

Mechanical performance evaluation of cassava peel ash as a sustainable cementitious material

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Abstract

The carbon footprint of Portland cement necessitates exploring Cassava Peel Ash (CPA) as a sustainable alternative. Cassava peel was calcined into ash to partially replace cement at mix proportions of CPA0, CPA5, CPA10, CPA15, to CPA20. Specimens were investigated for Abrams slump and mechanical performance at curing ages of 7, 14, 21, 28, and 56 days. The oxides of SiO₂, Al₂O₃, and Fe₂O₃, amounting to 73.38% of CPA, indicate a good pozzolanic material. The CPA10 maintained 48 mm slump at the S1/S2 classification threshold. The compressive strength increased with curing age across the mixtures, with CPA-modified concrete exhibiting continued strength development beyond 28 days. At 28 days, CPA5 and CPA10 achieved 20.93 MPa and 19.96 MPa, corresponding to 96.45% and 91.98% of the 21.70 MPa control strength, respectively. At 56 days, the strengths increased to 22.90 MPa and 22.10 MPa for CPA5 and CPA10, respectively, exceeding the control strength by 5.53% and 1.84%. The tensile strength activity index remains above 75% up to CPA20. The optimization revealed that CPA5 and CPA10 achieve a balance between mechanical strengths and fresh concrete properties.

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1. Introduction

Concrete is the most popular construction material in the world because it is versatile, durable and comparatively cheap to produce [1, 2]. Portland cement is the primary binder in concrete and when mixed with water, it triggers the hydration and hardening of concrete [3]. Cement manufacturing has significant environmental consequences [4, 5]. Cement production is energy-intensive and a driver of global greenhouse gas emissions [6]. About 0.8-0.9 tons of carbon dioxide are released in one ton of cement production, which almost equals 7-8% of all the global CO₂ emissions [7]. These are emissions that are primarily caused by the calcination of limestone and burning of fossil fuels necessary to maintain kiln temperatures in excess of 1400 °C [8]. With the constant growth in demand for cement-based infrastructure across the globe, one of the most important concerns of sustainability in construction has been to lower the environmental impact of this material [9]. Incorporating supplementary cementitious materials (SCMs) is a primary strategy for reducing clinker content, thereby mitigating the substantial carbon footprint and energy intensity of concrete production [10]. The SCMs consist of either pozzolanic or latent hydraulic materials that enhance both sustainability and durability [11]. The reaction of finely divided SCMs with calcium hydroxide released during cement hydration produces more calcium silicate hydrate (C-S-H) gel [12], thus strengthening the microstructure and mechanical qualities of concrete [13, 14]. However, the long-term viability of non-renewable energy is declining due to the global transition toward renewable energy sources [15]. Driven by these shortages, current research is pivoting toward indigenous resources as sustainable, low-carbon alternatives to traditional binders [16].

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The utilization of agricultural by-products as potential SCMs has received growing scholarly attention, driven by the need for sustainable alternatives in concrete production [17]. Agricultural residues such as rice husk ash, palm oil fuel ash, sugarcane bagasse ash, corn cob ash, and bamboo leaf ash have been widely investigated for their pozzolanic properties and potential applications in cement-based composites [17-20]. Agro-based SCMs in the manufacture of concrete have many benefits from a sustainability perspective [21, 22]: lesser environmental impacts through reduced levels of pollution, Improved waste management methods, Conservation of natural resources, and an overall decrease in the costs of construction materials [23-26]. Among the various agricultural wastes available in tropical regions, cassava peel waste represents a particularly promising resource [27-29]. Cassava (*Manihot esculenta*) is one of the most widely cultivated food crops particularly in Africa, Asia, and South America [30-33]. Cassava generates high amounts of cassava peels as by-products [34, 35]. These peels are normally treated as waste and in most cases, they are dumped in uncontrolled dumps or disposed of by open burning, which in turn causes pollution to the environment and degradation of the land [36, 37]. The controlled calcination of the peels results in the formation of ash that contains large quantities of amorphous silica that can be used as a pozzolanic agent [38, 39]. This ash is also referred to as Cassava Peel Ash (CPA) which is used together with the calcium hydroxide generated during the hydration of cement to make more cementitious compounds [40, 41]. Several studies have reported the potential of cassava peel ash as a partial substitute of cement in concrete and mortar [40, 42]. Low replacement levels have been observed to preserve acceptable compressive strength with increased replacement levels possibly lowering early age strength because of slower pozzolanic reactions [43, 44]. However, the performance of CPA-modified concrete is largely affected by the factors of calcination temperature, particle fineness, chemical composition, and replacement ratio [45]. The anomalies in the process of producing ash have in most instances led to differences in the material characteristics and it has been hard to come up with standardized procedures for using ash in practical situations [46]. Although more attention is paid to the use of agricultural wastes as the basis of cementitious materials, however, the general research on cassava peel ash cassava peels where sun in structural concrete is scarce. Further studies are required to get to know more about the impact of CPA on fresh and hardened concrete properties and to determine the best replacement rates that can be sustained between mechanical performance and sustainability opportunities [44]. Accordingly, the present study addresses this gap by providing an integrated assessment of cassava peel ash (CPA) as a partial cement replacement in concrete over a replacement range of 0-20% and curing ages of 7-56 days. Unlike studies that primarily examine CPA at selected replacement levels or individual performance indicators, this study evaluates the combined effects of CPA on fresh concrete workability, density, compressive strength development, splitting tensile strength, and pozzolanic activity. The mechanical response is further examined using strength activity indices, regression analysis, analysis of variance, and post-hoc comparison to distinguish systematic effects from experimental variability. A multi-response performance index is also used to assess the practical balance among strength and workability indicators.

