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Mechanical Performance Assessment of High-Strength Concrete Incorporating Cassava Peel Ash as A Partial Cement Replacement

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Abstract

The high cost and environmental impact of cement production necessitate sustainable alternatives. This study investigates cassava peel ash (CPA) as a partial cement replacement to enhance concrete performance.Concrete properties were evaluated through chemical characterization of CPA, particle size distribution and mechanical strength of aggregates, workability assessment via slump and compaction tests, and mechanical performance evaluation using compressive and splitting tensile strength tests, complemented by regression analysis. XRF analysis revealed CPA contained 59.50% SiO_2, 8.00% Al_2O_3, and 2.50% Fe_2O_3. Coarse aggregates passed standard sieve sizes; ACV ranged 23.30–23.80% and AIV 21.35–21.42%. Slump values decreased from 75 mm (control) to 35 mm (15% CPA); compaction factors ranged 0.95–0.87. Compressive strengths for 3–42 days varied from 23.05–27.36 N/mm² (control) and 10.62–25.48 N/mm² (CPA mixes). Splitting tensile strength ranged 2.85–3.86 N/mm² (control) and 2.19–4.24 N/mm² (CPA mixes). Regression analysis indicated strong correlation (R^2 = 0.981–1.000) between CPA replacement and strength development. CPA can replace up to 10% cement without significantly affecting concrete performance; higher levels reduce mechanical integrity.

Keywords: Cassava peel ash, concrete, compressive strength, tensile strength.

Introduction

Cement is an indispensable material in the production of concrete, serving as the backbone of modern infrastructure development. Nevertheless, its production process is among the largest contributors to global carbon dioxide (CO_2) emissions, accounting for approximately 8–10% of total greenhouse gas outputs (Poudyal and Adhikari, 2021). With global cement demand projected to rise beyond four billion tonnes by 2040 (McDonald et al., 2019), the industry faces a critical sustainability challenge. The rising consumption of cement not only accelerates the depletion of limestone reserves, its primary raw material, but also heightens environmental degradation, energy consumption, and associated socio-economic risks (Naik, 2008). Consequently, research has increasingly turned toward sustainable alternatives such as supplementary cementitious materials (SCMs), carbon capture technologies, and nanotechnology, which collectively aim to reduce the carbon footprint of construction (Habert et al., 2020).

Furthermore, cement production is an energy-intensive process requiring up to six million BTU to manufacture a single ton, underscoring the urgent need for greener alternatives (Tafazzoli, 2017). Recent studies have shown that incorporating sustainable practices into construction can lower emissions by as much as 25%, thereby supporting global climate goals (Olsson et al., 2025). The integration of SCMs has emerged as one of the most efficient strategies to achieve this objective, with materials such as limestone powder, fly ash, and blast furnace slag already demonstrating significant success in reducing clinker dependency (Habert et al., 2020).

In this context, cassava peel ash (CPA) has attracted increasing attention as a potential cement replacement in concrete. Cassava, a staple food crop, is widely cultivated in sub-Saharan Africa and Southeast Asia, producing vast amounts of waste. Global cassava production reached nearly 296 million tonnes in 2020, with 20–35% generated as peels during processing (Awolusi et al., 2024). When indiscriminately disposed of, these peels contribute to environmental pollution, land degradation, and greenhouse gas emissions from uncontrolled decomposition (Moses et al., 2021). Studies have demonstrated that calcining cassava peels at approximately 700 °C for 90 minutes yields a highly pozzolanic material containing over 70% of combined silica, alumina, and ferric oxides (Raheem et al., 2020).

Thus, the use of cassava peel ash not only addresses environmental concerns associated with improper waste management but also provides an alternative route for reducing the over-reliance on cement. By converting agro-waste into a value-added material, CPA supports circular economy practices while enhancing the sustainability of the construction industry. Moreover, this approach aligns with several United Nations Sustainable Development Goals (SDGs), including responsible consumption and production, sustainable cities, and climate action (Ogunbode et al., 2023). These interlinkages justify the growing academic and industrial interest in assessing the performance of CPA in high-strength concrete production, with particular focus on its mechanical and durability properties.

Concrete, while indispensable for urbanization and economic growth, has been identified as a major contributor to global carbon emissions, with cement production alone responsible for approximately 36% of construction-related CO_2 releases (Habert et al., 2020). This situation underscores the pressing need to explore sustainable SCMs. In Nigeria, the largest cassava-producing country, over 59 million metric tons of cassava are harvested annually, generating massive volumes of peels as waste (Ikuemonisan et al., 2020). These wastes are often disposed of indiscriminately along roadsides, open fields, and water bodies, causing environmental pollution and health risks (Moses et al., 2021). The utilization of cassava peel ash based cement in high-strength concrete production thus represents a strategic intervention to mitigate environmental hazards while reducing the consumption of cement and its associated emissions.

Previous studies have confirmed the potential of cassava peel ash (CPA) as a supplementary cementitious material in concrete production. Optimization approaches using central composite design have demonstrated improved compressive and flexural strengths in conventional concrete mixes (Iro *et al.*, 2024). Similarly, investigations on bamboo-reinforced CPA concrete highlighted moderate strength reductions but improved durability-related properties such as reduced water absorption (Awolusi *et al.*, 2024). More recently, nano-silica modification of CPA has shown significant strength enhancement in high-strength concrete, achieving compressive strengths above 70 MPa at optimized dosages (Babu and Rose, 2025).

