, satisfying the ASTM C618 and NIS 444-1:2003 minimum pozzolanic threshold of 70%, while CCA recorded 64.85%, marginally below the individual threshold but still capable of contributing complementary filler and residual pozzolanic action within a ternary system.

The ternary blended concrete outperformed the control concrete in compressive strength at every curing age investigated, recording percentage strength gains of 15.4%, 46.3%, 41.1% and 29.3% at 7, 28, 56 and 90 days, respectively, with the most pronounced improvement occurring at 28 days. The 90-day strength of the ternary blend (41.5 N/mm²) substantially exceeded both the Grade 25 design target and the corresponding control strength, confirming that a 15% combined cement replacement using RHA and CCA in a 10:5 ratio is not only technically feasible but mechanically advantageous. These outcomes are consistent with a mechanism in which RHA supplies the principal reactive silica source for pozzolanic C-S-H formation, while CCA contributes complementary micro-filler action and secondary reactivity, together producing a denser and mechanically superior cementitious matrix relative to plain PLC concrete.

The study demonstrates that RHA-CCA ternary blended concrete represents a technically sound and environmentally beneficial alternative to conventional concrete for structural applications requiring Grade 25 strength, offering a pathway to reduce clinker demand, valorize agricultural residues, and lower the overall carbon footprint of concrete production, particularly in agrarian economies where rice

husk and corn cob are abundantly and consistently available as by-products of existing agricultural value chains.

5. RECOMMENDATION

Based on the findings of this study, it is recommended that a combined cement replacement of 10% RHA and 5% CCA be considered for the production of Grade 25 structural concrete where enhanced compressive strength and sustainability objectives are desired, subject to confirmation through site-specific trial mixes and quality control testing of locally sourced ashes, since the chemical composition of agro-waste ashes can vary with combustion temperature, source material, and processing method.

Further research is recommended to investigate the durability properties of the RHA-CCA ternary blend, including water absorption, sorptivity, rapid chloride penetration, and resistance to sulfate and acid attack, to comprehensively establish its long-term performance in aggressive service environments. Given the demonstrated relevance of elevated-temperature performance for RHA-blended systems reported in recent literature, dedicated experimental investigation of the residual mechanical properties of the RHA-CCA ternary blend after exposure to elevated temperatures is also recommended, to establish its suitability for structural elements with fire-resistance requirements. Additionally, microstructural investigation using scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), X-ray diffraction (XRD) and thermogravimetric analysis (TGA-DSC) is recommended to directly characterize the C-S-H and C-A-S-H reaction products responsible for the observed strength enhancement, thereby providing mechanistic confirmation of the trends established through mechanical testing in this study. Finally, optimization studies varying the individual and combined replacement ratios of RHA and CCA beyond the 10:5 combination examined here are recommended to identify the threshold beyond which further replacement begins to compromise workability or strength, thereby establishing the optimal ternary blend ratio for practical field application.

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