2. Materials and Methods

2.1 Materials

The materials used in this research were cement, aggregates, cassava peel ash, and water (Figure 1a_e). CEM II/B-L Portland limestone cement of strength class 42.5 N was used as the primary binder in accordance with BS EN 197-1 [47]. Natural river sand was used as fine aggregate while crushed granite with a nominal maximum size of 19 mm was used as coarse aggregate [48]. Potable tap water complying with the requirements of BS EN 1008 [49] was used for concrete mixing and curing. Cassava peel ash was produced from cassava peels collected for the study. Fresh cassava peels were sun-dried for 14 days until their moisture content was reduced to below 10%. The dried peels were subsequently subjected to open-air burning to remove most organic and carbonaceous components. The resulting ash was calcined in a controlled laboratory muffle furnace at 750 °C for approximately 3 hours. After calcination, the ash was allowed to cool inside the furnace before removal. The cooled ash was ground and sieved, with more than 90% passing through a 75 µm sieve.



(a) Cement



(b) Aggregates



(c) Open burning of Cassava Peel



(d) Controlled muffle-furnace calcination

Fig. 1. Materials and production of cassava peel ash

2.2 Experimental Methods

2.2.1 Properties of Cement and CPA

The experimental methods in figure 2 followed the investigations of properties of cement and CPA (fineness, initial and final setting time, consistency, penetration test), aggregates (particle size distribution, specific gravity, aggregate crushing value, aggregate impact value), composition of cement and CPA, concrete mix design, and properties of fresh and hardened CPA modified concrete. The fineness of the cement and CPA was determined in accordance with BS EN 196-6:2018 [50]. Standard consistency and setting times were determined using the procedures specified in BS EN 196-3:2016 [51] and composition of cement and CPA were determined BS EN 196-2:2025 [52].



Fig. 2. Cement/CPA paste preparation for determination of physical properties



(a) Sieve Analysis



(b) Specific gravity

Fig. 3. Particle size distribution of fine and coarse aggregates

2.2.2 Properties of Aggregates

The particle size distribution (Figure 3a) of both the fine and coarse aggregates in compliance with BS EN 933-1 was determined through sieve analysis [53]. The percentage passing through each

sieve was computed alongside the corresponding coefficient of uniformity (Cu) and coefficient of gradation (Cc). The specific gravity, density, and porosity of the aggregates were evaluated using ASTM C127-07 [54], while in the determination of the aggregate Crushing Value (ACV), the weight of compacted samples was filled into cylinders and carefully moved into the plunger, positioned on the platform of a compression testing machine with a compressive load applied at a uniform rate of 40 kN/min until reaching a total load of 400 kN for 10 minutes. The Aggregate Impact Value (AIV) was examined using compacted aggregates in a steel cup, which were carefully emptied of the impact testing machine. Once secured, the hammer of the machine was allowed to fall freely from a height of 380 ± 5 mm onto the aggregates, with 15 successive blows applied to simulate sufficient impact.

2.2.3 Composition of Cement and Cassava Peel Ash

The chemical wet analysis was employed to examine the elemental oxide composition of cement and CPA. The major oxides (SiO₂, Al₂O₃, Fe₂O₃) were determined by the gravimetric method; CaO, MgO, and other soluble oxides were determined by the titrimetric and or volumetric method. In the analysis, finely ground CPA samples were fused with sodium carbonate (Na₂CO₃) and, decomposed using hydrofluoric acid (HF) and sulfuric acid (H₂SO₄) to dissolve insoluble silicates.

2.3 Mix Design Proportion of Concrete Samples

The concrete mixtures were designed to maintain consistent mixture proportions while varying the level of cement replacement with CPA at 0%, 5%, 10%, 15%, and 20%. The mix design followed BS 8500-2 [55] for normal strength concrete with a targeted designed strength of 20 MPa at 28 days and a water-to-binder ratio of 0.50, as shown in Figure 4a-c. The total binder content was maintained constant across all mix designs, while the cement content was progressively reduced and replaced by an equivalent mass of CPA. The mix proportions used for the five concrete mixtures are presented in Table 1.

Table1. Mix design proportion of concrete (Kg/m³)

Mix ID	Percentage CPA Replacement	Cement	CPA	Aggregates Fine	Coarse	Water
Control (CPA0)	0	394	0.00	680	1170	197
CPA5	5	374.30	19.70	680	1170	197
CPA10	10	354.60	39.40	680	1170	197
CPA15	15	334.90	59.10	680	1170	197
CPA20	20	315.2	78.80	680	1170	197



(a) Batching and mixing



(b) Casting



(c) Curing of specimens

Fig. 4. Preparation of concrete specimens and curing

Three (3) groups of specimens were prepared for each test curing age. For the compressive-strength programmed, five 150 mm cube specimens were prepared for each mixture at each curing age of 7, 14, 21, 28, and 56 days. Five replicate cubes were tested for each mixture at each age, resulting in 25 cubes per mixture and 125 cubes in total for the compressive-strength test. For splitting tensile strength, five 100 × 200 mm cylindrical specimens were prepared for each mixture, giving a total of 25 cylinders, all of which were tested at 28 days. The concrete specimens were prepared using moulds conforming to the applicable requirements for specimen shape and

dimensions specified in BS EN 12390-1 [56] and were cured under controlled laboratory conditions until their respective testing ages.