Despite these advancements, existing research predominantly addresses normal-strength or moderately enhanced systems, with limited systematic evaluation of nano-modified CPA under high-strength concrete conditions characterized by low water–binder ratios and dense microstructures. Furthermore, comprehensive assessment of mechanical performance, including tensile and flexural behavior alongside microstructural refinement, remains insufficiently explored. Variations in replacement levels and nano-modifier dosages also lack unified performance benchmarks for structural-grade applications. Accordingly, a distinct research gap persists regarding the mechanical reliability and optimization of nano-modified CPA in high-strength concrete systems, thereby justifying the present investigation.

Methodology

The methodology encompasses the chemical characterization of cassava peel ash using X-ray fluorescence, the assessment of fresh properties of CPA-blended high-strength concrete, the evaluation of its mechanical performance through compressive and splitting tensile strength tests across specified curing ages, and the development of regression-fit models to predict the concrete's mechanical response based on curing duration and replacement level.

Cassava Peel Ash Characterization

Fresh cassava peels were collected from local processing centers, sun-dried to reduce moisture content, and stored in airtight bags to prevent contamination before calcination. The dried peels were incinerated in a controlled muffle furnace at 700 ± 20 °C for 90 minutes, ensuring complete combustion while limiting uncontrolled emissions. The resulting ash was cooled and sieved through a 75 µm mesh to obtain a fine, pozzolanic powder suitable for partial cement replacement in concrete.

The chemical composition of the cassava peel ash was determined using X-Ray Fluorescence (XRF) spectroscopy, providing quantitative insight into its oxide constituents. The analysis confirmed the presence of key pozzolanic oxides such as silica (SiO_2), alumina (Al_2O_3), and calcium oxide (CaO), which are critical for cementitious reactions and strength development in concrete. These results indicate that the CPA possesses the necessary chemical characteristics to contribute to the mechanical performance and durability of high-strength concrete when used as a partial cement replacement.

Aggregate Impact Value (AIV) Test

The Aggregate Impact Value test was conducted to determine the resistance of coarse aggregates to sudden impact loading. Aggregates passing the 12.5 mm sieve and retained on the 10 mm sieve were oven-dried at 105–110 °C and filled into a standard cylindrical mould in three layers, each compacted with 25 blows of a tamping rod. The mould was placed under the impact testing machine, and a standard hammer was allowed to fall freely from a height of 380 mm for 15 blows. The crushed material was then sieved through a 2.36 mm sieve, and the percentage of fines produced relative to the original sample mass was calculated as the AIV.

Aggregate Crushing Value (ACV) Test

The Aggregate Crushing Value test was performed to assess the resistance of aggregates to gradual compressive loading. Oven-dried aggregates of standard size were placed in a cylindrical mould in three compacted layers. The mould assembly was positioned in a compression testing machine, and a load of 400 kN was applied uniformly over 10 minutes. After unloading, the crushed sample was sieved through a 2.36 mm sieve, and the ratio of the fines produced to the original sample mass, expressed as a percentage, was recorded as the ACV.

Mix Proportioning and Sample Preparation

Concrete mixes were designed for a target compressive strength of 45 MPa at 28 days, with a water–binder ratio of 0.45. Mix proportions followed a 1:1:2 ratio (cementitious material: fine aggregate: coarse aggregate). Four concrete test samples were prepared containing different CPA as percentage replacement by weight of cement, these are 0, 5, 10 and 15%. The sample with 0% CPA served as the control. Superplasticizer dosage was maintained at 1.22 L/100 kg of binder across all mixes.

Mixing was performed in a tilting drum mixer (250 L capacity, CAG Machinery, China). For each mix, concrete cubes of size 150 × 150 × 150 mm and cylinders of 100 × 200 mm were cast. Moulds were lubricated with oil and filled in three layers, each compacted by 25 blows of a 16 mm diameter tamping rod. Samples were demoulded after 24 hours and cured using two curing methods: water immersion and wet sand curing, at specified ages of 3, 7, 10, 14, 21, 28, 35, and 42 days.

Evaluation of Fresh Concrete Property

Workability was assessed using the slump cone test (BS EN 12350-2, 2019). The apparatus included a slump cone (300 mm height, 200 mm base diameter, 100 mm top diameter, manufactured by Matest, Italy), tamping rod, and steel baseplate. The slump value was determined as the difference between the original cone height and the subsided height of concrete.

Mechanical Strength Assessment Tests

Compressive Strength

Compressive strength tests were conducted using a 2000 kN digital compression testing machine (Controls Group, Italy) according to BS EN 12390-3 (2019). Compressive strength was calculated as using Equation 1:

$$f_c = \frac{P}{A} \qquad (1)$$

Where fc = compressive strength (N/mm²), P = maximum load at failure (N), A = cross-sectional area (mm²).

Splitting Tensile Strength

Cylindrical specimens were tested in accordance with BS EN 12390-6 (2009) using the same compression machine with steel loading strips. Splitting tensile strength was calculated as using Equation 2:

$$f_t = \frac{2P}{\pi LD} \qquad (2)$$

Where ft = splitting tensile strength (N/mm²), P = maximum load at failure (N), L = length of cylinder (mm), D = diameter of cylinder (mm).