2.4 Abrams Slump Test (Concrete Consistency)

The workability and consistency of the fresh concrete mixtures were evaluated using the Abrams slump test in accordance with BS EN 12350-2 [57] and shown in Figure 5: a-b. The test was conducted immediately after mixing at an ambient laboratory temperature of 27 °C. The slump cone had a base diameter of 200 mm, a top diameter of 100 mm, and a height of 300 mm. The fresh concrete was placed in three layers, with each layer compacted using 25 strokes of a 16 mm diameter tamping rod. After filling and compacting, the mould was lifted vertically and the resulting subsidence of the concrete was measured as the slump. Three slump measurements were obtained for each concrete batch and the average value was reported.



Fig. 5. Slump test



Fig. 6. Compressive strength test



Fig. 7. Splitting tensile strength test

2.5 Compressive Strength

The compressive strength of the concrete specimens was determined using 150 mm cube specimens in accordance with BS EN 12390-3 [58]. Five replicate cubes were tested for each mixture at 7, 14, 21, 28, and 56 days of curing (Figure 6). The mean compressive strength obtained using Equation 1 was used as the representative value for each mixture and curing age. The inclusion of the five curing ages enabled assessment of both early-age strength development and the subsequent contribution of the pozzolanic reaction associated with CPA.

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

Where: f_c = compressive strength (MPa); P = maximum load (N); A = cross-sectional area.

2.6 Splitting Tensile Strength

The splitting tensile strength of the CPA-modified concrete was determined at 28 days using cylindrical specimens measuring 100 × 200 mm in accordance with the applicable requirements of BS EN 12390-6 [59]. The cylinders were tested for each mixture as shown in (Figure 7) and the reported tensile strength calculated using the equation 2 for each mixture represents the mean value obtained from the five replicate cylinders. Unlike compressive strength, splitting tensile strength was evaluated only at 28 days.

$$f_{ct} = \frac{2P}{\pi DL} \quad (2)$$

Where: f_{ct} = splitting tensile strength (MPa), P = applied load at failure (N), D = specimen diameter (mm), L = specimen length (mm)

2.7 Statistical Analysis for Compressive and Tensile Strengths

The experimental data were analyzed using descriptive and inferential statistical techniques. The five replicate cube specimens were analyzed for each CPA replacement level at each curing age at $\alpha = 0.05$. A two-way analysis of variance (ANOVA) was conducted to evaluate the effects of CPA replacement level and curing age on compressive strength and the interaction between CPA

replacement level and curing age. The null hypotheses assumed that CPA replacement, curing age, and their interaction had no significant effects on compressive strength. Where significant main effects were detected, Tukey's Honestly Significant Difference (HSD) post-hoc test was used for pairwise comparisons while controlling the family-wise error rate. Effect magnitudes were considered alongside p-values to distinguish statistical significance from practical engineering significance. For splitting tensile strength, a one-way ANOVA was conducted using the five replicate cylinders tested at 28 days. Pearson correlation and linear regression were used only to describe associations and trends within the experimental range. Correlation and regression results were not interpreted as evidence of causation. All statistical decisions were made at the 95% confidence level.

2.8 Optimization-Based Analysis: Multi-Response Performance Framework

A multi-response performance framework was employed to identify the CPA replacement level that provided the most favorable overall balance between mechanical performance and fresh-concrete workability. Because the experimental programme involved multiple performance criteria with different units and practical implications, the responses were first converted to dimensionless normalized values relative to the control concrete. Three performance criteria were considered: compressive strength, splitting tensile strength, and slump. The compressive and splitting tensile strengths were treated as strength-performance criteria for which higher values are desirable, while slump was used as an indicator of fresh-concrete workability. The optimization was based on the corresponding experimental measurements at 28 days for mechanical properties and in the fresh state for slump. The normalized responses were combined using a Weighted Performance Index (WPI) in equation 3.

$$WPI = 0.5 \frac{f_c}{f_{c0}} + 0.3 \frac{f_t}{f_{t0}} + 0.2 \frac{S}{S_0} \quad (3)$$

where f_c = compressive strength, f_t = tensile strength, and S = slump, respectively. While f_{c0} , f_{t0} , and S_0 correspond to control mix values. The weighting coefficients (0.5, 0.3, 0.2) adopted resulted in a weighting of unity and therefore specified as an engineering decision criterion rather than estimated statistically from the experimental data. The resulting index was used to rank the investigated CPA mixtures according to their combined mechanical and workability performance. Because the WPI depends on the selected criteria, reference values and weighting factors, the resulting ranking is interpreted as a decision-support measure within the experimental conditions rather than as an absolute or statistically unique optimum.

3. Results and Discussion

3.1 Properties of Cement and Cassava Peel Ash

The results of the laboratory tests on the cement and CPA are presented in Table 2. The CPA exhibited a slightly lower residue of 3.5% than cement at 3.9%, corresponding to 10.26% difference. This indicates that the CPA contained a relatively fine particle fraction after grinding and sieving. Although sieve residue alone does not directly quantify specific surface area, the relatively fine particle size of CPA is relevant to its potential reactivity because finer particles generally provide a greater available surface for dissolution and interaction with the alkaline pore solution. The initial setting time of CPA was 61.47 min compared with 66.12 min for cement, while the final setting time decreased from 420 to 385 min. Thus, CPA-containing paste exhibited somewhat faster setting characteristics than the cement paste tested under the same conditions. A similar trend was reported by [60] and [61], who noted that finer ash particles improve early-stage reactions in blended cement systems. CPA had a lower consistency value of 22.9 compared to cement's 26.4, suggesting it may require less water to reach a standard paste thickness. According to BS EN 197_1 [47], the fineness satisfied the requirement of maximum 10% residue on a 90µm sieve. The higher fineness of CPA suggests it may have a high surface area, which typically aids in the reactivity of pozzolanic materials. The cement and CPA met the standard threshold of ≥ 60

minutes for initial setting and stay well within the 600-minute (10-hour) limit for final setting. The faster setting time of CPA would be an advantage for partial replacement of cement. The 8.90% difference in consistency indicated that CPA was just at the lower edge of the requirement range. This suggests that CPA would require slightly less water to achieve a standard paste thickness, which could potentially improve the overall strength of the final concrete mix.

The measured properties demonstrate that the CPA possessed physical characteristics suitable for further investigation as a supplementary cementitious material. However, the cement requirements specified in BS EN 197-1 [47] and Ganesan et al. [62] are not interpreted as direct compliance criteria for CPA because CPA is not a standardized Portland cement constituent under the cement classification considered in this study.

Table 2. Properties of cement and cassava peel ash

Properties	Fineness (%)	Initial Setting Time (min)	Final Setting Time (min)	Consistency
Cement	3.90	66.12	420.00	28.40
Cassava Peel Ash	3.50	61.47	385.00	25.98
Percentage Difference	10.26	7.29	8.33	8.90
BS EN 197-1:2011 Requirement	Max 10% residue (90 μ m sieve)	≥ 60 min (for class 32.5/42.5)	≤ 600 min (10 hrs)	Normal range: 26% – 33%

3.2 Properties of Aggregates

The aggregate characteristics presented in Table 3 provide basis for interpreting the subsequent concrete behavior and in accordance with BS EN 933-1 [53]. The fine aggregate contained 3.63% material passing the 0.075 mm sieve and 26.97% passing the 0.425 mm sieve, indicating a relatively controlled fines content and a particle-size distribution suitable for concrete production. The calculated coefficient of uniformity of 6.45 and coefficient of curvature of 1.32 indicate a broad and continuous particle-size distribution within the adopted classification framework. The specific gravity of the sand was 2.36, while that of granite was 2.75. These values indicate that the aggregates possessed substantially higher particle densities than CPA would be expected to have. Consequently, replacing a portion of the cementitious phase with lower-density CPA contributes to the gradual reduction in concrete density observed with increasing CPA content. The density reduction in Table 5 should therefore not be attributed solely to changes in workability; it is also a consequence of the lower density of the replacement material.

Table 3. Properties of aggregates

Properties	Fine Aggregate (Sand)	Coarse Aggregate (Granite)	Classification Requirement
% Passing 0.075 sieve	3.63	-	$\leq 5\%$ (clean sand)
% Passing 0.425 sieve	26.97	-	15–35% (well-graded sand)
Coefficient of Uniformity (Cu)	6.45	1.78	$Cu \geq 6$ (sand, well-graded); $Cu \geq 4$ (gravel)
Coefficient of Curvature (Cc)	1.32	1.05	$1 \leq Cc \leq 3$
Specific gravity (g)	2.36	2.75	2.3 – 2.9
Bulk Density (kg/m ³)	1411	1527	1200 – 1800
Organic content (%)	4.74	-	$\leq 5\%$ (acceptable)
ACV (%)	-	28.60	$\leq 30\%$ (structural concrete)
AIV (%)	-	16.70	$\leq 20\%$ (strong aggregate)
Classification	Well-graded sand (SW)	Well-graded gravel (GW)	Based on gradation limits

The granite exhibited an ACV of 28.60% and an AIV of 16.70%, indicating adequate resistance to crushing and impact under the adopted test conditions. The relatively robust coarse aggregate skeleton therefore reduces the likelihood that the aggregate itself was the dominant source of the observed changes in compressive strength. The systematic changes in strength with CPA replacement are consequently more reasonably associated with modifications to the cementitious matrix arising from cement dilution, particle packing, water demand, and subsequent pozzolanic activity.

3.3 Composition of Cement and Cassava Peel Ash

Table 4 presents the major oxide composition of the cement and CPA. The cement contains a high CaO content of 65.13%, accompanied by SiO₂ (2.75%), Al₂O₃ (3.23%), and Fe₂O₃ (2.73%), which is consistent with the calcium-rich composition expected of Portland limestone cement. The oxide composition of the cement falls generally within the compositional ranges reported for the cement type considered in BS EN 197-1 [47]. In comparison, CPA is characterized by a high silica content (61.33%), together with Al₂O₃ (7.78%) and Fe₂O₃ (4.27%).

The combined content of SiO₂ + Al₂O₃ + Fe₂O₃ was 73.38%, which exceeds the 70% criterion specified for Class N pozzolans in ASTM C618, while its LOI of 9.38% was below the 10% maximum limit. These results indicate that CPA satisfies the relevant chemical criteria considered in this study.