Regression Modelling of Performance

Experimental data were statistically analyzed using IBM SPSS Statistics (Version 26, IBM Corp., USA). Regression analysis was employed to establish relationships between compressive and tensile strengths, while residual diagnostics tested the validity of the models.

Results and Discussion

Chemical Properties of Cassava Peel Ash

The chemical composition of cassava peel ash (CPA) provides critical insight into its potential as a supplementary cementitious material. XRF analysis revealed that silicon dioxide (SiO_2) predominates at 59.50%, indicating strong pozzolanic potential. The reactive silica can interact with calcium hydroxide during hydration to form additional calcium silicate hydrate (C–S–H) gel, enhancing both strength and durability in blended concrete. This aligns with findings by Adisa *et al.* (2025), who reported that agro-waste ashes with silica content above 50% exhibit significant pozzolanic activity and contribute to long-term concrete performance. Additionally, aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3) were present at 8.00% and 2.50%, respectively, collectively exceeding 70% of the total oxides alongside silica, meeting ASTM C618 requirements for pozzolanic materials. Their presence supports the formation of cementitious compounds upon hydration, consistent with observations by Kilani *et al.* (2022), who highlighted the role of these oxides in improving early-age strength in blended cements.

Calcium oxide (CaO) accounted for 7.50% of CPA as shown in Table 1 and contributes to the acceleration of the hydration process, providing free lime to balance pozzolanic reactions (Sadoon *et al.*, 2025). Potassium oxide (K_2O) was 10.50%, enhancing solubility and early reactivity, although high alkali content can trigger alkali-silica reactions; controlled proportions mitigate this risk (Obianyo, 2020). Minor oxides such as Na_2O (0.80%), MgO (1.20%), P_2O_5 (2.50%), and SO_3 (1.30%) contribute to chemical stability, with MgO levels within acceptable limits to avoid delayed hydration issues (Olaiya *et al.*, 2025). Trace oxides, including TiO_2, MnO, ZnO, CuO, Cr_2O_3, and SnO_2, though present in minute quantities, enhance microstructural packing and matrix compactness (Onuche, 2021). The loss on ignition (LOI) of 6.00% indicates efficient combustion during calcination, reducing unburnt carbon and volatile matter, thereby ensuring adequate workability and setting of cementitious composites (Adegbemileke *et al.*, 2024). Collectively, the chemical profile confirms that CPA possesses the essential oxides and pozzolanic characteristics suitable for partial cement replacement in high-strength concrete.

Table 1: Chemical Composition of Cassava Peel Ash

S/N	Basic Oxides	Formulae	Percentage Composition (%)
1	Silicon Oxide	SiO_2	59.50
2	Aluminium Oxide	Al_2O_3	8.00
3	Iron Oxide	Fe_2O_3	2.50
4	Calcium Oxide	CaO	7.50
5	Potassium Oxide	K_2O	10.50
6	Sodium Oxide	Na_2O	0.80
7	Magnesium Oxide	MgO	1.20
8	Phosphorus Oxide	P_2O_5	2.50
9	Titanium Oxide	TiO_2	0.05
10	Manganese Oxide	MnO	0.05

11	Zinc Oxide	ZnO	0.02
12	Copper Oxide	CuO	0.01
13	Sulphate (as SO_3)	SO_3	1.30
14	Chromium Oxide	Cr_2O_3	0.02
15	Tin (IV) Oxide	SnO_2	0.01
16	Loss on Ignition	LOI	6.00

Particle Size Distribution of Coarse Aggregates

The particle size distribution (PSD) of coarse aggregates provides essential insight into their grading characteristics, which significantly influence packing density, workability, and mechanical performance of concrete as shown in Figure 1. All aggregate sizes (3/8″, 1/2″, and 3/4″) passed the 37.5 mm sieve, confirming compliance with standard structural concrete requirements and ensuring proper compaction while minimizing segregation. This observation aligns with Rasak *et al.* (2024), who emphasized that well-graded aggregates improve concrete stability and reduce void content. As sieve sizes decrease, differences between aggregate sizes become evident. At the 20 mm sieve, 3/8″ and 1/2″ aggregates achieved 100% passing, whereas 3/4″ aggregates recorded 84.70% passing, indicating a coarser profile for the larger size. Similarly, at 14 mm, 3/8″ aggregates maintained 100% passing, while 1/2″ and 3/4″ aggregates had 82.40% and 26.30% passing, respectively. Finer aggregates provide a larger surface area for bonding with cement paste, enhancing compressive strength as reported by Oparinde *et al.* (2024).

At smaller sieves (10 mm, 5 mm, 2.36 mm), the 3/8″ aggregates contained higher percentages of fines, improving packing density and reducing voids, while larger aggregates contributed minimal fines. Excessive fines, however, can increase water demand and negatively affect workability, a trend similarly observed by Ibrahim *et al.* (2024). Coefficients of uniformity (Cu) of 0.80, 0.72, and 0.75 and curvature (Cc) of 1.00, 0.95, and 0.87 for 3/8″, 1/2″, and 3/4″ aggregates indicate relatively uniform or gap grading. Poorly graded aggregates may reduce matrix packing and increase void ratios, but combining them with well-graded fine aggregates can compensate, achieving a dense particle structure. This agrees with Mkpaidem *et al.* (2022), who noted that well-graded coarse aggregates with higher Cu and Cc values enhanced compressive and flexural strengths compared to uniformly graded aggregates.

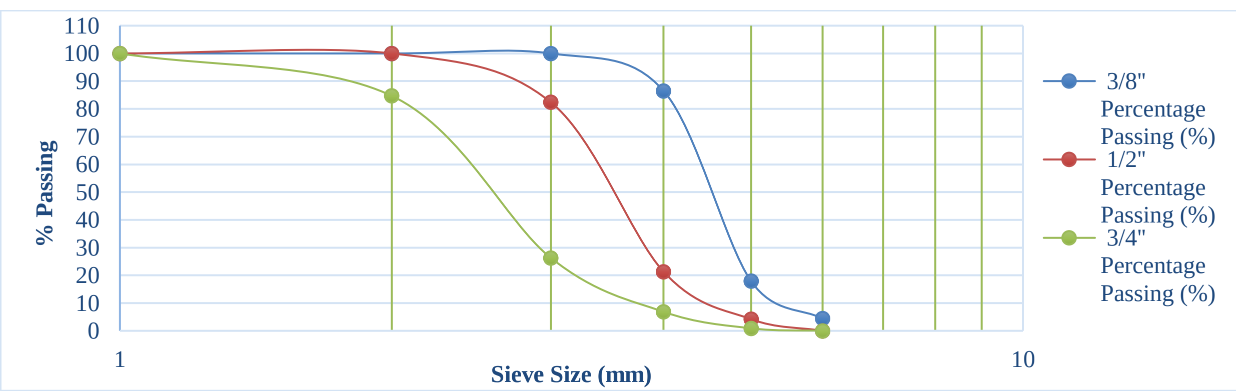

Figure 1: Particle Size Distribution of Coarse of Aggregates.

Strength Properties of Coarse Aggregates

The strength properties of coarse aggregates were evaluated through aggregate crushing value (ACV) and aggregate impact value (AIV), both critical for assessing their suitability in concrete production as presented in Table 2. The average ACV values for 3/8″, 1/2″, and 3/4″ aggregates were 23.80%, 23.73%, and 23.30%, respectively, all well below the Federal Ministry of Works limit of 45%, indicating adequate resistance to crushing under gradually applied loads. Individual ACV results showed minor variations: 21.20–26.50% for 3/8″, 20.40–27.90% for 1/2″, and 18.80–31.10% for 3/4″ aggregates. Even the highest ACV of 31.10% for 3/4″ aggregates remains within acceptable limits, suggesting that coarser aggregates offer slightly higher resistance due to larger contact surfaces and better interlocking, as observed by Sun et al. (2017).

The AIV results further confirmed aggregate suitability, with average values of 21.42% for 3/8″, 21.35% for 1/2″, and 21.35% for 3/4″ aggregates, all below the 45% threshold. Individual AIVs ranged from 19.08–23.85% for 3/8″, 18.36–25.11% for 1/2″, and 20.97–27.99% for 3/4″ aggregates, demonstrating consistent mechanical performance across all sizes. The similar average values indicate uniform toughness and resistance to sudden impacts, making them suitable for high-strength concrete applications, in agreement with Kumar et al. (2024). Both ACV and AIV collectively reflect the mechanical integrity of the aggregates under static and dynamic loading. The consistently low values suggest that these aggregates meet standard specifications and can reliably enhance concrete durability and performance in structural applications, supporting the observations of Anjoorin and Adegbola (2024) regarding long-term resistance to degradation under combined loading effects.

Table 2: Strength Properties of Coarse Aggregates.

Strength Properties	3/8"		1/2"		3/4"		Specified Limit (≤ 45%, FMW 1997)
ACV	23.80	23.73	23.30	23.78	18.80	26.93	Satisfactory
	26.50		27.90		31.10		
	23.40		23.50		28.90		
	21.20		20.40		28.90		
AIV	21.42	21.35	21.35	21.49	20.97	25.25	Satisfactory
	23.85		25.11		27.99		
	21.06		21.15		26.01		
	19.08		18.36		26.01		

Slump Test

The slump test results indicate a clear influence of cassava peel ash (CPA) replacement on the workability of fresh concrete. The control mix, with no ash, recorded the highest slump of 75 mm, reflecting good fluidity and ease of placement. This demonstrates that the absence of supplementary cementitious material preserves the dominance of cement paste in binding aggregates, consistent with Fapohunda *et al.* (2021), who reported higher slump values in conventional mixes without agro-waste additives.

Moreover, introducing 5% CPA reduced the slump to 65 mm, indicating a slight decrease in workability. The reduction is attributed to the angular and porous nature of ash particles, which increases internal friction and water demand within the mix. Despite this decline, the mix remains workable and suitable for normal placement, aligning with Olaiya *et al.* (2025), who observed that low levels of agro-waste ash moderately reduce slump without compromising handling properties. At 10% replacement, the slump further decreased to 50 mm, showing a more pronounced loss in workability. This drop reflects increased paste viscosity due to the higher volume and surface area of ash, which absorbs water and reduces free water for lubrication, a trend noted by Emah *et al.* (2025).