Table 4. Composition of cement and cassava peel ash

Oxide	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	CaO	Fe ₂ O ₃	SiO ₂ +Al ₂ O ₃ +Fe ₂ O ₃	LOI
Cement (%)	1.02	1.93	3.23	2.75	65.13	2.73	-	3.51
Cassava Peel Ash (%)	3.97	3.49	7.78	61.33	8.45	4.27	73.38	9.38
BS EN 197-1 Requirement for cement	≤ 0.6–1.0	≤ 5	-	-	60–67	0.5–6	-	≤ 10
ASTM C618-2 Requirement for Calcined Natural Pozzolan	-	-	Included in sum	Include d in sum	>18.0	Inclu ded in sum	≥ 70% (Class N pozzolan)	≤ 10

The relatively high silica content of CPA therefore provides a chemical basis for its potential reactivity when incorporated into the cementitious system, while the experimentally determined strength activity results provide further evidence of its performance, which aligned with the findings by Olutoge et al. and Al-Shugaa et al. [63, 64]. The CaO content of CPA was 8.45%. Unlike the calcium-rich cement, this relatively low CaO concentration indicates that CPA should not be regarded as a primary hydraulic cementitious material on the basis of its oxide composition alone. Rather, its potential contribution to the cementitious system is more appropriately associated with its silica-, alumina-, and iron-rich composition and the possibility of secondary pozzolanic reactions with calcium hydroxide released during cement hydration. Consequently, the role of CPA in the present study is interpreted primarily as a supplementary pozzolanic material rather than as a replacement for cement based on independent hydraulic cementing capacity [65]. The LOI of CPA was 9.38%, compared with 3.51% for the cement. The LOI value should not be interpreted as evidence of the absence of carbon. Rather, the relatively elevated LOI may indicate the presence of residual unburnt carbon and/or other volatile constituents remaining after ash production. Such constituents can influence the performance of ash-containing cementitious systems, particularly through their potential effects on water demand and workability. The observed reduction in slump with increasing CPA content is therefore considered alongside the ash's particle characteristics and chemical composition when interpreting its fresh-state behavior.

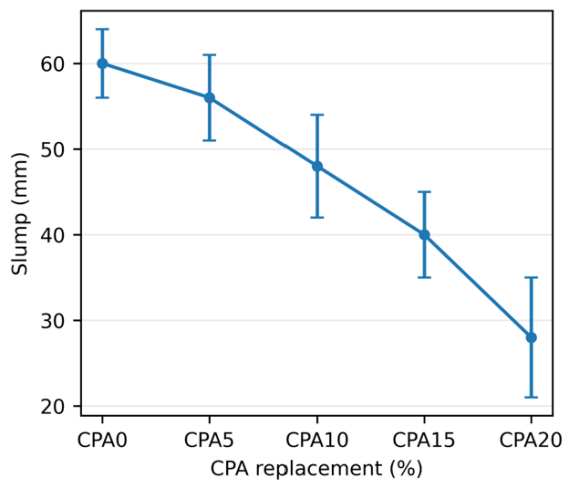
3.4 Abrams Slump (Concrete Consistency) Performance

The progressive reduction in slump from 60 mm for the control to 28 mm for CPA20 in Table 5 and Figure 8 demonstrates a clear relationship between CPA replacement and fresh-state workability. The relative slump loss increased from 6.67% at CPA5 to 53.33% at CPA20. This trend was consistent with the increasing proportion of fine ash particles in the binder system. As CPA replacement increases, the total surface area requiring wetting and lubrication also increases. A greater proportion of the available mixing water is therefore associated with particle surfaces, reducing the amount of free water available to promote flow. In addition, the relatively fine CPA particles can increase interparticle friction and promote particle agglomeration, thereby reducing the mobility of the fresh concrete.

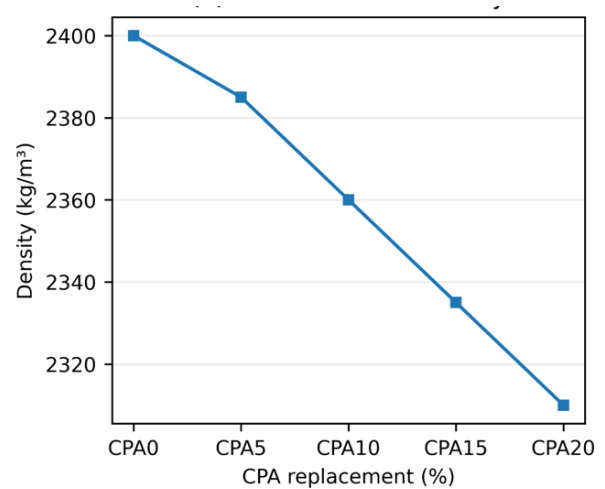
The elevated LOI of CPA may also indicate residual carbonaceous constituents capable of influencing water demand. The observed density reduction provides an additional physical explanation for the fresh-state response. Concrete density decreased progressively from 2400 kg/m³ for the control to 2310 kg/m³ for CPA20. Because CPA replaces cement by mass and has a different particle density from the original cementitious material, increasing CPA content alters the mass-volume relationship of the paste phase. Thus, the decrease in density reflects both the material substitution and the changing fresh mixture characteristics. The practical implication is particularly evident at higher replacement levels. CPA5 retained a slump of 56 mm and remained within the S2 range, whereas CPA15 and CPA20 produced slumps of 40 and 28 mm, respectively. This indicates that increasing CPA replacement beyond moderate levels progressively compromises fresh-state mobility. The workability response therefore becomes an important constraint when determining a practical replacement level, even where later-age mechanical performance remains acceptable.

Table 5. Abrams slump (concrete consistency) characteristics of design mixes

Mix ID	Slump (mm)	Standard Deviation (mm)	Coefficient of Variation (%)	Relative Slump Loss (%)	Density (kg/m ³)	Class (BS EN 12350-2)
Control (CPA0)	60	±4	6.67	0.00	2400	S2 (50–90 mm)
CPA5	56	±5	8.93	6.67	2385	S2 (50–90 mm)
CPA10	48	±6	12.50	20.00	2360	S1/S2 (borderline)
CPA15	40	±5	12.50	33.33	2335	S1 (10–40 mm)
CPA20	28	±7	25.00	53.33	2310	S1



(a) Slump



(b) Density

Fig. 8. Effect of CPA replacement on fresh concrete slump and density

3.5 Compressive Strength

The compressive strength of all concrete mixtures increased progressively with curing age, although the magnitude of strength development varied with CPA replacement level (Figure 9).