Furthermore, at 15% replacement, slump declined sharply to 35 mm as shown in Figure 2, producing a stiff mix with limited workability. Such low slump may hinder compaction, increase the risk of honeycombing, and potentially affect hardened concrete performance if not addressed. The results suggest that higher ash contents disrupt the balance of cementitious paste and exacerbate internal resistance to flow. This observation supports Olaiya *et al.* (2025), who highlighted that while low CPA replacements enhance sustainability without severely affecting workability, higher replacement levels significantly increase water demand and reduce dispersion of ash, adversely impacting fresh concrete performance.

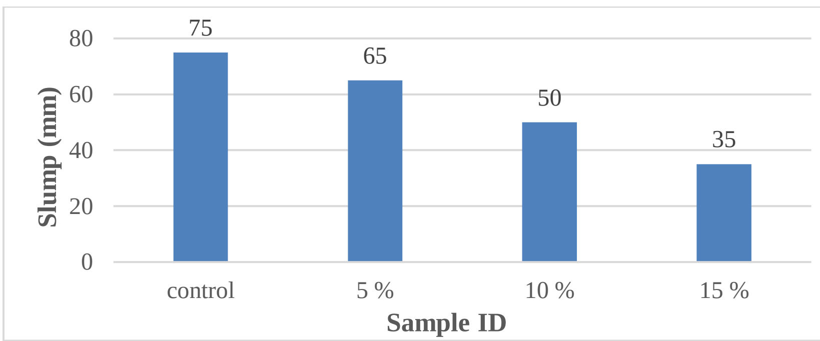

Figure 2: Slump Values of Concrete with Varying Levels of Cassava Peel Ash Replacement.

Compaction Test

The compaction factor results illustrate the influence of cassava peel ash (CPA) replacement on the workability and densification of fresh concrete. Initially, the control mix recorded the highest compaction factor of 0.95, reflecting excellent workability and ease of compaction under minimal effort. This performance is attributed to sufficient cement paste, which provides lubrication for aggregate movement and ensures dense placement. This observation is consistent with Fode *et al.* (2023), who reported that mixes without supplementary cementitious materials typically exhibit higher compaction factors due to enhanced cohesiveness and reduced internal resistance.

Subsequently, at 5% CPA replacement, the compaction factor slightly decreased to 0.93 as illustrated in Figure 3. Although the reduction is marginal, it indicates that the inclusion of ash begins to alter rheological properties, as the porous and angular ash particles increase inter-particle friction. Nevertheless, the mix still maintains satisfactory workability, supporting the findings of Ofuyatan *et al.* (2021), who emphasized that low ash content produces only moderate changes in workability while retaining acceptable compaction performance. Furthermore, increasing the CPA content to 10% caused the compaction factor to decline more significantly to 0.90, demonstrating a stronger effect on fresh concrete. At this stage, the higher volume and increased surface area of ash absorb additional water, thereby reducing effective lubrication and disrupting particle packing, a trend similarly reported by Adedokun *et al.* (2024).

Finally, at 15% replacement, the compaction factor dropped sharply to 0.87, indicating a stiff mix with poor workability. Consequently, inadequate consolidation and air void entrapment may occur, potentially weakening hardened concrete. This pronounced decline highlights that excessive CPA replacement compromises fresh concrete properties, which aligns with Solaja *et al.* (2025), who noted that high ash content negatively affects densification and structural performance.

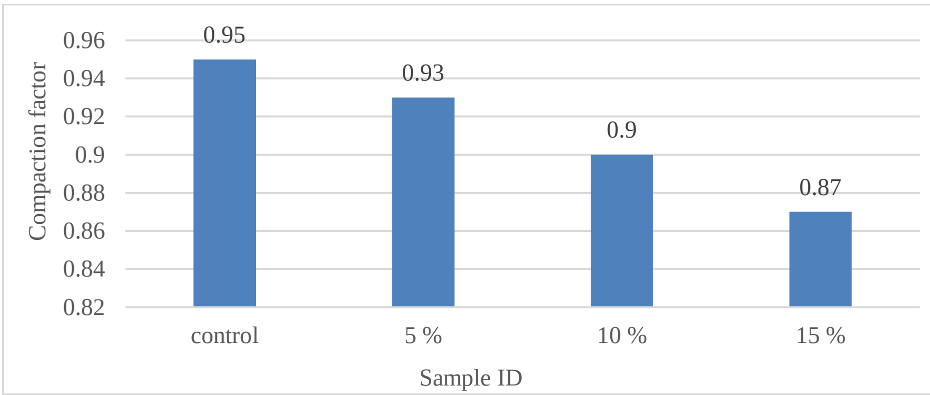

Figure 3: Compaction Factors of Concrete with Varying Levels of Cassava Peel Ash Replacement.

Compressive Strength

The compressive strength results illustrate the effect of cassava peel ash (CPA) replacement on concrete performance under soaked and wet sand curing conditions as shown in Figure 4. Initially, the control mixes exhibited consistently higher strengths compared to ash-blended mixes across all curing ages. At 3 days, the soaked control achieved 23.05 N/mm², while the wet sand control recorded 20.58 N/mm². However, as curing progressed, the wet sand control surpassed the soaked mix, attaining 27.36 N/mm² at 21 days compared to 25.94 N/mm² for the soaked control, highlighting the beneficial role of sustained moisture in promoting hydration and strength gain, as similarly noted by Miah *et al.* (2023).