The control mixture increased from 14.61 MPa at 7 days to 21.70 MPa at 28 days, then remained at 21.70 MPa at 56 days. In contrast, the CPA-modified mixtures continued to develop appreciable strength beyond 28 days. From 28 to 56 days, the strength of CPA5 increased from 20.93 to 22.90 MPa (9.41%), while CPA10 increased from 19.96 to 22.10 MPa (10.72%). Similarly, CPA15 and CPA20 increased by 11.93% and 13.27%, respectively, over the same period. This continued later-age strength development is consistent with the contribution of secondary pozzolanic reactions associated with the reactive silica-rich CPA. At 28 days, increasing CPA replacement resulted in a progressive reduction in compressive strength relative to the control. CPA5, CPA10, CPA15, and CPA20 recorded 20.93, 19.96, 18.94, and 18.01 MPa, respectively, compared with 21.70 MPa for the control. These correspond to strength activity indices for 28-day strength were 96.45%, 91.98%, 87.28%, and 83.00%, respectively, in Table 6A. The corresponding strength reductions were 3.55%, 8.02%, 12.72%, and 17.00%. Nevertheless, the substantial strength recovery observed between 28 and 56 days, particularly at 5% and 10% CPA, indicates that the initial reduction associated with cement dilution was partly offset by continued hydration and pozzolanic reaction. The coefficient of variation ranged from 4.06% to 7.11%, indicating relatively low variability among the replicate compressive strength measurements. The increasing later-age strength of the CPA mixtures provides further evidence that the silica-rich ash contributed to the development of the cementitious matrix. However, the extent of this contribution depended on the replacement level, with moderate CPA contents providing a more favorable balance between cement reduction and mechanical performance. The two-way ANOVA in table 6B demonstrated that both CPA replacement level and curing age had significant effects on the compressive strength while curing age had a substantially larger effect. However, the CPA and curing age interaction was not significant. Thus, although the descriptive results showed differences in the rate of strength development among the mixtures, the statistical evidence did not establish a significant interaction between CPA content and curing age. The strong effect of curing age is consistent with the progressive development of compressive strength observed across the experimental programmed.

Table 6A. Compressive strength of CPA modified concrete at different curing ages

Mix ID	7 days	14 days	21 days	28 days	56 days	SD	COV (%)	SAI (%)	Strength Reduction (%)
Control (CPA0)	14.61	19.53	20.62	21.70	21.70	0.95	4.06	100	0.00
CPA5	13.08	18.84	19.88	20.93	22.90	1.05	4.59	96.45	3.55
CPA10	12.97	17.96	18.96	19.96	22.10	1.15	5.20	91.98	8.02
CPA15	11.37	17.05	17.99	18.94	21.20	1.30	6.13	87.28	12.72
CPA20	11.71	16.21	17.11	18.01	20.40	1.45	7.11	83.00	17.00

Table 6B. Summary of two-way ANOVA for compressive strength

Source	Sum of Squares (SS)	df	F-value	P-value	Partial Contribution
CPA replacement	150.455	4	32.183	<0.0001	10.62%
Curing age	1129.884	4	241.691	<0.0001	79.75%
CPA x Age	19.584	16	1.047	0.415	1.38%
Error	116.873	100			8.25%

The significant main effect of CPA replacement indicates that the level of cement substitution influenced the overall compressive-strength response. Tukey's HSD analysis showed that the overall difference between the control and CPA20 was statistically significant at $p = 0.0147$, whereas the differences between the control and the lower CPA replacement levels were not statistically significant after adjustment for multiple comparisons. This infers that the overall statistical evidence strongly detects an effect of CPA replacement, but the moderate replacement

levels (CPA5 and CPA10) are not statistically distinguishable from the control when averaged across all curing ages. The 56-day result values numerically exceeded the control at 56 days, while the statistical analysis does not justify describing them as statistically superior. Rather, the results indicate that moderate CPA replacement can achieve comparable, and in some cases numerically higher, later-age compressive strength than the control mixture.

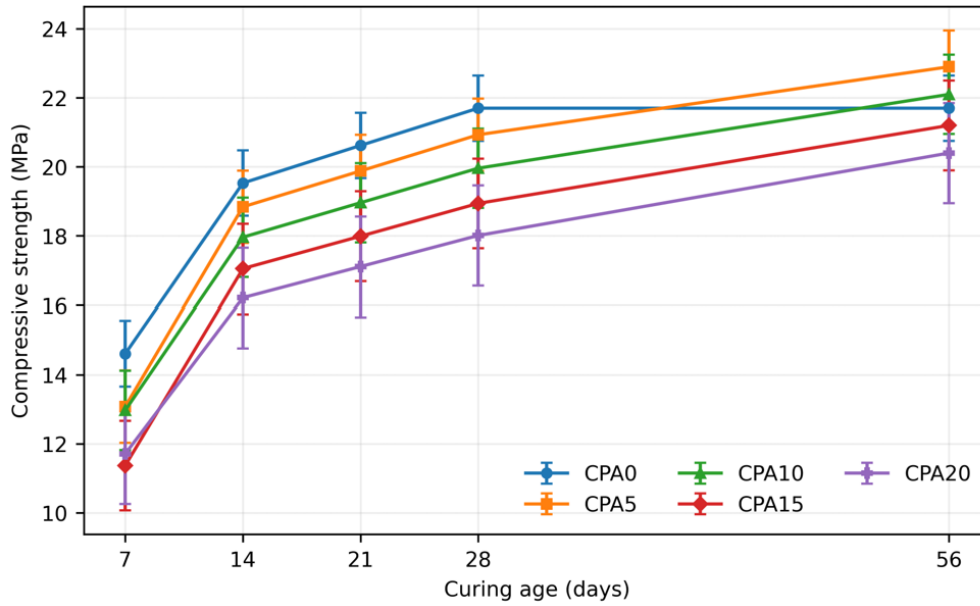


Fig. 9. Compressive strength of concrete samples

3.6 Split Tensile Strength

The 28-day splitting tensile strength in Table 7A decreased progressively with increasing CPA replacement, from 3.20 MPa for the control mixture to 2.50 MPa at 20% CPA. The tensile activity index remains above 75% up to mix ID CPA20, an acceptable performance of CPA as a partial replacement cementitious material. The regression model demonstrates a strong inverse linear relationship ($R^2 = 0.982$), indicating that tensile strength decreases predictably with increasing CPA mixes. The ANOVA in Table 7B further confirmed that CPA replacement had a statistically significant effect on splitting tensile strength, $F(4,20) = 15.48$, $p < 0.0001$, at $\alpha = 0.05$. The relatively small reductions observed at CPA5 and CPA10 indicate that these replacement levels provide a comparatively favorable balance between cement substitution and tensile performance. A linear regression model describing the relationship between CPA replacement (%) and 28-day split tensile strength is expressed in Equation 4.

$$f_t = 3.21 - 0.035(CPA) \quad (4)$$

Where: f_t = Split tensile strength (MPa), CPA = Cassava peel ash replacement (%)

Table 7A. Split tensile strength of CPA-modified concrete

Mix ID	28 Days Tensile Strength (MPa)	Std. Dev. (MPa)	Coefficient of Variation (%)	Strength Activity Index (%)	Strength Reduction (%)
Control (CPA0)	3.20	0.12	3.75	100	0.00
CPA5	3.08	0.14	4.55	96.25	3.75
CPA10	2.90	0.16	5.52	90.63	9.37
CPA15	2.68	0.18	6.72	83.75	16.25
CPA20	2.50	0.20	8.00	78.13	21.88

Table 7B. Summary of ANOVA of one-way ANOVA for 28-day splitting tensile strength

Source of Variation	Sum of Squares (SS)	df	Mean Square (MS)	F-value	P-value
Between Groups	1.6344	4	0.4086	15.4773	<0.0001
Within Groups	0.5280	20	0.0264		
Total	2.1624	24			

3.7 Pozzolanic Activity Index (PAI) of CPA-Modified Concrete

The Pozzolanic Activity Index (PAI) results in Table 8 and Figure 10 indicate that all CPA mixtures exceeded the 75% strength activity threshold at 7 and 28 days, as considered in ASTM C618 [66]. The additional measurements at 14, 21 and 56 days were included to characterize the evolution of strength relative to the control.

Table 8. Pozzolanic activity index (PAI) of CPA-modified concrete

Mix ID	Pozzolanic Activity Index (%)					ASTM Requirement
	7 days	14 days	21 days	28 days	56 days	
Control (CPA0)	100	100.00	100.00	100	100	-
CPA5	89.53	92.00	93.64	96.45	105.53	≥ 75
CPA10	88.78	90.92	90.56	91.98	101.84	≥ 75
CPA15	77.82	81.68	83.54	87.28	97.69	≥ 75
CPA20	80.15	81.06	81.97	82.99	94.01	≥ 75

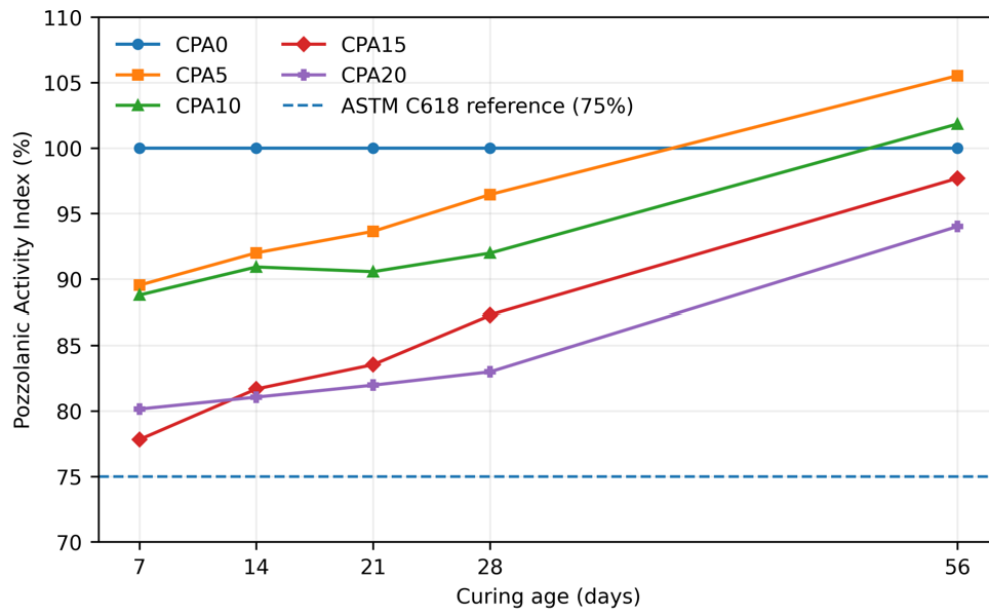


Fig. 10. Pozzolanic activity index of CPA-modified concrete at different curing ages

The lower PAI values of 77.82 to 89.53% at 7 days show the slow initial reactivity of CPA due to delayed pozzolanic action and a steady increase in PAI was observed with curing age. CPA5 and CPA10 perform above 100% at 56 days, indicating long-term strength development compared to the control.