For 5% CPA replacement, compressive strengths remained close to the control, though slightly lower. At 7 days, soaked and wet sand mixes achieved 21.00 N/mm² and 18.07 N/mm² respectively, but by 28 and 35 days, strengths reached 25.48 N/mm² and 25.47 N/mm², approaching control values. This indicates that low ash content permits adequate hydration and strength development, aligning with Omoniyi (2023), who observed that limited agro-waste ash substitution complements cement hydration effectively.

Increasing CPA to 10% caused a more pronounced decline, particularly at early ages. At 3 days, soaked and wet mixes recorded 18.19 N/mm² and 14.56 N/mm², respectively, rising to 25.43 N/mm² and 22.30 N/mm² at 42 days. The reduction is attributed to dilution of the cement binder and higher water demand from porous ash, a trend reported by Onyenokporo (2022). At 15% replacement, strengths were lowest throughout, with 3-day values of 10.62 N/mm² (soaked) and 11.17 N/mm² (wet) and 42-day values of 16.47 N/mm² and 18.13 N/mm², respectively. These results indicate that excessive CPA substitution compromises structural integrity, consistent with Assumptor *et al.* (2024), who emphasized that while moderate ash replacement may enhance strength via pozzolanic reactions, higher levels detrimentally affect mechanical performance. Overall, the findings underscore the critical need to optimize CPA replacement for sustainable yet structurally sound concrete.

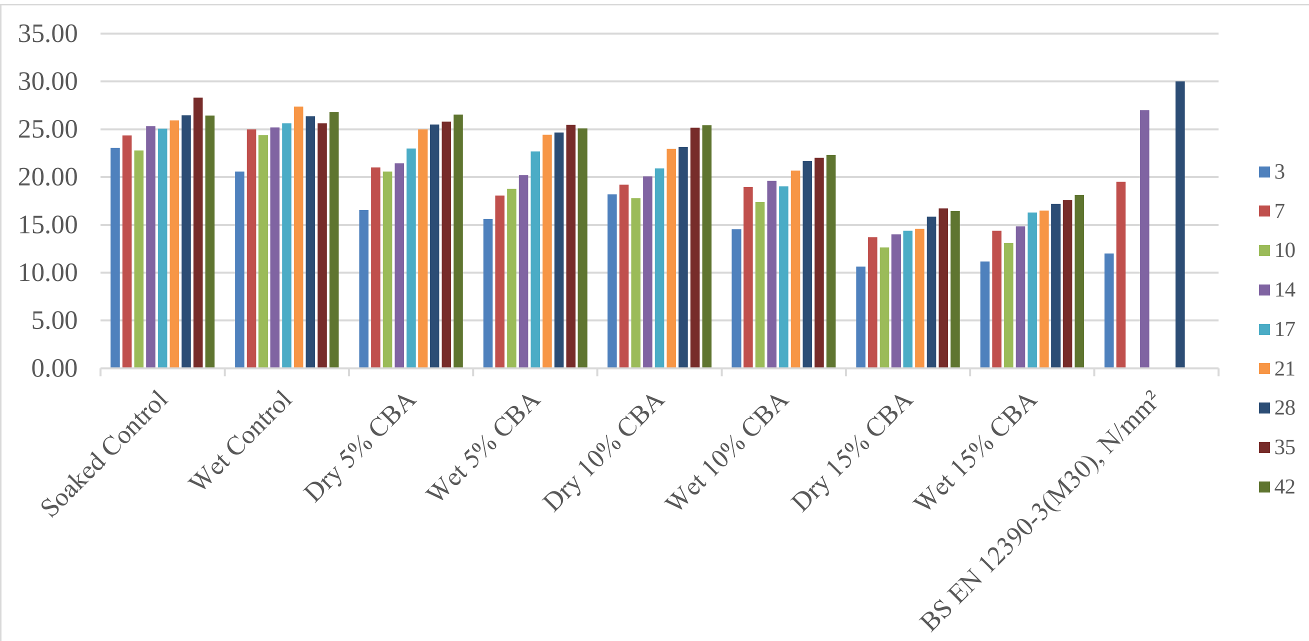

Figure 4: Compressive Strength of CBA Concrete.

Splitting Tensile Strength

The splitting tensile strength results reveal the effect of cassava peel ash (CPA) replacement on the tensile performance of concrete under soaked and wet sand curing conditions. Initially, the control mixes demonstrated moderate tensile strengths, with the soaked control reaching 3.86 N/mm² and the wet sand control 2.85 N/mm² at 28 days. These values satisfy the minimum tensile requirements for M30 concrete, indicating adequate matrix cohesion. The slightly lower tensile strength under wet sand curing may be due to differences in hydration kinetics and stress distribution, a phenomenon similarly noted by Orogbade *et al.* (2024).

For 5% CPA replacement, tensile strengths improved relative to the control. At 3 days, soaked and wet sand mixes recorded 2.73 N/mm² and 3.05 N/mm², respectively, while peak values at 14 days reached 4.00 N/mm² (soaked) and 4.24 N/mm² (wet), surpassing the control. This enhancement is attributed to secondary pozzolanic reactions, which generate additional calcium silicate hydrate (C–S–H) and densify the interfacial transition zone, thereby improving matrix cohesion, as reported by Odeyemi *et al.* (2025).