3.8 Optimization of Mechanical Properties

The multi-response performance analysis was used to assess the combined influence of CPA replacement on mechanical performance and workability and the WPI are presented in Table 9. The control mixture provided the reference performance, with a WPI of 1.00. Among the CPA-modified mixtures, CPA5 achieved the highest WPI of 0.95, followed by 0.89 for CPA10. The relatively high WPI values obtained for CPA5 and CPA10 reflect their comparatively favorable balance of compressive strength, splitting tensile strength, and workability. At 28 days, CPA5 and CPA10 retained 96.45% and 91.98% of the control compressive strength, respectively, while their

corresponding splitting tensile strengths retained approximately 96.25% and 90.63% of the control value. Their workability factors were 0.93 and 0.80, respectively. These results indicate that moderate CPA replacement levels provided a more favorable combination of mechanical performance and fresh-state behavior than the higher replacement levels investigated.

The multi-response analysis identifies 5% CPA as the most favorable replacement level among the CPA-modified mixtures under the selected weighting scheme, with 10% CPA representing a second viable option. The optimization therefore supports the use of moderate CPA replacement levels where the objective is to reduce cement consumption while maintaining an acceptable balance between mechanical performance and workability. The WPI ranking should, however, be interpreted within the specific criteria and weighting factors adopted in this study rather than as an absolute optimum independent of design priorities.

Table 9. Optimized performance ranking

Mix ID	Normalized Strength	Normalized Tensile	Workability Factor	WPI	Rank
CPA0	1.00	1.00	1.00	1.00	1
CPA5	0.96	0.96	0.93	0.95	2
CPA10	0.92	0.91	0.80	0.89	3
CPA15	0.87	0.84	0.67	0.82	4
CPA20	0.83	0.78	0.47	0.74	5

3.9 Statistical Analysis

Statistical evaluation of the experimental results included standard deviation (SD), coefficient of variation (COV), strength activity index (SAI), and pozzolanic activity index (PAI). The COV values for compressive strength ranged from 4.06% to 7.11%, indicating good experimental reliability and consistency within acceptable limits (<10%). The Strength Activity Index (SAI) was calculated at 28 and 56 days to assess the effectiveness of CPA as a supplementary cementitious material, while the Pozzolanic Activity Index (PAI) was determined as the ratio of CPA-modified strength to control strength, consistent with ASTM C618. All mixes exceeded the minimum requirement of 75%, confirming adequate pozzolanic performance. Additionally, regression analysis revealed a strong inverse relationship between CPA content and mechanical strength, while ANOVA results ($p < 0.05$) confirmed that CPA replacement significantly influences compressive and tensile strength. The statistical indicators collectively validate the reliability and significance of the experimental findings.

Conclusions

This study evaluated the performance of concrete incorporating cassava peel ash (CPA) as a partial replacement for Portland cement at replacement levels of 0%, 5%, 10%, 15%, and 20%. Based on the experimental findings, the following conclusions were drawn:

- The fine aggregate exhibited a fineness modulus within the range associated with medium-grained aggregates, supporting satisfactory particle packing and concrete workability.
- Chemical analysis showed that CPA contained 61.33% SiO_2 , while the combined $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ content was 73.38%. This exceeded the 70% criterion commonly used for Class N pozzolanic materials in ASTM C618 and indicates pozzolanic potential. However, the chemical composition alone does not establish pozzolanic activity; the subsequent mechanical-performance results provide additional evidence of CPA behavior in the cementitious system.
- The workability of the fresh concrete decreased progressively with increasing CPA content, with the slump reducing from 60 mm for the control mixture to 28 mm at 20% CPA. Nevertheless, mixtures containing up to 10% CPA maintained comparatively favorable workability for practical concrete applications.
- Compressive strength increased with curing age for all mixtures, although the CPA mixtures exhibited more pronounced strength development beyond 28 days. At 28 days, CPA5 and

CPA10 attained 96.45% and 91.98% of the control strength, respectively. By 56 days, however, CPA5 and CPA10 achieved 22.90 and 22.10 MPa, corresponding to 105.53% and 101.84% of the control strength of 21.70 MPa. This later-age strength development indicates that continued hydration and pozzolanic reactions partly compensated for the initial strength reduction associated with cement replacement.

- Splitting tensile strength decreased progressively with increasing CPA replacement at 28 days, from 3.20 MPa for the control to 2.50 MPa at 20% CPA. Nevertheless, the 5% and 10% CPA mixtures retained 96.25% and 90.63% of the control tensile strength, respectively, indicating comparatively limited reductions at moderate replacement levels.
- Statistical analysis demonstrated significant effects of CPA replacement on mechanical performance, while the strong relationships observed between curing age and strength development indicate that the strength contribution of CPA becomes more evident at later ages.

The findings indicate that replacing 5-10% of cement with CPA provides a favorable balance between cement reduction, workability, and mechanical performance. In particular, the 56-day results demonstrate that moderate CPA replacement can achieve or exceed the compressive strength of the control concrete, supporting the potential use of CPA as a supplementary pozzolanic material for more sustainable concrete production.

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