At 10% replacement, tensile strengths declined, with early-age values of 1.91 N/mm² (soaked) and 2.67 N/mm² (wet), rising modestly to 2.39 N/mm² by 28 days. The reduction results from dilution of cementitious material and increased water demand due to the porous nature of CPA. Similarly, 15% replacement recorded the lowest strengths, with 28-day values of 2.72 N/mm² (soaked) and 2.65 N/mm² (wet), reflecting slower development and compromised matrix cohesion as shown in Figure 5. These trends indicate that higher CPA levels adversely affect tensile integrity by limiting the formation of sufficient C–S–H bonds, consistent with findings by Iro *et al.* (2025).

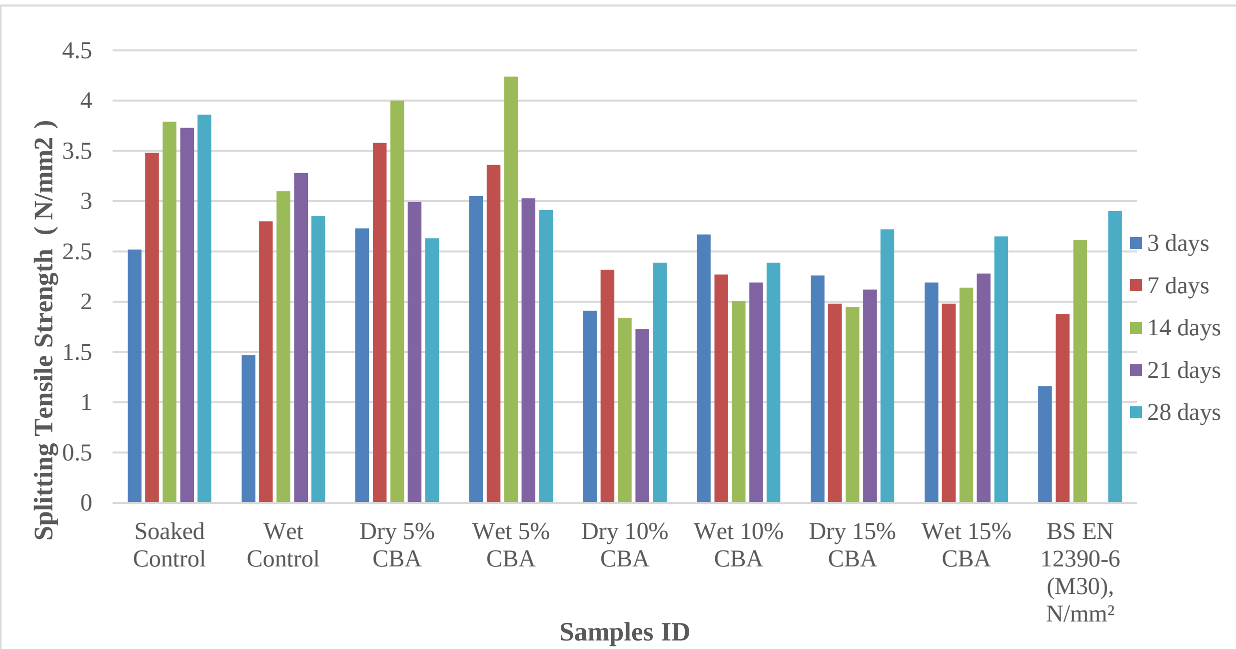

Figure 5: Splitting Tensile Strength of CBA Concrete

Statistical Analysis

The regression analysis provides a quantitative assessment of the influence of cassava peel ash (CPA) replacement on the development of both compressive and splitting tensile strength over time. For compressive strength, the model summary demonstrates a strong correlation between predictors and observed strength, with an R value of 0.991 and an R^2 of 0.981, indicating that 98.1% of the variability in compressive strength is accounted for by the model (Figure 6a). The adjusted R^2 of 0.962 and low standard error of estimate (2.544) confirm the model's reliability in predicting age-dependent strength development, consistent with the findings of Oyesanya and Onyia (2025). ANOVA results further validate the model's significance ($F = 52.139$, $p = 0.001$), highlighting that varying CPA levels exert a statistically significant influence on compressive performance.

Analysis of regression coefficients indicates nuanced effects of individual mixes. The control mix shows a negative coefficient of -8.956 ($p = 0.017$), suggesting an inverse contribution when considered alongside CPA replacements. The 5% CPA mix exhibits a positive but non-significant coefficient (2.212, $p = 0.156$), while the 10% replacement shows a statistically significant positive effect (5.959, $p = 0.023$), demonstrating enhanced strength. The 15% replacement, however, has a limited effect (2.018, $p = 0.478$), reflecting diminished contribution at higher levels. Despite multicollinearity concerns among predictors (VIF up to 36.226), residual analysis shows minimal deviation from predicted values (-2.359 to 2.485, SD = 1.799; Figure 7a), confirming the robustness of the model.

Similarly, regression analysis for splitting tensile strength indicates an exceptionally strong correlation, with $R = 1.000$ and $R^2 = 1.000$, suggesting near-complete explanation of variability by the model (Figure 6b). The adjusted R^2 of 0.998 and low standard error (0.599) demonstrate excellent predictive accuracy, consistent with Akeke *et al.* (2023). ANOVA results ($F = 722.403$, $p = 0.028$) confirm statistical significance, demonstrating the combined influence of control and CPA replacements on tensile behavior. Regression coefficients reveal differential effects: the control mix contributes positively (10.258, $p = 0.039$), while 5% CPA exhibits a minor negative effect (-2.048, $p = 0.232$).

The 10% replacement further reduces tensile strength (-9.421, $p = 0.116$), likely due to matrix dilution, whereas the 15% replacement shows a strong positive impact (26.579, $p = 0.035$), indicating enhanced tensile performance through secondary pozzolanic reactions and improved microstructural densification (Daramola *et al.*, 2023). Residuals remain low (-0.481 to 0.312, SD = 0.268; Figure 7b), confirming model accuracy despite moderate multicollinearity (VIF up to 10.399).

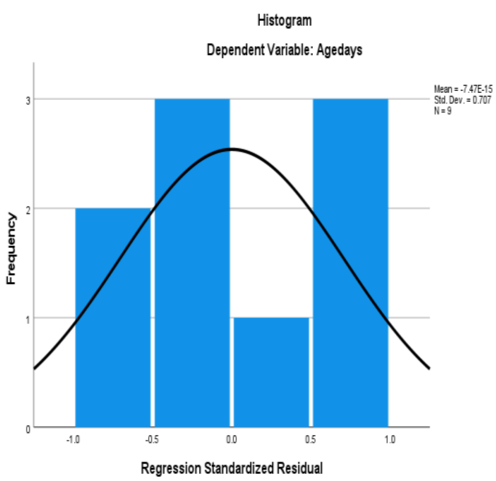

Figure 6a: Histogram of Regression Standardized Residual for Compressive Strength

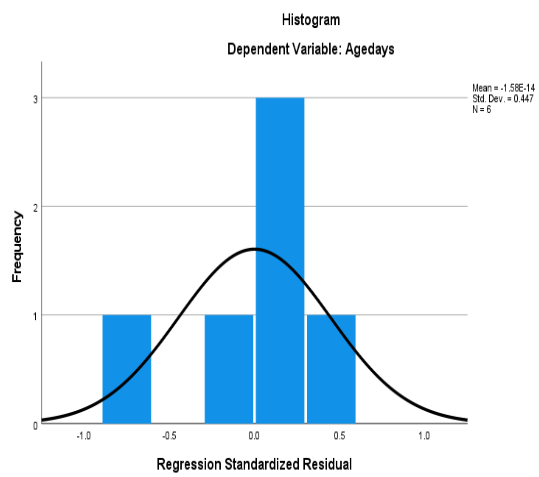

Figure 6b: Histogram of Regression Standardized Residual for Splitting Tensile Strength

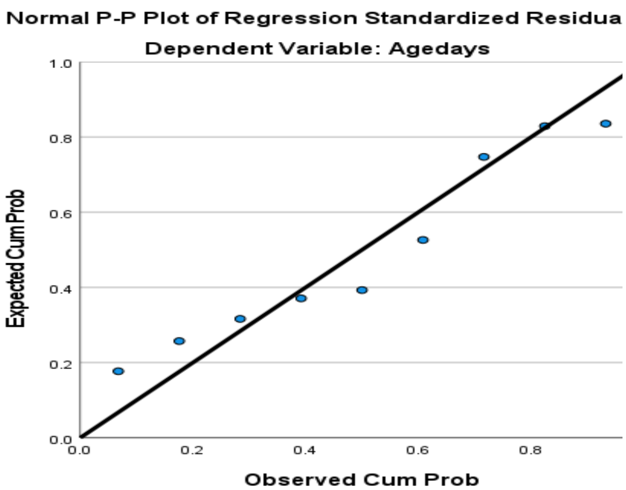

Figure 7a: Normal P–P Plot of Regression Standardized Residual for Compressive Strength

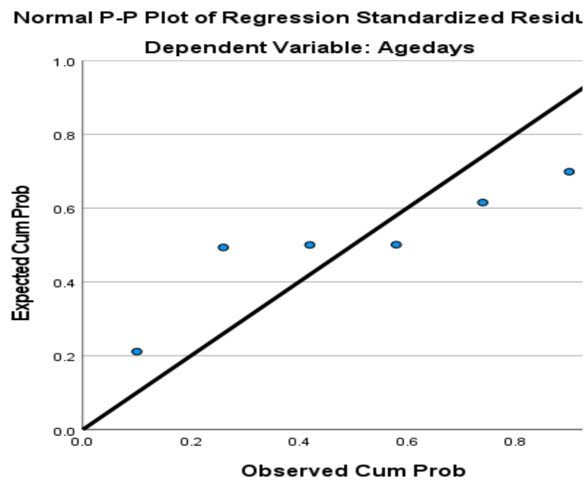

Figure 7b: Normal P–P Plot of Regression Standardized Residual for Splitting Tensile Strength

Conclusions

Cassava peel ash (CPA) demonstrates significant pozzolanic potential, with high SiO_2 and combined $Al_2O_3 + Fe_2O_3$ content meeting ASTM C618 requirements. Coarse aggregates exhibited satisfactory grading and mechanical strength. Increasing CPA replacement reduced workability and compaction, yet compressive and splitting tensile strengths under soaked and wet sand curing remained comparable to control mixes at 5–10% replacement, attributed to secondary pozzolanic reactions. Excessive replacement (15%) adversely affected fresh and hardened properties. Thus, CPA can sustainably replace up to 10% of cement in concrete without compromising structural performance.

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